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ХАБАРШЫСЫ

HERALD

OF THE KAZAKH-BRITISH TECHNICAL UNIVERSITY

ВЕСТНИК

КАЗАХСТАНСКО-БРИТАНСКОГО ТЕХНИЧЕСКОГО УНИВЕРСИТЕТА

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[1]*Gulam Dastagir Khan,
Assistant Professor, ORCID ID: 0000-0001-8002-3904,
*e-mail: G.khan1@squ.edu.om
[1]Ahmed Juma Al-Kaabi,
student, e-mail: s124136@student.squ.edu.om
[1]Husam Ahmed Al-Kharusi,
student, e-mail: s124556@student.squ.edu.om
[1]Mohammed Sulaiman Al-Rawahi,
student, e-mail: s123883@student.squ.edu.om

[1]College of Engineering, Sultan Qaboos University (SQU), Muscat, 123, Oman

SMART SENSOR BASED TOUCHLESS FINGERPRINT SYSTEM

Abstract

his paper introduces a touchless fingerprint recognition system, offering a hygienic alternative to conventional touch-based systems. The primary objective is to develop and evaluate a comprehensive solution that addresses hygiene-related concerns and mitigates the risks associated with disease transmission, particularly in the context of the ongoing Covid-19 pandemic. The proposed system utilizes a state-of-the-art touchless sensor to capture intricate fingerprint images, subsequently processing, storing, and retrieving them for matching purposes. By eliminating the need for physical contact, the system effectively tackles issues related to inconsistent pressure and prolonged collection times. The touchless fingerprint technology showcased in this system holds great promise for diverse applications that demand secure and hygienic fingerprint recognition. The proposed method overcomes the limitations inherent in touch-based systems, making it well-suited for environments where health and safety considerations are paramount. The integration of this touchless technology not only enhances security but also contributes significantly to public health by reducing the risk of cross-contamination in shared touchpoints. As the world navigates the challenges posed by the pandemic, the adoption of touchless fingerprint recognition systems represents a crucial step toward creating safer and more hygienic environments.

Key words: Touchless fingerprint technology, Touch-based systems, Hygiene, Disease Transmission, Security, Accuracy.

Introduction

Biometrics, a field that harnesses unique biological or physical attributes to authenticate individuals, encompasses various technologies, such as fingerprint mapping, facial recognition, and

retina scans. Biometrics can be categorized into three primary types: biological, morphological, and behavioral [1].

Among the morphological biometrics, fingerprint recognition stands out as a highly reliable, cost-effective, rapid, secure, and efficient method for authentication. It involves comparing captured fingerprint patterns with stored samples, exploiting the distinct ridges and grooves that characterize individual fingerprints. The minutiae points, which represent specific features like the endpoints of ridges or the locations of scars, play a pivotal role in creating a minutiae template for matching purposes [2]. Fingerprint recognition finds applications in a myriad of domains, including border control, banking, attendance management, elections, identification, law enforcement, and criminal investigation [3].

While fingerprint recognition systems have achieved widespread use, they often rely on touch-based interactions, which introduce certain limitations, such as elastic deformation, extended data collection times, and hygiene concerns. The COVID-19 pandemic has underscored the need for secure and hygienic fingerprint identification systems. To address these shortcomings, a touchless fingerprint identification system has been proposed.

The touchless system seeks to circumvent the drawbacks associated with touch-based systems by employing intelligent sensors capable of capturing fingerprint images without physical contact. This comprehensive system encompasses the entire fingerprint recognition process, from fingerprint acquisition to storage, retrieval, and matching.

The touchless approach offers a multitude of advantages, including enhanced safety, accuracy, speed, and efficiency. By eliminating the need for physical contact, it reduces the risk of disease transmission and ensures a hygienic method of fingerprint recognition. This system holds promise for various applications that demand dependable and secure fingerprint identification.

The development of a touchless fingerprint identification system is instrumental in enhancing both user experience and public health, offering a trustworthy and safe solution for fingerprint recognition across diverse domains.

Literature Review

Touch-based fingerprint recognition has been a subject of extensive research for several decades, initially finding applications in law enforcement and forensics and later expanding into the mobile market and nationwide systems [1-3]. Despite their prevalence, touch-based systems face challenges such as low-contrast signals, latent fingerprints, and distortions caused by finger pressure, along with concerns related to the acquisition process and hygiene [4]. Particularly, the COVID-19 pandemic has accentuated the need for secure and hygienic fingerprint identification systems. To overcome these limitations, touchless fingerprint identification systems have been proposed.

The pioneering touchless fingerprint recognition scheme by Song et al. in 2004 marked the inception of a growing body of research aimed at improving the reliability and user-friendliness of these systems [5]. Contributions by Parziale and Chen [6] and Khalil and Wan [7] distinguished between 2D and 3D acquisition technologies, processing strategies, and quality considerations, with additional insights into presentation attack detection (PAD) schemes. However, existing reviews lack a comprehensive discussion of current approaches. Notably, Malhotra et al. [8], Mil'shtein and Pillai [9], and Labati et al. [10] have explored various facets of touchless fingerprint recognition, providing valuable insights into mobile touchless recognition, comparative reviews, and a comprehensive overview of the entire recognition pipeline.

The touchless system aims to address the drawbacks of touch-based systems by employing intelligent sensors capable of capturing fingerprint images without physical contact. This approach offers advantages such as enhanced safety, accuracy, speed, and efficiency, eliminating the risk of disease transmission and ensuring a hygienic method of fingerprint recognition. Its potential applications span diverse domains, promising a trustworthy and safe solution for fingerprint identification.

The increasing popularity of mobile biometric technology, displacing more expensive scanners, is evident in law enforcement's preference for biometric traits such as fingerprints, face, and iris [11–14]. Leading players like Samsung, TBS, TrueID, and Diamond Fortress are incorporating touchless fingerprint recognition features into their products, advancing the integration of cutting-edge biometric technologies.

Studies [15–23] investigating finger image capture with smartphone cameras and various segmentation techniques have demonstrated progress. For instance, researchers [16] successfully captured finger images using smartphone cameras under uncontrolled conditions, emphasizing different techniques for feature extraction and minutiae analysis. Another study [17] utilized non-conventional scale-invariant texture features (SURF) for matching finger images, evaluating a dataset captured under uncontrolled conditions. However, smartphone-captured touchless finger photo databases face challenges such as preprocessing requirements, increased processing time, storage costs, and vulnerability to cyberattacks [21].

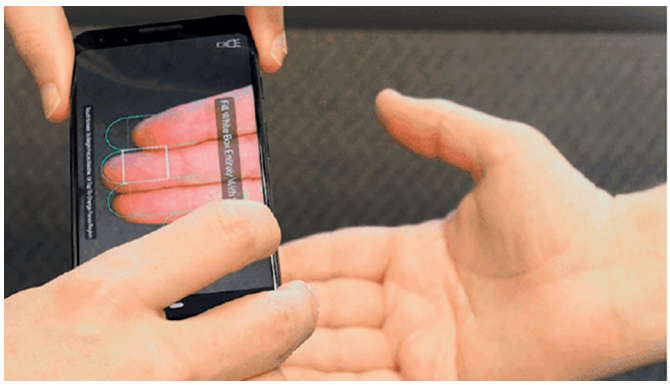

Figure 1 – An illustration of unrestricted fingerprint scanning

In the realm of touchless biometric systems, our research paper presents an innovative touchless fingerprint recognition system that marks a significant advancement in security compared to conventional touchless alternatives. Our approach integrates state-of-the-art touchless sensors, facilitating the capture of intricate fingerprint images. This system ensures rapid processing, efficient storage, and seamless retrieval for matching purposes. Noteworthy is our unique standalone device capturing and storage methodology, setting our approach apart as a secure alternative in contrast to touchless fingerprint recognition systems reliant on smartphones. This distinctive feature enhances the overall security and reliability of our proposed method.

Key Provisions
Materials and Methodology

In the conventional fingerprint recognition paradigm, the process typically involves three sequential stages: image preprocessing, feature extraction, and matching. Image preprocessing techniques enhance fingerprint image quality, while feature extraction identifies unique traits like minutiae points, ridge patterns, and texture. The matching stage compares extracted features with a stored fingerprint database to determine a match [2, 8].

Our proposed touchless fingerprint recognition system comprises three fundamental components: fingerprint scanning, storing, and retrieving. For touchless fingerprint capture, we employ optical devices, which may be modified general-purpose devices or specialized prototype hardware designs. These devices incorporate features such as LED illumination for optimal contrast and reduced external disturbances, with the additional use of colored lights to enhance fingerprint trait visibility.

Figure 2 – Hamster Air – SecuGen's New Contactless USB Fingerprint Reader

In instances where the capture system lacks on-screen guidance or dedicated hardware-based finger guiding, a finger detection algorithm is imperative. This algorithm serves as the foundation for an automatic capture system by detecting the location and direction of the finger. The fingerprint-containing area is then clipped and segmented, utilizing techniques like sharpness, shape, contrast, color, and image depth information [1]. Figure 1 illustrates an unrestricted fingerprint scanning.

Fingerprint recognition poses two main challenges: verification and identification. While verification involves a 1:1 comparison, identification requires a database search and a 1:N comparison, which is the focus of this paper. Identification outcomes include positive matches, false positives, rejections, or false rejections. Achieving accuracy in identification is challenging due to the need for multiple correct verifications and the risk of a single failure leading to a wrong identification.

Our touchless fingerprint system employs a structured methodology for accuracy and reliability. We utilize SecuGen fingerprint readers (Figure 2) known for consistent performance and security across various applications. These readers have a strong reputation backed by industry-leading warranty, extensive field use, and proven reliability in extreme conditions.

The process begins with the sensor detecting the fingerprint upon insertion. Once identified, the system captures its image, utilizing sophisticated image processing techniques to assess clarity and integrity. If the image meets quality standards, the system proceeds to extract unique fingerprint features using advanced algorithms and pattern recognition techniques. If the fingerprint is not registered, the system securely stores the captured image and associated information.

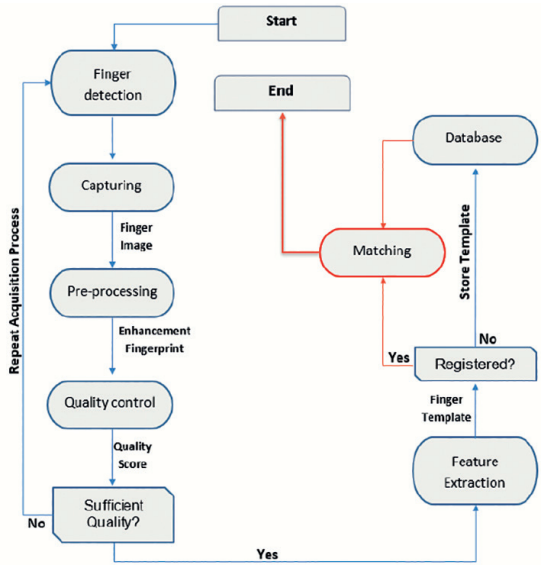

Figure 3 – Flow chart illustrating the methodology
for a smart sensor-based touchless fingerprint system

In cases where the fingerprint is already registered, the system performs a matching process by comparing the extracted features with the registered template, determining similarity or dissimilarity. Throughout the process, strict adherence to quality standards is maintained. If image quality falls below criteria, the system initiates a new attempt, returning to the detection stage for an improved image capture. For a visual representation of the process, refer to Figure 3, displaying a comprehensive flow chart of the touchless fingerprint system's step-by-step execution.

The Proposed System: Sensor-Computer Interface, Desktop Application Design, and Database Construction.

Sensor-Computer Interface: The initial step involved finding a suitable driver to establish compatibility between the sensor and the computer. Subsequently, we obtained the software development kit (SDK) to facilitate sensor integration and enable programming of the desktop application.

Sensor Testing on Demo Website: After successfully connecting the sensor to the computer, we conducted tests on a demo website to verify the sensor's functionality, assess image resolution, and determine if image processing was required.

Designing the Desktop Application: The desktop application was developed using the Java programming language, incorporating essential features to enable seamless interaction with the sensor. The user interface components of the application are illustrated in Figure 4.

Capturing Function: The «Capture R2» button initiates the process of capturing the user's fingerprint image using the SecuGen fingerprint device and extracting a template for subsequent processing. The steps involved in this function include retrieving the current image buffer, obtaining the fingerprint image, evaluating image quality, extracting relevant finger information, performing image quality checks, creating a template, and assessing template quality.

Matching Function: The «Button Register Action Performed» function within the biometric system facilitates the registration of fingerprints by comparing two captured fingerprint images. The steps encompass image comparison, determination of image matching, displaying registration success or failure, and adding the fingerprint to the database.

Sensor-Application Connection: The Main() function, acting as a constructor for an unspecified class, initializes and configures various user interface elements. Key actions performed by this function include initializing components, enabling or disabling buttons, connecting the SecuGen sensor device, retrieving device information, and updating the device's connection status.

Database Construction: Upon successful verification, this process updates fingerprint details for specified user(s) in the database. It involves retrieving user ID(s), modifying relevant fields in the employee table, executing SQL queries, displaying success or failure messages, and creating a new instance of the Biometric class.

Connecting the Database to the Application: The getUser() method retrieves user information from the employee table in a MySQL database. This process includes loading the MySQL driver, establishing a database connection, executing an SQL query, extracting column values, adding them to a table model, terminating the connection, and handling any exceptions that may arise. For a visual representation of the desktop application and its user interfaces, please refer to Figure 4 (p. 15), which showcases the front page, user information registration, biometric verification, and identity matching interfaces.

Results and Discussion

Having successfully integrated all the essential functions, the touchless fingerprint system is now fully operational, with seamless integration of both hardware and software components. This integration empowers the system to proficiently capture, match, and store fingerprint images in the database.

The integration of capturing functions involves a series of crucial steps. It commences by detecting whether the object inserted into the sensor is indeed a fingerprint. The LED is judiciously controlled

to ensure optimal illumination for precise image capture. The system captures the fingerprint image with correct dimensions and conducts a quality test to ensure alignment with the required standards.

The database functionality has been successfully integrated and subjected to rigorous testing. This ensures the accurate storage of individuals' information, associating the captured fingerprint image with the corresponding data. As an additional security measure, the information is encrypted and securely stored locally.

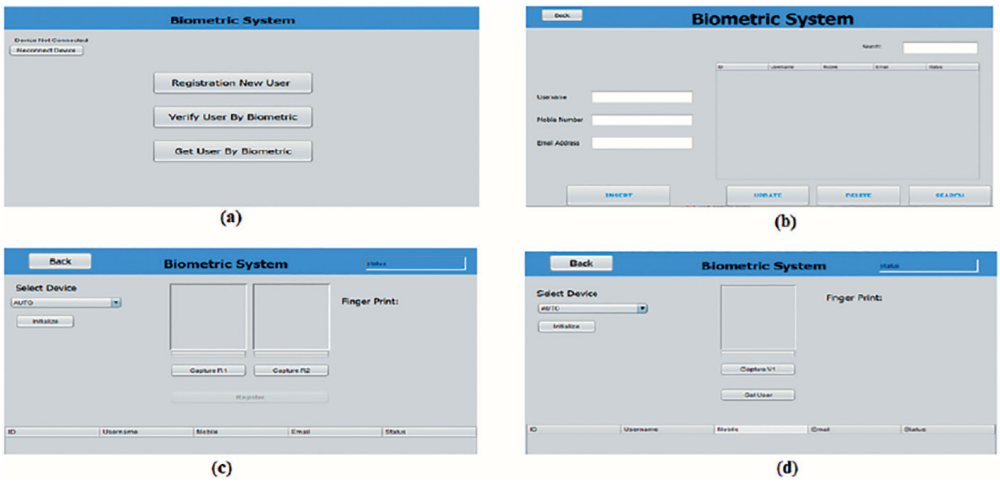

Figure 4 – (a) Front page of the application displaying the initial interface. (b) User-interface for registering the personal information of the user, allowing input of necessary details. (c) User interface for biometric verification, utilizing the biometric data registered in (a) to authenticate the user. (d) User-interface for identity matching, prompting the user to place their finger for identity verification

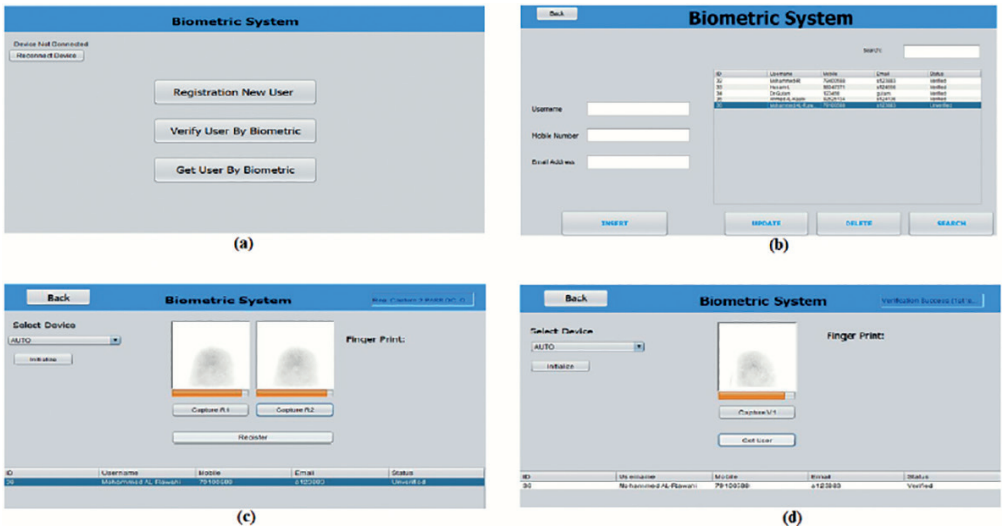

Figure 5 – (a) Front page of the application displaying the initial interface. (b) User-interface for registering the personal information of the user, allowing input of necessary details. (c) User-interface for biometric verification, utilizing the biometric data registered in (a) to authenticate the user. (d) User-interface for identity matching, prompting the user to place their finger for identity verification

For matching purposes, the capturing process is iterated and thoroughly tested. The system performs a comparison between the captured fingerprint image and the stored image in the database, subsequently verifying and retrieving the user's previously saved information. At this stage, the application undergoes comprehensive final testing, confirming the correct functioning of all application functions. The provided figures visually demonstrate the successful execution of these functions.

During the verification stage, users select an unverified ID, capturing their fingerprint image twice to enhance image quality, and proceed to register their personal information along with their fingerprint in the database.

In the retrieval stage, the system prompts users to insert their fingerprint for image capture. Upon capturing the image, users press the «Get User» button to retrieve their personal information from the database. Figure 5 provides a visual representation of the successful functioning of these integrated functions.

Conclusion and Future Work

In conclusion, the successful culmination of our touchless fingerprint system represents a significant milestone, addressing critical aspects and adhering to specified standards, all while considering the heightened importance of hygiene, particularly in the context of the ongoing COVID-19 pandemic. The system stands out for its precise and dependable fingerprint capturing, matching, and storage capabilities, all of which align with the current emphasis on touchless technologies for public health and safety.

We envision extending the reach of the developed system to cater to the requirements of both government services and private enterprises, acknowledging the demand for touchless solutions that align with hygiene standards. This expansion aims to provide a diverse user base with access to advanced capabilities, thereby contributing to heightened security and streamlined identification processes.

In our continuous pursuit of innovation, our future endeavors involve advancing the touchless fingerprint system even further. This includes exploring additional features and potential applications across various domains such as law enforcement, access control, and identity verification. Through ongoing research and development efforts, we strive to remain at the forefront of technological evolution, offering solutions that not only meet but redefine the standards of fingerprint recognition technology in the ever-evolving landscape, with a heightened awareness of hygiene concerns.

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[1]*Гулам Дастагир Кхан,
ассистент-профессор, ORCID ID: 0000-0001-8002-3904,
e-mail: G.khan1@squ.edu.om
[1]Ахмед Юма Ал-Кааби,
студент, e-mail: s124136@student.squ.edu.om
[1]Хусам Ахмед Ал-Кхаруси,
студент, e-mail: s124556@student.squ.edu.om
[1]Мохаммед Сулаиман Ал-Ращахи,
студент, e-mail: s123883@student.squ.edu.om

[1]Инженерный колледж Университета Султана Кабуса (SQU), Маскат, 123, Оман

БЕСКОНТАКТНАЯ СИСТЕМА ОТПЕЧАТКОВ ПАЛЬЦЕВ НА БАЗЕ ИНТЕЛЛЕКТУАЛЬНОГО ДАТЧИКА

Аннотация

В статье представлена бесконтактная система распознавания отпечатков пальцев, предлагающая гигиеничную альтернативу традиционным сенсорным системам. Основной целью является разработка и оценка комплексного решения, которое позволит устранить проблемы, связанные с гигиеной, и снизить риски передачи заболеваний, особенно в связи с продолжающейся пандемией Covid-19. Предлагаемая система

использует современный бесконтактный датчик для захвата сложных изображений отпечатков пальцев, их последующей обработки, хранения и извлечения данных для дальнейшего сопоставления. Устраняя необходимость физического контакта, система эффективно решает проблемы, связанные с непостоянным давлением и длительным временем сбора данных. Бесконтактная технология отпечатков пальцев, представленная в этой системе, имеет большие перспективы для различных приложений, требующих безопасного и гигиеничного распознавания отпечатков пальцев. Предлагаемый метод преодолевает ограничения, присущие сенсорным системам, что делает его хорошо подходящим для сред, где вопросы здоровья и безопасности имеют первостепенное значение. Интеграция этой бесконтактной технологии не только повышает безопасность, но и вносит значительный вклад в здравоохранение за счет снижения риска перекрестного заражения в общих точках соприкосновения. В то время как мир преодолевает проблемы, связанные с пандемией, внедрение бесконтактных систем распознавания отпечатков пальцев представляет собой решающий шаг на пути к созданию более безопасной и гигиеничной среды.

Ключевые слова: бесконтактная технология отпечатков пальцев, сенсорные системы, гигиена, передача заболеваний, безопасность, точность.

[1]*Гулам Дастагир Кхан,
ассистент-профессор, ORCID ID: 0000-0001-8002-3904,
e-mail: G.khan1@squ.edu.om
[1]Ахмед Юма Ал-Кааби,
студент, e-mail: s124136@student.squ.edu.om
[1]Хусам Ахмед Ал-Кхаруси,
студент, e-mail: s124556@student.squ.edu.om
[1]Мохаммед Сулаиман Ал-Ращахи,
студент, e-mail: s123883@student.squ.edu.om

[1]Сұлтан Кабус университетінің инженерлік колледжі (SQU), Маскат, 123, Оман

ЗИЯТКЕРЛІК ДАТЧИККЕ НЕГІЗДЕЛГЕН САУСАҚ ІЗІНІҢ БАЙЛАНЫССЫЗ ЖҮЙЕСІ

Аңдатпа

Мақалада дәстүрлі сенсорлық жүйелерге гигиеналық балама ұсынатын байланыссыз саусақ ізін тану жүйесі ұсынылған. Басты мақсат – гигиенаға байланысты мәселелерді жоятын және аурудың, әсіресе жалғасып жатқан Covid-19 пандемиясына байланысты вирустардың таралу қаупін азайтатын кешенді шешімді әзірлеу және бағалау. Ұсынылған жүйе күрделі саусақ ізі кескіндерін түсіру, оларды өңдеу, әрі қарай сәйкестендіру үшін деректерді сақтау мен алуда жетілдірілген байланыссыз сенсорды пайдаланады. Физикалық байланыс қажеттілігін жою арқылы жүйе тұрақсыз қысыммен және деректерді жинаудың ұзақтығымен байланысты мәселелерді тиімді шешеді. Бұл жүйеде ұсынылған байланыссыз саусақ ізі технологиясы саусақ ізін қауіпсіз және гигиеналық тануды қажет ететін әртүрлі бағдарламалар үшін үлкен перспективаға ие. Ұсынылған әдіс сенсорлық жүйелерге тән шектеулерді жеңе отырып, денсаулық пен қауіпсіздік мәселелері бірінші кезектегі ортада қолайлы құралға айналу мүмкіндігіне ие. Бұл байланыссыз технологияны біріктіру қауіпсіздікті арттырып қана қоймайды, сонымен қатар ортақ байланыс нүктелерінде айқаспалы инфекция қаупін азайту арқылы денсаулық сақтау саласына айтарлықтай үлес қосады. Әлем пандемиямен байланысты қиындықтарды жеңген уақытта, байланыссыз саусақ ізін тану жүйелерін енгізу қауіпсіз және гигиеналық ортаны құру жолындағы шешуші қадам болады.

Тірек сөздер: байланыссыз саусақ ізі технологиясы, сенсорлық жүйелер, гигиена, аурудың таралуы, қауіпсіздік, дәлдік.

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[1]Алдибекова А.Н.,
магистр, ORCID ID: 0000-0003-4736-6686,
e-mail: aitkul.aldibekova@gmail.com

[1]Алматы технологиялық университеті, Алматы қ., 050012, Қазақстан

МАГНИТ ӨРІСІ КӨМЕГІМЕН СҮТ САПАСЫН БАҚЫЛАУ ЖӘНЕ БАСҚАРУ ТЕХНОЛОГИЯСЫ

Аңдатпа

Өндірісте физикалық және химиялық талдау арқылы өндірілетін өнімнің сапасын бақылаудың әртүрлі әдістері жетіп артылады. Соңғы жылдары азық-түлік өндірісі кезінде технологиялық процесстерді басқару мен бақылау кезінде ядролық магниттік резонанс (ЯМР) құбылысының принципін кеңірек пайдалану қолға алынуда. Берілген жұмыста сүт сапасын магнит өрісі арқылы автоматтандырылған басқару мақсатында ядролық магниттік резонанс құбылысын қолдану мүмкіндіктері қарастырылған. Аталған өнімнің ЯМР спектрлерінің изотоптарын зерттей отырып өнімнің табиғи немесе қоспа екенін, яғни оның құндылығы мен сапасын анықтауға болады. Сондай-ақ бұл жұмыста технологиялық процесстің құрылымдық сызбасы ұсынылып, автоматтандырылған басқару жүйесінде электромагниттердің көмегімен магнит өрісін тудыра отырып ЯМР-дің сигналдарын қабылдап, оны өңдеудің өрнектеріне түсініктеме берілген. Аталмыш әдіс тек процессті бақылап қана қоймай, сүт және сүт өнімдерінің физикалық қасиеттерінің өзгеруіне ықпал ете отырып, сапасын арттыруға мүмкіндік береді. Ол үшін тудырылған магнит өрісінің оңтайлы мәнін таңдап, орнықтырып алғаннан кейін оны өте жоғары дәлдікпен бақылап ұстап тұру қажет. Магнит өрісінің таңдалып алынатын мәні өнімнің әр физикалық қасиетіне байланысты өзгеріп отыруы қажеттігін айта кету керек.

Тірек сөздер: магнит өрісі, сүт сапасын бақылау, ядролық магниттік резонанс, автоматтандыру және басқару.

Кіріспе

Сұйық өнімді магниттеуге арналған құрылғыларда сүттің физико-химиялық қасиеттерін жақсы жаққа өзгерту үшін бірнеше шамаларды тұрақтандыру қажет [1]. Шығыс параметрлердің тұрақтанған мәндерін алу үшін бір жағынан түтіктен өтіп жатқан сүттің ағу жылдамдығын өте жоғары дәлдікпен қадағалап және оны біраз уақыт бойы ұстап тұру керек болса, екінші жағынан өнімге әсер етуші магнит өрісін де қырағылықпен бақылап тұру қажет. Аталған шамалар қондырғының типіне байланысты белгілі бір өлшемдерді ғана өзгерте алады [2].

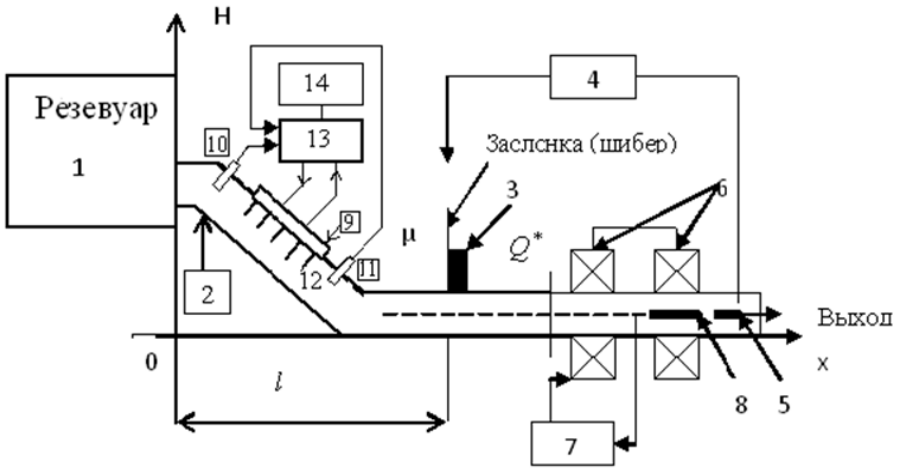
Құбыр бойымен сұйық ағынының жылдамдығын тұрақты ұстап тұрудың әртүрлі жолдары бар [3, 4], мысалы, модификацияланған Мариотт түтіктерін қолдану. Берілген жұмыста тәжірибелік қондырғыда тұрақтандырылған сұйықтық ағынын алудың жалпылама тәсілі қарастырылған [5].

Жазылған ғылыми мақаланың негізгі міндеті: ядролық магниттік резонанс құбылысының принципін қолдана отырып сүт және сүт өнімдерінің сапасын бақылау мен басқару мақсатында автоматтандырылған басқару жүйесін құру.

Негізгі ережелер

1-суретте қондырғының құрылымдық сызбасы ұсынылған [6]. Сүт фермаларынан келген сүт көлемді ыдысқа (1) құйылады, ол құбыр (2) арқылы реттеуіш құрылғыға (3) келіп жетеді, бұл бөлік құбырдағы сұйықтың ағыс жылдамдығын басқарып отыратын датчикке жалған-

ған (5) автореттеуіш жүйесімен (4) жабдықталған. Ары қарай сүт магнит өрісінің туындататын қос квадрапульді линзалары (6) арқылы ағып өтеді, ал оның шамасы манит өрісі кернеулігінің датчигіне (8) жалғанған автоматтандырылған басқару жүйесімен (7) реттеліп отырады.



Сурет 1 – Қондырғының жалпы құрылымдық сызбасы

Бұл магниттелу жүйесіне келіп түскен өнімнің температурасы 3–4 ^{0}C болуы керек. Осы мақсатта Пельте эффектісінің негізіндегі сұйықты реттеу жүйесі қолданылады. Реттегіш Пельте элементінің (9) көмегімен салқындатып тұратын құрал құбырдың ішіне орнатылған жазық параллель алюминийден жасалған пластиналардан (12) тұрады. Ол жердегі жоғары температура құбырдың сыртында орналасқан ауаны салқындатып тұратын радиатордың (14) көмегімен сыртқа шығарылып отырады. Құбырдағы сүттің температурасын 3±0,5 ^{0}C арасында ұстап тұру үшін температура реттегішінің тізбегіне кіретін термиялық кедергілер ретінде қолданылатын температура датчиктеріне (10, 11) қосылған электронды басқару құрылғысы (13) пайдаланылады [7].

Материалдар мен әдістер

Сұйықтың магниттелу бөлімін қарастырайық. Ядролық магниттік шығындарды алғашқы түрлендіргіш екі бөліктен тұрады: В индукциялы тұрақты магнит өрісін тудыратын поляризатор мен Лармор жиілігінің айнымалы магнит өрісінің әсері арқылы туындайтын ядролық магниттік резонансты (ЯМР) туындататын резонатор. Поляризатор мен «резонатордың» арасына ядроның магниттелуі векторына әсер ететін нутация катушкасы орнатылады және онымен ЯМР-дің сигналының мәні емес, онымен байланысты кейбір басқа шамалар, мысалы, нутационды катушкадағы ток күші немесе одан ЯМР сигналын қабылдайтын катушкаға дейінгі өнімнің қозғалу уақыты сияқты параметрлер өлшенеді [8].

Поляризатор М сұйықтың магниттелу векторының тұрақтылығын және жеткілікті жоғары мәнін қамтамасыз етіп тұратын магниттен тұратын болса, ал резонатор бөлігі тұрақты магниттен, екі модуляция катушкасынан, ядролық магниттік резонанс сигналдарын қабылдап алып, оларды қоздыратын катушкадан құрастырылған. Сұйық ағып өтетін құбырдың екі жағына қондырылған модуляция катушкасы төменгі жиілігі ω_p генератордан қорек алып отырады. Осындай жиілікте бұл катушкалар B_p тұрақты магнит өрісінің индукциясын өзгерте алады, ендеше, оның резонансы жиілік шамасы $\omega_p=\gamma$ болатындай өзгереді. Бұл ЯМР сигналының шу мен кедергіден ω_m резонансы арқылы бөлінуін жеңілдету үшін жасалады. М магниттелу проекциясына пропорционал және B_p өрісіне перпендикуляр болып келетін қабылдап отыратын катушкадағы ЯМР сигналдарын алу үшін B_p өрісіне перпендикулярлы

түрде бағытталған ωр резонансты жиілікте болатын айналмалы магнит өрісімен сұйықтыққа әсерін тигізу керек [9].

Магнит өрісін тудырушы катушкаларды екі бөлек қолданған кезде, сұйық ағып жатқан құбырды қоршап тұрғаны қабылдауыш, ал бірінші аталған өріс пен өрістің $B_р$ индукциясына перпендикуляр бағытталып тұрғаны қоздырғыш рөлін атқарады [10]. Қоздырушы катушка құбырдың екі жағына бекітілген екі секциялы бөліктен тұрады. Ары қарай ол жоғары жиілікті генераторға жалғана отырып ωр жиіліктегі резонансты магнит өрісін туындатады. Қабылдағыш катушка зорайтқышқа жалғанады. Оның ұзындығы қоздырғыш катушкадан қысқа болған себепті одан өткен кезде сұйықтың ядролық магниттелу релаксация әсерін азайтуға ықпал етеді. Оның l_k ұзындығын l_k<<T_1v шартынан таңдаған жөн, мұндағы T_1 – релаксация уақыты, v – сұйықтың орташа жылдамдығы.

Тағы бір әдісі бір мезетте $ω_р$ жиіліктегі резонансты өрісті қоздыратын, әрі ЯМР сигналдарын қабылдай алатын құбырды қоршап тұрған бір катушканы қолдану тәсілі [11]. Соңғысы резонансты өрісті қоздыратын катушкаға жалғанған жоғары жиілікті генератор тудыратын кернеудің фонында қабылданады. Алдыңғы жағдайда екі түрлі катушка үшін ЯМР сигналдары қоздырғыш катушканың кедергі фонында байқалады.

Екі жағдайда да фоннан сигналды оқшаулау үшін фазаға сезімтал тізбектер қолданылады [12]. Мұндағы фоны бар фазадағы сигнал компоненті абсорбциялық сигнал, ал фаза бойымен π/2-ге ығысқан компонент дисперсиялық сигнал деп аталады.

Поляризатордың магнитінің қажетті lп ұзындығын оның шығысындағы магниттелу векторының Mn жеткілікті мәнін алу шартынан анықтауға болады. Сұйықтың поляризаторға жету уақыты $t = V_п/Q_0$, ал мұндағы $V_п = \frac{\pi d^2 l_п}{4}$ – поляризатор магнитіндегі құбырдың көлемі деп алсақ, онда төмендегідей өрнекті аламыз [13]:

$$M_n = M_k(1 - e^{-m}) \quad (1)$$

мұндағы $m = V_n/Q_0T_1$.

Егер *m=2* болса, онда $M_п$=0,865$M_к$ және *m=3* кезінде $M_п$=0,95$M_к$ болады. Демек, $M_п$ магниттелу векторы поляризатордан шыққандағы $M_к$-ке тең шамасының мүмкін шекті мәннің 95%-нан кем болмайтындай $V_п \geq 3Q_0T_1$ немесе $l_n \geq 3vT_1$ теңсіздіктерін қанағаттандыру қажет, v – құбырдағы орташа жылдамдық.

Бұл айтылғандар тек турбулентті ағыс кезінде орынды, ал ламинарлы ағын кезінде v жылдамдығының бірдей мәні бірдей болғандықтан сұйықтың магниттелуі аз болады. Сондықтан $v_п$ және $l_п$ шамаларын анықтау үшін төмендегідей теңсіздік ұсынылады:

$$V_п \geq 4Q_0T_1 \quad и \; l_n \geq 4vT_1 \quad (2)$$

Бұл өрнектегі Q_{max} өскен сайын $l_п$ ұзындығын ұзарту керек немесе диаметрін ұлғайту керек. Бірақ диаметрі үлкен болса күшті магнит өрісін туындату қиынға соғады, ал магниттің $l_п$ ұзындығын қоса отырып v жылдамдығын арттырғанның өз шегі бар. Сол себепті ядролық магниттік шығын өлшеуіш диаметрі кіші құбырлардағы (әдетте 100–150 мм-ден аспайтын) шығынды өлшеуге ғана жарамды. $V_п$ ағын жылдамдығы берілген мәнде қол жеткізуге болатын ең максимал болатын Q_{max} шығыны келесі өрнекпен беріледі:

$$Q_{max} = \frac{v_n}{mT_1}. \quad (3)$$

Бұл шығынның максимал мәнін m шамасын 1,5–2-ге дейін төмендете отырып $M_п$ магниттелу векторын азайту арқылы арттыруға болады.

Келесі талаптар поляризаторды «резонатормен» байланыстырушы, сұйықтың келіп жету уақыты $t=V_c/Q_0$ болатын құбырдың l_c ұзындығы мен V_c көлеміне қойылады. B_c индукциясы бар шашыраңқы өрісте орналасқан бұл түтіктегі ядролардың деполяризациясын азайту үшін t уақытын азайтуға ұмтылуымыз керек.

M_c магниттелуінің байланыстырушы құбырдың шығысындағы тәуелділігі келесі өрнекпен беріледі:

$$M_c = \chi_0 B_c(1 - e^{-n}) + M_n e^{-n} \quad (4)$$

мұндағы $n = V_c/Q_0T_1$, χ_0 – статикалық ядролық магниттік сезімталдылығы.

Егер $B_c << B_п$ екенін ескеретін болсақ, $M_c \cong M_п e^{-n}$ шамасын аламыз. Онда n=0,1 кезінде $Mc = 0,9\ M_п$, ал n=1 кеінде $M_c = 9\ M_п$ тең болады.

Байланыстырушы құбырдың шығынын азайтқан сайын ондағы сұйықтың ішінде кідіру t уақыты ұзарады да оның мүмкін болу Q_{min} минимал шығынын мынандай теңдеу арқылы табуға болады:

$$Q_{min} = \frac{V_c}{nT_1} \quad (5)$$

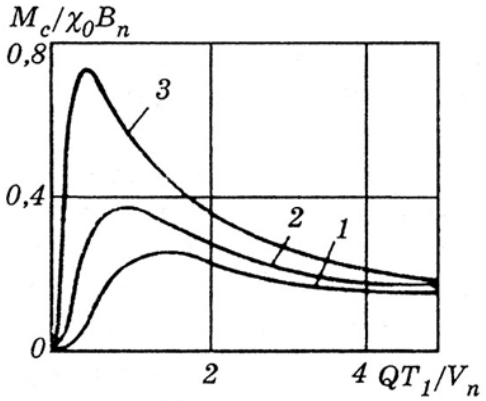
Егер Q_{max} –ды Q_{min} –ға бөлетін болсақ:

$$Q_{max}/Q_{min} = nk/m \quad (6)$$

теңдігін аламыз, мұндағы $k = V_n/V_c$.

Өлшеу диапазонын кеңейту үшін *к*-ның мәнін арттыру керек, $Q_{max}/Q_{min} = 10$-ға тең болса, $k = 10n/m$ мәнін аламыз.

M векторының Q_0T_1/V_n қатынасы мен *k* шамасына тәуелділігі 2-суретте көрсетілген.



Сурет 2 – $M_c = \chi_0 B_n$ магниттелу векторының
әр түрлі $k = V_n/V_c$ 1— k=1; 2– k=2; 3– k=10 мәндегі шығынға тәуелділік графигі

k-ның мәнін ұлғайтқан сайын $Q_{опт}$ азая отырып M_{cmax} мәніне жетеді. $Q_{опт}$ шамасын және оған сәйкес M_{cmax} мәнін төмендегідей формуламен анықтауға болады:

$$Q_{опт} = V_n/T_1 \ln(1 + k) \quad (7)$$

$$M_{c_{max}} = \chi_0 B_n k/(1 + k)^{(1+k)/k} \quad (8)$$

$Q_{опт}$ шамасымен салыстырғандағы шығынды азайту байланыстырушы құбырдағы сұйықтың деполяризациясының M_c деңгейін төмендетеді, ал ұлғайу – поляризатордағы сұйықтың тұру уақытының қысқаруына байланысты M_c төмендейді.

$Q_{опт}$ шамасымен салыстырғандағы шығынды азайту байланыстырушы құбырдағы сұйықтың деполяризациясының M_c деңгейін төмендетеді, ал ұлғаю – поляризатордағы сұйықтың тұру уақытының қысқаруына байланысты M_c төмендейді.

Нәтижелер мен талқылау

Жоғарыда талданып қарастырылған жүйелі магнит өрісі кернеулігінің мәнін өзгерте отырып, сиыр сүтін сыртынан катушкалар орнатылған құбыр желісінен ағызып өткізгеннен кейін өнімнің сапалық көрсеткіштерінің өзгерісін анықтау мақсатында Алматы технологиялық университетінің «Өндірістік тағамдардың сапасы мен қауіпсіздігін бағалау» зертханасында «Лактан 1–4 М» анализаторын қолдана отырып, эксперименттік талдаулар жасалды. Жасалған талдаулардың хроматограммалары сұйық, газ хромотографиясын және ультракүлгін аймақта көрінетін спектроскопия жүйелерін басқаруға арналған Agilent ChemStation бағдарламалық пакеті арқылы алынды [15]. Төменде ұсынылған 1 және 2-кестелерде магниттік өңдеуден өткен сиыр сүтінің кейбір көрсеткіштеріне тигізген әсері көрсетілген:

Кесте 1 – Магнит өрісінен өңдеуден өтпеген сүттің көрсеткіштері

Майлылығының %-дық шамасы	ҚМСҚ-ның %-дық шамасы	тығыздығының шамасы, град/ л	лактозасының шамасы, г/ 100 мл
3,72	8,50	29,26	9,500

Кесте 2 – Магниттік өңдеуден өткізілген сүттің көрсеткіштері

берілген кернеу мәндері, U,В	тұрақ ты тоқтың мәндері I_1, А	айымалы тоқтың мәндері, I_2, А	Магнит өрісінің индукция векторының мәні, В, Тл	Майлылық, %-бен	ҚМҚС %-бен	тығыздық, град/л	лактоза г/100мл
11,24	8	5,77	8,66	3,96	8,54	29,23	13,740
11,20		5,24		3,87	8,57	29,40	11,479
11,36		5,75		3,93	8,22	29,83	13,215
11,36		5,71		3,91	8,49	29,07	25,683

Сүттің магниттік өңдеуге дейінгі және кейінгі жағдайына байланысты ұсынылған екі кестені салыстырып қарастыратын болсақ, көрсеткіштерінде өзгерістер бар екені байқалады. Мысалы, өңдеуге дейін сүттің құрамында 9, 500 г/100 мл лактоза болса, магнит өрісінің әсерінен кейін 25,683 г/100 мл шамасын құрап тұр. Бұл өзгеріс катушкаға 11,36 В кернеу мен 5,71 А айнымалы ток кезінде туындаған 8,66 Тл магнит өрісінің әсері және т.с.с. [15].

Қорытынды

Демек біз бұл жұмыста өндірілетін өнімнің сапасын анықтауда жоғары дәлдікке ие болғандықтан ЯМР-ды қолдана отырып, сүт сапасын автоматтандырылған басқару жүйесін құрудың тиімді екенін көрсетуге тырыстық [14]. Сонымен қатар катушкалар тудырған магнит өрісі ортаға биологиялық белсенді фактор ретінде де әсер етіп, залалсыздандыру қызметін де атқара алады. Бұл өз кезегінде аталмыш өнімнің ұзағырақ сақталуына ықпалын тигізеді [15]. Сондықтан жоғарыдағы әдісті сүт және сүт өнімдері өнеркәсібімен айналысатын кішігірім орындарда, сондай-ақ, сүт сапасы мен қауіпсіздігін бақылау және бағалау зертханаларында қолдануға болады.

Осы мақсатта сүт сапасының параметрлерін (майдың массалық үлесі, құрғақ майсыздандырылған сүт қалдығының массалық үлесі, тығыздығы, қосылған судың массалық үлесі, салқындау температурасы, ақуыздың массалық үлесі, қышқылдығы және тұтқырлығы) басқару үшін автоматтандырылған басқару жүйесі жасалды (АБЖ) [16, 17, 18].

Эксперименттік зерттеулер жүргізе келе магнит өрісі арқылы өңдеуден өткізу шынымен де сүттің физикалық қасиеттеріне әсерін тигізетіні белгілі болды [15]. Ең көп әсері 16 мТл шамасында қышқылдығына, 11 мТл мәнінде тұтқырлығына ықпал еткені байқалды [19, 20].

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[1]Aldibekova A.N.,
master, ORCID ID: 0000-0003-4736-6686,
e-mail: aitkul.aldibekova@gmail.com

[1]Almaty Technological University, Almaty, 050012, Kazakhstan

TECHNOLOGY FOR CONTROL AND MANAGEMENT OF MILK QUALITY USING MAGNETIC FIELD

Abstract

In production, various methods are used to control the quality of manufactured products due to physical and chemical effects. In recent years, the principle of the phenomenon of nuclear magnetic resonance (NMR) has been increasingly used in the management and control of technological processes in food production. This paper examines the possibility of using the phenomenon of nuclear magnetic resonance for the purpose of automated control of milk quality by a magnetic field. By studying the isotopes of the NMR spectra of the specified product, it is possible to determine whether the product is natural or artificial, that is, its cost and quality. This work also provides a block diagram of the technological process and explains the expressions for receiving NMR signals and processing them with the creation of a magnetic field using electromagnets in an automated control system. This method allows not only to control the process, but also to determine the physical properties of milk and dairy products, contributing to changes in quality. To do this, it is necessary to maintain the optimal value of the generated magnetic field with very high accuracy.

Key words: magnetic field, milk quality control, nuclear magnetic resonance, automation and control.

[1]Алдибекова А.Н.,
магистр, ORCID ID: 0000-0003-4736-6686,
e-mail: aitkul.aldibekova@gmail.com

[1]Алматинский технологический университет, г. Алматы, 050012, Казахстан

ТЕХНОЛОГИЯ КОНТРОЛЯ И УПРАВЛЕНИЯ КАЧЕСТВОМ МОЛОКА С ИСПОЛЬЗОВАНИЕМ МАГНИТНОГО ПОЛЯ

Аннотация

В производстве используются различные методы контроля качества производимой продукции за счет физического и химического воздействия. В последние годы все шире используется принцип явления ядерного магнитного резонанса (ЯМР) при управлении и контроле технологических процессов при производстве продуктов питания. В данной работе рассмотрены возможности применения явления ядерного магнитного резонанса с целью автоматизированного управления качеством молока магнитным полем. Изучая изотопы спектров ЯМР указанного продукта, можно определить, является ли продукт натуральным или искусственным, то есть его себестоимость и качество. Также в данной работе приведена структурная схема технологического процесса, даны объяснения выражений приема сигналов ЯМР и его обработки с созданием магнитного поля с помощью электромагнитов в автоматизированной системе управления. Данный метод позволяет не только контролировать процесс, но и определять физические свойства молока и молочных продуктов, способствуя изменению качества. Для этого необходимо поддерживать оптимальное значение создаваемого магнитного поля с очень высокой точностью.

Ключевые слова: магнитное поле, контроль качества молока, ядерный магнитный резонанс, автоматизация и управление.

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[1]Samigulina Z.I.,
PhD, ORCID ID: 0000-0002-5862-6415, e-mail: z.samigulina@kbtu.kz
[1]Kurmasheva A.K.,
Bachelor, ORCID ID: 0009-0008-9570-0021, e-mail: kurmasheva-2002@mail.ru
[1]*Kazbek M.K.,
Bachelor, ORCID ID: 0009-0009-7573-2429, *e-mail: mad_kazbek@gmail.com

[1]Kazakh-British Technical University, 050000, Almaty, Kazakhstan

DEVELOPMENT OF A PROCESS AUTOMATION SYSTEM FOR HEATING, VENTILATION AND AIR CONDITIONING FOR THE FOOD INDUSTRY ON THE BASIS OF HONEYWELL EQUIPMENT

Abstract

Currently, the development of industrial automation makes it possible to implement high-precision control systems that consider the dynamic properties of complex objects. The construction of distributed control systems based on modern software products provides decentralized management of technological processes. The modernization of existing control systems with the help of modern industrial equipment makes it possible to increase the productivity of enterprises and safety at work. This study is devoted to the development of an automated control system for heating, ventilation, and air conditioning processes for the food industry. In this study, a heat exchanger was selected as the control object. A mathematical model of the control object for stability, controllability, and observability was investigated. A PID regulator was synthesized, and its coefficients of the PID regulator were obtained. A comparative analysis of the behavior of the system dynamics at different regulator coefficients was carried out. The results of the modeling and experiments were carried out using real industrial equipment at the Honeywell laboratory at JSC KBTU. Software implementation was carried out using the Experion PKS distributed control system. The configuration of the C300 controller is presented. A Safety Instrumented System (SIS) was developed for the safe and trouble-free operation of the system. SIS was also developed using the Safety Manager and Safety Controller tools. Risk reduction factors (RRF) and Safety Integrity Level (SIL) were calculated and analyzed. A process-controlled mnemonic was developed.

Key words: Heating, ventilation, and air conditioning, food industry, manufacturing, programmable logic controller, complex object.

Introduction

It is crucial to understand the effects of condensation on food-processing plants before delving into remedies. Surfaces, equipment, and even air handling systems can experience condensation. Increased moisture encourages the development of bacteria, moulds, and fungi, which can taint food and harm human health. The slippery conditions for plant employees can result from condensation on floors and other surfaces.

Dehumidification systems play a vital role in mitigating excess moisture, averting condensation-related issues, and maintaining optimal humidity. These systems function by directing air through a cooling coil to extract moisture, thereby creating a dry, conducive environment.

The conditions found in food processing plants are notoriously complicated, involving a wide range of machinery and equipment that must operate at various temperatures and humidity levels. Condensation is one of the major problems faced by these facilities. Significant problems such as mould growth, contamination, and equipment malfunction can result from condensation formation.

Investing in efficient HVAC systems yields various benefits including enhanced product quality, regulatory compliance, energy conservation, and improved worker comfort and safety. This translates into extended shelf life for food products, adherence to industry regulations, reduced energy consumption, operational cost savings, and a safer working environment. Effective management of condensation-related challenges in food processing facilities necessitates the implementation of expert HVAC strategies. By prioritizing elements such as systematic system design, incorporation of dehumidification systems, insulation practices, and implementation of routine maintenance, food processing establishments can ensure a secure and optimal working environment. Investment in efficient HVAC systems not only safeguards product quality, but also guarantees compliance with industry standards while simultaneously reducing energy consumption and operational costs.

Literature Review

In the modern world, it is important to design modern systems for the automatic regulation of air ventilation across diverse production environments. However, in the course of development, novice specialists may encounter confusion when confronted with terms such as Air Handling Unit (AHU) and Heating, Ventilation, and Air Conditioning (HVAC), leading to uncertainty regarding their distinctions. In [1], the authors indicated that there is no difference between HVAC and AHU, as AHU is a subsection of the HVAC system, where the main focus is on the movement of air around the room. For any HVAC system, there are four basic requirements: primary equipment, space requirements, air distribution, and piping. Each of these requirements was discussed in the research [2]. Modern hardware and software tools are widely used for HVAC systems. Various solutions have been offered for the creation of HVAC systems. In particular, a study on automated design for HVAC layouts [3] proposed a new methodology for an algorithmic method that fully automates the HVAC air system's air duct design, selection, and hydraulic computation. This study presents a strategy that can increase designer productivity, reduce human error in design, and provide code-compliant air duct designs. Additionally, [4] examined the basic concepts of HVAC and its components, which provide the necessary means to maintain indoor environments at comfort levels according to American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards, including temperature, humidity, and air quality measurements. It examines how the standards are supported by regulating the amount of clean air and heat supplied to the heaters and removed from coolers. The authors of [5] discussed the importance of monitoring the internal HVAC environment (temperature, humidity, and wind speed) to determine optimal control. In addition, evidence that operating conditions are important for humidifier performance was found in [6], and a parameterization and optimization study of a new drying system consisting of a large solid binderless humidifier with water cooling and heating devices was explored.

Paper [7] showed that many HVAC systems in existing buildings use high energy, with older buildings being particularly affected. To reduce energy consumption in the building sector, it is important to prioritize upgrading the HVAC systems in existing buildings. Some research [8] examined recent research in the HVAC sector to improve system efficiency and provide occupants with more thermal comfort in climate-controlled interior spaces. A recent study on thermal modelling [9] underscored the pivotal role of HVAC systems in humidity and temperature control to ensure production quality in manufacturing processes. Despite the relatively stable energy consumption of the machinery sector, escalating production demands necessitate a strategic focus on energy-efficient management, with HVAC systems identified as a key area for potential energy reduction. Another study [10] highlighted the effectiveness of asynchronous optimization in coordinating manufacturing and HVAC schedules, achieving a notable 15.1% reduction in peak energy demand without compromising manufacturing productivity. This innovative approach presents an energy-efficient management methodology for manufacturing facilities. The developed model demonstrated a high level of accuracy, with 96.5% precision in predicting energy consumption and the ability to

accurately identify patterns in energy profiles. Additionally, a study on energy dynamics in hotter regions [11] provides an overview of the energy dynamics in tropical insular regions. This paper argues that the abundant renewable resources in these areas make them suitable for smart microgrids and energy storage technologies, with a notable 40% of energy consumption dedicated to space cooling owing to consistently high temperatures.

However, this is not the only problem. Paper [12] pointed out that desiccant regeneration is only 28.2%, and that there are significant heat losses when utilizing a conventional system with an adsorption drier. Heat loss was minimized in this study by directly heating the adsorbents through the unique electrothermal adsorption of the installation. According to an article [13], solid desiccants are economical, have a high rate of moisture removal, as well as a low regeneration temperature and stability, which makes the dehumidification process environmentally friendly and effective in all senses. There are other types of air conditioning systems. One such type is the goal of this study [14]. This study evaluated the performance of vapor compression refrigeration installations and developed a prototype dehumidifier based on it. Vapor-compression refrigeration, also known as a vapor-compression refrigeration system (CRS), is a refrigeration cycle in which the refrigerant changes phases. It is the most popular type of air-conditioning system in buildings.

HVAC systems are an important aspect of the food industry. Any errors in the system can have severe consequences. The authors of [15] made recommendations to improve the existing systems in the food industry. For example, in rooms with significant heat emissions, the air supply to the work area should be provided by standard air diffusers, emissions from the upper areas should be concentrated, and drying sections should be provided with local exhaust air conditioning. Moreover, a review of the relationship between HVAC systems and the Coronavirus disease (COVID-19) pandemic [16] emphasizes the need to update crucial components in air conditioning systems to mitigate virus transmission risks.

Some studies have proposed methods that use artificial intelligence and machine learning. For instance, a study on high-temperature generators [17] sought to use AI approaches to analytically depict the absorption chiller performance while accounting for solar intermittency, whereas some [18] investigated various HVAC and weather combinations using fuzzy-based approaches and Building Information Modelling (BIM) to reduce uncertain variables. Additionally, a review on natural ventilation [19] explored approaches for validating Computational Fluid Dynamics models and investigating the natural ventilation of large air masses, while others [20] proposed a domain-specific technique that can operate HVAC systems while adapting to changes in the building environment.

By optimizing energy efficiency in manufacturing processes to address challenges in existing buildings, studies emphasize the need for continuous advancements and innovative solutions in the field.

Statement of the problem is to develop a ventilation system that maintains a certain temperature and humidity in the food production sector using Honeywell equipment.

Main provision

Before understanding dehumidification, it is crucial to understand the basics of psychometrics, that is, the study of the properties of air and how they relate to human comfort and HVAC processes. Psychrometric charts are valuable tools for HVAC engineers to assess air conditions including temperature, humidity, and enthalpy.

The primary principle behind dehumidification is cooling the air below its dew point temperature. When the air is cooled, it reaches its dew point, causing moisture to condense into liquid water. This condensed moisture was then collected and drained away, leaving air with reduced humidity levels.

Temperature control via an HVAC system can be achieved in two ways. The first method is Air Heating. The HVAC heating unit should be turned on if air heating is required. Electronic heating components are used in the heating function of the HVAC system. The heating element may be a

thermostat, induction coil, electronic heater, etc. In the route of the suction air, the heating element creates a heated zone; when the air flows through the heated region, it heats. In this manner, warm air was introduced into the space. The second method is Air Cooling. The cooling unit was turned on to chill the air. Air is carried via a coil, which is a component of the heat exchanger, in the cooling unit. The heat exchangers may be of the cross-flow coil or shell and tube type. The refrigerant in the exchanger unit expels heat from the suction air, and only the cooled air is introduced into the space. The compressor that liquefies the refrigerant is built into cooling units.

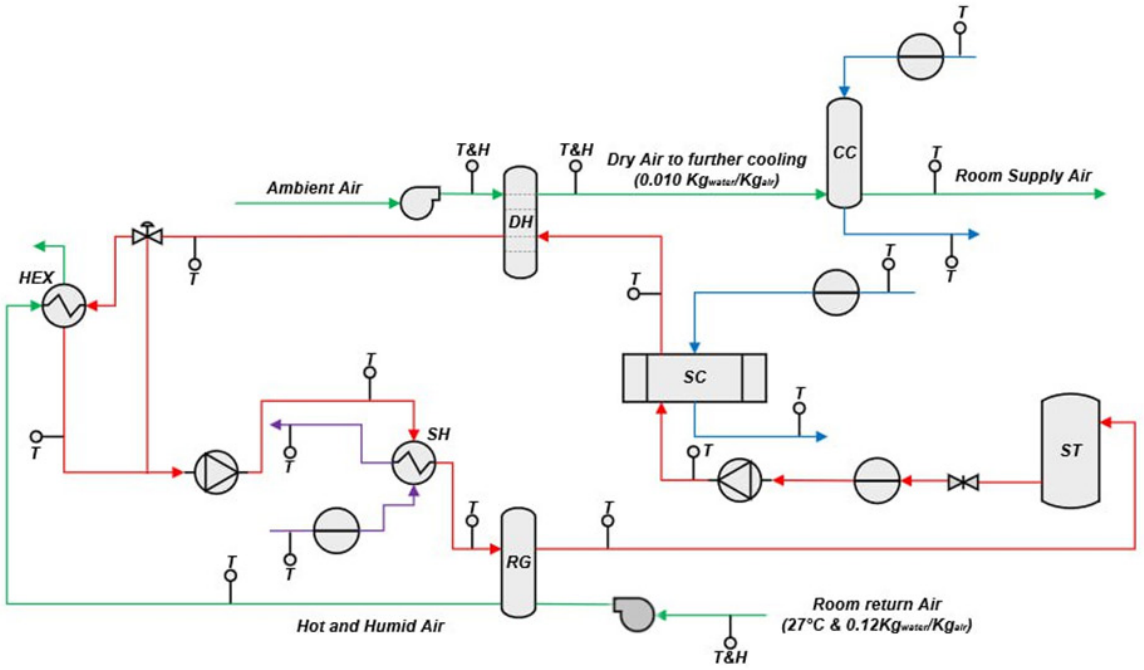

Figure 1 – Structural scheme of the dehumidification process

For a better understanding, the following symbols of the liquid desiccant air conditioning system coupled to the chiller technological process diagram are used: HEX – air solution heat exchanger; SH – solution heater; DH – dehumidifier; RG – regenerator; SC – solution cooler; CC – cooling coil; ST – solution storage tank.

Description of technological process

Air conditioners function by taking heat from the surrounding air and releasing it from the space. This produces cool air that is subsequently circulated around the space, ultimately chilling it. The heat exchanger oversees this function, and the effectiveness of the AC component defines the cooling capability of the unit.

A heat exchanger is a device that transfers heat between two fluids, without mixing them. The dynamics of a heat exchanger depend on many factors, such as the temperature difference, heat transfer area, flow rate of fluids, and flow patterns. Heat exchangers are widely used in a variety of sectors, including petroleum, food, petrochemicals, power generation, nuclear energy, and spacecraft.

Shell and tube heat exchangers are arguably the most popular forms of heat exchangers that can operate over a wide range of temperatures and pressures. It offers a higher surface-to-volume ratio than double-pipe heat exchangers and is simple to construct for a wide range of sizes and configurations. The shell and tube heat exchanger can withstand high pressures, and its design allows easy disassembly for routine maintenance and cleaning. A shell-and-tube heat exchanger is

a variation of the double-pipe design. A shell-and-tube heat exchanger, as opposed to a single pipe within a larger pipe, is composed of a bundle of pipes or tubes contained within a cylindrical shell. In a shell-and-tube heat exchanger, one fluid flows through the tubes, whereas another fluid flows through the shell. One fluid passed through the tubes, and a second fluid flowed between the tubes and shell in the shell and tube heat exchanger.

The role of HVAC systems is undeniable and pivotal in the field of food processing. These systems not only provide the essential environmental conditions necessary for food safety and quality but also contribute significantly to energy efficiency and overall operational sustainability.

The HVAC systems in food processing facilities maintain precise temperature and humidity levels, thereby ensuring that food products are stored, processed, and preserved under optimal conditions. This is critical for preventing spoilage, extending the shelf life, and adhering to strict industry regulations and standards.

Materials and Methods

Mathematical modelling is a fundamental part in implementation of serious control processes, especially in analysis and design stages, and results of such a model are present through the whole development of the project.

In constructing a mathematical model [21], the system's behaviour and characteristics are studied and represented using mathematical equations, particularly it is described with differential equations. In this document a control plant, specifically, a heat exchanger is considered. Heat and mass transfer processes in the heat exchanger are described using a set of nonlinear equations:

$$G_{oil}\rho_{oil}C_{oil}(T_{oil}-T_{oil.in})+m_{oil}C_{oil}\frac{dT_{oil}}{dt}+a_{oil}F_{ins}(T_{oil}-T_{pipe})=0 \quad (1)$$

$$m_{pipe}C_{pipe}\frac{dT_{pipe}}{dt}-\alpha_{oil}F_{ins}(T_{pipe}-T_{air})=0 \quad (2)$$

$$G_{air}\rho_{air}C_{air}(T_{air}-T_{air.in})=\alpha_{air}F_{ex}(T_{pipe}-T_{air}) \quad (3)$$

The parameters used in the equations are described in the Table 1.

Table 1 – Parameters of the equation

Parameter	Description
1	2
G_{oil}	volumetric flow rates of oil
G_{air}	volumetric flow rates of air
ρ_{oil}	densities of oil
ρ_{air}	densities of air
C_{oil}	heat capacities of oil
C_{air}	heat capacities of air
m_{oil}	mass of oil
m_{air}	mass of pipe
α_{oil}	heat transfer coefficient from the oil to the tube wall of the heat exchanger

Continuation of table 1

1	2
α_{air}	heat transfer coefficient from the tube wall of the heat exchanger to air
F_{ins}	internal heat exchange areas
F_{ex}	external heat exchange areas
T_{oil}	average value of oil temperatures at the outlet of the air-cooling device
T_{air}	average value of air temperatures at the outlet of the air-cooling device
$T_{oil.in}$	average value of oil temperatures at the inlet of the air-cooling device
$T_{air.in}$	average value of air temperatures at the inlet of the air-cooling device
T_{pipe}	average temperature of the pipe
t	time

The first and third equations in the system represent the conservation of power for the heat flows of oil and air, respectively. The second equation is a heat balance, accounting for the heat supplied to the tube, heat given to the air, and heat accumulated in the heat exchanger material. In the oil air cooler, the input control is the volumetric air flow rate, controlled by the average oil temperature at the heat exchanger outlet. Perturbing factors include changes in the oil temperature and air temperature at the inlet of the air-cooling device, as well as variations in the volumetric oil flow rate.

Equation system demonstrates that the heat exchange process in the oil air cooler is a nonlinear control object. Nonlinearity primarily arises from the multiplication of variables such as G_{oil} and G_{air}, as well as $T_{oil}\ and\ T_{air}$.

A linearized system of equations describing the dynamics of the heat exchange process in the air-cooling device is obtained by transitioning in equation to increments, breaking down the primary nonlinearities using a Taylor series expansion, and limiting the expansion to the first terms:

$$(m_{oil}C_{oil}p + G_{oil}\rho_{oil}C_{oil} + \alpha_{oil}F_{ins})\Delta T_{oil} - \alpha_{oil}F_{ins}\Delta T_{pipe} = 0 \quad (4)$$

$$\left(m_{pipe}C_{pipe}p + \alpha_{oil}F_{ins}\right)\Delta T_{pipe} - \alpha_{oil}F_{ins}\Delta T_{oil} + \alpha_{air}F_{ex}\Delta T_{pipe} - \alpha_{air}F_{ex}\Delta T_{ex} = 0 \quad (5)$$

$$\rho_{air}C_{air}(T_{air0} - T_{air.in0})\Delta G_{air} + (G_{air0}\rho_{air}C_{air} + \alpha_{air}F_{ex})\Delta T_{ex} = \\ = \alpha_{air}F_{ex}\Delta T_{pipe} \quad (6)$$

These calculations are useful when it comes to Laplace method by marking $T_{oil}(p) = L\{\Delta T_{oil}\}, G_{air}(p) = L\{\Delta G_{air}\}$, we will find the transfer function of the heat exchange process concerning the control input:

$$W_{air2}(p) = \frac{T_{oil}(p)}{T_{air.in}(p)} = \frac{k_{air2}}{a_0 p^2 + a_1 p + 1} \quad (7)$$

Where k_{air2} is represented as below:

$$k_{air2} = \frac{\frac{\alpha_{oil}F_{ins}\alpha_{air}F_{ex}G_{air0}\rho_{air}C_{air}}{G_{air0}\rho_{air}C_{air} + \alpha_{air}F_{ex}}}{(G_{oil}\rho_{oil}C_{oil} + \alpha_{oil}F_{ins})\left(\alpha_{oil}F_{ins} + \alpha_{air}F_{ex} - \frac{\alpha_{air}^2F_{ex}^2}{G_{air0}\rho_{air}C_{air} + \alpha_{air}F_{ex}}\right) - a_{oil}^2F_{ins}^2} \quad (8)$$

Indeed, for an oil air cooler with the following parameters of those represented in Table 2 below.

Table 2 – Values of the parameters

Parameter	Value
G_{air0}	$13.6m^3/s$
G_{oil}	$0.0166m^3/s$
ρ_{oil}	$843kg/m^3$
ρ_{air}	$1.1839kg/m^3$
C_{oil}	$1670J/kgK$
C_{pipe}	$460J/kgK$
C_{air}	$1005J/kgK$
m_{oil}	$434kg$
m_{pipe}	$1215kg$
α_{oil}	$286W/m^2K$
α_{air}	$11W/m^2K$
T_{air0}	$36.83°C$
$T_{air.in0}$	$25°C$
F_{in}	$144m^2$
F_{ex}	$1135m^2$

The transfer function will take the following form:

$$W_y(p) = -\frac{0{,}1781}{286{,}0733p^2+50{,}1418p+1} \quad (9)$$

According to the results of the Routh-Hurwitz analysis shown in Table 3, the system is stable.

Table 3 – Routh-Hurwitz table of the system

s2	286.1	1
s1	50.14	0
s0	1	0

From the calculations, it was concluded that the PID coefficients were as follows: P = 9.4737; I = 0.32842; D = 32.1799. Figure 2 (p. 35) shows the difference in the step response, comparing controller usage with modified parameters.

Through the mathematical model, an optimization of the design and operation of the heat exchanger has been made possible, with factors such as fluid flow rates, heat transfer coefficients, and material properties being considered. This optimization can lead to significant energy savings, decreased operational costs, and enhanced overall performance of HVAC systems.

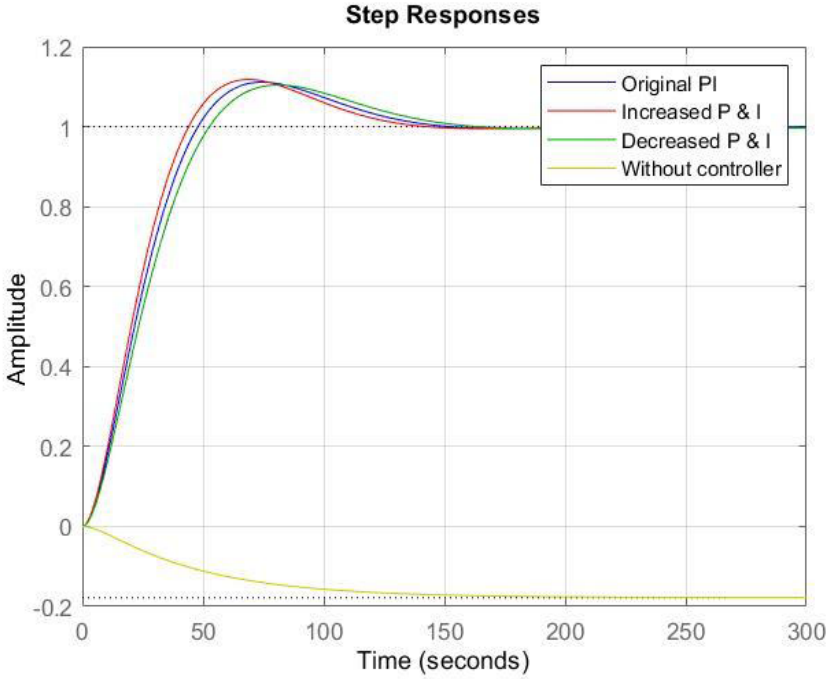

Figure 2 – Plot of the modified step response

Results and Discussion

The experiment was conducted at the Honeywell Laboratory at the Kazakh-British Technical University, as shown in Figure 3.

Figure 3 – Laboratory «Honeywell», C300 controller and Safety Manager

1. C300 controller configuration and HMI realization

For this system, a Honeywell C300 controller was programmed. The logic of fan control module code can be seen in Figure 4 (p. 36)

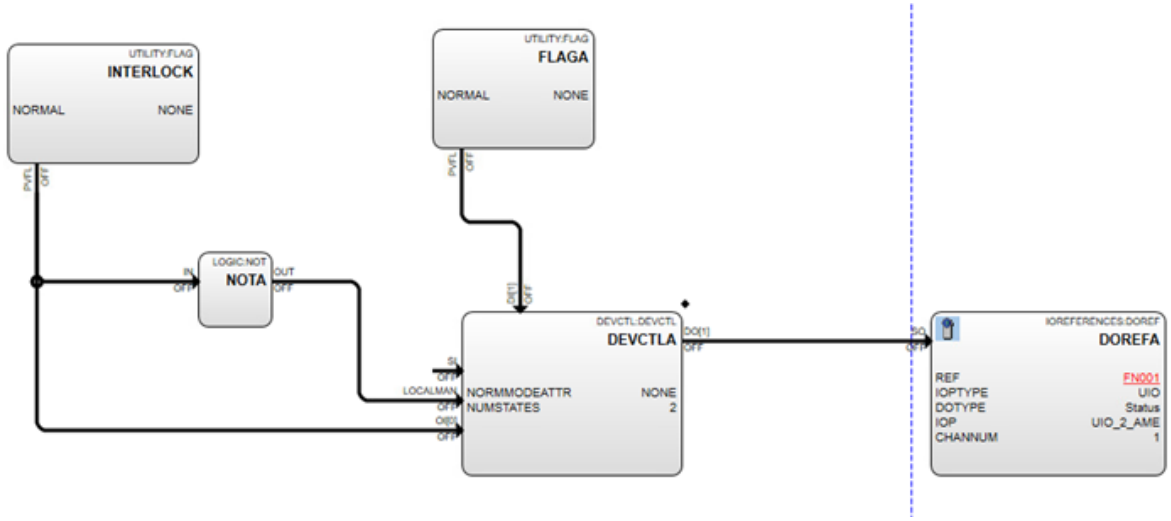

Figure 4 – Fan control module logic

The HMI panel in the HMI Web Display Builder is depicted in Figure 5, showcasing the process of air and desiccant solution flow through the regenerator, solution heater, and heat exchanger, as well as auto and manual modes and tabs for trend representation of the tuned parameters. The figure displays the outcomes of the PID controller implemented through a digital signal processing device, the coefficients of which were equal to those of the mathematical model.

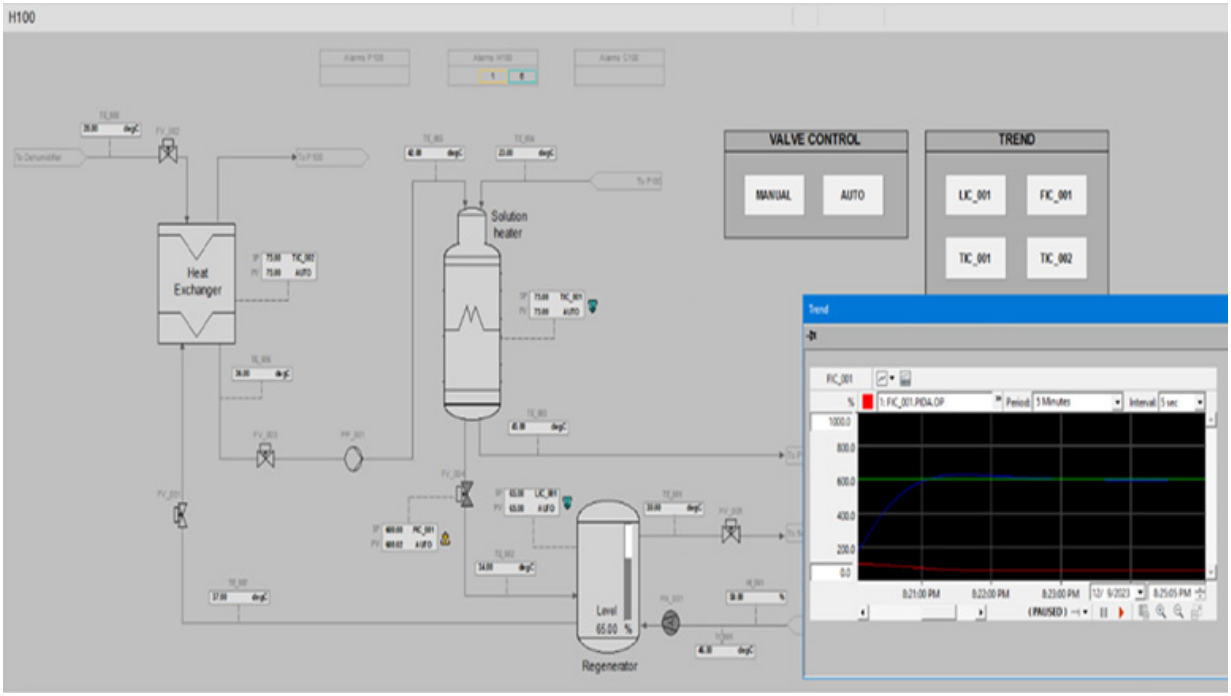

Figure 5 – HMI display with a dynamic trend for PID tuning

2 Safety System realization

The Safety Manager, a second-generation safety platform, adopts the Quadruple Modular Redundant (QMR) architecture seen in its earlier predecessors. Operating on a fully redundant

(2oo4D) architecture, Safety Manager seamlessly integrates process safety data, applications, system diagnostics, and critical control strategies. It executes SIL-defined safety application logic, ensuring a robust safety framework.

Figure 6 below presents the structural diagram of the safety function implementation on the control object with additional valves.

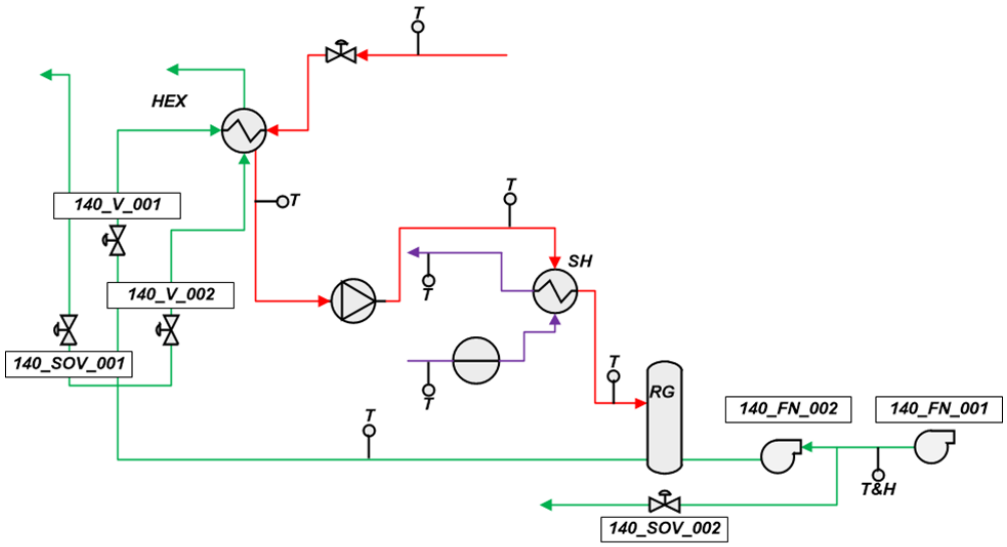

Figure 6 – Structural scheme of the safety function

Calculating RRF is necessary to determine SIL. RRF is a measure of the effectiveness of a risk mitigation or control measure in reducing the risk of a particular event or outcome. Using the created Fault Tree Analysis (FTA) diagram RRF can be calculated by formulas. In this process RRF = 11.327. After that, we can measure the SIL, which is used to quantify the level of risk reduction required to achieve an acceptable level of safety. The higher the SIL, the greater the required risk reduction.

Table 4 – SIL Determination

Safety Integrity Level (SIL)	Probability of Failure on Demand (PFD)	Safety Availability (1 – PFD)	Risk Reduction Factor (1/PFD)
4	0.0001 – 0.00001	99.99 – 99.999%	10000 – 100000
3	0.001 – 0.0001	99.9 – 99.99%	1000 – 10000
2	.01 – .001	99 – 99.9%	100 – 1000
1	0.1 – 0.01	90 – 99%	10 – 100

In this analysis, SIL 1 emerged as the most appropriate level to achieve an acceptable balance between risk reduction and the associated costs and complexities of safety measures. The determination of SIL 1 reflects a nuanced consideration of the specific context, aiming to implement effective safety measures without unnecessary over-engineering. This decision aligns with the overall goal of maintaining a safe and reliable system while optimizing resources and ensuring a pragmatic approach to functional safety.

Figure 7 (p. 38) shows how the safety function that is connected to Control Builder works.

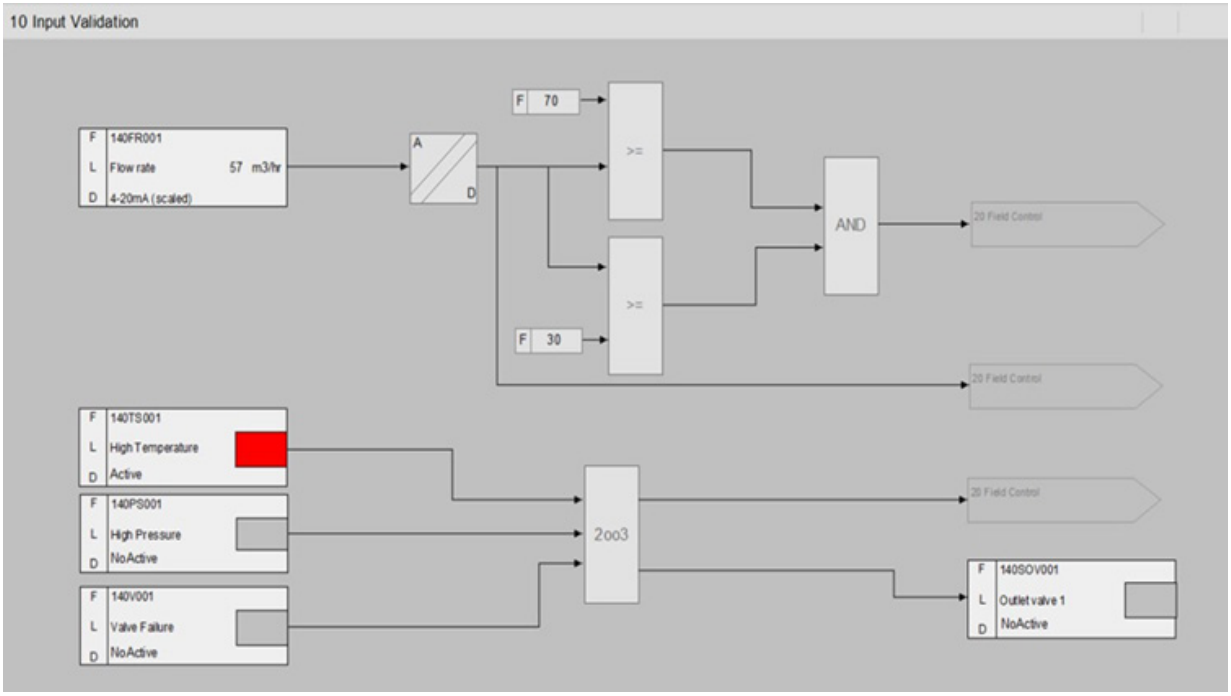

Figure 7 – Simulation of the safety function in HMI

The implementation of the program on the Honeywell Experion Process Knowledge System (PKS) has proven to be a pivotal step in enhancing control and automation within the system. Leveraging the advanced features and robust capabilities of the Experion PKS platform, that have successfully incorporated intricate logic, such as the 2oo3 voting principle, to ensure efficient and reliable field control.

Conclusion

The creation of HVAC systems for food industry course projects has been a thorough endeavor to explore the complex procedures related to polycondensation. Careful monitoring of the project's temperature, coolant flow, and material supply is necessary to guarantee the creation of an excellent product that complies with the specifications. The undertaking became even more complicated when random disturbances affecting the system dynamics were considered.

The utilization of mathematical modelling, particularly through the MATLAB software, plays a pivotal role in understanding and optimizing the control system. The study involved examining the mathematical model of the heat exchange process, incorporating the principles of physics-thermodynamics, and the specifics of air cooling. Acknowledging the prevalence of nonlinear differential equations in real-world scenarios, the mathematical model was appropriately simplified for practical application. Further scrutiny of the model's stability using the Hurwitz criteria, along with the synthesis of a regulator, demonstrated a systematic approach to the control system design.

The selection of programmable logic controllers from reputable manufacturers, such as Honeywell and various vendors, underscores a commitment to reliability and functionality. The development of control system software using Experion PKS and Safety Manager showcased the

seamless integration of theoretical knowledge into practical implementation. The operator's control panel, featuring real-time control graphs and various indicators, adds a crucial dimension to monitor and manage the polycondensation process.

The project's documentation, including the technological process scheme, automation scheme, technical instrumentation, and electrical schemes, provides a comprehensive resource for understanding and replicating the developed system. In essence, this HVAC system course project has not only explored the technical intricacies of polycondensation but has also successfully translated theoretical knowledge into a practical, automated control system with economic viability and safety considerations at its core.

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[1]Самигулина З.И.,
PhD, ORCID ID: 0000-0002-5862-6415, e-mail: z.samigulina@kbtu.kz
[1]Курмашева А.К.,
бакалавр, ORCID ID: 0009-0008-9570-0021, e-mail: kurmasheva-2002@mail.ru
[1]*Қазбек М.Қ.,
бакалавр, ORCID ID: 0009-0009-7573-2429, *e-mail: mad_kazbek@gmail.com

[1]Қазақстан-Британ техникалық университеті, 050000, Алматы қ., Қазақстан

HONEYWELL ЖАБДЫҚТАРЫНДА ТАМАҚ ӨНЕРКӘСІБІ ҮШІН ЖЫЛЫТУ, ЖЕЛДЕТУ ЖӘНЕ АУАНЫ БАПТАУ ПРОЦЕСІН АВТОМАТТАНДЫРУ ЖҮЙЕСІН ӘЗІРЛЕУ

Аңдатпа

Қазіргі уақытта өнеркәсіптік автоматиканың даму деңгейі күрделі объектілердің динамикалық қасиеттерін ескеретін жоғары дәлдіктегі басқару жүйелерін жүзеге асыруға мүмкіндік береді. Заманауи бағдарламалық өнімдер негізінде таратылған басқару жүйелерін құру технологиялық процестерді орталықтандырылмаған басқаруды қамтамасыз етеді. Қазіргі заманғы өнеркәсіптік жабдықтардың көмегімен қолданыстағы басқару жүйелерін жаңғырту кәсіпорындардың өнімділігі мен өндірістегі қауіпсіздікті арттыруға мүмкіндік береді. Мақала тамақ өнеркәсібі үшін жылыту, желдету және ауаны баптау процестерін басқарудың автоматтандырылған жүйесін әзірлеуге арналған. Мақалада басқару объектісі жылу алмастырғышты таңдайды. Басқару объектісінің тұрақтылыққа, басқаруға, бақылауға арналған математикалық моделі зерттелді. PID реттегіші синтезделді, PID реттегішінің коэффициенттері алынды. Реттегіштің әртүрлі коэффициенттеріндегі жүйе динамикасының мінез-құлқына салыстырмалы талдау жүргізілді. Модельдеу мен эксперименттердің нәтижелері «ҚБТУ» АҚ жанындағы «Honeywell» зертханасының базасында нақты өнеркәсіптік жабдықтар базасында жүргізілді. Бағдарламалық жасақтама Experion PKS таратылған басқару жүйесінде жүзеге асырылды. C300 контроллерінің конфигурациясы ұсынылған. Жүйенің қауіпсіз және ақаусыз жұмыс істеуі үшін авариядан қарсы автоматты қорғау жүйесі (АҚЖ) әзірленді. АҚЖ сонымен қатар Safety Manager және Safety Sontroller құралының көмегімен жасалады. Тәуекелді төмендету факторлары мен қауіпсіздік тұтастығының деңгейі есептеліп, талданады. Процесті басқарудың мнемикалық схемасы жасалды.

Тірек сөздер: жылыту, желдету және ауаны баптау, тамақ өнеркәсібі, өңдеу өнеркәсібі, бағдарламаланатын логикалық контроллер, күрделі нысан.

[1]Самигулина З.И.,
PhD, ORCID ID: 0000-0002-5862-6415, e-mail: z.samigulina@kbtu.kz
[1]Курмашева А.К.,
бакалавр, ORCID ID: 0009-0008-9570-0021, e-mail: kurmasheva-2002@mail.ru
[1]*Қазбек М.Қ.,
бакалавр, ORCID ID: 0009-0009-7573-2429, *e-mail: mad_kazbek@gmail.com

[1]Казахстанско-Британский технический университет, 050000, г. Алматы, Казахстан

РАЗРАБОТКА СИСТЕМЫ АВТОМАТИЗАЦИИ ПРОЦЕССОМ ОТОПЛЕНИЯ, ВЕНТИЛЯЦИИ И КОНДИЦИОНИРОВАНИЯ ВОЗДУХА ДЛЯ ПИЩЕВОЙ ПРОМЫШЛЕННОСТИ НА ОБОРУДОВАНИИ ФИРМЫ HONEYWELL

Аннотация

В настоящее время уровень развития промышленной автоматики позволяет реализовать высокоточные системы управления, учитывающие динамические свойства сложных объектов. Построение распределенных систем управления на основе современных программных продуктов обеспечивает децентрализованное управление технологическими процессами. Модернизация действующих систем автоматизации с помощью современного промышленного оборудования позволяет повысить производительность предприятий и безопасность на производстве. Статья посвящена разработке автоматизированной системы управления процессами отопления, вентиляции и кондиционирования воздуха для пищевой промышленности. В статье объектом управления выбран теплообменник. Исследована математическая модель объекта управления на устойчивость, управляемость, наблюдаемость. Синтезирован ПИД регулятор, получены коэффициенты ПИД регулятора. Проведен сравнительный анализ поведения динамики системы при разных коэффициентах регулятора. Результаты моделирования и экспериментов проводились на базе реального промышленного оборудования лаборатории «Honeywell» при АО «КБТУ». Программная реализация осуществлялась на распределенной системе управления Experion PKS. Представлена конфигурация контроллера C300. Разработана система противоаварийной автоматической защиты (ПАЗ) для безопасной и безотказной работы системы. ПАЗ также выполнена с применением инструмента Safety Manager и Safety Controller. Рассчитаны и проанализированы факторы снижения риска и уровень целостности безопасности. Разработана мнемосхема управления процессом.

Ключевые слова: отопление, вентиляция и кондиционирование воздуха, пищевая промышленность, обрабатывающая промышленность, программируемый логический контроллер, сложный объект.

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[1]*Zhumabayeva N.,
Master student, ORCID ID:0000-0003-3477-2781
*e-mail: n.zhumabayeva@kbtu.kz
[1]Mezin A.,
Senior junior researcher,
e-mail: a.mezin@kbtu.kz
[1]Knysheva A.,
Master of Arts in Media Studies, ORCID ID: 0000-0001-6644-7778,
e-mail: a.knysheva@kbtu.kz

[1]Kazakh-British Technical University, 050000, Almaty, Kazakhstan

THE IMPACT OF GAMIFICATION WITH AN EMPHASIS ON EXTERNAL MOTIVATION IN MOOCS FOR STUDENTS IN EMERGING REGIONS FROM AN UNDERPRIVILEGED GROUP: A CASE STUDY OF THE LEVEL UP COURSE BY GAMELAB KBTU AND UNICEF IN KAZAKHSTAN

Abstract

This paper examines the impact of gamification and external motivation on the engagement and completion rates of Massive Open Online Courses (MOOCs), with a focus on underprivileged groups in emerging regions. The research centres around the "LEVEL UP" course, a gamified MOOC designed to enhance STEM skills among young women in Kazakhstan, developed by GameLab KBTU in collaboration with UNICEF. Utilizing a combination of quantitative data analysis and literature review, the study investigates the efficacy of gamification strategies in increasing course completion rates, which are traditionally low in MOOCs. The findings indicate that the inclusion of gamification and external motivational elements, such as competitive elements and rewards, can improve completion rates. The LEVEL UP course, for example, achieved a completion rate of 10%, which is higher than the average completion rate of MOOC courses, which 5-8%. However, the study also highlights the complexity of balancing external and internal motivational factors to sustain long-term engagement and deep learning. Limitations encountered, including technical issues and platform constraints, underline the challenges of implementing such strategies effectively. Recommendations for further research include exploring the long-term impact of gamification, the optimal balance of motivational elements, and the customization of gamification to individual learner needs. This paper contributes to the growing body of evidence supporting the use of gamification in education, emphasizing the need for nuanced approaches that enhance both engagement and learning outcomes, particularly in the context of democratizing education for learners worldwide.

Key words: gamification, massive open online courses (MOOCs), external motivation, STEM education, underprivileged groups, emerging regions, course completion rates.

Introduction

The burgeoning utilization of Massive Open Online Courses (MOOCs) has become a transformative vector in disseminating knowledge, especially within underprivileged groups in emerging regions. Such online educational platforms promise a democratization of learning, potentially reaching vast numbers of students. However, a significant challenge emerges in the form of course completion rates; traditional, non-gamified MOOCs see completion rates languishing below 10% [5, 17, 18]. This paper posits gamification, with a focus on external motivation, as a potential solution to enhance student engagement and course completion. This paper will examine the efficacy of gamification with an emphasis on external motivation through the lens of the LEVEL UP project data, evaluating its impact on the completion rate of the course.

Literature review

Gamification in Informal Education

Gamification is the application of game design elements in non-game contexts. [1, 2, 3, 4, 13, 20] Research shows that gamification helps to increase students' learning engagement and motivation [1].

The application of gamification in non-formal education, including online platforms, significantly improves student satisfaction, enjoyment of the learning process and intention to participate in future activities, and positively affects knowledge acquisition [2].

Despite the positive results of gamification in MOOCs, the paper also identifies several research gaps, particularly the focus on developed countries [2, 21, 22, 23, 24] and the lack of evidence regarding gamification's effectiveness in developing country contexts. This oversight becomes even more critical considering that learners from developing countries tend to have lower MOOC completion rates [7, 8], highlighting an urgent need for research and targeted interventions to bridge these educational disparities. Additionally, further research is essential to understand how external motivation can be effectively integrated within gamified learning environments. [12]

This paper emphasizes the need for comprehensive research on the effects of gamification on MOOCs for students from underprivileged groups in developing regions. It is particularly important to examine how external motivational factors integrated into gamified MOOCs can influence learning engagement, motivation and academic success.

MOOC as a means of informal education in emerging regions

Massive Open Online Courses (MOOCs) have transformed the landscape of education, offering scalable and accessible learning opportunities worldwide. In emerging regions, MOOCs play a pivotal role in bridging educational gaps and providing informal education to underprivileged groups, facilitating skill development and lifelong learning.

Studies emphasize the importance of digital competencies for the successful completion of MOOCs, highlighting that individuals with higher digital skills are more likely to complete courses. This underscores the digital divide in emerging regions, where limited access to technology and internet connectivity can hinder the effectiveness of MOOCs [5].

The social aspect of MOOCs, including peer interactions and community engagement, is critical for learner retention and success. This dimension is especially significant in emerging regions, where educational resources are scarce, and MOOCs can provide a sense of community and shared learning experience [6].

While MOOCs offer considerable opportunities for informal education in emerging regions, challenges remain in maximizing their impact. There is a need for more targeted research on effective strategies to support learners from underprivileged backgrounds, ensuring that MOOCs are not only accessible but also inclusive and equitable.

This review highlights the complex interplay between technology, social factors, and educational outcomes in the context of MOOCs in emerging regions. By addressing the identified gaps, future research can contribute to the development of more effective, contextually appropriate MOOC offerings that truly democratize education for all learners, regardless of their geographical or socio-economic status.

External motivation in informal education

External motivation, as conceptualized within the framework of Self-Determination Theory (SDT), plays a crucial role in informal education settings, particularly in the context of gamification. Unlike internal motivation, which stems from an individual's internal desires and interests [10], external motivation involves external rewards or pressures [9, 11] that influence an individual's engagement in learning activities [12]. This segment of the literature review focuses on the role of external motivation in enhancing learning experiences and outcomes in informal educational contexts.

A critical examination of gamification practices reveals a common misapplication of motivational strategies, where excessive reliance on external rewards may undermine internal motivation, potentially leading to decreased long-term engagement [13].

Research on gamification design grounded in SDT suggests that while external motivators can be effective in initiating engagement, they should be carefully balanced with strategies that support autonomy, competence, and relatedness to foster internal motivation [12].

Studies have highlighted the nuanced impact of external motivation on learning, indicating that while it can drive initial participation, its effectiveness in sustaining engagement and promoting deep learning is limited. This underscores the importance of integrating external motivators with internal motivational elements [10].

The literature on external motivation in informal education underscores a complex interplay between external rewards and internal desires. While external motivators are effective in drawing learners into educational activities, their potential to detract from the internal value of learning poses a significant challenge. Furthermore, there is a gap in understanding how external motivators can be optimally designed to complement rather than detract from internal motivation, particularly in gamified learning environments.

There is also a need for empirical research focused specifically on the impact of external motivation in informal education settings, such as MOOCs or gamified learning platforms, especially in emerging regions or among underprivileged groups. Such studies could provide deeper insights into how external rewards influence learner engagement and achievement in these contexts.

This review highlights the critical need for a balanced approach to incorporating external motivation in informal education, emphasizing the design of motivational strategies that not only attract learners but also support their internal motivation and foster meaningful engagement with the learning material. By addressing these gaps, future research can contribute to more effective and sustainable educational practices that leverage external motivation to enhance, rather than undermine, the learning experience.

Underprivileged groups and emerging regions

The term “underprivileged groups” refers to social groups that face systemic barriers to accessing resources, opportunities, and rights. These barriers may be related to economic status, race, ethnicity, gender, or place of residence [27]. Women are often included in this category because of historical gender stereotypes and discrimination that limit their access to quality education and professional opportunities, especially in male-dominated fields such as Science, Technology, Engineering, and Mathematics. [28]

The concept of “emerging regions” refers to geographic and economic areas that are on the path to rapid socio-economic development but still face key challenges in education, health, and infrastructure. Kazakhstan, with its rapid economic growth and urbanization, is classified as an emerging region. [25, 26]

Studies aimed at analyzing and improving educational opportunities for underprivileged groups in emerging regions like Kazakhstan are of particular importance. They contribute to the development of strategies and approaches that address the unique challenges and needs of these groups, including women seeking STEM education and professional development. Gamification and digital learning technologies can play a key role in increasing motivation, engagement, and learning success among these groups by providing innovative and accessible pathways for learning and professional development. Such research not only helps to narrow educational and professional gaps, but also supports broader goals of social justice and equal opportunity. [29]

Research methods

About online course LEVEL UP

The “LEVEL UP: Introduction to Video Games and Gamification” course, developed by GameLab KBTU in collaboration with UNICEF, forms a component of a global initiative to enhance STEM skills among young women. This educational program in game development and gamification is aligned with the broader mission to foster inclusive educational opportunities. The curriculum,

designed to be accessible to all interested individuals, culminates in a selection process where 50 exemplary participants are chosen to partake in a three-day hackathon at the KBTU campus in Almaty, Kazakhstan. This event focuses on the gamification of the UniSat educational program, another UNICEF endeavor aimed at assembling nanosatellites, further providing participants with a practical application of their learning and an introduction to potential career paths in STEM. The course's lectures, delivered by KBTU faculty and industry experts, provide a comprehensive overview of the gaming industry, game development processes, and the educational potential of gamification, with a particular focus on the UniSat program as the primary object of gamification. Through this course, students are equipped with the tools to create their own games and explore engaging methods of learning, thereby expanding their skills and opening new vocational avenues.

The course was structured in the format of a Massive Open Online Course (MOOC), embodying distinctive characteristics such as the absence of live interaction with instructors, pivoting instead on an online model for content dissemination. This digital pedagogical approach facilitated a broad-reaching, inclusive educational experience, allowing participants from diverse geographical locations to engage with the curriculum at their own pace. Furthermore, the course content was hosted on the Learning Passport platform [31], a digital learning environment developed in collaboration between UNICEF and its partners.

Participants

The research focuses on the impact of gamification, particularly emphasizing external motivation in MOOCs designed for students in emerging regions of Kazakhstan, targeting underprivileged groups, specifically women. This demographic is critically important due to the global underrepresentation of women in STEM (Science, Technology, Engineering, and Mathematics) fields [14, 15], a disparity more pronounced in developing regions of Kazakhstan.

In 2023, the Global Gender Gap Report highlighted that women constitute only 29.2% of the STEM workforce across 146 nations, compared to nearly 50% in non-STEM occupations, underscoring the significant gender gap in these critical fields. This gap is not just a matter of workforce diversity but also reflects broader issues of access, opportunity, and equity in STEM education and careers for women, particularly in developing and emerging economies [14].

The participants for the LEVEL UP course by GameLab KBTU and UNICEF in Kazakhstan, were chosen aiming to address these disparities by engaging young women from underprivileged backgrounds in STEM-related learning through MOOCs. This initiative recognizes the importance of providing equitable access to quality STEM education as a means to empower women and encourage their participation in these fields, thereby contributing to reducing the gender gap.

Despite the fact that the gaming industry is a young and quite progressive industry when it comes to gender equality, even here women face underrepresentation and some barriers that prevent them from being realized in the industry [15]. Studies and reports, including those analyzing the esports industry, highlight the persistent gender disparities, with women often facing barriers to entry and progression [16]. These barriers are not just about access but also involve cultural and societal norms, stereotypes, and a lack of visible role models and mentors for young women aspiring to enter STEM fields.

By focusing on courses for underprivileged young women in Kazakhstan, this research aims to shed light on the specific challenges and opportunities that gamification and external motivational strategies present in informal educational settings. It seeks to understand how these approaches can be tailored to effectively engage and retain female students in STEM courses, thereby contributing to broader efforts to build a more inclusive and diverse STEM workforce.

Particularly, participants from emerging regions are at the heart of this initiative, with an appended table below showcasing the cities of those participants who successfully completed the course, further illustrating the geographic diversity and reach of this program within underprivileged demographics.

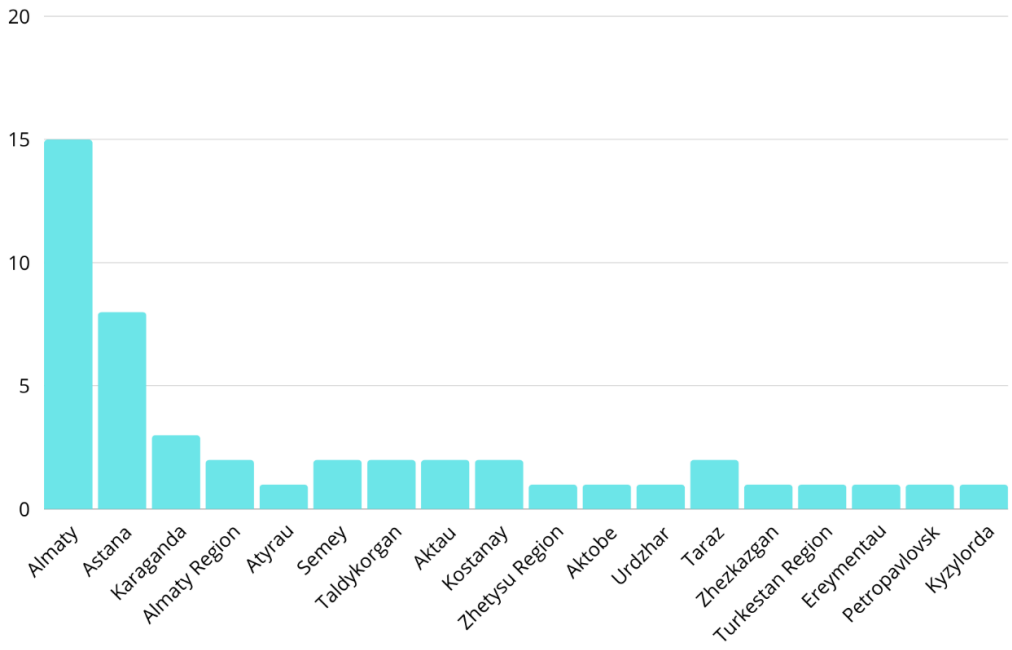

Figure 1 – Cities of participants and the number of participants from each city

Research design

Structure of course

The "LEVEL UP" course is segmented into three distinct parts, each comprising several sections that are further broken down into units or lessons. The structure is as follows:

Part 1 encompasses a general course overview, an in-depth look at the gaming industry, and the foundational elements of game development. Part 2 transitions into the creative aspects, covering the basics of game design, and extends into the practical applications of serious games and gamification. Part 3 is the technical culmination, providing a detailed exploration of the tools and technologies used in the field, alongside alternative methods and practices. The course concludes with a wrap-up in Section 8.

Table 1 – Course structure and topics

Part 1	Part 2	Part 3
Section 1 Course overview	Section 4 Game Design Basics	Section 6 Tools and Technologies
Section 2 Game Industry	Section 5 Serious Games & Gamification	Section 7 Alternative Techs and Methods
Section 3 Game Development		Section 8 Course wrap up

For successful course completion, students are required to navigate through all three parts. Assignments within the course are designed to be skippable and self-regulated, offering flexibility to accommodate various learning paces and styles. The entire course content is intended to be completed over a two-month period, allowing for a measured yet consistent progression through the material.

Education cycle

The educational methodology of the "LEVEL UP" course is bifurcated into minor and major educational cycles. The minor cycle is the foundational element, comprising a self-regulated assignment leading to a fully automated quiz, ensuring reinforcement of learned concepts. This is supplemented by a richly illustrated article and concluded with a video lecture, offering a multifaceted

approach to learning. The major cycle encapsulates the minor cycles, culminating in a comprehensive section quiz that integrates all previously encountered quizzes with additional questions to assess cumulative knowledge. The pinnacle of this structure is the project assignment, which is an integral part of the course project, allowing students to apply their knowledge in a practical, project-based context.

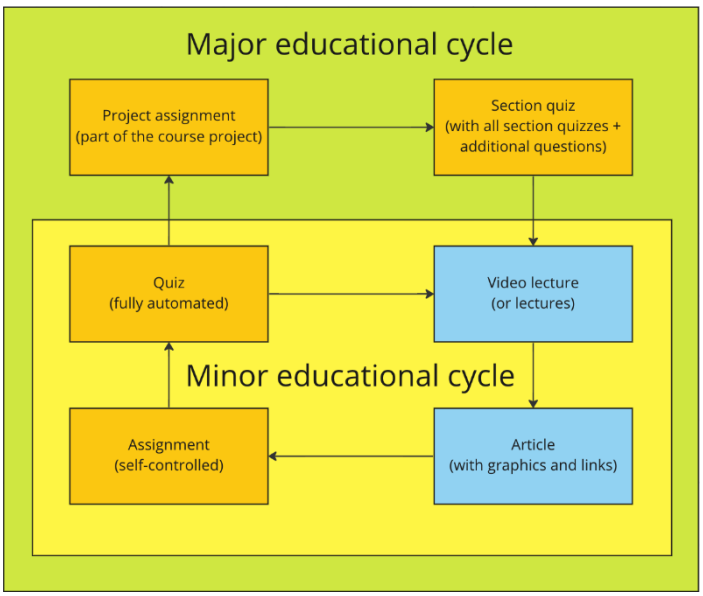

Figure 2 – Education cycle

Elements of gamification

In the “LEVEL UP” course [31], gamification was strategically implemented to enhance engagement through competitive elements, acting as external motivators. The course’s structure incorporated a merit-based selection mechanism where the top 50 performers, as evidenced by their course outcomes and certification, were granted the opportunity to participate in a specialized hackathon. This incentivized participation by offering comprehensive logistical support, including transportation to Almaty, accommodation, and sustenance, thereby removing potential barriers to entry.

The post-course hackathon, centered on the gamification of the UniSat nanosatellite assembly and launch course [32], presented a time-bound challenge to devise innovative project ideas. The competitive environment of the hackathon, characterized by its awarding of the best project proposals, not only provided a platform for the practical application of the course’s teachings but also served as a powerful external incentive, propelling students towards higher achievement and engagement within the educational framework.

Data analysis

Average completion rates of MOOC

The completion rates for MOOCs have been a focal point of educational research, revealing a broad range of outcomes. Studies show that average completion rates for MOOCs without gamification strategies linger between 5% to 8% [5, 17, 18] underscoring the challenge of keeping students engaged through course completion. However, when gamification strategies are applied, a notable increase is observed, with completion rates rising to an average of 14.43% compared to 6.162% in courses lacking these elements [17].

These findings are primarily based on data from developed countries, which may not fully represent the experiences of underprivileged groups in developing regions such as Kazakhstan. Our study targets this demographic, specifically focusing on young women, to assess whether competitive gamification mechanics emphasizing external rewards can influence completion rates differently.

It is imperative to acknowledge that our research was not conducted under uniform conditions. The course utilized to evaluate the impact of gamification, while distinct from others in its content and objectives, adhered to the Massive Open Online Course (MOOC) format, incorporating its specific attributes as detailed in Section 3.1. This context underscores the necessity to consider the unique structural and delivery mechanisms of MOOCs when interpreting the outcomes of our study.

Completion rates of LEVEL UP course

This section investigates the completion rates of the LEVEL UP course [30], focusing on participants' successful course progression. A total of 500 individuals registered for the course, with completion defined as successfully finishing all three parts of the course and obtaining a certification. Particular attention is paid to the distribution of completions across course segments. Out of the 500 participants, only 50 completed all three parts, resulting in a 10% overall completion rate. Further analysis reveals varying completion rates for each segment, with Part 1 showing the highest rate at 13.6%, followed by Part 2 at 10.2%, and Part 3 at 10%.

Comparison of completion rates of course with external motivation with average completion rates of course without external motivation

In the context of examining the impact of gamification strategies on MOOC completion, analyzing the completion rates of the LEVEL UP course where competitive and external motivation elements were applied compared to the average completion rates of courses without these elements reveals visible differences. Based on the data provided, the average completion rates of MOOCs without gamification strategies fluctuate between 5% and 8%, highlighting the difficulty of keeping students engaged until the end of the course. In contrast, the LEVEL UP course demonstrated a completion rate of 10%, a marked improvement.

This increase in completion rate can be attributed to the implementation of gamification mechanics emphasizing external motivation and competition, which is hypothesized to increase the level of engagement and motivation among students. These findings support the assumption that gamification can serve as a powerful tool to increase course completion rates, especially in MOOC contexts where students may feel less motivated due to the lack of direct interaction and support.

However, it is important to keep in mind that these findings on average MOOC completion rates are predominantly based on studies conducted in developed countries and may not fully reflect the experiences of underprivileged groups in emerging regions such as Kazakhstan. Our study targets this demographic, particularly young women, to assess whether competitive gamification mechanics emphasizing external rewards may affect completion rates differently.

In summary, the results point to the benefit of using gamification elements with external motivation in MOOC courses to increase completion rates among participants. This highlights the potential of gamification as a strategy for improving educational outcomes in digital environments, especially for students from emerging regions and underprivileged groups.

Results

In conclusion, our research underscores the positive impact of gamification, particularly with competitive elements and a focus on external motivation, on the completion rates of MOOC courses, evidenced by at least a 2% increase. This finding is significant within the broader discourse on educational engagement and retention strategies, especially in emerging regions where MOOCs serve as pivotal platforms for democratizing education. The nuanced application of gamification strategies, while beneficial in enhancing course completion, warrants cautious implementation to avoid undermining internal motivation and learner engagement.

Our investigation into the LEVEL UP course reveals that while external motivators can indeed foster initial engagement, their long-term effectiveness in sustaining participation and deep learning remains limited [12]. This aligns with the literature, suggesting that while external rewards can draw

learners into educational activities, their potential to detract from the internal value of learning poses a significant challenge [9, 13]. Therefore, a balanced approach, integrating both external and internal motivational elements, is essential for designing effective and engaging educational experiences.

Our study highlights the potential of gamification in the setting of emerging regions, offering insights into strategies that could mitigate the digital divide and promote inclusive and equitable learning opportunities. Carefully designed gamification strategies, which consider the specific needs and challenges of learners in emerging regions, can significantly enhance engagement and completion rates.

Looking ahead, the prospects for using gamification and external motivation in education, particularly in emerging regions, are promising. As we continue to explore these methodologies, it is crucial to adopt a nuanced approach that respects the complex interplay between different motivational drivers. Empirical research focused on diverse contexts, especially among underprivileged groups, will be pivotal in refining our understanding of how gamification can best be utilized to support equitable and engaging learning experiences.

Our findings contribute to the growing body of evidence supporting the efficacy of gamification in education. They underscore the need for ongoing research to optimize gamification strategies, ensuring they not only attract but also retain learners, fostering meaningful engagement and enhancing learning outcomes. As the educational landscape continues to evolve, leveraging the potential of gamification and external motivation in a balanced and thoughtful manner will be key to democratizing education and enabling learners worldwide to realize their full potential.

Discussion

Limitations

This study was subject to several limitations that may have affected its outcomes and interpretations. First, technical difficulties related to platform authentication impeded some students' access to their accounts, resulting in participant dropout. Moreover, the division of the course into three segments, necessitated by platform constraints, marked a departure from its intended design as a unified course. Additionally, platform-related glitches, including the loss of course progress that required students to repeat sections, contributed to student dissatisfaction and further dropout. Furthermore, a limitation of our analysis was the absence of proprietary data on course completion rates in the absence of gamification strategies. Consequently, we resorted to comparing with the average completion rate observed in similar educational settings.

Recommendation for further research

The findings of this study contribute insights into the potential of gamification and external motivation to enhance engagement and completion rates in MOOCs, particularly for underprivileged groups in emerging regions. However, several avenues for further research have emerged, which are crucial for deepening our understanding of these mechanisms and optimizing their application in informal education settings. These recommendations include:

1. Comparative studies across different regions: While this study focused on underprivileged groups in Kazakhstan, further research should explore the impact of gamification in MOOCs across various geographical and socio-economic contexts. Comparative studies could reveal nuanced understandings of gamification's effectiveness, accounting for cultural differences and varying levels of digital literacy.
2. Longitudinal impact of gamification: Investigate the long-term effects of gamification on learner engagement and educational outcomes. This includes studying the sustainability of external motivation over time and its influence on internal motivation, to determine whether gamified learning leads to lasting interest in the subject matter.
3. Integration of internal and external motivational elements: Future research should explore the optimal balance between internal and external motivational strategies within gamified learning

environments. This involves designing gamification elements that not only attract and retain learners but also foster a deeper engagement with the learning material, promoting meaningful and lasting educational experiences.

4. Customization of gamification elements: Examine how personalized gamification strategies can enhance learning experiences and outcomes. Research could focus on adaptive gamification systems that tailor challenges, rewards, and feedback to individual learner profiles, preferences, and performance levels.

5. Barrier analysis and inclusivity measures: Conduct in-depth analyses of barriers to MOOC completion among underprivileged groups, including gender-specific challenges in STEM fields. Studies should aim to identify and address the specific needs and obstacles faced by these learners, proposing targeted strategies to improve access, inclusivity, and equity.

6. Technological enhancements and platform usability: Given the technical challenges encountered in this study, further research is needed to understand the impact of platform usability on learner engagement and course completion rates. This includes the development and testing of more user-friendly and resilient educational platforms that minimize technical barriers to learning.

7. Impact on career trajectories and skill development: Investigate the long-term career and educational impacts of gamified MOOCs on participants, particularly those from underprivileged groups. This research could assess whether participation in such courses leads to improved employment opportunities, skill development, and increased participation in STEM fields.

8. Psychological and social factors: Explore the psychological and social dimensions of gamification in education, including how social interactions, community building, and peer support within MOOCs influence learning motivation and outcomes. This includes studying the role of gamification in fostering a sense of belonging and community among learners from diverse backgrounds.

By addressing these recommendations, future research can significantly contribute to the development of more effective, engaging, and inclusive educational practices that leverage gamification and external motivation. This will not only enhance learning experiences but also support broader efforts to democratize education and empower learners worldwide.

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[1]*Жұмабаева Н.,
магистрант, ORCID ID:0000-0003-3477-2781
*e-mail: n.zhumabayeva@kbtu.kz
[1]Мезин А.,
аға ғылыми қызметкер,
e-mail: a.mezin@kbtu.kz
[1]Кнышева А.,
медиа зерттеулер саласындағы өнер магистрі,
ORCID ID: 0000-0001-6644-7778, e-mail: a.knysheva@kbtu.kz

[1]Қазақстан-Британ техникалық университеті, 050000, Алматы қ., Қазақстан

ДАМУШЫ АЙМАҚТАРДАҒЫ ХАЛЫҚТЫҢ АЗ ҚАМТЫЛҒАН ТОПТАРЫНЫҢ СТУДЕНТТЕРІ ҮШІН ЖАОК-ҚА СЫРТҚЫ МОТИВАЦИЯҒА БАҒЫТТАЛҒАН ГЕЙМИФИКАЦИЯНЫҢ ӘСЕРІ: ҚАЗАҚСТАНДАҒЫ GAMELAB KBTU ЖӘНЕ UNICEF-ТІҢ LEVEL UP КУРСЫНА ТАҚЫРЫПТЫҚ ЗЕРТТЕУ

Андатпа

Бұл мақалада геймификация және сыртқы мотивацияның жаппай ашық онлайн курстарға (ЖАОК) қатысу және аяқтау көрсеткіштеріне әсері дамушы аймақтардағы аз қамтылған топтарға назар аударыла отырып зерттелді. Зерттеу орталығында STEM саласындағы дағдыларды дамыту мақсатында Қазақстанның жас әйелдеріне арналған ЮНИСЕФ-пен бірлесіп GAMELAB KBTU әзірлеген level up геймификацияланған ЖАОК курсы қарастырылды. Сандық деректерді талдау мен әдебиеттерді шолудың үйлесімін пайдалана отырып, зерттеу ЖАОК-та дәстүрлі түрде төмен курсты аяқтау деңгейін арттырудағы геймификация стратегияларының тиімділігін зерттейді. Зерттеу нәтижелері геймификация және бәсекелестік элементтер мен марапаттар сияқты сыртқы ынталандырушы элементтерді қосу курсты аяқтау көрсеткіштерін жақсартуға мүмкіндік береді деп болжайды. Мысалы, LEVEL UP курсының аяқтау көрсеткіші 10% құрайды, бұл жаппай ашық онлайн курстардың 5–8%-ға тең орташа аяқтау көрсеткішінен жоғары. Дегенмен зерттеу сондай-ақ сыртқы және ішкі мотивациялық факторларды ұзақ мерзімді қызығушылықты және терең оқуды сақтауда теңгерімді ұстаудың күрделілігін атап өтеді. Кездескен шектеулер, соның ішінде техникалық мәселелер мен платформа шектеулері мұндай стратегияларды тиімді жүзеге асырудағы қиындықтарды көрсетеді. Әрі қарайғы зерттеулер үшін ұсыныстар геймификацияның ұзақ мерзімді әсерін, мотивациялық элементтердің оптималды теңгерімін және жеке оқушы қажеттіліктеріне арналған геймификацияны бейімдеуді зерттеуді қамтиды. Бұл мақала білім беруде геймификацияны қолдануды қолдауға арналған дәлелдемелердің көбеюіне үлес қосады, әлем бойынша оқушылар үшін білімді демократиялаудың контекстінде қызығушылық пен оқу нәтижелерін арттыратын күрделі тәсілдерге мұқтаж екенін атап өтеді.

Тірек сөздер: геймификация, жаппай ашық онлайн курстар (ЖАОК), сыртқы мотивация, STEM білім беру, аз қамтылған топтар, дамушы аймақтар, курстарды аяқтау көрсеткіштері.

[1]*Zhumabayeva N.,
магистрант, ORCID ID:0000-0003-3477-2781
*e-mail: n.zhumabayeva@kbtu.kz
[1]Mezin A.,
ст. научный сотрудник,
e-mail: a.mezin@kbtu.kz
[1]Knysheva A.,
магистр искусств в области медиаисследований,
ORCID ID: 0000-0001-6644-7778, e-mail: a.knysheva@kbtu.kz

[1]Казахстанско-Британский технический университет, 050000, г. Алматы, Казахстан

ВЛИЯНИЕ ГЕЙМИФИКАЦИИ С АКЦЕНТОМ НА ВНЕШНЮЮ МОТИВАЦИЮ В MOOK ДЛЯ СТУДЕНТОВ В РАЗВИВАЮЩИХСЯ РЕГИОНАХ ИЗ МАЛООБЕСПЕЧЕННЫХ ГРУПП НАСЕЛЕНИЯ: ТЕМАТИЧЕСКОЕ ИССЛЕДОВАНИЕ КУРСА LEVEL UP ОТ GAMELAB KBTU И UNICEF В КАЗАХСТАНЕ

Аннотация

В данной статье рассматривается влияние геймификации и внешней мотивации на вовлеченность и уровень завершения массовых открытых онлайн-курсов (МООК) с акцентом на малообеспеченные группы населения в развивающихся регионах. В центре исследования курс LEVEL UP, геймифицированный МООК, разработанный GameLab KBTU в сотрудничестве с ЮНИСЕФ для молодых женщин Казахстана с целью развития навыков в области STEM. Используя сочетание количественного анализа данных и обзора литературы, в исследовании изучается эффективность стратегий геймификации в повышении уровня завершения курса, который традиционно низок в МООК. Результаты показывают, что включение геймификации и внешних мотивирующих элементов, таких как соревновательные элементы и вознаграждения, может улучшить показатели завершения курса. Например, курс LEVEL UP достиг уровня завершения в 10%, что выше среднего уровня завершения курсов МООС, который составляет 5–8%. Однако исследование также подчеркивает сложность баланса внешних и внутренних мотивационных факторов для поддержания долгосрочной вовлеченности и глубокого обучения. Возникшие ограничения, включая технические проблемы и ограничения платформы, подчеркивают трудности эффективной реализации таких стратегий. Рекомендации для дальнейших исследований включают изучение долгосрочного воздействия геймификации, оптимального баланса мотивационных элементов и адаптации геймификации к индивидуальным потребностям учащихся. Данная работа вносит вклад в растущее число фактов, поддерживающих использование геймификации в образовании, подчеркивая необходимость применения нюансированных подходов, которые повышают вовлеченность и результаты обучения, особенно в контексте демократизации образования для учащихся во всем мире.

Ключевые слова: геймификация, массовые открытые онлайн-курсы (МООК), внешняя мотивация, STEM образование, малообеспеченные группы, развивающиеся регионы, показатели завершения курсов.

МАТЕМАТИКАЛЫҚ ҒЫЛЫМДАР
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[1,2]Mambetov S.A.,
doctoral student, ORCID ID: 0000-0003-3394-756X,
e-mail: samatmambetov09@gmail.com

[1]Al-Farabi Kazakh National University, Almaty, 050040, Kazakhstan
[2]Institute of Mathematics and Mathematical Modeling, Almaty, 050010, Kazakhstan

INITIAL-BOUNDARY VALUE PROBLEMS TO THE TIME-NONLOCAL DIFFUSION EQUATION

Abstract

This article investigates a fractional diffusion equation involving Caputo fractional derivative and Riemann-Liouville fractional integral. The equation is supplemented by initial and boundary conditions in the domain defined by the interval by space $0 < x < 1$ and interval by time $0 < t < T$. The fractional operators are defined rigorously, utilizing the Caputo fractional derivative of order β and the Riemann-Liouville fractional integral of order α, where $0 < \alpha < \beta \leq 1$. The main results include the presentation of well-known properties associated with fractional operators and the establishment of the unique solution to the given problem. The key findings are summarized through a theorem that provides the explicit form of the solution. The solution is expressed as a series involving the two-parameter Mittag-Leffler function and orthonormal eigenfunctions of the Sturm-Liouville operator. The uniqueness of the solution is proven, ensuring that the problem has a single, well-defined solution under specific conditions on the initial function. Furthermore, the article introduces and proves estimates related to the Mittag-Leffler function, providing bounds crucial for the convergence analysis. The convergence of the series is investigated, and conditions for the solution to belong to a specific function space are established. The uniqueness of the solution is demonstrated, emphasizing its singularity within the given problem. Finally, the continuity of the solution in the specified domain is confirmed through the uniform convergence of the series.

Key words: fractional derivative, integral equation, the method of separation variables, time-nonlocal diffusion equation.

Introduction

Over the course of millennia, fractional partial differential equations (FPDEs) have evolved into essential tools for representing complex systems and anomalous phenomena [1]-[3]. A comprehensive exploration of the applications of these equations across disciplines such as chemistry, technology, and physics is presented in the book [4]. Notably, the book discusses the utilization of fractional derivatives to modify the classical diffusion equation, resulting in the equation of fractional diffusion in time. Additionally, [5] investigates initial-boundary value problems for the diffusion equation with variable coefficients, considering both Dirichlet and Neumann conditions.

In [6], Luchko extends the maximum principle to the generalized diffusion equation involving a fractional time derivative. This extension is applied to establish uniqueness and existence results for the initial-boundary value problem associated with the fractional diffusion equation.

The work in [7] focuses on exploring the generalized solution for the initial-boundary value problem of the diffusion equation with fractional time. Fractional calculus has emerged as a powerful tool for modeling and analyzing complex phenomena in various scientific disciplines. In this article, we delve into the realm of fractional partial differential equations, specifically exploring a novel equation involving Caputo fractional derivative and Riemann-Liouville fractional integral.

The equation, defined over the domain $\Omega = \{(x,t): 0 < x < 1, 0 < t < T\}$, is accompanied by carefully crafted initial and boundary conditions. Motivated by the intricate nature of fractional operators, we introduce the Caputo fractional derivative of order β and the Riemann-Liouville fractional integral of order α. These operators play a pivotal role in formulating and solving the fractional partial differential equation under consideration. To establish the groundwork, we present fundamental properties associated with these fractional operators, drawing upon existing literature [9, 10, 11, 12, 13, 14].

In summary, this article navigates through the complexities of fractional calculus, unraveling the unique features and behaviors of the presented partial differential equation. The insights gained here pave the way for a deeper comprehension of fractional operators and their applications in mathematical modeling.

In this article we consider the following equation

$$\left(D_{0+}^{\beta}u\right)(x,t) - \frac{\partial^2}{\partial x^2}\left(I_{0+}^{\alpha}u\right)(x,t) = 0, \text{ in } \Omega = \{(x,t): 0 < x < 1, 0 < t < T\} \quad (1.1)$$

with initial and boundary conditions

$$u(x,0) = \varphi(x) \text{ on } x \in [0,1], \quad (1.2)$$

$$u(0,t) = u(1,t) = 0,\ 0 \le t \le T, \quad (1.3)$$

where $0 < \alpha < \beta \le 1$ and the function φ is continuous. The operator D_{0+}^{β} stands for the Caputo fractional derivative of order $\beta \in (0,1)$ is defined by

$$\left(D_{0+}^{\beta}u\right)(x,t) = I_{0+}^{1-\beta}\left[\frac{\partial}{\partial t}u(x,t)\right] = \frac{1}{\Gamma(1-\beta)}\int_0^t (t-s)^{-\beta}\frac{\partial}{\partial s}u(x,s)ds$$

and the operator I_{0+}^{α} is the Riemann-Liouville fractional integral of order $\alpha > 0$, defined as

$$\left(I_{0+}^{\alpha}u\right)(x,t) = \frac{1}{\Gamma(\alpha)}\int_0^t (t-s)^{\alpha-1}u(x,s)ds, t \in (0,T].$$

The case when, instead of the operator I_{0+}^{α}, the time-degenerate diffusive coefficient t^{β} with $\beta > -\alpha$ is used, studied for the one-dimensional linear time-fractional diffusion equation in [9]

$$\left(D_{0+}^{\beta}u\right)(x,t) - t^{\beta}u_{xx}(x,t) = 0 \text{ in } (x,t) \in \mathbb{R} \times (0,\infty).$$

The authors have found an explicit solution by using the Kilbas-Saigo function. Moreover, the convergence, the existence and uniqueness of the solution of the problem are confirmed.

Solving such problems may involve using techniques like Laplace transforms, Fourier transforms, or other integral transforms to handle the nonlocal term. The well-known traits associated with fractional operators are presented below [15, 16, 17, 18].

Main provisions. Material and methods

The main purpose of this article is to present the key conclusions related to the classical solution. A central theorem provides an explicit expression for the solution, revealing a series representation involving the two-parameter Mittag-Leffler function. The uniqueness of the solution is rigorously proven, contingent upon specific conditions governing the initial function.

Furthermore, we introduce and prove estimates for the Mittag-Leffler function, crucial for understanding its behavior and ensuring convergence. The convergence of the series solution is scrutinized, and conditions for the solution to reside in a particular function space are derived. Emphasis is placed on the singularity of the solution within the given problem.

In the subsequent sections, we delve into the proof of continuity for the solution in the specified domain, demonstrating its uniform convergence. These results contribute significantly to the broader understanding of fractional partial differential equations and shed light on the intricacies associated with the involved operators [19.20].

Lemma 1.1. [3, P. 95] If $0 < \beta < 1$ for $T \in AC[0,T]$ or $T \in C'(0,T)$, then

$$I_{0+}^{\beta}\left[\left(D_{0+}^{\beta}T\right)(t)\right] = T(t) - T(0)$$

holds true.

Lemma 1.2. [3, P. 101] Let $T \in C[0,T]$. If $\alpha + \beta \leq 1$, then

$$I_{0+}^{\beta}[(I_{0+}^{\alpha}T)(t)] = \left(I_{0+}^{\alpha+\beta}T\right)(t).$$

Next, we have an estimate of the two-parameter Mittag-Leffler function $E_{\alpha,\beta}(-z)$.

Lemma 1.3. [8, P. 9] For every $\lambda \geq 0$ one has the optimal bounds

$$\left|E_{\xi,\beta}\left(-\lambda t^{\xi}\right)\right| \leq \frac{C}{1+|\lambda t^{\xi}|} \leq C,\ t \geq 0,\ b \geq 0,$$

$$\lambda t^{\xi}\left|E_{\xi,\beta}\left(-\lambda t^{\xi}\right)\right| \leq C,\ 0 < \xi < 2,\ \beta \in \mathbb{C}.$$

Results and discussion

This section summarizes the key findings of this article.

Theorem 2.1. Let $\varphi(x) \in C[0,1], \varphi'(x) \in L_2(0,1)$, then the unique solution of problem (1.1) – (1.3) is the function $u(x,t) \in C(\bar{\Omega})$, which has the form

$$u(x,t) = \sum_{k=1}^{\infty} \varphi_k X_k(x) E_{\alpha+\beta,1}(-\lambda_k t^{\alpha+\beta}), \tag{2.1}$$

where

$$\varphi_k = \sqrt{2}\int_0^1 \varphi(x)\sin(k\pi x)$$

and $E_{\alpha,\beta}(-z)$ is the two-parameter Mittag-Leffler function.

Proof. In view of the method separation of variables, any solution of problem (1.1)-(1.3) can be represented as

$$u(x,t) = \sum_{k=1}^{\infty} X_k(x)T_k(t), \quad (x,t) \in (0,1)\times(0,T), \tag{2.2}$$

and the function $\varphi(x)$ given in the following form

$$\varphi(x) = \sum_{k=1}^{\infty} \varphi_k X_k(x), \quad x \in (0,1),$$

where φ_k defined by

$$\varphi_k = \sqrt{2}\int_0^1 \varphi(x)X_k(x).$$

By substituting (2.2) into the equations (1.1)-(1.3), we have a separate problem for the variable t

$$\left(D_{0+}^{\beta}T_k\right)(t) + \lambda_k(I_{0+}^{\alpha}T_k)(t) = 0,\ t > 0 \tag{2.3}$$

and respect to x

$$X_k''(x) + \lambda_k X_k(x) = 0, \tag{2.4}$$

$$X_k(0) = X_k(1) = 0\ . \tag{2.5}$$

It is well-known the orthonormal eigenfunctions and related eigenvalues of the Dirichlet problem (2.4)-(2.5) are given by $X_k(x) = \sin(k\pi x)$ and $\lambda_k = (k\pi)^2$, respectively.

Applying I_{0+}^{β} to equation (2.3), we have

$$I_{0+}^{\beta}\left[\left(D_{0+}^{\beta}T_k\right)(t) + \lambda_k(I_{0+}^{\alpha}T_k)(t)\right] = 0.$$

Using Lemma 1.1 and Lemma 1.2 we obtain the following equation

$$\lambda_k\left(I_{0+}^{\alpha+\beta}T_k\right)(t) + T_k(t) = T_k(0),\ t > 0.$$

The integral equation has a unique solution (se [3], P.231)

$$T_k(t) = T_k(0)E_{\alpha+\beta,1}\left(-\lambda_k t^{\alpha+\beta}\right). \tag{2.6}$$

Consequently, we obtain the solution the problem (1.1)-(1.2)

$$u(x,t) = \sum_{k=1}^{\infty} \varphi_k X_k(x)E_{\alpha+\beta,1}(-\lambda_k t^{\alpha+\beta}), \quad (x,t) \in (0,1)\times(0,T). \tag{2.7}$$

Next, we consider the function (2.7), where
$0 < \alpha < \beta \leq 1, \varphi_k = (\varphi, X_k), X_k(x) = \sqrt{2}\sin\sqrt{\lambda_k}x$, $\lambda_k = (k\pi)^2$.

At this stage, we should prove that $u(x,t) \in C(\bar{\Omega})$ for $\Omega = \{(x,t): 0 < x < 1, 0 < t < T\}$. For this, we have to show the uniform convergence of series (2.7) in a closed domain $\bar{\Omega}$. Now, let us estimate the coefficients φ_k. By definition

$$\varphi_k = (\varphi, X_k) = \sqrt{2}\int_0^1 \varphi(x)\sin(k\pi x)dx \,. \tag{2.8}$$

Integrating by parts the integral (2.8), we obtain

$$\varphi_k = \sqrt{2}\int_0^1 \varphi(x)d\left[-\frac{\cos(k\pi x)}{k\pi}\right]$$

$$= -\varphi(x)\frac{\sqrt{2}\cos(k\pi x)}{k\pi}\Bigg|_{x=0}^{x=1} + \frac{\sqrt{2}}{k\pi}\int_0^1 \varphi'(x)\cos(k\pi x)dx.$$

If the conditions $\varphi(0) = \varphi(1) = 0$ are holds true, then it yields that

$$\varphi_k = \frac{1}{k\pi}\varphi_k^{(1)}, \tag{2.9}$$

where the function $\varphi_k^{(1)}$ defined by

$$\varphi_k^{(1)} = \int_0^1 \sqrt{2}\varphi'(x)\cos(k\pi x)\,dx. \tag{2.10}$$

In view of (2.9) and Lemma 1.3, also from the inequality $|X_k(x)| \leq C$, we get

$$|u(x,t)| \leq C\sum_{k=1}^{\infty}|\varphi_k| = C\sum_{k=1}^{\infty}\frac{1}{k}\left|\varphi_k^{(1)}\right|.$$

Therefore, we investigate the convergence of the series $\sum_{k=1}^{\infty}\frac{1}{k}\left|\varphi_k^{(1)}\right|$.

Using the Cauchy-Schwarz inequality, we have

$$\sum_{k=1}^{\infty}\frac{1}{k}\left|\varphi_k^{(1)}\right| \leq \sqrt{\sum_{k=1}^{\infty}\frac{1}{k^2}}\sqrt{\sum_{k=1}^{\infty}\left|\varphi_k^{(1)}\right|^2}\,.$$

Moreover, we also know that the system $Y_k(x) = \{\sqrt{2}\cos(k\pi x)\}_{k=1}^{\infty}$ is orthonormal in space $L_2(0,1)$ and for any function $g(x) \in L_2(0,1)$ the Bessel inequality holds

$$\sum_{k=1}^{\infty}|\varphi_k|^2 \leq \| \varphi(x) \|_{L_2}^2 = \int_0^1 \varphi^2(x)dx,$$

where

$$\varphi_k = (\varphi, Y_k) = \sqrt{2}\int_0^1 \varphi(x)\cos(k\pi x)\,dx.$$

So, if

$$\varphi(x) \in L_2(0,1) \Leftrightarrow \int_0^1 \varphi^2(x)dx < \infty,$$

then

$$\sum_{k=1}^{\infty} |\varphi_k|^2 < \infty,$$

i.e. the series converges.

Further, if $\varphi'(x) \in L_2(0,1)$, then for coefficients $\varphi_k^{(1)}$ of equality (2.10) using Bessel's inequality, we conclude $\sum_{k=1}^{\infty}\frac{1}{k}\left|\varphi_k^{(1)}\right|$.

Thus, if $\varphi'(x) \in L_2(0,1)$, then the number series $\sum_{k=1}^{\infty}\frac{1}{k}\left|\varphi_k^{(1)}\right|$ converges, when the next conditions hold true

$$\varphi(x) \in C[0,1], \varphi'(x) \in L_2[0,1],\ \varphi(0) = \varphi(1) = 0. \tag{2.11}$$

Consequently, the series (2.8) converges uniformly in the closed region $\bar{\Omega}$.

Therefore, the sum of this series, i.e. the function $u(x,t)$ of equality (2.1) belongs to class $C(\bar{\Omega})$.

Now let us show that the solution is unique. Assume that $u_1(x,t)$ and $u_2(x,t)$ are two solutions to the problem (1.1)-(1.3). We choose $u(x,t) = u_1(x,t) - u_2(x,t)$ so that $u(x,t)$ satisfies the equation and the initial and boundary conditions (1.2)-(1.3). Consider the following identity

$$T_k(t) = \int_0^1 u(x,t)\sin(k\pi x)dx,\ k \in N,\ t \geq 0\,. \tag{2.12}$$

Noting (2.3), we apply the operator D_{0+}^{β} to the left side of the equation (2.12)

$$\begin{aligned}\left(D_{0+}^{\beta}T_k\right)(t) &= \int_0^1 \left(D_{0+}^{\beta}u\right)(x,t)\sin(k\pi x)dx \\ &= -(k\pi)^2 I_{0+}^{\alpha}\int_0^1 u(x,t)\sin(k\pi x)dx \\ &= -(k\pi)^2 (I_{0+}^{\alpha}T_k)(t),\ k \in N,\ t \geq 0.\end{aligned}$$

As a result of (1.2) and (1.3) we have

$$T_k(0) = \int_0^1 u(x,0)\sin(k\pi x)dx = \int_0^1 \varphi(x)\sin(k\pi x)dx = 0.$$

In view of (2.6) we deduce that

$$T_k(t) = T_k(0)E_{\alpha+\beta,1}\left(-\lambda_k t^{\alpha+\beta}\right) = 0.$$

Since $T_k(0) = 0$, which means $u(x,t) = 0$. Hence $u_1(x,t) = u_2(x,t)$, and the problem (1.1)-(1.3) has a unique solution.

By applying the operators D_{0+}^{β} and I_{0+}^{α} to the identity (2.7), we get

$$(D_{0+}^{\beta}u)(x,t) = D_{0+}^{\beta}[\sum_{k=1}^{\infty}\varphi_k X_k(x)E_{\alpha+\beta,1}(-\lambda_k t^{\alpha+\beta})]$$
$$= \sum_{k=1}^{\infty}\varphi_k X_k(x)D_{0+}^{\beta}[E_{\alpha+\beta,1}(-\lambda_k t^{\alpha+\beta})] \quad (2.13)$$
$$= -\sum_{k=1}^{\infty}\varphi_k X_k(x)\lambda_k t^{\alpha}E_{\alpha+\beta,\alpha+1}(-\lambda_k t^{\alpha+\beta})$$

and

$$(I_{0+}^{\alpha}u)(x,t) = I_{0+}^{\alpha}[\sum_{k=1}^{\infty}\varphi_k X_k(x)E_{\alpha+\beta,1}(-\lambda_k t^{\alpha+\beta})]$$
$$= \sum_{k=1}^{\infty}\varphi_k X_k(x)I_{0+}^{\alpha}[E_{\alpha+\beta,1}(-\lambda_k t^{\alpha+\beta})] \quad (2.14)$$
$$= -\sum_{k=1}^{\infty}\varphi_k X_k(x)t^{\alpha}E_{\alpha+\beta,\alpha+1}(-\lambda_k t^{\alpha+\beta})$$

.

By using the operator $\frac{\partial^2}{\partial x^2}$ to the (2.14), we deduce that

$$\frac{\partial^2}{\partial x^2}(I_{0+}^{\alpha}u)(x,t) = \sum_{k=1}^{\infty}\varphi_k \frac{\partial^2}{\partial x^2}X_k(x)t^{\alpha}E_{\alpha+\beta,\alpha+1}(-\lambda_k t^{\alpha+\beta})$$
$$= \sum_{k=1}^{\infty}\varphi_k X_k(x)\lambda_k t^{\alpha}E_{\alpha+\beta,\alpha+1}(-\lambda_k t^{\alpha+\beta}).$$

Next, we show that $D_{0+}^{\beta} \in C(\Omega)$ and $I_{0+}^{\alpha} \in C(\Omega)$.

Let δ be an arbitrary, sufficiently small positive number. Then for all $0 < \delta \leq t$, from Lemma 1.3 , we get

$$\left|D_{0+}^{\beta}u(x,t)\right| = \left|\sum_{k=1}^{\infty}\varphi_k X_k(x)\lambda_k t^{\alpha}E_{\alpha+\beta,\alpha+1}\left(-\lambda_k t^{\alpha+\beta}\right)\right|$$
$$= \left|\sum_{k=1}^{\infty}\varphi_k X_k(x)t^{-\beta}\lambda_k t^{\alpha+\beta}E_{\alpha+\beta,\alpha+1}\left(-\lambda_k t^{\alpha+\beta}\right)\right|$$
$$\leq C\sum_{k=1}^{\infty}|\varphi_k|$$

and

$$|I_{0+}^{\alpha}u(x,t)| = \left|\sum_{k=1}^{\infty}\varphi_k X_k(x)\lambda_k t^{\alpha}E_{\alpha+\beta,\alpha+1}\left(-\lambda_k t^{\alpha+\beta}\right)\right|$$
$$= \left|\sum_{k=1}^{\infty}\varphi_k X_k(x)t^{-\beta}\lambda_k t^{\alpha+\beta}E_{\alpha+\beta,\alpha+1}\left(-\lambda_k t^{\alpha+\beta}\right)\right|$$
$$\leq C\sum_{k=1}^{\infty}|\varphi_k|.$$

If the conditions (2.11) hold true, the series $\sum_{k=1}^{\infty}|\varphi_k|$ converges, and then the series (2.13) and (2.14) representing the function $D_{0+}^{\beta}u(x,t)$ and $\frac{\partial^2}{\partial x^2}(I_{0+}^{\alpha}u)(x,t)$ converges uniformly in any closed subdomain $\bar{\Omega}_{\delta}$ of the domain Ω. Therefore, due to the arbitrariness of the number δ, we have $D_{0+}^{\beta}u \in C(\Omega)$ and $I_{0+}^{\alpha}u \in C(\Omega)$.

Conclusion

In this paper, the main results include the presentation of well-known properties associated with fractional operators and the establishment of a classical solution to this problem. The key conclusions are summarized using a theorem that provides an explicit form of the solution. The solution is expressed as a series including the two-parameter Mittag-Leffler function and orthonormal eigenfunctions of the Sturm-Liouville operator. The uniqueness of the solution is proved, which guarantees that the problem has a unique solution.

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[1,2]Мамбетов С.А.,
докторант, ORCID ID 0000-0003-3394-756X,
e-mail: samatmambetov09@gmail.com

[1]әл-Фараби атындағы Қазақ ұлттық университеті, Алматы қ., 050040, Қазақстан
[2]Математика және математикалық модельдеу институты, Алматы қ., 050010, Қазақстан

УАҚЫТ БОЙЫНША БЕЙЛОКАЛДЫ ДИФФУЗИЯ ТЕҢДЕУІ ҮШІН БАСТАПҚЫ-ШЕТТІК ЕСЕП

Аңдатпа

Бұл мақалада Капуто мағынасындағы бөлшек ретті туынды мен Риман-Лиувилл мағынасындағы бөлшек ретті интегралдау операторлары қатысқан бөлшек ретті диффузия теңдеуі қарастырылады. Теңдеу кеңістік бойынша $0<x<1$ кесіндісінде және уақыт бойынша $0<t<T$ кесіндісінде анықталған аймағында бастапқы және шекаралық шарттармен толықтырылған. Бөлшек операторлар $0<\alpha<\beta\leq 1$ арқылы, яғни β ретті Капутоның бөлшек ретті туындысы және α ретті Риман-Лиувилл бөлшек ретті интегралы арқылы анықталады. Негізгі нәтижелер – бөлшек операторлармен байланысты белгілі қасиеттерді ұсыну мен жалғыз шешімнің болуы. Негізгі тұжырымдар шешімнің айқын формасын қамтамасыз ететін теорема арқылы жалпыланған. Шешім екі параметрлі Миттаг-Леффлер функциясын және Штурм-Лиувилл операторының ортонормалды меншікті функцияларын қамтитын қатар түрінде көрсетіледі. Шешімнің жинақтылығы дәлелденді, бұл есептің бастапқы функция үшін белгілі бір жағдайларда жалғыз, нақты анықталған шешімі болуын қамтамасыз етеді. Сонымен қатар мақалада жинақтылықты талдау үшін, Миттаг-Леффлер функциясымен байланысты маңызды бағалаулар енгізіліп, дәлелденеді. Қатардың жинақтылығы зерттеледі және шешімнің белгілі бір функционалды кеңістікке жату шарттары белгіленеді. Бұл есептің шеңберінде оның ерекшелігін көрсететін жалғыз шешім көрсетіледі. Көрсетілген аймақтағы шешімнің үздіксіздігі қатардың біркелкі жинақты болуымен дәлелденді.

Тірек сөздер: бөлшек туынды, интегралдық теңдеу, айнымалыларды ажырату әдісі, уақыт бойынша бейлокалды диффузия теңдеуі.

[1,2]Мамбетов С.А.,
докторант**,** ORCID ID 0000-0003-3394-756X,
e-mail: samatmambetov09@gmail.com

[1]Казахский Национальный университет им. аль-Фараби, г. Алматы, 050040, Казахстан
[2]Институт математики и математического моделирования, г. Алматы, 050010, Казахстан

НАЧАЛЬНО-КРАЕВЫЕ ЗАДАЧИ ДЛЯ УРАВНЕНИЯ НЕЛОКАЛЬНОЙ ПО ВРЕМЕНИ ДИФФУЗИИ

Аннотация

В этой статье исследуется уравнение дробной диффузии, включающее дробную производную Капуто и дробный интеграл Римана-Лиувилля. Уравнение дополнено начальными и граничными условиями в области, определяемой интервалом $0<x<1$ по пространственной переменной и $0<t<T$ по временной перемен-

ной. Дробные операторы определены строго, используя дробную производную Капуто порядка β и дробный интеграл Римана-Лиувилля порядка α, где $0<\alpha<\beta\leq 1$. Основные результаты включают представление хорошо известных свойств, связанных с дробными операторами, и установлено единственное решение данной задачи. Ключевые выводы обобщены с помощью теоремы, которая обеспечивает явную форму решения. Решение выражается в виде ряда, включающего двухпараметрическую функцию Миттага-Леффлера и ортонормированные собственные функции оператора Штурма-Лиувилля. Доказана единственность решения, гарантирующая, что задача имеет единственное, четко определенное решение при определенных условиях для исходной функции. Кроме того, в статье вводятся и доказываются оценки, связанные с функцией Миттага-Леффлера, предоставляя оценки, имеющие решающее значение для анализа сходимости. Исследуется сходимость ряда и устанавливаются условия принадлежности решения определенному функциональному пространству. Демонстрируется единственное решение, подчеркивающее его необычность в рамках данной задачи. Непрерывность решения в указанной области подтверждается равномерной сходимостью ряда.

Ключевые слова: дробная производная, интегральное уравнение, метод разделения переменных, уравнение диффузии бейлокала по времени.

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[1,2]Бакирова Э.А.,
ф-м.ғ.к., ORCID ID: 0000-0002-3820-5373, e-mail: bakirova1974@mail.ru
[1]Искакова Н.Б.,
ф-м.ғ.к., ORCID ID: 0000-0002-0680-4099, e-mail: narkesh@mail.ru
[1,3]Темешева С.М.,
ф-м.ғ.д., ORCID ID: 0000-0002-3341-4539, e-mail: temeshevasvetlana@gmail.com
[1,4]*Кадирбаева Ж.М.,
ф-м.ғ.к., ORCID ID: 0000-0001-8861-4100, e-mail: zhkadirbayeva@gmail.com

[1]Математика және математикалық моделдеу институты, Алматы қ., Қазақстан
[2]Қазақ ұлттық қыздар педагогикалық университеті, Алматы қ., Қазақстан
[3]әл-Фараби атындағы Қазақ ұлттық университеті, Алматы қ., Қазақстан
[4]Халықаралық ақпараттық технологиялар университеті, Алматы қ., Қазақстан

ПАРАМЕТРІ БАР ДИФФЕРЕНЦИАЛДЫҚ ТЕҢДЕУ ҮШІН ШЕТТІК ЕСЕПТІҢ БІРМӘНДІ ШЕШІЛІМДІЛІГІ ТУРАЛЫ

Аңдатпа

Ақырлы интервалда параметрлеу әдісі негізінде параметрі бар дифференциалдық теңдеу үшін сызықтық шеттік есеп зерттеледі. Интервалды бөлу, бөлу нүктелерінде қосымша параметрлерді және жаңа функцияларды енгізу арқылы зерттелді. Параметрі бар шеттік есеп эквивалентті параметрлері бар көп нүктелі шеттік есепке келтірілді. Алынған эквивалентті шеттік есеп жаңа функцияларға қатысты жай дифференциалдық теңдеулер үшін Коши есептерін қамтиды. Коши есебінің шешімінің кейіптемесін шешімнің үзіліссіздік шарттары мен шеттік шарттарына қою арқылы енгізілген параметрлерге қатысты сызықтық алгебралық теңдеулер жүйесі құрастырылды. Параметрлері бар шеттік есептің шешімін табу алгоритмі құрастырылды. Параметрлері бар шеттік есептің бірмәнді шешілімділігінің жеткілікті шарттары туралы теореманың тұжырымы ұсынылды. Бастапқы шеттік есептің бастапқы берілімдер терминінде оның бірмәнді шешілімділігінің жеткілікті шарттары алынды. Теоремалардың шарттарының орындалуын көрсететін мысал келтірілді.

Тірек сөздер: параметрі бар дифференциалдық теңдеу, шеттік есеп, шешілімділік, параметрлеу әдісі.

Ұсынылып отырған жұмыста параметрі бар дифференциалдық теңдеу үшін шеттік есеп қарастырылады

$$\frac{dz}{dt} = \mathcal{A}(t)z + \mathcal{A}_0(t)\mu + f(t), \qquad t \in (0,T), \qquad z \in \mathbb{R}^n, \qquad \mu \in \mathbb{R}^l, \qquad (1)$$

$$B_1 z(0) + P_1\mu + C_1 z(T) = d_1, \qquad d_1 \in \mathbb{R}^n, \qquad (2)$$

$$B_2 z(0) + P_2\mu + C_2 z(T) = d_2, \qquad d_2 \in \mathbb{R}^l, \qquad (3)$$

мұндағы $(n \times n)$ – өлшемді $\mathcal{A}(t)$. $(n \times l)$ – өлшемді $\mathcal{A}_0(t)$ матрицалары және n – өлшемді $f(t)$ вектор – функциясы $[0,\ T]$ аралығында үзіліссіз, $(n \times n)$ – өлшемді B_1, C_1 матрицалары, $(l \times n)$ – өлшемді B_2, C_2 матрицалары, $(n \times l)$ – өлшемді P_1 матрицасы және $(l \times l)$ – өлшемді P_2 матрицасы – тұрақты, $\|z\| = \max\limits_{i=1,n}|z_i|$, $\|z\|_1 = \max\limits_{t\in[0,T]}\|z(t)\|$, $\|\mathcal{A}(t)\| \le \alpha$, $\|\mathcal{A}_0(t)\| \le \alpha_0$, α, α_0 – const.

(1)–(3) есебінің шешімі деп $t \in [0,T]$ аралығында $\mu = \mu^*$ мәндері үшін (1) дифференциалдық теңдеуін және (2), (3) шеттік шарттарын қанағаттандыратын $(z^*(t), \mu^*)$ жұбын айтамыз, мұндағы $z^*(t) \in C^1([0,T], \mathbb{R}^n)$, μ^* – параметр.

Кіріспе

Параметрі бар дифференциалдық теңдеулер үшін шеттік есептер қолданбалы математиканың, физиканың, биологияның, медицинаның және т.б. салаларда қолданылады. Сонымен қатар мұндай есептер әртүрлі процестерді модельдеу үшін ғылым мен инженерияда кеңінен қолданылады.

Параметрі бар дифференциалдық теңдеулер жүйесі үшін шеттік есептерді шешуде тиімділеу әдістерін, ауытқу әдістерін, ақырлы айырымдық әдістерін, максимум қағидаты мен тағы басқа әдістерді қолдану көптеген ғалымдардың жұмыстарында [1–9] қарастырылған. Соған қарамастан, параметрі бар дифференциалдық теңдеулер жүйесі үшін шеттік есептердің бірмәнді шешілімділігін бастапқы берілімдер терминінде тағайындау және оның жуық шешімдерін табудың алгоритмдерін құру мәселелері ашық болып қалып отыр.

Параметрі бар шеттік есептерді зерттеу мен шешудің конструктивті әдістерінің бірі параметрлеу әдісі. Бұл әдіс Д.С. Жұмабаевтың [10] жұмысында жай дифференциалдық теңдеулер жүйесі үшін шеттік есептерді зерттеуге және шешуге арналып жасалған. Ары қарай параметрлеу әдісі дифференциалдық теңдеулердің әртүрлі кластары үшін шеттік есептерді шешуде Д.С. Жұмабаевтың [11, 12] және оның оқушыларының жұмыстарында [13–22] орын алды.

Ұсынылып отырған жұмыста Жұмабаевтың параметрлеу әдісі негізінде (1)–(3) есебінің бірмәнді шешілімділігінің шарттары алынып, оның шешімін табудың алгоритмдері құрылады.

Материалдар мен әдістер

Параметрлеу әдісінің сүлбесін пайдаланып, $[0,T]$ аралығын келесі бөліктерге бөлейік:

$$[0,T) = \bigcup_{r=1}^{N} [(r-1)h, rh).$$

Ізделінді $z(t)$ функциясының бөлінген аралықтарға сығылуын $z_r(t), \quad t \in [(r-1)h, rh), \quad r = \overline{1,N}$, деп белгілейік. $\lambda_r = z_r((r-1)h)$, $r = \overline{1,N}$, қосымша параметрлерін енгізіп және әрбір $[(r-1)h, rh), r = \overline{1,N}$, аралықтарында $u_r(t) = z_r(t) - \lambda_r, r = \overline{1,N}$, алмастыруларын жасасақ, онда келесі параметрлері бар пара-пар шеттік есебін аламыз:

$$\frac{du_r}{dt} = \mathcal{A}(t)(u_r(t) + \lambda_r) + \mathcal{A}_0(t)\mu + f(t), \quad t \in [(r-1)h, rh), \ r = \overline{1,N}, \quad (4)$$

$$u_r((r-1)h) = 0, \qquad r = \overline{1,N}, \quad (5)$$

$$B_1\lambda_1 + P_1\mu + C_1\lambda_N + C_1 \lim_{t \to T-0} u_N(t) = d_1, \quad (6)$$

$$B_2\lambda_1 + P_2\mu + C_2\lambda_N + C_2 \lim_{t \to T-0} u_N(t) = d_2, \quad (7)$$

$$\lambda_s + \lim_{t \to sh-0} u_s(t) = \lambda_{s+1}, \qquad s = \overline{1,N-1}, \quad (8)$$

мұндағы (8) – шешімнің үзіліссіздік шарттары.

(4)–(8) есебінің шешімі деп $(\Lambda^*, u^*[t])$ жұбын айтамыз, мұндағы

$$\Lambda^* = (\lambda_1^*, \lambda_2^*, \dots, \lambda_N^*, \mu^*) \in \mathbb{R}^{nN+l},$$

$$u^*[t] = \left(u_1^*(t), u_2^*(t), \dots, u_N^*(t)\right),\ u_r^*(t) \in C^1([(r-1)h, rh), \mathbb{R}^n),\ r = \overline{1,N}.$$

(1)–(3) және (4)–(8) есептері пара-пар есептер болады. Егер $(z^*(t), \mu^*)$ жұбы (1)–(3) есебінің шешімі болса, онда келесі $(\Lambda^*, u^*[t])$ жұбы, мұндағы

$$\Lambda^* = \left(z^*(0), z^*(h), \dots, z^*\left((N-1)h\right), \mu^*\right),$$

$$u^*[t] = \left(z^*(t) - z^*(0), z^*(t) - z^*(h), \dots, z^*(t) - z^*\left((N-1)h\right)\right)$$

(4)–(8) есебінің шешімі болады. Керісінше, егер $\left(\widehat{\Lambda}, \hat{u}[t]\right)$ жұбы (4)–(8) есебінің шешімі болса, онда

$$\hat{z}(t) = \hat{\lambda}_r + \hat{u}_r(t),\ t \in [(r-1)h, rh),\ r = \overline{1,N},$$

$$\hat{z}(T) = \hat{\lambda}_N + \lim_{t \to T-0} \hat{u}_N(t),$$

теңдіктерімен анықталатын $(\hat{z}(t), \hat{\mu})$ жұбы бастапқы (1)–(3) есебінің шешімі болады, мұнда $\hat{\mu}$ параметрі $\widehat{\Lambda}$ векторының соңғы компонентіне тең.

$\mu,\ \lambda_r,\ r = \overline{1,N}$, параметрлерінің бекітілген мәндерінде (4), (5) Коши есептері келесі интегралдық теңдеулерге пара-пар болады:

$$u_r(t) = \int_{(r-1)h}^{t} \mathcal{A}(\tau)(u_r(\tau) + \lambda_r)d\tau + \int_{(r-1)h}^{t} \mathcal{A}_0(\tau)\mu d\tau + \tag{9}$$

$$+ \int_{(r-1)h}^{t} f(\tau)d\tau,\ t \in [(r-1)h, rh),\ r = \overline{1,N}.$$

Енді интегралдың астындағы $u_r(\tau), r = \overline{1,N}$, функцияларының орнына (9) теңдеуінің сәйкес оң жақтарын қойып, бұл үдерісті $\nu\ (\nu = 1,2,\dots)$ рет қайталасақ, онда $u_r(t)$, $r = \overline{1,N}$, функцияларының келесі кейіптемелерін аламыз

$$u_r(t) = D_{\nu r}(t)\lambda_r + H_{\nu r}(t)\mu + G_{\nu r}(u,t) + F_{\nu r}(t), \tag{10}$$

мұндағы

$$D_{\nu r}(t) = \int_{(r-1)h}^{t} \mathcal{A}(\tau_1)d\tau_1 + \int_{(r-1)h}^{t} \mathcal{A}(\tau_1) \int_{(r-1)h}^{\tau_1} \mathcal{A}(\tau_2)d\tau_2 d\tau_1 + \dots +$$

$$+ \int_{(r-1)h}^{t} \mathcal{A}(\tau_1) \dots \int_{(r-1)h}^{\tau_{\nu-2}} \mathcal{A}(\tau_{\nu-1}) \int_{(r-1)h}^{\tau_{\nu-1}} \mathcal{A}(\tau_\nu)d\tau_\nu d\tau_{\nu-1} \dots d\tau_1,$$

$$M_{\nu r}(t) = \int_{(r-1)h}^{t} \mathcal{A}_0(\tau_1)d\tau_1 + \int_{(r-1)h}^{t} \mathcal{A}(\tau_1) \int_{(r-1)h}^{\tau_1} \mathcal{A}_0(\tau_2)d\tau_2 d\tau_1 + \dots +$$

$$+\int_{(r-1)h}^{t}\mathcal{A}(\tau_1)\dots\int_{(r-1)h}^{\tau_{\nu-2}}\mathcal{A}(\tau_{\nu-1})\int_{(r-1)h}^{\tau_{\nu-1}}\mathcal{A}_0(\tau_\nu)d\tau_\nu\,d\tau_{\nu-1}\dots d\tau_1,$$

$$F_{\nu r}(t)=\int_{(r-1)h}^{t}f(\tau_1)d\tau_1+\int_{(r-1)h}^{t}\mathcal{A}(\tau_1)\int_{(r-1)h}^{\tau_1}f(\tau_2)d\tau_2\,d\tau_1+\dots+$$

$$+\int_{(r-1)h}^{t}\mathcal{A}(\tau_1)\dots\int_{(r-1)h}^{\tau_{\nu-2}}\mathcal{A}(\tau_{\nu-1})\int_{(r-1)h}^{\tau_{\nu-1}}f(\tau_\nu)d\tau_\nu\,d\tau_{\nu-1}\dots d\tau_1,$$

$$G_{\nu r}(u,t)=\int_{(r-1)h}^{t}\mathcal{A}(\tau_1)\dots\int_{(r-1)h}^{\tau_{\nu-2}}\mathcal{A}(\tau_{\nu-1})\int_{(r-1)h}^{\tau_{\nu-1}}\mathcal{A}(\tau_\nu)u_r(\tau_\nu)d\tau_\nu\,d\tau_{\nu-1}\dots d\tau_1.$$

(10) теңдеулерінен $\lim\limits_{t\to rh-0}u_r(t)$, $r=\overline{1,N}$, шектерге сәйкес өрнектерді тауып, оларды (6)–(8) шарттарына қойып және (6), (7) өрнектерінің екі жағын да $h>0$ көбейтсек, $\mu,\ \lambda_r,\ r=\overline{1,N}$, параметрлер үшін келесі теңдеулер жүйесін аламыз:

$$Q_\nu(h)\Lambda=-F_\nu(h)-G_\nu(u,h),\quad \Lambda\in R^{nN+l}, \tag{11}$$

мұндағы

$$Q_\nu(h)=\begin{vmatrix} hB_1 & 0 & 0 & \cdots & 0 & hC_1(I+D_{\nu N}(T)) & hP_1+hC_1M_{\nu N}(T)\\ hB_2 & 0 & 0 & \cdots & 0 & hC_2(I+D_{\nu N}(T)) & hP_2+hC_2M_{\nu N}(T)\\ I+D_{\nu 1}(h) & -I & 0 & \cdots & 0 & 0 & M_{\nu 1}(h)\\ 0 & I+D_{\nu 2}(2h) & -I & \cdots & 0 & 0 & M_{\nu 2}(2h)\\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots\\ 0 & 0 & 0 & \cdots & I+D_{\nu,N-1}((N-1)h) & -I & M_{\nu,N-1}((N-1)h) \end{vmatrix}$$

$$F_\nu(h)=\left(-hd_1+hC_1F_{\nu N}(T),\ -hd_2+hC_2F_{\nu N}(T),\ F_{\nu 1}(h),\dots,F_{\nu,N-1}\left((N-1)h\right)\right),$$

$$G_\nu(u,h)=\left(hC_1G_{\nu N}(u,T),\ hC_2G_{\nu N}(u,T),\ G_{\nu 1}(u,h),\dots,G_{\nu,N-1}(u,(N-1)h)\right).$$

Сонымен белгісіз $\Lambda=(\lambda_1,\ \lambda_2,\dots,\lambda_N,\mu)$, параметрлерін табу үшін (11) сызықты алгебралық теңдеулер жүйесін алдық, ал белгісіз $u[t]=\left(u_1(t),u_2(t),\dots,u_N(t)\right)$ функциясын (4), (5) Коши есебінен табамыз. Енді (4) – (8) есебінің шешімі төмендегі алгоритм арқылы анықталатын $(\Lambda^{(k)},u^{(k)}[t]),k=0,1,2,\dots$ жұптар тізбегінің шегі ретінде ізделінеді.

0-ші қадам:

а) $Q_\nu(h)$ матрицасы қайтарымды деп жорамалдап, Λ параметрлерінің бастапқы жуықтауын $Q_\nu(h)\Lambda=-F_\nu(h)$ теңдеуінен табамыз, яғни $\Lambda^{(0)}=-[Q_\nu(h)]^{-1}F_\nu(h)$;

б) табылған $\Lambda^{(0)}$ қолданып және $t\in[(r-1)h,rh),\quad r=\overline{1,N},$ аралықтарында $\lambda_r=\lambda_r^{(0)},r=\overline{1,N},\mu=\mu^{(0)}$ болғанда (4), (5) Коши есептерін шешіп $u^{(0)}[t]=$ $=\left(u_1^{(0)}(t),\dots,u_N^{(0)}(t)\right)$ функцияларын табамыз.

k-ші қадам:

а) Табылған $u^{(k-1)}[t] = \left(u_1^{(k-1)}(t), \dots, u_N^{(k-1)}(t)\right)$, $k = 1,2, \dots,$ функцияларын (11) сызықты алгебралық теңдеулер жүйесінің оң жағына қойып,

$$Q_\nu(h)\Lambda = -F_\nu(h) - G_\nu\left(u^{(k-1)}, h\right)$$

теңдеуінен $\Lambda^{(k)} = \left(\lambda_1^{(k)}, \dots, \lambda_N^{(k)}, \mu^{(k)}\right), k = 1,2, \dots,$ параметрін табамыз;

б) $t \in [(r-1)h, rh), \quad r = \overline{1,N}$ аралықтарында $\lambda_r = \lambda_r^{(k)}, r = \overline{1,N}, \mu = \mu^{(k)}$,

$k = 1.2, \dots,$ болғанда (4), (5) Коши есебін шешіп $u^{(k)}[t] = \left(u_1^{(k)}(t), \dots, u_N^{(k)}(t)\right)$, $k = 1,2, \dots,$ функцияларын табамыз.

Сонымен $\left(\Lambda^{(k)}, u^{(k)}[t]\right), k = 0,1,2, \dots$ жұптар жүйесін аламыз.

Ұсынылып отырған алгоритмнің жүзеге асуы мен жалғыз шешімге жинақталуының жеткілікті шарттары және (4)–(8) параметрі бар шеттік есебінің бірмәнді шешілімді болатыны келесі теоремада келтірілген:

Теорема 1. Егер кез келген $\nu \in \mathbb{N}$, $h > 0$ үшін $Q_\nu(h)$ матрицасының кері матрицасы бар болса және

$$\|[Q_\nu(h)]^{-1}\| \le \gamma_\nu(h),$$

$$q_\nu(h) = \gamma_\nu(h)\max(1, h\|C_1\|, h\|C_2\|)\left\{e^{\alpha h} - \sum_{j=0}^{\nu}\frac{(\alpha h)^j}{j!} + \right.$$

$$\left. + \alpha_0 h\left(e^{\alpha h} - \sum_{j=0}^{\nu-1}\frac{(\alpha h)^j}{j!}\right)\right\} < 1,$$

онда (4)–(8) есебі бірмәнді шешілімді болады.

(1)–(3) және (4)–(8) есептері пара-пар болғандықтан келесі тұжырым орын алады.

Теорема 2. Егер кез келген $\nu \in \mathbb{N}$, $h > 0$ үшін $Q_\nu(h)$ матрицасы қайтарымды болса және жоғарыда келтірілген теореманың теңсіздіктері орындалса, онда (1)–(3) параметрі бар шеттік есебінің $(z^*(t), \mu^*)$ жалғыз шешімі болады және ол үшін келесі теңсіздік орынды:

$$\max(\|z^*\|_1, \|\mu^*\|) \le \mathcal{M}_\nu(h)\max(\|d_1\|, \|d_2\|, \|f\|),$$

$$\mathcal{M}_\nu(h) = \left\{\gamma_\nu(h)(1+\alpha_0 h)e^{\alpha h}\frac{\max(1, h\|C_1\|, h\|C_2\|)}{1-q_\nu(h)}\frac{(\alpha h)^\nu}{\nu!} + 1\right\} \times$$

$$\times\left\{\gamma_\nu(h)[e^{\alpha h} - 1 + \alpha_0 h e^{\alpha h}] \cdot max\left(1 + h\|C_1\|\sum_{j=0}^{\nu}\frac{(\alpha h)^j}{j!},\right.\right.$$

$$\left.\left. 1 + h\|C_2\|\sum_{j=0}^{\nu}\frac{(\alpha h)^j}{j!}, \sum_{j=0}^{\nu}\frac{(\alpha h)^j}{j!}\right) + e^{\alpha h}\right\} h +$$

$$+\gamma_\nu(h)\max\left(1 + h\|C_1\|\sum_{j=0}^{\nu}\frac{(\alpha h)^j}{j!}, 1 + h\|C_2\|\sum_{j=0}^{\nu}\frac{(\alpha h)^j}{j!}, \sum_{j=0}^{\nu}\frac{(\alpha h)^j}{j!}\right)h.$$

1 және 2 теоремаларының дәлелдеуі [22] жұмысындағы теоремаларға ұқсас дәлелденеді.

Нәтижелер мен талқылау

$[0,\ 1]$ кесіндісінде параметрі бар дифференциалдық теңдеу үшін төмендегідей шеттік есепті қарастырайық

$$\frac{dz}{dt}=\begin{pmatrix}\frac{1}{4} & \frac{t}{8}\\ \frac{t^2}{4} & -\frac{1}{2}\end{pmatrix}z+\begin{pmatrix}\frac{1}{2} & 0 & \frac{t}{4}\\ -\frac{t}{2} & -\frac{1}{3} & \frac{1}{4}\end{pmatrix}\mu+\begin{pmatrix}f_1(t)\\ f_2(t)\end{pmatrix},\quad z\in\mathbb{R}^2,\qquad \mu\in\mathbb{R}^3, \tag{12}$$

$$\begin{pmatrix}1 & 2\\ 5 & 6\end{pmatrix}z(0)+\begin{pmatrix}1 & 2 & 4\\ 5 & 6 & 0\end{pmatrix}\mu+\begin{pmatrix}1 & -1\\ 2 & 0\end{pmatrix}z(T)=\begin{pmatrix}d_{11}\\ d_{12}\end{pmatrix}, \tag{13}$$

$$\begin{pmatrix}1 & 3\\ 0 & -5\\ 6 & 7\end{pmatrix}z(0)+\begin{pmatrix}2 & 3 & 4\\ 6 & 7 & 0\\ -3 & 6 & 9\end{pmatrix}\mu+\begin{pmatrix}2 & 0\\ 1 & 1\\ -1 & 1\end{pmatrix}z(T)=\begin{pmatrix}d_{21}\\ d_{22}\\ d_{32}\end{pmatrix}. \tag{14}$$

Параметрлеу әдісінің сүлбесін ескере отырып берілген $[0,1]$ аралығын келесідей бөліктерге бөлейік: $[0,1)=\cup_{r=1}^{2}[(r-1)h,rh)$, мұндағы $h=\frac{1}{2}$. Ізделінді функцияның бөлінген аралықтарға сығылуын $z_r(t)=z(t),t\in[(r-1)h,rh)$, $r=\overline{1,2}$, деп белгілеп, $\lambda_r=z_r((r-1)h)$, $r=\overline{1,2}$, қосымша параметрлерін енгізіп және әрбір $\lambda_r=z_r((r-1)h)$ $r=\overline{1,2}$, аралығында $u_r(t)=z_r(t)-\lambda_r$, $r=\overline{1,2}$, алмастыруларын жасайық. Соның нәтижесінде келесі параметрі бар шеттік есепті аламыз:

$$\frac{du_r}{dt}=\begin{pmatrix}\frac{1}{4} & \frac{t}{8}\\ \frac{t^2}{4} & -\frac{1}{2}\end{pmatrix}[u_r(t)+\lambda_r]+\begin{pmatrix}\frac{1}{2} & 0 & \frac{t}{4}\\ -\frac{t}{2} & -\frac{1}{3} & \frac{1}{4}\end{pmatrix}\mu+\begin{pmatrix}f_1(t)\\ f_2(t)\end{pmatrix},t\in\big((r-1)h,rh\big),$$

$$u_r\big((r-1)h\big)=0,\qquad r=\overline{1,2},$$

$$\begin{pmatrix}1 & 2\\ 5 & 6\end{pmatrix}\lambda_1+\begin{pmatrix}1 & 2 & 4\\ 5 & 6 & 0\end{pmatrix}\mu+\begin{pmatrix}1 & -1\\ 2 & 0\end{pmatrix}\lambda_2+\begin{pmatrix}1 & -1\\ 2 & 0\end{pmatrix}\lim_{t\to1-0}u_2(t)=\begin{pmatrix}d_{11}\\ d_{12}\end{pmatrix},$$

$$\begin{pmatrix}1 & 3\\ 0 & -5\\ 6 & 7\end{pmatrix}\lambda_1+\begin{pmatrix}2 & 3 & 4\\ 6 & 7 & 0\\ -3 & 6 & 9\end{pmatrix}\mu+\begin{pmatrix}2 & 0\\ 1 & 1\\ -1 & 1\end{pmatrix}\lambda_2+$$

$$+\begin{pmatrix}2 & 0\\ 1 & 1\\ -1 & 1\end{pmatrix}\lim_{t\to1-0}u_2(t)=\begin{pmatrix}d_{21}\\ d_{22}\\ d_{32}\end{pmatrix},$$

$$\lambda_1+\lim_{t\to\frac{1}{2}-0}u_1(t)=\lambda_2$$

$\nu = 2$ болғанда $Q_2\left(\frac{1}{2}\right)$ матрицасы келесі түрде болады:

$$Q_2\left(\frac{1}{2}\right) = \begin{pmatrix} 0.5 & 1 & 0.5287 & -0.4524 & 0.7166 & 1.079 & 1.9883 \\ 2.5 & 3 & 1.1359 & 0.099 & 2.7568 & 2.9913 & 0.1055 \\ 0.5 & 1.5 & 1.1359 & 0.099 & 1.2568 & 1.4913 & 2.1055 \\ 0 & -2.5 & 0.6072 & 0.5514 & 3.0402 & 3.4123 & 0.1171 \\ 3 & 3.5 & -0.5287 & 0.4524 & -1.7166 & 2.921 & 4.5117 \\ 1.1329 & 0.0326 & -1 & 0 & 0.2646 & -0.0035 & 0.0352 \\ 0.0114 & 1.0002 & 0 & -1 & -0.0605 & -0.1667 & 0.1252 \end{pmatrix}$$

Теореманың шарттарының орындалуын тексерейік:

$$\left\| \left[Q_2\left(\frac{1}{2}\right) \right]^{-1} \right\| \leq 12.0884,$$

$$q_2\left(\frac{1}{2}\right) = 12.0884 \cdot \left[e^{\frac{1}{4}} - 1 - \frac{1}{4} - \frac{(1/4)^2}{2} + 1.0833 \cdot \frac{1}{2} \cdot \left(e^{\frac{1}{4}} - 1 - \frac{1}{4} \right) \right] = 0.2563 < 1.$$

Теореманың барлық шарттары орындалып тұр, олай болса берілген (12)–(14) параметрі бар шеттік есептің жалғыз шешімі болады.

Қорытынды

Ұсынылып отырған жұмыста параметрі бар дифференциалдық теңдеу үшін сызықтық шеттік есеп Жұмабаевтың параметрлеу әдісі негізінде зерттелген. Бастапқы берілімдер терминінде оның бірмәнді шешілімділігінің жеткілікті шарттары алынған.

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[1,2]Bakirova E.A.,
Can. Phys.-Math.Sc., ORCID ID: 0000-0002-3820-5373, e-mail: bakirova1974@mail.ru
[1]Iskakova N.B.,
Can. Phys.-Math.Sc., ORCID ID: 0000-0002-0680-4099, e-mail: narkesh@mail.ru
[1,3]Temesheva S.M.,
Dr. Phys.-Math.Sc., ORCID ID: 0000-0002-3341-4539, e-mail: temeshevasvetlana@gmail.com
[1,4*]Kadirbayeva Zh.M.,
Can. Phys.-Math.Sc., ORCID ID: 0000-0001-8861-4100, *e-mail: zhkadirbayeva@gmail.com

[1]Institute of Mathematics and Mathematical Modeling, Almaty, Kazakhstan
[2]Kazakh National Women's Teacher Training University, Almaty, Kazakhstan
[3]Al-Farabi Kazakh National University, Almaty, Kazakhstan
[4]International Information Technology University, Almaty, Kazakhstan

ON THE UNIQUE SOLVABILITY OF A BOUNDARY VALUE PROBLEM FOR DIFFERENTIAL EQUATIONS WITH PARAMETER

Abstract

A linear boundary value problem for a differential equation with a parameter is investigated on a finite interval by the parameterization method. The studied boundary value problem with parameter is reduced to an equivalent multipoint boundary value problem with parameters by splitting the interval, introducing additional parameters at the points of splitting and new functions. The obtained equivalent boundary value problem contains Cauchy problems for ordinary differential equations with respect to new functions. By substituting the solution representation of the Cauchy problem into the boundary conditions and continuity conditions of the solution, a system of linear algebraic equations with respect to the introduced parameters is compiled. An algorithm for finding a solution to the boundary value problem with parameters is constructed. The formulation of the theorem on sufficient conditions of unique solvability of the boundary value problem with parameters is given. Sufficient conditions of its unique solvability are obtained in terms of the data of the original boundary value problem. An example showing the fulfillment of the conditions of the theorem is given.

Key words: differential equation with parameter, boundary value problem, solvability, parameterization method.

[1,2]Бакирова Э.А.,
к.ф-м.н., ORCID ID: 0000-0002-3820-5373, e-mail: bakirova1974@mail.ru
[1]Искакова Н.Б.,
к.ф-м.н., ORCID ID: 0000-0002-0680-4099, e-mail: narkesh@mail.ru
[1,3]Темешева С.М.,
д. ф.-м. н., ORCID ID: 0000-0002-3341-4539, e-mail: temeshevasvetlana@gmail.com
[1,4*]Кадирбаева Ж.М.,
к.ф-м.н., ORCID ID: 0000-0001-8861-4100, E-mail: zhkadirbayeva@gmail.com

[1]Институт математики и математического моделирования, г. Алматы, Казахстан
[2]Казахский национальный женский педагогический университет, г. Алматы, Казахстан
[3]Казахский национальный университет им. аль-Фараби, г. Алматы, Казахстан
[4]Международный университет информационных технологий, г. Алматы, Казахстан

ОБ ОДНОЗНАЧНОЙ РАЗРЕШИМОСТИ КРАЕВОЙ ЗАДАЧИ ДЛЯ ДИФФЕРЕНЦИАЛЬНЫХ УРАВНЕНИЙ С ПАРАМЕТРОМ

Аннотация

На конечном интервале методом параметризации исследуется линейная краевая задача для дифференциального уравнения с параметром. Путем разбиения интервала, введения дополнительных параметров в

точках разбиения и новых функций исследуемая краевая задача с параметром сводится к эквивалентной многоточечной краевой задаче с параметрами. Полученная эквивалентная краевая задача содержит задачи Коши для обыкновенных дифференциальных уравнений относительно новых функций. С помощью подстановки представления решения задачи Коши в краевые условия и условия непрерывности решения составляется система линейных алгебраических уравнений относительно введенных параметров. Построен алгоритм нахождения решения краевой задачи с параметрами. Приведена формулировка теоремы о достаточных условиях однозначной разрешимости краевой задачи с параметрами. В терминах данных исходной краевой задачи получены достаточные условия ее однозначной разрешимости. Приводится пример, показывающий выполнение условий теорем.

Ключевые слова: дифференциальное уравнение с параметром, краевая задача, разрешимость, метод параметризации.

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[1,2]Судоплатов С.В.,
д.ф.-м.н., профессор, ORCID ID: 0000-0002-3268-9389,
e-mail: sudoplat at math.nsc.ru
[3*]Вербовский В.В.,
д.ф.-м.н., доцент, ORCID ID: 0000-0001-5177-8523,
e-mail: verbovskiy at math.kz

[1]Институт математики имени С.Л. Соболева СО РАН, 630090, г. Новосибирск, Россия
[2]Новосибирский государственный технический университет, 630073, г. Новосибирск, Россия
[3]Институт математики и математического моделирования, 050010, г. Алматы, Казахстан

О ПОНЯТИЯХ ВЫПУКЛОСТИ И СЛАБОЙ О-МИНИМАЛЬНОСТИ ДЛЯ ЧАСТИЧНО УПОРЯДОЧЕННЫХ СТРУКТУР

Аннотация

В данной работе мы рассматриваем обобщение понятия слабой о-минимальности на частично упорядоченные множества. Однако понятие слабой о-минимальности основано на понятии выпуклого множества, прямой перенос которого на частичные порядки, как будет показано в работе, не является, на наш взгляд, самым удачным, поскольку тогда в классе слабо о-минимальных частично упорядоченных структур возможно определить любую математическую структуру. Причем, как будет показано, это можно сделать при помощи такой простой операции, как пересечение интервалов. Статья посвящена поиску различных обобщений понятия выпуклого множества на частичные порядки. Так как выпуклые множества на прямой обладают и другими свойствами, такими, например, как возможность их представить в виде объединения или пересечения интервалов, выпуклые множества связны, все эти свойства могут быть положены в основу определения выпуклого множества для частично упорядоченных структур. Так, представление выпуклого множества в виде объединения вложенных друг в друга интервалов (полуинтервалов, отрезков) дает нам понятие внутренне выпуклого множества, а пересечение интервалов дает понятие внешне выпуклого множества. В статье будут построены примеры, которые показывают неэквивалентность вводимых понятий.

Ключевые слова: линейно упорядоченное множество, частично упорядоченное множество, слабая о-минимальность, выпуклое множество.

Введение

Понятие слабой о-минимальности основано на понятии выпуклого множества, или промежутка. Вспомним, что подмножество A линейно упорядоченной структуры M называется *выпуклым*, если для любых элементов $a, b \in A$ и $c \in M$ неравенство $a < c < b$ влечет, что $c \in A$. Линейно упорядоченная структура называется *слабо о-минимальной*, если любое ее формульное подмножество есть конечное объединение выпуклых множеств [1].

Определение 1 (К.Ж. Кудайбергенов [3]). Частично упорядоченная структура $\mathcal{M}$ называется *слабо о-минимальной*, если любое ее формульное подмножество является конечным объединением выпуклых множеств.

В работе К.Ж. Кудайбергенова [2] были рассмотрены другие варианты определения слабой о-минимальности, которые представляют интерес, но выходят за рамки обсуждаемой здесь темы, поэтому мы их касаться не будем. Кроме того, следует отметить работы [4–5].

При переходе от линейных порядков к частичным прямолинейный перенос понятия выпуклого множества несет в себе такие неудобства, что любая антицепь является выпуклым множеством, а это делает класс слабо о-минимальных частично упорядоченных структур чрезмерно большим для исследования. Действительно, имеет место следующий очевидный факт.

Предложение 2. *Пусть* $\mathcal{M} = (M, \Sigma)$ *– произвольная структура сигнатуры* Σ*, которая не содержит символ* $\preceq$*. Тогда обогащение* $\mathcal{M}^+ = (M, \Sigma \cup \{\preceq\})$ *структуры* $\mathcal{M}$ *отношением* $\preceq$*, которое проинтерпретировано так, что совпадает с равенством:* $x \preceq y \Leftrightarrow x = y$*, является слабо о-минимальным относительно частичного порядка* $\preceq$*.*

Заметим, что если в структуре есть несколько частичных порядков, то относительно одного порядка структура может быть слабо о-минимальной, а относительно другого – нет. Например, $(\mathbb{R}, \leq, \preceq, Q)$, где $\leq$ – это естественный порядок на вещественных числах, $\preceq$ совпадает с равенством, а одноместный предикат Q выделяет подмножество рациональных чисел. Очевидно, что относительно естественного порядка данная структура не является слабо о-минимальной, а относительно $\preceq$ является.

Мы предлагаем некоторые варианты обобщения понятия выпуклого множества на частичные порядки. Иначе говоря, статья посвящена способам определения понятия выпуклого множества на частичных порядках. Как будет видно, эта задача оказалась достаточно трудной, нет единственного способа задать такое определение. Вполне допустимо, что можно исследовать слабо о-минимальные структуры на основе каждого из предложенных ниже определений выпуклого множества. Кроме того, поскольку на линейном порядке все эти понятия эквивалентны, представляет интерес описание частичных порядков, где те или иные понятия, вводимые ниже, совпадают.

Основные положения

Определение 3. В частично упорядоченной структуре $\mathcal{M}$ с частичным порядком $<$ множество A называется l*-выпуклым*, если A выпукло и состоит из сравнимых элементов. Структура $\mathcal{M}$ называется l*-слабо о-минимальной*, если любое ее формульное подмножество является конечным объединением l-выпуклых множеств.

По определению любая слабо о-минимальная линейно упорядоченная структура является l-слабо о-минимальной. Также l-слабо о-минимальной является дизъюнктное объединение любого конечного числа слабо о-минимальных линейно упорядоченных структур. При этом l-слабая о-минимальность нарушается при взятии дизъюнктного объединения любого бесконечного числа линейно упорядоченных структур. Более того, не является l-слабо о-минимальной любая частично упорядоченная структура с бесконечной антицепью.

Таким образом, морлизация любой l-слабо о-минимальной структуры представляется в виде объединения конечного числа слабо о-минимальных линейно упорядоченных структур. В частности, справедливо следующее:

Предложение 4. *Дизъюнктное объединение слабо о-минимальных линейно упорядоченных структур* $\mathcal{M}_i$*,* $i \in I$*,* l*-слабо о-минимально тогда и только тогда, когда множество* I *конечно.*

Определение 5. Частично упорядоченная структура $\mathcal{M}$ удовлетворяет *условию сравнимости*, если любое ее бесконечное формульное подмножество содержит сравнимые элементы.

Предложение 6. *Для любой частично упорядоченной структуры* $\mathcal{M} = (M, <, \dots)$ *следующие условия эквивалентны:*

(1) $\mathcal{M}$ удовлетворяет условию сравнимости;

(2) любое бесконечное формульное подмножество в $\mathcal{M}$ содержит бесконечную цепь.

Доказательство. Импликация $(2) \Rightarrow (1)$ очевидна.

$(1) \Rightarrow (2)$. Пусть подмножество A формульно. Предположим, что любая цепь в множестве A конечна. Тогда любая цепь в A содержит минимальный элемент. Поскольку множество $A_{\min}$ минимальных в A элементов формульно, а минимальные элементы попарно несравнимы, то $A_{\min}$ конечно. Пусть $A_{\min} = \{a_1, \dots, a_n\}$, а $A_i = \{a \in A : a > a_i\}$. Очевидно, что объединение всех множеств A_i дает A, иначе существовал бы элемент, под которым нет минимального, но в этом случае мы получили бы бесконечную убывающую цепь. Следовательно, хотя бы одно из множеств A_i бесконечно, скажем, A_{i_1}. Повторим наши рассуждения, заменив множество A на A_{i_1}. Предположим, что множество $A_{i_1,\dots,i_k}$ построено и бесконечно. Поскольку мно-

жество $(A_{i_1,\dots,i_k})_{\min}$ минимальных в $A_{i_1,\dots,i_k}$ элементов формульно, а минимальные элементы попарно несравнимы, то $(A_{i_1,\dots,i_k})_{\min}$ конечно. Пусть $(A_{i_1,\dots,i_k})_{\min} = \{a_{i_1,\dots,i_k,1}, \dots, a_{i_1,\dots,i_k,n_{k+1}}\}$, а $A_{i_1,\dots,i_k,i} = \{a \in A_{i_1,\dots,i_k} : a > a_{i_1,\dots,i_k,i}\}$. Очевидно, что объединение всех множеств $A_{i_1,\dots,i_k,i}$ дает $A_{i_1,\dots,i_k}$, следовательно, хотя бы одно из множеств $A_{i_1,\dots,i_k,i}$ бесконечно, скажем, $A_{i_1,\dots,i_k,i_{k+1}}$. В итоге мы получаем бесконечную цепь

$$a_{i_1} < a_{i_1,i_2} < \dots < a_{i_1,i_2,\dots,i_k} < \dots,$$

что и требовалось доказать.

Пусть частично упорядоченная структура $\mathcal{M} = (M, <, \dots)$ удовлетворяет условию сравнимости, а бесконечное множество $A \subseteq M$ формульно. Как мы знаем из предложения 6, множество A содержит бесконечную цепь. Предположим, что $A = \mathbb{N} \times \mathbb{Q}$, а порядок задан следующим образом: имеет место $(n_1, q_1) < (n_2, q_2)$ тогда и только тогда, когда $n_1 = n_2$ и $q_1 < q_2$. Тогда множество A выпукло. Несложно доказать, что разбиение множества A на множества $\{n\} \times \mathbb{Q}$ равномерно определимо, поэтому отношение эквивалентности E на множестве A, чьи классы в точности $\{n\} \times \mathbb{Q}$, формульно. Теперь на фактор-множестве A/E, которое образует антицепь, можно определить любую структуру, и эта структура, как не сложно понять, будет слабо о-минимальной. Получается, что условия сравнимости недостаточно, чтобы класс слабо о-минимальных частично упорядоченных структур не был чересчур богатым.

Определение 7. Частично упорядоченная структура $\mathcal{M}$ удовлетворяет *условию сравнимости для воображаемых элементов*, если для любого отношения эквивалентности E, такого что отношение на E-классах, заданное формулой $[a]_E \prec [b_E]$, если $a < b$, не зависит от выбора представителя класса эквивалентности и задает частичный порядок, сорт, порождаемый отношением эквивалентности E с порядком $\prec$, удовлетворяет условию сравнимости.

Будем считать, что интервал (c, d) вложен в интервал (a, b), если $a \le c \le d \le b$.

Определение 8. Подмножество A частично упорядоченного множества M называется

1. $\cup$-*выпуклым*, или *внутренне выпуклым*, если оно является одноэлементным или объединением вложенных друг в друга отрезков, интервалов или полуинтервалов;

2. $\cap$-*выпуклым*, или *внешне выпуклым*, если оно является одноэлементным или пересечением вложенных друг в друга отрезков, интервалов или полуинтервалов;

3. *Двусторонне выпуклым*, если оно является и $\cup$-выпуклым, и $\cap$-выпуклым; и

4. *Односторонне выпуклым*, если оно является $\cup$-выпуклым или $\cap$-выпуклым.

Можно ввести и более сложную классификацию выпуклых множеств.

Определение 9. Подмножество A частично упорядоченного множества M называется

0. Σ_0-*выпуклым*, или Π_0-*выпуклым*, или Δ_0-*выпуклым*, если оно является отрезком, интервалом или полуинтервалом;

1.

(a) Σ_1-*выпуклым*, или *внутренне выпуклым*, если оно является одноэлементным или объединением вложенных друг в друга отрезков, интервалов или полуинтервалов;

(b) Π_1-*выпуклым*, или *внешне выпуклым*, если оно является одноэлементным или пересечением вложенных друг в друга отрезков, интервалов или полуинтервалов;

(c) Δ_1-*выпуклым*, или *двусторонне выпуклым*, если оно является и Σ_1-выпуклым, и Π_1-выпуклым; и

(d) ∇_1-*выпуклым*, или *односторонне выпуклым*, если оно является Σ_1-выпуклым или Π_1-выпуклым.

$n+1$.

(a) Σ_{n+1}-*выпуклым*, если оно является Σ_n-выпуклым или объединением вложенных друг в друга Π_n-выпуклых множеств;

(b) Π_{n+1}-*выпуклым*, если оно является Π_n-выпуклым или пересечением вложенных друг в друга Σ_n-выпуклых множеств;

(c) Δ_{n+1}-*выпуклым*, если оно является и Σ_{n+1}-выпуклым, и Π_{n+1}-выпуклым; и

(d) ∇_{n+1}-*выпуклым*, если оно является Σ_{n+1}-выпуклым или Π_{n+1}-выпуклым.

Заметим, что в линейно упорядоченных структурах понятия односторонней и двусторонней выпуклостей совпадают. Было бы интересно описать все частично упорядоченные множества, в которых имеет место такое совпадение.

Рассмотрим решетку всех замкнутых подмножеств множества $\mathbb{R}$ в топологии, индуцированной естественным порядком, с отношением частичного порядка, заданного как «быть подмножеством». Каждое замкнутое множество A можно представить в виде отрезка $[\emptyset, A]$. Тогда бесконечное объединение замкнутых вложенных друг в друга множеств дает нам Σ_1-выпуклое множество. А бесконечное пересечение Σ_1-выпуклых множеств дает Π_2-выпуклое множество. Далее можно перенести классификацию борелевских множеств на определение *-выпуклости. Как известно, классы борелевских множеств никогда не стабилизируются, поэтому, например, класс Π_2-выпуклых множеств не совпадает с классом Σ_1-выпуклых множеств.

Определение 10. Частично упорядоченная структура M называется *-*слабо о-минимальной*, если любое ее формульное подмножество является конечным объединением *-выпуклых множеств, где $*\in \{\cup,\ \cap$, односторонне, двусторонне$\}$.

Определение 11. Частично упорядоченная структура M называется *-*слабо булево о-минимальной*, или *-*слабо б-о-минимальной*, если любое ее формульное подмножество является булевой комбинацией *-выпуклых множеств, где $*\in \{\cup,\ \cap$, односторонне, двусторонне$\}$.

В линейных порядках непустое пересечение двух интервалов само является интервалом. Верно это и в решетках. В общем же случае, пересекая два интервала, можно получить и бесконечную антицепь, чего мы хотим избежать. Действительно, рассмотрим структуру

$$\mathcal{M} = (M, <) = (Q \times Q \cup \{-\infty, +\infty\}, <),$$

где $(a, b) < (c, d)$, если $a < b$ и $c < d$ в классическом смысле, элемент $-\infty$ наименьший, а элемент $+\infty$ наибольший. Заметим, что таким образом заданный порядок на $\mathbb{Q} \times \mathbb{Q}$ называется порядком Парето. Выберем в этой структуре произвольную бесконечную антицепь, например, $A = \{(q, -q): q \in \mathbb{Q}\}$. Построим теперь новую структуру следующим образом. Для множеств

$$A^- = \{b \in M: \exists a \in A(b < a)\}, A^+ = \{b \in M: \exists a \in A(b > a)\}$$

создадим их непересекающиеся с ними копии $\tilde{A}^-$ и $\tilde{A}^+$ (при помощи биекций π^- и π^+ соответственно). Пусть $\tilde{M} = A^- \cup A \cup A^+ \cup \tilde{A}^- \cup \tilde{A}^+$, на множестве $A^- \cup A \cup A^+$ порядок старый. Определим биекцию π из $A^- \cup A \cup A^+$ в $\tilde{A}^- \cup A \cup \tilde{A}^+$ как объединение π^-, id и π^+. Тогда частичный порядок на множестве $\tilde{A}^+ \cup A \cup \tilde{A}^-$ индуцирован порядком на $A^- \cup A \cup A^+$ при помощи биекции π. Для завершения процедуры определения частичного порядка на $\tilde{M}$ осталось только взять транзитивное замыкание построенного выше отношения. Так как $-\infty \in A^-$ и $+\infty \in A^+$, то соответствующие им элементы в множествах $\tilde{A}^-$ и $\tilde{A}^+$ обозначим $-\tilde{\infty}$ и $+\tilde{\infty}$ соответственно. Тогда $(-\infty, +\infty) \cap (-\tilde{\infty}, +\tilde{\infty}) = A$, то есть пересечение данных интервалов дает бесконечную антицепь.

Заметим, что данную конструкцию можно модифицировать. Выберем произвольное подмножество $B \subseteq A$. Для него можно проделать все то же самое, что и для A, добавим к структуре $\tilde{\mathcal{M}}$ еще множества $\hat{A}^-$ и $\hat{A}^+$, построенные аналогично $\tilde{A}^-$ и $\tilde{A}^+$, только с целью, чтобы пересечение $(-\infty, +\infty) \cap (-\tilde{\infty}, +\tilde{\infty})$ давало бы B. Понятно, что, продолжая расширять структуру $\tilde{\mathcal{M}}$, можно получить такую структуру, где пересечение интервалов дает любое наперед заданное подмножество множества A. Поскольку декартово произведение частично упорядоченных множеств само является частично упорядоченным, можно построить и такое расширение структуры $\mathcal{M}$, где пересечение интервалов давало бы любое наперед заданное подмножество некоторой декартовой степени множества A. Получаем, что любую структуру можно определить в некоторой частично упорядоченной структуре только при помощи пересечения интервалов. Ясно, что изучение такого богатого класса непродуктивно, изучению более «ручных» подклассов и посвящена данная работа.

В линейных порядках пересечение выпуклых множеств выпукло (или пусто, но пустое множество мы считаем выпуклым). Рассмотрим пересечение двух ∪-выпуклых множеств $A = \bigcup_{i\in I} (a_i, b_i)$ и $C = \bigcup_{j\in J} (c_j, d_j)$. Поскольку в представлении $\bigcup_{i\in I} (a_i, b_i)$ интервалы могут повторяться, можно считать, что множества индексов I и J равномощны, поэтому впредь мы будем опускать их и писать просто $\bigcup_i (a_i, b_i)$. Предположим, что $A \cap C \neq \emptyset$, то есть

$$\left(\bigcup_i (a_i, b_i)\right) \cap \left(\bigcup_i (c_i, d_i)\right) \neq \emptyset$$

Тогда для некоторых i и j пересечение $(a_i, b_i) \cap (c_j, d_j) \neq \emptyset$. Поскольку мы рассматриваем возрастающие системы интервалов, то $(a_k, b_k) \cap (c_k, d_k) \neq \emptyset$, где $k = \max(i, j)$. Кроме того, так как $\bigcup_{i\leq\alpha} (a_i, b_i) = (a_\alpha, b_\alpha)$, мы можем $A \cap C$ представить как

$$\bigcup_i ((a_i, b_i) \cap (c_i, d_i)),$$

причем, не умаляя общности, считать, что все пересечения $(a_i, b_i) \cap (c_i, d_i)$ не являются пустыми.

Рассмотрим пример. Пусть M будет объединением непересекающихся копий $\mathbb{Q}$ и $\mathbb{N}$, а отношение порядка в структуре $\mathcal{M} = (M, <)$ задано следующим образом. На копии $\mathbb{Q}$ имеем естественный порядок, на $\mathbb{N}$ порядок тривиальный, то есть никакие два элемента не являются сравнимыми, и каждый элемент из $\mathbb{Q}$ меньше каждого элемента из $\mathbb{N}$. Рассмотрим обогащение $\mathcal{M}_P$ структуры $\mathcal{M}$ одноместным предикатом R, который выделяет $\mathbb{N}$. Это множество является ∩-выпуклым. Очевидно, что $R(\mathcal{M})\backslash\{a\}$, где $a \in \mathbb{N}$, является формульным, но не является *-выпуклым для всех вариантов значения *. Поэтому структура $\mathcal{M}_R$ не является *-слабо о-минимальной. Тем не менее при помощи элиминации кванторов нетрудно доказать, что $\mathcal{M}_R$ является ∩-слабо б-о-минимальной. Заметим, что предикат R формулен и в исходном языке, для этого можно взять дополнение интервала $(-\infty, a)$, где $a \in \mathbb{N}$.

Проведем теперь анализ ∪- и ∩-слабой о-минимальности. Предположим, что множество A является ∪-выпуклым, то есть $A = \bigcup_i (a_i, b_i)$. Рассмотрим дополнение $\overline{A}$ множества A. В силу ∪-слабой о-минимальности оно является конечным объединением ∪-выпуклых множеств C_1, …, C_n, где $C_k = \bigcup_i (c_i^k, d_i^k)$. Тогда

$$\overline{A} = \overline{\bigcup_i (a_i, b_i)} = \bigcup_{k=1}^{n} \bigcup_i (c_i^k, d_i^k)$$

Отсюда получаем, что

$$A = \bigcap_{k=1}^{n} \bigcap_i \overline{(c_i^k, d_i^k)}$$

Заметим, что в частичных порядках $\neg(x < a)$ эквивалентно дизъюнкции формул $x \geq a$ и $x \parallel a$, где $x \parallel a$ говорит, что элементы x и a несравнимы. Тогда

$$\neg(c < x < d) \Leftrightarrow \neg(c < x) \vee \neg(x < d) \Leftrightarrow x \geq c \vee x \parallel c \vee d \leq x \vee x \parallel d$$

Формулу $x \parallel y$ мы будем обозначать также $P(x, y)$, тогда множество всех решений формулы $x \parallel a$ в структуре $\mathcal{M}$ можно будет обозначить как $P(\mathcal{M}, a)$ (это удобнее обозначения $(x \parallel a)^{\mathcal{M}}$). Получаем, что дополнение $\overline{(c, d)}$ интервала (c, d) равно

$$(-\infty, c] \cup [d, +\infty) \cup P(\mathcal{M}, c) \cup P(\mathcal{M}, d)$$

Очевидно, что пары множеств $(-\infty, c]$ и $[d, +\infty)$, $(-\infty, c]$ и $P(\mathcal{M}, c)$, $[d, +\infty)$ и $P(\mathcal{M}, d)$ не пересекаются. Если элемент лежит в $(-\infty, c]$, то в силу транзитивности он меньше элемента d, поэтому не лежит в $P(\mathcal{M}, d)$, следовательно, множества $(-\infty, c]$ и $P(\mathcal{M}, d)$ не пересекаются. По аналогичным причинам не пересекаются множества $[d, +\infty)$ и $P(\mathcal{M}, c)$. Отсюда следует, что множества $(-\infty, c]$, $[d, +\infty)$ и $P(\mathcal{M}, c) \cup P(\mathcal{M}, d)$ попарно не пересекаются.

Теперь множество A можно представить в следующем виде:

$$A = \bigcap_{k=1}^{n} \bigcap_i \overline{(c_i^k, d_i^k)} =$$
$$= \bigcap_{k=1}^{n} \bigcap_i ((-\infty, c_i^k] \cup [d_i^k, +\infty) \cup (P(\mathcal{M}, c_i^k) \cup P(\mathcal{M}, d_i^k))) =$$
$$= \bigcap_{k=1}^{n} ((\bigcap_i (-\infty, c_i^k]) \cup (\bigcap_i [d_i^k, +\infty)) \cup (\bigcap_i (P(\mathcal{M}, c_i^k) \cup P(\mathcal{M}, d_i^k))))$$
$$= (\bigcap_i \bigcap_{k=1}^{n} (-\infty, c_i^k]) \cup (\bigcap_i \bigcap_{k=1}^{n} [d_i^k, +\infty)) \cup (\bigcap_i \bigcap_{k=1}^{n} (P(\mathcal{M}, c_i^k) \cup P(\mathcal{M}, d_i^k))).$$

Отсюда получаем следующую лемму.

Лемма 12. *Если структура $\mathcal{M}$ является $\cup$-слабо о-минимальной и любое конечное пересечение интервалов в $\mathcal{M}$ с одним концом в бесконечности является интервалом, а множества вида $\bigcap_i \bigcap_{k=1}^{n} \bigcup_{m=1}^{p} P(\mathcal{M}, c_{km}^i)$ являются конечными объединениями $\cap$-выпуклых множеств, то $\mathcal{M}$ является и $\cap$-слабо о-минимальной.*

Проделаем аналогичные рассуждения для $\cap$-слабой о-минимальности. Предположим, что множество A является $\cap$-выпуклым, то есть $A = \bigcap_i (a_i, b_i)$. Рассмотрим дополнение $\overline{A}$ множества A. В силу $\cap$-слабой о-минимальности оно является конечным объединением $\cap$-выпуклых множеств C_1, …, C_n, где $C_k = \bigcap_i (c_i^k, d_i^k)$. Тогда

$$\overline{A} = \overline{\bigcap_i (a_i, b_i)} = \bigcup_{k=1}^{n} \bigcap_i (c_i^k, d_i^k).$$

Отсюда получаем, что

$$A = \bigcap_{k=1}^{n} \bigcup_i \overline{(c_i^k, d_i^k)}.$$

Теперь множество A можно представить следующим образом:

$$A = \bigcap_{k=1}^{n} \bigcup_i \overline{(c_i^k, d_i^k)} =$$
$$= \bigcap_{k=1}^{n} \bigcup_i ((-\infty, c_i^k] \cup [d_i^k, +\infty) \cup (P(\mathcal{M}, c_i^k) \cup P(\mathcal{M}, d_i^k))) =$$
$$= \bigcap_{k=1}^{n} ((\bigcup_i (-\infty, c_i^k]) \cup (\bigcup_i [d_i^k, +\infty)) \cup (\bigcup_i (P(\mathcal{M}, c_i^k) \cup P(\mathcal{M}, d_i^k))))$$
$$= (\bigcap_{k=1}^{n} \bigcup_i (-\infty, c_i^k]) \cup (\bigcap_{k=1}^{n} \bigcup_i [d_i^k, +\infty)) \cup (\bigcap_{k=1}^{n} \bigcup_i (P(\mathcal{M}, c_i^k) \cup P(\mathcal{M}, d_i^k))).$$

Лемма 13. *Если структура $\mathcal{M}$ является $\cap$-слабо о-минимальной и любое конечное пересечение $\cup$-выпуклых множеств является конечным объединением $\cup$-выпуклых множеств, а множества вида $\bigcap_{k=1}^{n} \bigcup_i P(\mathcal{M}, c_i)$ являются конечными объединениями $\cup$-выпуклых множеств, то $\mathcal{M}$ является и $\cup$-слабо о-минимальной.*

Учитывая леммы 12 и 13, справедлива:

Теорема 14. *Понятия $\cup$-выпуклых и $\cap$-выпуклых множеств независимы. Классы $\cap$-слабо о-минимальных и $\cup$-слабо о-минимальных структур являются собственными подклассами класса односторонне слабо о-минимальных структур, который, в свою очередь, является собственным подклассом класса слабо о-минимальных структур.*

Определение 15. Частично упорядоченную $*$-слабо о-минимальную структуру $\mathcal{M} = (M, <, \dots)$ будем называть $(*)$-слабо о-минимальной, если любое ее бесконечное формульное выпуклое подмножество содержит некоторый бесконечный интервал.

По определению любая слабо о-минимальная структура является $(*)$-слабо о-минимальной.

Определение 16. В частично упорядоченной структуре $*$-*выпуклой компонентой* множества A назовем его наибольшее $*$-выпуклое подмножество.

Максимальное выпуклое подмножество множества A называется $*$-*выпуклой квазикомпонентой* множества A.

Подмножество A частично упорядоченного множества называется *связным*, если оно является слабо-связным в смысле теории графов, то есть если для любых элементов a и $b \in A$ существует последовательность $a = c_0, c_1, \ldots, c_n = b$ элементов из A, такая, что два соседних элемента последовательности сравнимы.

Семейство интервалов $\mathcal{I} = \{I_j : j \in J\}$ называется *связным*, если для любых двух его интервалов I и I' существует конечная последовательность его интервалов $I_{j_0}, \ldots, I_{j_n}$, начинающаяся с I и заканчивающаяся на I', такие, что любые два соседних в последовательности интервала имеют непустое пересечение.

Следующая лемма очевидна.

Лемма 17. *Внутренне выпуклое множество является связным и выпуклым.*

Лемма 18. *Пусть $\mathcal{M} = (M, \leq)$ является частично упорядоченной структурой и $A \subseteq M$ выпукло (в классическом понимании, то есть $[a, b] \subseteq A$ для любых $a, b \in A$, если $a < b$). Тогда следующие условия эквивалентны:*

(1) *множество A является связным*;

(2) *множество A является объединением отрезков из некоторого связного семейства отрезков*.

Доказательство. Если множество A одноэлементно, то лемма очевидна: одноэлементное множество связно, а в качестве семейства мы возьмем одноэлементное семейство $\{[a, a]\}$ отрезков, где элемент a такой, что $A = \{a\}$. Так что мы будем рассматривать только неодноэлементные множества.

Докажем импликацию (1) ⇒ (2). Пусть a и $b \in A$ – разные элементы. Тогда существует последовательность $a = c_0, c_1, \ldots, c_n = b$ элементов из A, такая, что два соседних элемента последовательности сравнимы. В силу выпуклости множества A получаем, что $[c_i, c_{i+1}] \subseteq A$. В качестве семейства возьмем все отрезки вида $[c_i, c_{i+1}]$, которые получаются из последовательностей, выбираемых для произвольных элементов a и $b \in A$. Докажем, что это семейство связно. Рассмотрим два произвольных отрезка $[c_i, c_{i+1}]$ и $[c_{j\prime}, c_{j+1}{}']$. Пары элементов c_i, c_{i+1} и $c_{j\prime}$, $c_{j+1}{}'$ лежат, соответственно, в последовательностях, соединяющих некоторые пары элементов a, b и a', b'. Построим еще последовательность элементов, соединяющую b и a', а затем соответствующую последовательность отрезков. Рассмотрим конкатенацию последовательностей отрезков, порожденных парой a, b, парой b и a' и парой a', b'. Легко понять, что в этой последовательности отрезков пересечение соседних отрезков непусто.

Докажем обратную импликацию (2) ⇒ (1). Пусть множество A является объединением отрезков из связного семейства интервалов $\mathcal{I}$. Пусть a и $b \in A$, а последовательность $a = c_0$, $c_1, \ldots, c_n = b$ элементов из A такая, что два соседних элемента последовательности сравнимы. Поскольку A является объединением отрезков, то каждый элемент c_i лежит в некотором отрезке $I_i \in \mathcal{I}$. Так как семейство $\mathcal{I}$ связно, то для каждой пары отрезков I_i, I_{i+1} существует последовательность отрезков $I_{i,0} = I_i, I_{i,1}, \ldots, I_{i,k_i} = I_{i+1}$, так что любые два соседних отрезка имеют непустое пересечение. Элемент из непустого пересечения $I_{i,j} \cap I_{i,j+1}$ мы обозначим $d_{i,j}$, начало отрезка $I_{i,j}$ обозначим $b_{i,j}$. Тогда конкатенация последовательностей

$$\langle a = c_0, b_{0,0}, d_{0,0}, b_{0,1}, d_{0,1}, \ldots, d_{0,k_0-1}, b_{0,k_0} \rangle,$$

$$\langle c_1, b_{1,0}, d_{1,0}, b_{1,1}, d_{1,1}, \ldots, d_{1,k_0-1}, b_{1,k_1} \rangle,$$

$$\ldots$$

$$\langle c_{n-1}, b_{n-1,0}, d_{n-1,0}, b_{n-1,1}, d_{n-1,1}, \ldots, d_{n-1,k_{n-1}-1}, b_{n-1,k_{n-1}}, c_n = b \rangle$$

и есть искомая.

Предложение 19. *Существует частично упорядоченная структура, в которой внешне выпуклое множество не является связным и, следовательно, внутренне выпуклым.*

Доказательство. Пусть $M = \{-\infty\} \times \mathbb{Q} \cup \mathbb{N} \times \mathbb{Q} \cup \{+\infty\} \times \mathbb{Q}$. Теперь в структуре $\mathcal{M} = (M, \leq)$ зададим частичный порядок следующим образом. На каждой копии $\mathbb{Q}$ порядок естественный. Каждый элемент из $\{-\infty\} \times \mathbb{Q}$ меньше любого элемента из $\{a\} \times \mathbb{Q}$, в том случае, когда $a \neq -\infty$. Каждый элемент из $\{+\infty\} \times \mathbb{Q}$ больше любого элемента из $\{a\} \times \mathbb{Q}$, где $a \neq +\infty$. Если $n \neq k$ – элементы из $\mathbb{N}$, то никакие элементы из $\{n\} \times \mathbb{Q}$ и $\{k\} \times \mathbb{Q}$ не являются сравнимыми.

Очевидно, что $\mathbb{N} \times \mathbb{Q} = \bigcap_{q \in \mathbb{Q}} ((-\infty, q), (+\infty, -q))$ является внешне выпуклым. Тем не менее, это множество не является связным.

Следующее предложение очевидно.

Предложение 22. *$\cup$-слабо о-минимальная структура является $(\cup)$-слабо о-минимальной.*

Предложение 23. *Пусть частично упорядоченная структура $\mathcal{M} = (M, <, \dots)$ с плотным порядком является $(*)$-слабо о-минимальной. Тогда не существует бесконечного формульного подмножества, у которого любые два элемента несравнимы.*

Доказательство. Предположим противное, что существует бесконечное формульное подмножество A, такое, что любые его два элемента несравнимы. В силу $(*)$-слабой о-минимальности множество A состоит из конечного числа выпуклых множеств, причем одно из них бесконечно. Поскольку это множество формульно, оно содержит интервал (a, b). Но тогда $a < b$, что противоречит выбору множества A.

Материалы и методы

Основные материалы в проведенной работе – это частично упорядоченные алгебраические структуры и их подмножества, которые можно было бы в том или ином смысле считать выпуклыми. Методы, которые применялись в исследовании, – это общие методы теории моделей, методы о-минимальности и слабой о-минимальности для линейно упорядоченных структур в их адаптации к исследованию частично упорядоченных структур.

Результаты и обсуждение

Результатом проведенного исследования является ряд обобщений понятия выпуклого множества на частично упорядоченные структуры и некоторые свойства $*$-слабо о-минимальных структур. Мы были бы рады, если бы читатели присоединились к обсуждению вариантов слабой о-минимальности для частично упорядоченных структур, перед нами стоит множество вопросов, в частности, описания насколько эти классы совпадают, описания чистых частичных порядков, где все или некоторые понятия $*$-слабой о-минимальности эквивалентны, описание свойств одноместных функций, взаимодействия типов и многие другие.

Заключение

В работе получены результаты, которые говорят, что перенос слабой о-минимальности на частичные порядки не является тривиальной задачей, были получены разнообразные классы слабо о-минимальных частично упорядоченных структур, для каждого из которых можно развивать свою теорию.

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[1,2]Судоплатов С.В.,
ф.-м.ғ.д., профессор, ORCID ID: 0000-0002-3268-9389,
e-mail: sudoplat at math.nsc.ru
[3*]Вербовский В.В.,
ф.-м.ғ.д., доцент, ORCID ID 0000-0001-5177-8523,
e-mail: verbovskiy at math.kz

[1] РҒА СБ С.Л. Соболев атындағы математика институты, 630090, Новосибирск қ., Ресей
[2] Новосібір мемлекетік техникалық университеті, 630073, Новосибирск қ., Ресей
[3]Математика және математикалық модельдеу институты, 050010, Алматы қ., Қазақстан

ЖАРТЫЛАЙ РЕТТЕЛГЕН ҚҰРЫЛЫМДАР ҮШІН ДӨҢЕСТІК ЖӘНЕ ӘЛСІЗ О-МИНИМАЛДЫЛЫҚ ТҮСІНІКТЕРІ ТУРАЛЫ

Аңдатпа

Бұл жұмыста біз әлсіз о-минималдылық концепциясын жартылай реттелген жиындарға жалпылауды қарастырамыз. Дегенмен әлсіз о-минималдылық концепциясы дөңес жиын тұжырымдамасына біздің ойымызша негізделген, яғни осы жұмыста ұсынылған ішінара тікелей тасымалдау, ең сәтті шешім емес. Себебі ендеше әлсіз о-минималды жартылай реттелген құрылымдар класында кез келген математикалық құрылымды анықтауға болады. Оның үстіне, көрсетілгендей, мұны интервалдардың қиылысуы сияқты қарапайым операция арқылы жүзеге асырады. Мақала ішінара реттерге «дөңес жиын» түсінігінің әртүрлі

жалпылауларын іздеуге арналған. Түзудегі дөңес жиындардың басқа да қасиеттері бар, мысалы, оларды интервалдардың бірігуі немесе қиылысы ретінде көрсету мүмкіндігі. Дөңес жиындар өзара байланысты болғандықтан, бұл қасиеттердің барлығы ішінара реттелген құрылымдар үшін дөңес жиынды анықтауға негіз бола алады. Осылайша, дөңес жиынды кірістірілген аралықтардың (жартылай интервалдар, сегменттер) бірігуі ретінде көрсету бізге «ішкі дөңес жиын» түсінігін, ал аралықтардың қиылысуы «сыртқы дөңес жиын» ұғымын береді. Мақалада енгізілген ұғымдардың эквивалентсіздігін көрсететін мысалдар құрастырылды.

Тірек сөздер: сызықтық реттелген жиын, жартылай реттелген жиын, әлсіз o-минималдылық, дөңес жиын.

[1,2]Sudoplatov S.V.,
Dr. Phys.-Math.Sc., Professor, ORCID ID: 0000-0002-3268-9389,
e-mail: sudoplat at math.nsc.ru
[3*]Verbovskiy V.V.,
Dr. Phys.-Math.Sc., ORCID ID: 0000-0001-5177-8523,
e-mail: verbovskiy at math.kz

[1]S.L. Sobolev Institute of Mathematics, 630090, Novosibirsk, Russia
[2]Novosibirsk State Technical University, 630073, Novosibirsk, Russia
[3]Institute of Mathematics and Mathematical Modeling, 050010, Almaty, Kazakhstan

ON THE CONCEPTS OF CONVEXITY AND WEAK O-MINIMALITY FOR PARTIALLY ORDERED STRUCTURES

Abstract

In this paper, we consider a generalization of the concept of weak o-minimality to partially ordered sets. However, the concept of weak o-minimality is based on the concept of a convex set, the direct transfer of which to partial orders, as it will be shown in the work, is not, in our opinion, the most successful, since then in the class of weakly o-minimal partially ordered structures, it is possible to define any mathematical structure. Moreover, as it will be shown, this can be done using such a simple operation as the intersection of intervals. The article is devoted to the search for various generalizations of the concept of "convex set" to partial orders. Since convex sets on a line also have other properties, such as the ability to represent them as a union or intersection of intervals, convex sets are connected, all these properties can be used as the basis for the definition of a "convex set" for partially ordered structures. Thus, the representation of a convex set as a union of nested intervals (half-intervals, segments) gives us the concept of an "internally convex set," and the intersection of intervals gives us the concept of an "externally convex set". In the article, we will build examples that show the non-equivalence of the introduced concepts.

Key words: linearly ordered set, partially ordered set, weak o-minimality, convex set.

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[1]*Турусбекова У.К.,
PhD, ORCID ID 0000-0002-0591-2143, *e-mail: umut.t@mail.ru
[2]Муратбеков М.М.,
PhD, ORCID ID 0000-0003-2197-4982, e-mail: Madimm@list.ru
[3]Алтынбек С.А.,
PhD, ORCID ID 0000-0002-8435-7773, e-mail: serik_aa@bk.ru

[1]Esil University, 010000, г. Астана, Казахстан
[2]Евразийский национальный университет им. Л.Н. Гумилева, 010008, г. Астана, Казахстан,
[3]Казахский университет технологии и бизнеса, 010000, г. Астана, Казахстан

ИССЛЕДОВАНИЕ АЛГОРИТМОВ ПОИСКА ПРИМИТИВНЫХ ЭЛЕМЕНТОВ КОНЕЧНОГО ПОЛЯ БОЛЬШОГО ПОРЯДКА

Аннотация

Одной из наиболее важных нерешенных и заведомо трудных задач в вычислительной теории конечных полей является разработка быстрого алгоритма для построения примитивных корней в конечном поле. С другой стороны, для многих приложений вместо примитивного корня достаточно элемента высокого мультипликативного порядка. Такие приложения включают, помимо прочего, криптографию, теорию кодирования, генерацию псевдослучайных чисел и комбинаторные схемы. Явные построения элементов высокого порядка обычно полагаются на методы комбинаторики, которые могут обеспечить доказуемую нижнюю границу порядка, но не вычисляют его точный порядок. Выполнение таких построений обычно основано на том, что факторизация порядка уже известна. В идеале мы должны иметь возможность получить примитивный элемент для любого конечного поля за разумное время. Однако если простая факторизация порядка группы неизвестна, этого сложно добиться. Таким образом, ставят менее амбициозную задачу – задачу построения элемента достаточно высокого порядка. В данной статье мы рассматриваем различные алгоритмы, которые находят элемент высокого порядка как для общих, так и для специальных конечных полей. Кроме того, в этой работе мы касаемся теории периодов Гаусса над конечными полями, их обобщениями и аналогами, которые, как известно, уже доказали свою полезность для ряда различных приложений.

Ключевые слова: конечное поле, примитивный элемент, простое число, простая факторизация, периоды Гаусса.

Введение

Известно, что мультипликативные группы конечных полей являются циклическими. Их мультипликативные порождающие иногда называют примитивными элементами. Важной проблемой в вычислительной теории чисел является поиск мультипликативного порождающего для конечного поля. Общеизвестно, что эта проблема сложна и все еще остается открытой. Трудность ее заключается не в недостатке примитивных элементов. В действительности, доказана следующая теорема.

Теорема 1. Пусть q – простая степень, а F_q – конечное поле, состоящее из q элементов. Число примитивных элементов в F_q, т.е. $\varphi(q-1)$, больше, чем $cq/\log\log q$, где $c > 0$ – абсолютная константа, а φ является функцией Эйлера [1, глава 1, теорема 5.1].

Функция $1/\log\log q$ является функцией от размера входных данных и очень медленно приближается к нулю по мере того, как q становится большим. Это означает, что, если выбрать случайный элемент, есть значительная вероятность получить именно примитивный элемент. Эквивалентно, если выбрать список из $(\log\log q)^{1+\varepsilon}$ множества случайных элементов, с вероятностью $1-o(1)$ в списке будет примитивный элемент. Однако очень трудно решить,

какой именно элемент будет примитивным. Единственный известный общий метод основан на следующем факте.

Предложение 2. Пусть $q-1=p_1^{e_1}p_2^{e_2}\ldots p_m^{e_m}$, где $p_1,\ldots,p_m$ – разные простые числа. Элемент α является примитивным в F_a тогда и только тогда, когда для любого p_i, где $1 \le i \le m$, выполняется неравенство $\alpha^{(q-1)/p_i} \neq 1$.

На основе этих утверждений можно построить рандомизированный алгоритм для нахождения примитивного элемента с предполагаемой временной сложностью $e^{O\left(\log^{1/3} q(\log\log q)^{2/3}\right)}$. Эта сложность равна сложности самого быстрого алгоритма общего назначения с коэффициентом $q-1$ и непрактична по мере увеличения q. Более того, нахождение примитивного элемента является крайним случаем нахождения элемента большого порядка.

На практике особенно полезны поля с небольшими характеристиками. Если характеристики полей малы, то часто поиск простой факторизации порядка является более сложной задачей, чем поиск порядка случайных простых полей. В этом контексте задачу об элементе большого порядка можно перефразировать следующим образом: для фиксированной простой степени q найти элемент в F_{q^n} с большим порядком за полиномиальное по n время. Еще одна актуальная, но при этом более простая задача: требуется найти число n, большее заданного числа N, и элемент порядка по крайней мере q^{n^c} в F_{q^n} для некоторой константы c. Логическое обоснование этого вопроса, называемого *проблемой специального конечного поля с элементами высокого порядка*, состоит в том, чтобы сначала рассмотреть вопросы, связанные со специальными конечными полями, а затем попытаться увеличить «плотность» последовательности из n, чтобы в итоге для всех расширений конечного поля можно было бы найти элементы высокого порядка. Напомним, что *плотностью последовательности* (A) по Шнирельману называется точная нижняя грань всех значений дроби $A(n)/n$, где $A(n)$ – число натуральных чисел последовательности (A), не превосходящих n. Поскольку $0 \le A(n) \le n$, получаем, что $0 \le A(n)/n \le 1$. Заметим, что от нас не требуется вычислять точный порядок элемента. Вместо этого нам нужно только предоставить доказательство того, что элемент имеет порядок, превышающий определенную границу.

Обзор литературы

Разработка быстрого алгоритма для построения примитивных элементов конечных полей является сложной задачей в вычислительной теории конечных полей. В зависимости от конкретных задач иногда достаточно изучить построения элементов высокого порядка. В своей классической работе [2] Ванг показал, что для простого конечного поля F_p наименее примитивный элемент ограничен $p^{1/4+\varepsilon}$. В работе [3] Шоуп улучшил его результат. В статье [4] показано, как построить множество мощности $O(\log^4 p)$, которое содержит по крайней мере один примитивный элемент, однако это построение основано на расширенной гипотезе Римана. В работах [5–6] показано, что в поле с простой степенью q примитивный элемент может быть найден с временной сложностью $q^{\frac{1}{4}+\varepsilon}$. В статье [7] приведен метод построения элементов в F_{q^n}, порядки которых больше любого многочлена от n, когда n становится большим. В работе [8] приводится тщательный анализ конструкции элементов высокого порядка в конечных полях, предложенной С. Гао. В статьях [9–11] представлен эффективный алгоритм, который для любого конечного поля малой характеристики находит расширение полиномиально ограниченной степени. Работы [12–14] основаны на алгоритме AKC (тест Агравала – Каяла – Саксены) тестирования простоты чисел.

Основные положения

Если известна факторизация порядка, то имеем эффективный рандомизированный алгоритм для построения примитивного элемента. Можно ли дерандомизировать алгоритм? Этот вопрос

сводится к задаче построения небольшого множества, содержащего примитивный элемент. Естественно, начинаем с небольших чисел. Определение верхней границы наименьшего примитивного элемента является интересной задачей в теории чисел. Предполагая РГР (расширенная гипотеза Римана), Ванг [2] показал, что наименьший примитивный корень в простом конечном поле F_p ограничен $O(\omega^6(p-1)\log^2 p)$, где ω – отображение, передающее положительное целое число числу его различных простых делителей. Можно доказать, что $\omega(n) = O(\log n / \log\log n)$. Шоуп [3] улучшил привязку к $\tilde{O}(\omega^4(p-1)\log^2 p)$. Здесь $\tilde{O}(f(n))$ означает $O(f(n)\log^c f(n))$ для некоторой константы c.

Следовательно, если РГР верна, можно сгенерировать множество, содержащее примитивный элемент, перечислив все числа, меньшие границы Шоупа, которая является полиномиальной в зависимости от размера входных данных. Бах [4] показывает, как при предположении истинности РГР построить множество мощности $O(\log^4 p)$, которое содержит по крайней мере один примитивный элемент. Вместо того чтобы использовать только небольшие числа, это множество состоит из более крупных элементов, которые являются произведением маленьких простых чисел.

Случай с полями малых характеристик кажется более простым. Шоуп [3] и – независимо – Шпарлински [5, теорема 2.4] показывают, что можно детерминистически построить множество размера $(np)^{O(1)}$, которое содержит по крайней мере один примитивный элемент в F_{p^n}.

Шпарлински [6] показал, что в F_q, где q – степень простого числа, примитивный элемент может быть найден с временной сложностью $q^{\frac{1}{4}+\varepsilon}$. Заметим, что наилучший детерминированный алгоритм для вычисления коэффициента N требует времени $N^{\frac{1}{4}+\varepsilon}$.

Материалы и методы

Предположим, что поле задано как $F_q[x]/(f(x))$, где $f(x)$ – неприводимый многочлен над F_q. Пусть $\alpha \equiv x \pmod{f(x)}$. Два разных многочлена могут представлять один и тот же элемент в поле. Например, $x+1$ и $1-x^3$ относятся к одному и тому же классу эквивалентности в $F_3[x]/(x^2+1)$. Тем не менее легко показать следующее.

Предложение 3. Если $f(x)$ и $g(x)$ не равны в $F_q[x]$ и их степени меньше n, то $f(\alpha) \neq g(\alpha)$.

Все построения следуют из вышеизложенной схемы. Целевой элемент β спроектирован таким образом, что мы можем найти множество U большой мощности, состоящее из целых чисел от 1 до $q^n - 1$, которое удовлетворяет следующим условиям:

1. Для любого $i \in U$, элемент β^i имеет простое представление порядка, меньшее n в $F_p[\alpha]$ (обычно мы получаем представление, используя линейность p-й степени);

2. Для любого $i, j \in U$, если $i \neq j$, то $\beta^i \neq \beta^j$. Поскольку степень β имеет представление малого порядка, мы можем перенести элемент в кольцо многочленов $F_q[x]$, где легче доказать различие двух элементов.

Если докажем эти два утверждения, то можно показать, что мощность множества U является нижней границей порядка.

Следуя этой схеме, Гао [7] представил алгоритм полиномиального времени, который для фиксированной простой степени q и целого числа n выводит элемент порядка по меньшей мере

$$n^{\frac{\log_q n}{4\log_q(2\log_q n)}-\frac{1}{2}}. \quad (1)$$

Он не доказал, что алгоритм всегда выводит такой элемент. Но такое предположение допустимо.

Для многочлена $g(x) \in F_q[x]$ определим $g^{(i)}(x)$ как i-кратную композицию функции g. Формально

$$g^{(0)}(x) = x \text{ и } g^{(i)}(x) = g^{(i-1)}(g(x)) \text{ для } i \geq 1.$$

Пусть m – наименьшая степень простого числа q, которая больше или равна n. Метод Гао проверяет, имеет ли $x^m - g(x)$ неприводимый множитель степени n для всех многочленов степени не более $2\log_q n$. Если это так, то он выводит корень такого многочлена, обозначаемого через β. Очевидно, что $F_q[\beta] = F_{q^n}$. Гао предположил, что такой многочлен $g(x)$ существует.

Рассмотрим порядок β. Обозначим степень $g(x)$ через ε. Можно показать, что

$$\beta^m = g(\beta),$$
$$\beta^{m^2} = g(\beta)^m = g(\beta^m) = g^{(2)}(\beta).$$

По индукции $\beta^{m^i} = g^{(i)}(\beta)$. Эта степень β^{m^i} растет со скоростью ε^i. Пусть

$$t = \left\lfloor \frac{\log_q n}{2\log_q \varepsilon} \right\rfloor \text{ и } U = \left\{ \sum_{i=0}^{t-1} a_i m^i \mid 0 \le a_i \le \sqrt{n} \right\}.$$

Для любого $u = \sum_{i=0}^{t-1} a_i m^i \in U$ положим, что $\beta^u = \prod_{i=0}^{t-1} g^{(i)}(\beta)^{a_i}$. Можно проверить, что многочлен $\prod_{i=0}^{t-1} g^{(i)}(x)^{a_i}$ имеет степень меньше n.

Пусть

$$u' = \sum_{i=0}^{t-1} a'_i m^i \in U.$$

Для того чтобы показать, что для любого $u \neq u' \in U$ имеет место $\beta^u \neq \beta^{u'}$, необходимо доказать неравенство

$$\prod_{i=0}^{t-1} g^{(i)}(\alpha)^{a_i} \neq \prod_{i=0}^{t-1} g^{(i)}(\alpha)^{a'_i}.$$

Это сводится к тому, чтобы показать

$$\prod_{i=0}^{t-1} g^{(i)}(x)^{a_i} \neq \prod_{i=0}^{t-1} g^{(i)}(x)^{a'_i}.$$

Это следует из утверждения о мультипликативной независимости $g^{(i)}(x)$, доказанного Гао:

Предложение 4. Предположим, что $f(x) \in F_q[x]$ не является ни одночленным, ни биномиальным вида $ax^{p^l} + b$. Тогда многочлены

$$f^{(1)}(x), f^{(2)}(x), \dots, f^{(n)}(x), \dots$$

являются мультипликативно независимыми, а именно для любых целых чисел $k_1, k_2, \dots, k_n$

$$\left(f^{(1)}(x)\right)^{k_1}\left(f^{(2)}(x)\right)^{k_2}\dots\left(f^{(n)}(x)\right)^{k_n} = 1$$

тогда и только тогда, когда $k_1 = k_2 = \dots = k_n = 0$.

Более тщательно проанализировав построение Гао, Конфлитти [8] показал, что в некоторых случаях нижняя граница для порядка β лучше, чем (1). Поскольку степень $g^{(i)}(x)$ растет экспоненциально с увеличением i, оба результата доказывают лишь незначительно суперполиномиальные нижние границы. Если поле обладает дополнительными структурами, то есть два метода, которые позволяют избежать проблемы и построить элемент порядка, большего, чем q^{n^c}, для константы c. Оба метода работают только в специальных полях.

Основываясь на свойствах периодов Гаусса, фон Цур Гатен и Шпарлински предложили алгоритм, который создает элемент субэкспоненциального порядка в некоторых специальных полях. Предположим, что $r = 2n + 1$ – простое число, не делящее q, а q – примитивный элемент в F_r. Разумеется, $r | q^{2n-1}$. Пусть ξ – примитивный r-й корень из единицы в $F_{q^{2n}}$.

Рассмотрим значение $\beta = \xi + \xi^{-1}$, также известное как период Гаусса типа (n, 2). Легко показать, что $\beta \in F_{q^n}$.

Пусть $h = \lfloor \sqrt{r} \rfloor - 1$,

$$U = \left\{ \sum_{i=1}^{h} a_i q^{s_i} \mid a_i \in \{0,1\} \right\},$$

где s_i – дискретный логарифм i по модулю r, а именно $q_i^s (mod\ r) \equiv i$. Таким образом, $|U| = 2^h$. Для $u = \sum_{i=0}^{h-1} a_i q^{s_i} \in U$, имеем

$$(\xi + \xi^{-1})^u = \prod_{i=1}^{h} \left(\xi^{q^{s_i}} + \xi^{-q^{s_i}}\right)^{a_i} = \prod_{i=1}^{h} (\xi^i + \xi^{-i})^{a_i} =$$

$$= \xi^{\sum_{i=1}^{h}(-a_i)} \prod_{i=1}^{h} (\xi^{2i} + 1)^{a_i}.$$

Пусть

$$u' = \sum_{i=0}^{h-1} a'_i q^{s_i} \in U.$$

Для любых двух $u \neq u' \in U$ докажем, что $\beta^u \neq \beta^{u'}$. Предположим, что

$$\sum_{i=1}^{h} a'_i \geq \sum_{i=1}^{h} a_i.$$

Мы должны доказать, что

$$\xi^{\sum_{i=1}^{h}(a'_i) - \sum_{i=1}^{h}(a_i)} \prod_{i=1}^{h} (\xi^{2i} + 1)^{a_i} - \prod_{i=1}^{h} (\xi^{2i} + 1)^{a'_i} \neq 0\,.$$

Степень многочлена

$$t(x) = x^{\sum_{i=1}^{h}(a'_i) - \sum_{i=1}^{h}(a_i)} \prod_{i=1}^{h} (x^{2i} + 1)^{a_i} - \prod_{i=1}^{h} (x^{2i} + 1)^{a'_i}$$

меньше $r - 1$. Поскольку минимальный многочлен от ξ над F_q имеет степень $r - 1$, необходимо доказать только, что в $F_q[x]$ многочлен $t(x)$ не является нулевым.

Если $\sum_{i=1}^{h} a_i \neq \sum_{i=1}^{h} a'_i$, это очевидно, поскольку $t(0) = -1$.

В противном случае предположим, что $\{i \mid a_i = 1\} \cap \{i \mid a'_i = 1\} = \emptyset$.

Пусть s – наименьшее i такое, что $a_i = 1$ или $a'_i = 1$. Можно проверить, что коэффициент x^s в $t(x)$ не равен нулю. На этом доказательство завершается.

Основываясь на этом аргументе, фон Цур Гатен и Шпарлински [9–11] получили следующие результаты:

Предложение 5. Пусть q – фиксированная простая степень. Для любого натурального числа N целое число $n \geq N$ с $n = O(N \log N)$ и элементом $\alpha \in F_{q^n}$ порядка не менее $2^{(2n)^{1/2}-2}$ может быть вычислено за полиномиальное по N время.

По сути, алгоритм ищет простое число r, большее чем $2N + 1$, такое, что q является примитивным элементом в F_r. Преимущество этого алгоритма в том, что полученный элемент также является нормальным элементом. Убрав это требование, докажем результат с более плотной последовательностью из n.

Предложение 6. Пусть q – фиксированная простая степень. Для любого натурального числа N целое число $n \geq N$ с $n = N + O(N/log^c N)$ и элементом $\alpha \in F_{q^n}$ порядка не менее $2^{10q^{-12}n^{1/2}-25}$ может быть вычислено за полиномиальное по N время.

Степень многочлена в ξ представлении $\xi^i \beta^{q^{s_i}}$ равна $2i$, которая линейно растет с i. Следовательно, они достигают субэкспоненциальной нижней границы $2^{o(\sqrt{n})}$. Далее рассмотрим результаты работы [12], в которой степень многочлена, представляющего β^{q^i}, фиксирована равной 1, и, следовательно, получается нижняя граница $2^{n^{1-\varepsilon}}$.

Результаты и обсуждения

Новый метод в алгоритме тестирования простоты АКС и его последующих улучшениях [13] заключается в использовании многочленов первой степени для генерации большой мультипликативной подгруппы по модулю целого числа и многочлена. Ченг [12] обнаружил связь со специальной задачей об элементах высокого порядка конечного поля и применил эту идею для получения нового решения специальной задачи об элементах высокого порядка конечного поля. Его результат показывает более плотную последовательность из n и гораздо более высокого порядка.

Рассмотрим расширение Куммера F_{q^n}, где $n \mid q-1$. Можно предположить, что $F_{q^n} = F_q[x]/(x^n - b)$, где $x^n - b$ – неприводимый многочлен над F_q. Как обычно, пусть $\alpha \equiv x (mod\ x^n - b)$. Пусть $\beta = \alpha + 1$. Рассмотрим порядок β. Получаем

$$\beta^q = (\alpha+1)^q = \alpha^q + 1 = (\alpha^n)^{\frac{q-1}{n}}\alpha + 1 = b^{\frac{q-1}{n}}\alpha + 1.$$

Обозначим $c = b^{\frac{q-1}{n}}$. Имеем

$$(\alpha+1)^{q^i} = b^{\frac{i(q-1)}{n}}\alpha + 1 = c^i\alpha + 1.$$

Пусть

$$U = \left\{ \sum_{i=1}^{n} a_i q^i \;\middle|\; \sum_{i=1}^{n} |a_i| = n-1, |\{i: a_i < 0\}| = \lfloor 0.292n \rfloor, \sum_{a_i<0} |a_i| = \lceil n/2 \rceil \right\}.$$

Имеем

$$|U| = \binom{n}{d_-}\begin{pmatrix} d & -1 \\ d_- & -1 \end{pmatrix}\begin{pmatrix} 2n-d_- & -d-2 \\ n-d_- & -1 \end{pmatrix} = \Omega(5.8^n).$$

где $d_- = \lfloor 0.292n \rfloor$ и $d = \lceil n/2 \rceil$. Пусть $u = \sum_{i=1}^{n} a_i q^i \in U$, имеем

$$\beta^u = \prod_{i=1}^{n} (c^i\alpha + 1)^{a_i} = \frac{\prod_{1\leq i\leq m, a_i\geq 0}(c^i\alpha+1)^{a_i}}{\prod_{1\leq i\leq m, a_i<0}(c^i\alpha+1)^{-a_i}}.$$

Докажем от противного, что для $u' = \sum_{i=1}^{n} a'_i q^i \in U$, если $u \neq u'$, тогда $\beta^u \neq \beta^{u'}$. Предположим, что эти два элемента равны, имеем

$$\prod_{1\leq i\leq m, a_i\geq 0} (c^i\alpha+1)^{a_i} \prod_{1\leq i\leq m, a'_i<0} (c^i\alpha+1)^{-a'_i} =$$

$$= \prod_{1\leq i\leq m, a_i<0} (c^i\alpha+1)^{-a_i} \prod_{1\leq i\leq m, a'_i\geq 0} (c^i\alpha+1)^{a'_i}.$$

Так как

$$\sum_{1\leq i\leq m, e_i\geq 0} a_i + \sum_{1\leq i\leq m, a'_i<0} (-a'_i) = \sum_{1\leq i\leq m, a_i<0} (-a_i) + \sum_{1\leq i\leq m, a'_i\geq 0} a'_i = m-1$$

получаем

$$\prod_{1\le i\le m, a_i\ge 0}(c^i x+1)^{a_i}\prod_{1\le i\le m, a_i'<0}(c^i x+1)^{-a_i'}=$$
$$=\prod_{1\le i\le m, a_i<0}(c^i x+1)^{-a_i}\prod_{1\le i\le m, a_i'\ge 0}(c^i x+1)^{a_i'}.$$

в кольце $F_q[x]$. Это противоречит единственности факторизации кольца. Использование отрицательных показателей было предложено Волохом [14].

Теперь можно обобщить результаты, вытекающие из приведенных выше рассуждений.

Теорема 2. Пусть q – фиксированная простая степень. Для достаточно большого натурального числа N можно вычислить за полиномиальное по N время целое число $n \in [N, 2qN]$ и элемент $\beta \in F_{q^n}$ с порядком больше $5.8^{n/\log_q n}$.

В этой теореме используем последовательность $q-1$, $2(q^2-1)$, …, $i(q^i-1)$, ... В следующей теореме будем использовать более плотную последовательность 2, 6, 20, …, $p(p-1)$,… где p пробегает все простые числа.

Теорема 3. Пусть q – фиксированная простая степень. Можно вычислить за полиномиальное по N время целое число $n \in [N, N + O(N^{0.77})]$ и элемент

$\beta \in F_{q^n}$ с порядком, большим $5.8^{\sqrt{n}}$.

При $n \geq \log q$ полагается, что β имеет порядок $q^{n/2}$. Эта гипотеза имеет важное значение, что рандомизированное доказательство простоты АКС имеет временную сложность $\tilde{O}(\log^3 p)$, где p – целое число.

Заключение

Поскольку задача с примитивными элементами сложна, в большинстве случаев криптографических приложений конечные поля выбираются таким образом, что известны полные разложения порядков полей на множители, следовательно, существует эффективный рандомизированный алгоритм для построения генераторов для этих полей. Таким образом, в работе мы обобщили результаты, вытекающие из приведенных выше рассуждений, и предложили алгоритмы, которые находят элемент высокого порядка как для общих, так и для специальных конечных полей.

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[1]*Турусбекова У.К.,
PhD, ORCID ID: 0000-0002-0591-2143, *e-mail: umut.t@mail.ru
[2]Муратбеков М.М.,
PhD, ORCID ID: 0000-0003-2197-4982, e-mail: Madimm@list.ru
[3]Алтынбек С.А.,
PhD, ORCID ID: 0000-0002-8435-7773, e-mail: serik_aa@bk.ru

[1]Esil University, 010000, Астана қ., Қазақстан
[2]Л.Н. Гумилев атындағы Еуразия ұлттық университеті, 010008, Астана қ., Қазақстан
[3]Қазақ технология және бизнес университеті, 010000, Астана қ., Қазақстан

ЖОҒАРЫ РЕТТІ АҚЫРЛЫ ӨРІСТІҢ ПРИМИТИВТІ ЭЛЕМЕНТТЕРІН ІЗДЕУ АЛГОРИТМДЕРІН ЗЕРТТЕУ

Аңдатпа

Ақырлы өрістерді есептеу теориясындағы ең маңызды шешілмеген және күрделі мәселелердің бірі ақырлы өрісте алғашқы түбірлерді құрудың жылдам алгоритмін дайындау. Екінші жағынан, көптеген қосымшалар үшін алғашқы түбірдің орнына жоғары мультипликативті ретті элемент жеткілікті. Мұндай қосымшаларға криптография, кодтау теориясы, псевдокездейсоқ сандар генерациясы және комбинаторлық схемалар кіреді, бірақ олармен шектелмейді. Жоғары ретті элементтердің айқын құрылыстары әдетте дәлелденетін төменгі реттік шекараны қамтамасыз ете алатын комбинаторика әдістеріне сүйенеді, бірақ бұл нақты ретті есептемейді. Оны орындау әдетте ретті факторизациялауды білуді білдіреді. Ең дұрысы, саналы уақыт ішінде кез келген ақырлы өріс үшін примитивті элементті ала алуымыз керек. Алайда егер топтық реттің қарапайым факторизациясы белгісіз болса, мақсатқа қалай жетуге болатыны белгісіз. Осылайша, мүмкіндігінше жоғары ретті элементті құру есебін қоямыз. Бұл мақалада жалпы немесе арнайы ақырлы өрістер үшін жоғары ретті элементті табатын әртүрлі алгоритмдер қарастырылады. Сонымен қатар ұсынылған жұмыс ақырлы өрістердегі Гаусс кезеңдерінің теориясына тағы бір үлес қосады және олардың әртүрлі қосымшалар үшін пайдалы екендігін дәлелдеген жалпылаулары мен аналогтар болады.

Тірек сөздер: ақырлы өріс, примитивті элемент, жай сан, қарапайым факторизация, Гаусс периодтары.

[1]*Turusbekova U.K.,
PhD, ORCID ID: 0000-0002-0591-2143, *e-mail: umut.t@mail.ru
[2]Muratbekov M.M.,
PhD, ORCID ID: 0000-0003-2197-4982, Madimm@list.ru
[3]Altynbek S.A.,
PhD, ORCID ID: 0000-0002-8435-7773, serik_aa@bk.ru

[1]Esil University, 010000, Astana, Kazakhstan
[2]L.N. Gumilyov Eurasian National University, 010008, Astana, Kazakhstan
[3]Kazakh University of Technology and Business, 010000, Astana, Kazakhstan

RESEARCH OF ALGORITHMS FOR SEARCHING PRIMITIVE ELEMENTS OF A FINITE FIELD OF HIGH ORDER

Abstract

One of the most important unsolved and notoriously difficult problems in computational finite field theory is the development of a fast algorithm for constructing primitive roots in a finite field. It is known that for many applications, instead of a primitive root, just an element of high multiplicative order is sufficient. Such applications include, but are not limited to, cryptography, coding theory, pseudorandom number generation, and combinatorial schemes. Explicit constructions of high-order elements usually rely on combinatory methods that can provide a provable lower bound on the order, but this does not compute the exact order. Its execution usually implies knowledge of the factorization of the order. Ideally, we should be able to get a primitive element for any finite field in a reasonable amount of time. However, if the simple factorization of the group order is unknown, it is difficult to achieve the goal. Thus, we set the task of constructing an element, probably of a high order. This article discusses various algorithms that find a high-order element for general or special finite fields. This work also represents another contribution to the theory of Gauss periods over finite fields and their generalizations and analogues, which have already proven their usefulness for a number of different applications.

Key words: finite field, primitive element, prime number, simple factorization, Gauss periods.

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[1*]**Askarbekkyzy A.,**
Doctoral student, ORCID ID: 0000-0003-0075-4438,
*e-mail: ms.askarbekkyzy@gmail.com
[2]**Iskakov A.M.,**
Master Student, ORCID ID: 0009-0005-2550-2079,
e-mail: bheadr73@gmail.com
[1]**Kalmurzayev B.S.,**
PhD., Associate Professor, ORCID ID: 0000-0002-4386-5915,
e-mail: birzhan.kalmurzayev@gmail.com

[1]Kazakh-British Technical University, Almaty, 050000, Kazakhstan
[2]Al-Farabi Kazakh National University, Almaty, 050000, Kazakhstan

ON THE STRUCTURE OF PUNCTUAL LINEAR ORDERS ISOMORPHIC TO THE LEAST LIMIT ORDINAL

Abstract

The algorithmic complexity of presentations for various structures receives significant attention in modern literature. The main tool for determining such complexities is reducibility. It is a mapping that preserves relations of signature (for example, equivalence relation, orders, and so on). This work is dedicated to the study of punctual representations of the least limit ordinal with respect to primitive recursive reducibility. We denote this structure as $\mathbf{PR}(\omega)$. In particular, the paper examines the properties of structures $\mathbf{\Omega}$, consisting of computable copies of the least limit ordinal with respect to computable reducibility, and $\mathbf{Peq}$, consisting of punctual equivalence relations with respect to primitive recursive reducibility. We say that the linear order L is reducible to the linear order R, if there exists a total function p such that $(x, y) \in L$ if and only if $(p(x), p(y)) \in R$. Reducibility is called computable (primitive recursive) if the function that performs the reducibility is computable (primitive recursive). It is shown that the degree of ω is not the least degree in $\mathbf{PR}(\omega)$, as it was in $\mathbf{\Omega}$. The structure $\mathbf{PR}(\omega)$ does not contain maximal degrees, and this structure is not dense. Also, an example of an incomparable pair that has the least upper bound is given.

Key words: primitive recursive function, linear order, primitive recursive reducibility, punctual representations of linear order, self-full orders.

Introduction

Kalimullin, Melnikov and Ng in [1] proposed a general approach to studying punctual structures: an infinite structure $\mathcal{S}$ (on a finite signature σ) is punctual, if its domain of the structure $\mathcal{S}$ is the set of natural numbers and all functions and relations of signature σ are primitive recursive. Inspired by this work, various authors began to explore punctual structures. For example, in the work [2] the authors studied the structure of punctual equivalence relations with respect to primitive recursive reducibility (They called this structure $\mathbf{Peq}$). Surprisingly, the $\mathbf{Peq}$ turned out to be very well-behaved compared to its computably enumerable counterpart, the structure of $\mathbf{Ceers}$, mainly studied in the works of [3, 4, 5, 6] and many others. That is, the structure $\mathbf{Peq}$ turned out to be a dense distributive lattice with the greatest element Id (where Id is the equality relation on natural numbers). The next fact shows that the structure $\mathbf{Peq}$ is neither rigid nor homogeneous and contains non-isomorphic lower cones. From the above, one might even think that elementary theory of the structure $\mathbf{Peq}$ is decidable, but this question remains open for now.

The structure of computable representations of the ordinal ω with respect to computable reducibility was studied in the works of [7, 8], the authors denoted this structure by $\mathbf{\Omega}$. Note that $\mathbf{\Omega}$ has the smallest degree – the standard representation of ω, has no principal or maximal degrees, and is only partially dense (in the sense that the density property does not hold everywhere). Following [7], a linear order L from $\mathbf{\Omega}$ is self-full if and only if L reduces to L only via an identity function. In [7] it is proved that the set of self-full linear orders is definable in $\mathbf{\Omega}$: L is self-full if and only if L has a strong minimal cover. The work [9] studies the complexities of index sets $\mathbf{\Omega}$ and self-full relations from $\mathbf{\Omega}$.

In this paper we will check whether the structure of punctual linear orders isomorphic to the ordinal ω (we denote this structure by $\mathbf{PR}(\omega)$) is as good as $\mathbf{Peq}$.

In Section 2 we provide the necessary facts, definitions and agreements for comfortable reading of the results of the work. Section 3 provides proofs of the main results on the structure of $\mathbf{PR}(\omega)$. In particular, it is proved that the degree of the standard copy of the ordinal ω is not the least element in $\mathbf{PR}(\omega)$, unlike in the structure $\mathbf{\Omega}$ (Proposition 1). Properties such as absence of universal and maximal elements (Theorem 3.1, Corollary 3.2), not being dense (Theorem 3.3) and having incomparable pairs with suprema (Corollary 3.4) in $\mathbf{\Omega}$ turned out to work in the structure $\mathbf{PR}(\omega)$.

Preliminaries

This work explores questions of linear orders using methods from computability theory. In particular, we will deal with sets and functions defined on the set of natural numbers $\omega = \{0, 1, 2, \dots\}$. We write the value of the standard bijective function of a pair from $\omega \times \omega$ onto ω as $\langle x, y\rangle$; we also define the functions $l(\langle x, y\rangle) = x$ and $r(\langle x, y\rangle) = y$ that restore the left and the right components of the pair, respectively. If f is some function, then $range(f)$ is the set of all possible values of f.

A linear order $(|L|, <_L)$ is called primitive recursive, if the main set $|L|$ and the order relation $<_L$ are primitive recursive. For convenience, we will denote L as the linear order $\langle |L|, <_L\rangle$. A linear order S is called a linear suborder of order L if $\forall s_1, s_2 \in S$

$$s_1 <_S s_2 \Rightarrow s_1 <_L s_2.$$

A linear suborder S is called an interval of linear order L if for any $a, b \in S$, $c \in L$ and

$$a \leq_L c \leq_L b \Rightarrow c \in S.$$

If a and b are the least and the greatest elements of the interval S, respectively, then we denote this interval in L as $[a, b]_L$.

Following the approach of [1, 10], we define the structure of punctual linear orders isomorphic to the given linear order. Let L and M be primitive recursive linear orders. We will say that the order L is primitively recursively reducible to the order M, denoted by $L \leq_{pr} M$, if there exists a primitive recursive function f such that for any $a, b \in L$

$$a <_L b \Leftrightarrow f(a) <_M f(b).$$

As usual, we will write $L \equiv_{pr} M$ if $L \leq_{pr} M$ and $M \leq_{pr} L$. A pr-degree of order L is the set $\deg_{pr}(L) = \{M : M \equiv_{pr} L\}$.

Note that if $L \leq_{pr} M$ and M is a primitive recursive order, then L is primitive recursive preorder.

Definition 1. For a primitive recursive linear order L we define the degree structure

$$\mathbf{PR}(L) = \left(\{\deg_{pr}(M) : M \text{ is a punctual linear order isomorphic to } L\}, \leq pr\right).$$

Let L and M be linear orders. We say that L and M are pr-incomparable, denoted by $L|_{pr}M$, if $L \not\leq_{pr} M$ and $M \not\leq_{pr} L$. For a linear order R and a natural number s, we denote the restriction of linear order R to s by $R \upharpoonright s$ as follows: $dom(R \upharpoonright s) = [0, s]$ and $x \leq_{R\upharpoonright s} y$ if and only if $x \leq_R y$.

Definition 2. Let P be a partially ordered set (poset) and $a \in P$. Then an element $b \in P$ is called a minimal cover for a if

1. $a < b$, i.e. $a \leq b$ and $a \neq b$.
2. $(\forall c \in P)[a \leq c \leq b \rightarrow (c = a \vee c = b)]$.

An element $b \in P$ is called a strong minimal cover for a, if b is a minimal cover for a and

$$(\forall c \in P)[c < b \rightarrow c \leq a].$$

Andrews and Sorbi [6] introduced a useful notion of self-fullness for positive equivalence relations. Later, Kabylzhanova [11] proposed this notion for positive preorders and Askarbekkyzy et al. [7] proposed for linear orders:

Definition 3. Preorder P is called self-full if for any function f that provides c-reducibility from P to P the following holds

$$\forall y \exists x\, [y\, P\, f(x)\, \&\, f(x)\, P\, y].$$

In other words, preorder is self-full iff every reduction to itself hits all classes.

Note that a computable linear order L is self-full if $L \leq_c L$ via only computable permutation.

Let $\{p_e\}_{e\in\omega}$ be an effective listing of all unary primitive recursive functions. It is well known that this list is computable, but not primitive recursive.

In the paper, we will often build primitive recursive functions and primitive recursive linear orders. It is convenient to use the following restricted Church-Turing thesis for primitive recursive functions: a function is primitive recursive if and only if it can be described by an algorithm that uses only bounded loops. For example, one can omit using statements “while ... do”, “repeat ... until”, and “goto” in Pascal-like programming languages. We will often apply the restricted Church-Turing thesis without explicitly mentioning the thesis itself.

In addition, for a given partial computable function $\varphi_e(x)$, we may assume that its standard approximation $\varphi_{e,s}(x)$ can be computed primitively recursively. Here, as usual, $\{\varphi_e\}_{e\in\omega}$ is a standard numbering of all partial computable unary functions.

Results and discussion

In this section we prove some results about the structure of $\mathbf{PR}(\omega)$.

It is well known that the degree of the standard copy of ω is the least in the structure $\boldsymbol{\Omega}$ (Folklore). First, we show that this claim does not hold in the primitive recursive setting.

Proposition 1. $\deg_{pr}(\omega)$ is not the least element in the poset $\mathbf{PR}(\omega)$.

Proof. Fortunately, the order ω is “well defined” in that sense that for any numbers a and b, where $a < b$, we can readily discern the number of elements that lie between a and b. In the following

construction we will use this fact. We will define the order L step by step and define helpful functions $r(x)$ and $k(x)$ that compute the index of the primitive recursive function used at stage.

Construction.

Stage 0. Assume $r(0) = 0, k(0) = 0$ and L_0 is linear order on one element set $\{0\}$.

Stage $s+1$. Assume $e = r(s)$, $N = k(s)$. Consider the following cases:

1. If $p_{e,s}(N)$ is not defined, then we assume that
$r(s+1) = r(s), k(s+1) = k(s)$ and $L_{s+1} = L_s \cup \{(x, s+1): x \leq s+1\}$.

2. If $p_{e,s}(N) = y_0$ and $(y_0, N) \in L$ then we assume
$r(s+1) = r(s)+1, k(s+1) = s+1$ and $L_{s+1} = L_s \cup \{(x, s+1): x \leq s+1\}$.

3. If $p_{e,s}(N) = y_0$, $(y_0, N) \notin L$ (here we can assume that $y_0 \leq s$) and $p_{e,s}(N+k+1)$ is not defined (where $k = card\{x: x \leq s \,\&\, (y_0, x) \in L_s\}$), then
$r(s+1) = r(s), k(s+1) = s,$
$L_{s+1} = L_s \cup \{(x, s+1): (x, y_0) \in L_s \,\&\, x \neq y_0\} \cup \{(s+1, x): (y_0, x) \in L_s\}$.

4. If $p_{e,s}(N) = y_0$,$(y_0, N) \notin L$ (here we can assume that $y_0 \leq s$) and $p_{e,s}(N+k+1)$ is not defined (where $k = card\{x: x \leq s \,\&\, (y_0, x) \in L_s\}$), then
$r(s+1) = r(s)+1, k(s+1) = s+1, L_{s+1} = L_s \cup \{(x, s+1): x \leq s+1\}$.

End of the construction. We define L as $\bigcup_{s \in \omega} L_s$.

Informally, in the construction do the following: Take some primitive recursive function with index e and wait until it converges on its witness (witness is N). While you wait, put new elements to the right. When the function converges and its image hits an element to the right of N, compute the number of elements that were listed to the right of the image (we assume this number is k). Then wait until the function converges on the argument $N+k+1$, and stop adding new elements to the right of $p_e(N)$ and start to add new elements to the left of $p_e(N)$. If p_e on $N+k+1$ converges, then p_e is not a reduction.

It is clear that L is a primitive recursive order because to determine if the pair (x, y) belongs to L it suffices to check if $(x, y) \in L_s$, where $s = \max(x, y)$. Each time when the construction comes to case 3 number y_0 will be greater (in the order L) than y_0's from the previous functions. Hence, the order L is isomorphic to ω.■

Next, we show that the structure $\mathbf{PR}(\omega)$ doesn't have any maximal elements.

Theorem 3.1. For every $R \in \mathbf{PR}(\omega)$ there exists $L \in \mathbf{PR}(\omega)$, such that $R <_{pr} L$.

Proof. We construct a linear order L above R, satisfying the following requirements:

Q_e: p_e is not a reduction from L to R.

First, we define a primitive recursive function f, that reduces R to L as follows:

$$f(x) = 2x \text{ for all } x \in \omega.$$

That is, we assume that all even numbers are already ordered in L at every stage. We will use only odd numbers in the construction.

Strategy for Q_e.

(1) First, pick $a = 2e$ and b, such that $a <_L b$ and there is no y with $a <_L y <_L b$;

(2) Wait for $p_e(a)$ and $p_e(b)$ to converge.

(3) (a) If $p_e(b) \leq_R p_e(a)$, then the requirement is satisfied. Go to the next strategy.

(b) Otherwise go to (4);

(4) Put sufficiently enough fresh odd numbers between a and b in L so that the following condition holds

$$\text{card}[a, b]_L = \text{card}[p_e(a), p_e(b)]_R + 1 \quad (1)$$

Construction

Stage 0. Assume L is defined on all even numbers as follows: $2x\ L_0\ 2y \Leftrightarrow x\ R\ y$;

Stage $s+1$. Assume $e = l(s)$. Proceed with the strategy Q_e to define L_{s+1}. In particular, if strategy Q_e reaches (4), then we compute cardinality of the set $\{x: p_e(a) \leq_R x <_R p_e(b)\ \&\ x \leq s\}$ and put as many odd numbers after a in order L_{s+1}.

The construction is completed. Every requirement will be met since the condition (1) cannot be true infinitely often due to the fact that $R \cong \omega$. The choice of the strategy $l(s)$ on step s guarantees, that each strategy is visited infinitely often, thus, eventually meeting its requirement. ■

Corollary 3.2. The structure $\mathbf{PR}(\omega)$ has no maximal elements.

To prove the next fact, we will use the following definition.

Definition 4. A function f is called predecessor for a linear order L, if

f – is primitive recursive;

$f(x) = x$ if x is the least element in L and otherwise $f(x) = y$ such that

$$(\nexists z)[y <_L z <_L x].$$

Theorem 3.3. The structure $\mathbf{PR}(\omega)$ is not dense.

Proof. To prove this, it is sufficient to construct a linear order from $\mathbf{PR}(\omega)$ that has a minimal cover. We construct a linear order L satisfying the following requirements:

R_e: p_e is not a predecessor function for L.

Q_e: if $p_e(x) \neq \mathrm{id}$, then p_e is not a reduction from L to L.

Strategy for R_e.

(1) Choose a witness x_e;

(2) Wait for $p_e(x_e)$ to converge. While waiting, we successively put fresh elements to the right of L.

(3) (a) If $p_e(x_e) <_L x_e$ and

$$(\nexists y)[p_e(x_e) <_L y <_L x_e],$$

Then put a fresh number between $p_e(x_e)$ and x_e.

(b) Otherwise, go to the next strategy.

Strategy for Q_e.

(1) Choose a witness x_e for the strategy;

(2) Wait for the number $N \geq x_e$ with $p_e(N) >_L N$;

(3) Let $c = p_e(N)$;

(4) Wait for $p_e(c)$ to converge. While waiting, put fresh elements to the right of L;

(5) When $p_e(c)$ converges, check the condition $p_e(c) >_L c$;

(a) If $p_e(c) >_L c$, then put k many fresh elements after N (here, $k = \mathrm{card}([c, p_e(c)]_L)$). Initialize low priority strategies with witnesses greater than $p_e(c)$.

(b) If $p_e(c) \leq_L c$, then the requirement is satisfied. Go to the next strategy.

Construction

We order requirements as follows:

$$R_0 < Q_0 < R_1 < Q_1 < \cdots$$

We do not move to the new strategy until the active strategy isn't completed. We call every R_e strategy active until the requirement R_e is not satisfied. A Q_e strategy is active if the requirement Q_e is not satisfied and the stage (1) is witnessed. If a strategy is satisfied at some stage s, we move to the least active strategy in the ordering above.

The construction is completed. It is not hard to see that every requirement will eventually be met.

Now, we show that a linear order $1 + L$ defined below is a minimal cover for L:

$$x\ (1+L)\ y \Leftrightarrow x = 0 \vee (x > 0\ \&\ y > 0\ \&\ (x-1)\ L\ (y-1)).$$

Towards a contradiction, assume that there exists a linear order S such that $L \leq_{pr} S \leq_{pr} 1 + L$. Moreover, let f and g be primitive recursive functions witnessing the reductions $L \leq_{pr} S$ and $S \leq_{pr} 1 + L$ respectively. Assume that $\{a_0 <_{1+L} a_1 <_{1+L} \ldots\}$, $\{s_0 <_S s_1 <_S \ldots\}$ and $\{b_0 <_L b_1 <_L \ldots\}$ are ordered elements in $1 + L$, S and L respectively. There are three possible cases:

Suppose the reduction g misses some element a_k, i.e., $a_k \notin range(g)$. In this case one can define a primitive recursive function h with the following property: $a_0 \notin range(h)$ and it is still a reduction from S to $1 + L$. Without loss of generality, we can assume that $g(s_i) = a_{k-1}$ and $g(s_{i+1}) = a_{k+1}$ for some $i \in \omega$. Define a function h as follows: for all $x \in \omega$

$$p(x) = \begin{cases} a_{k+1}, & \text{if } x = s_k \leq_S s_i, \\ g(x), & \text{otherwise} \end{cases}$$

Then the function $h(x) - 1$ is a reduction from S to L, a contradiction.

Suppose the reduction f misses some element s_i, i.e., $s_i \notin range(f)$. In this case one can define a primitive recursive function q with the following conditions:

$$q(x) = \begin{cases} s_k, & \text{if } x = a_k \leq_{1+L} a_i, \\ f(x-1), & \text{otherwise.} \end{cases}$$

Then the primitive recursive function q reduces $1 + L$ to S.

The last case is when $g(s_i) = a_i$ and $f(b_i) = s_i$, that both reductions are onto. Then a primitive recursive function $g(f(b_i)) - 1$ is a predecessor for L, a contradiction.

Thus, $1 + L$ is a minimal cover for L. ■

Corollary 3.4. There exist $L, L_0 \in \mathbf{PR}(\omega)$ such that $L|_{pr} L_0$ and $\sup(L, L_0) = 1 + L$.

Proof. Let L be a linear order constructed in Theorem 3.3, then there exists an order $L_0 <_{pr} 1 + L$ such that $L_0|_{pr} L$.

Let f be a primitive recursive bijection from L onto L, such that f^{-1} is not primitive recursive (the existence of such functions can be found in [12] and [13]). We define a linear order L_0 as follows:

$$f^{-1}(x)\, L_0\, f^{-1}(y) \Leftrightarrow x\, (1 + L)\, y.$$

First, we show the pr-incomparability of L and L_0.

Note that in the Q_e strategies of the Theorem 3.3 one can replace primitive recursive functions $\{p_e\}_{e\in\omega}$ with partial recursive functions $\{\varphi_e\}_{e\in\omega}$. In this case, however, during the construction we have to perform the actions of each strategy at the current stage. Hence, we can assume that L is self-full with respect to $\leq_c$.

Since, $L_0 \equiv_c 1 + L$ and $1 + L$ is a strong minimal cover for L under $\leq_c$ (see Proposition 2.1. in [7]), then $L_0 \not\leq_{pr} L$. The fact that $L \not\leq_{pr} L_0 <_{pr} 1 + L$ also follows from the fact that $1 + L$ is a strong minimal cover for L under $\leq_c$. Thus, orders L and L_0 are pr-incomparable.

Now we show that a linear order $1 + L$ is a supremum of L and L_0. Let S be an arbitrary upper bound for L and L_0 and p a primitive recursive function witnessing the reduction from L to S. Assume that $\{s_0 < s_1 < s_2 < \cdots\}$ and $\{l_0 < l_1 < l_2 < \cdots\}$ are ordered elements in S and L respectively. It is obvious that $S \not\equiv_c L$, since otherwise we get

$$L <_c 1 + L \equiv_c L_0 \leq_{pr} S \equiv_c L.$$

Hence, the reduction $p\colon L \leq_{pr} S$ misses some class s_i, i.e. $s_i \notin range(p)$ for some $i \in \omega$. Without loss of generality, we can assume that $p(l_k) = s_{i-1}$ and $p(l_{k+1}) = s_{i+1}$ for some $k \in \omega$. Then the following primitive recursive function reduces $1 + L$ to S:

$$h(x) = \begin{cases} s_0, & \text{if } x = 0, \\ p(x-1)+1, & \text{if } x \neq 0 \text{ and } x \leq l_k, \\ p(x-1), & \text{otherwise.} \end{cases}$$

Hence, $1 + L \leq_{pr} S$ and $\sup(L, L_0) = 1 + L$. ■

Conclusion

It was shown that the structure $\mathbf{PR}(\omega)$ differs from the structure $\boldsymbol{\Omega}$. We proved that structure has no maximal elements, and it is not dense and constructed a pair of primitive recursive linear orders with a supremum.

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[1*]**Асқарбекқызы А.,**
докторант, ORCID ID: 0000-0003-0075-4438,
*e-mail: ms.askarbekkyzy@gmail.com
[2]**Искаков А.М.,**
магистрант, ORCID ID: 0009-0005-2550-2079,
e-mail: bheadr73@gmail.com
[1]**Калмурзаев Б.С.,**
PhD, қауымдастырылған профессор, ORCID ID: 0000-0002-4386-5915,
e-mail: birzhan.kalmurzayev@gmail.com

[1]Қазақстан-Британ техникалық университеті, Алматы қ., 050000, Қазақстан
[2]Әл-Фараби атындағы Қазақ ұлттық университеті, әл-Фараби к-сі, 71,
Алматы қ., 050000, Қазақстан

ЕҢ КІШІ ШЕКТІК ОРДИНАЛҒА ИЗОМОРФТЫ ПУНКТУАЛДЫ СЫЗЫҚТЫ РЕТТЕРДІҢ ҚҰРЫЛЫМЫ

Аңдатпа

Заманауи әдебиеттерде түрлі құрылымдардың кескіндерінің алгоритмдік күрделілігіне көп көңіл бөлінуде. Аталған күрделіліктерді анықтаудың басты құралы көшірулер. Бұл сигнатура қатынастарын (мысалы, эквиваленттік қатынастар, реттер, т.с.с.) сақтайтын бейнелеу. Мақала ең кіші шектік ординалдың примитивті рекурсивті көшіруге қатысты пунктуалды кескіндерін зерттеуге бағытталған. Бұл құрылымды $\mathbf{PR}(\omega)$ деп белгілейміз. Атап айтқанда, мақалада ω ординалының есептелімді көшіруге қатысты есептелімді көшірмесі $\boldsymbol{\Omega}$ құрылымының және примитивті рекурсивті көшіруге қатысты пунктуалды эквивалент қатынастардан тұратын $\mathbf{Peq}$ құрылымының қасиеттерінің орындалуы зерттеледі. Егер $(x,y) \in L \leftrightarrow (p(x),p(y)) \in R$ шарты орындалатындай p функциясы табылса, L сызықты реті R сызықты ретіне көшіріледі деп атаймыз. Егер көшіруді орындайтын функция есептелімді (примитив рекурсив) болса, бұл көшіру есептелімді (примитив рекурсив) деп аталады. ω ретінің стандартты көшірмесінің деңгейі $\boldsymbol{\Omega}$ құрылымында ең кіші болғанымен, $\mathbf{PR}(\omega)$ құрылымында ең кіші емес екендігі дәлелденді. $\mathbf{PR}(\omega)$ құрылымында максимал және бас деңгейлер жоқ, сонымен қатар бұл құрылым тығыз емес. Ең кіші жоғарғы шегі бар салыстырылмайтын жұптың мысалы келтірілді.

Тірек сөздер: примитивті рекурсив функциясы, сызықты рет, примитивті рекурсивті көшіру, сызықты реттің пунктуалды кескіндері, өзін-өзі толықтырушы реттер.

[1*]**Аскарбеккызы А.,**
докторант, ORCID ID: 0000-0003-0075-4438,
*e-mail: ms.askarbekkyzy@gmail.com
[2]**Искаков А.М.,**
магистрант, ORCID ID: 0009-0005-2550-2079,
e-mail: bheadr73@gmail.com
[1]**Калмурзаев Б.С.,**
Ph.D., ассоц., профессор, ORCID ID: 0000-0002-4386-5915,
e-mail: birzhan.kalmurzayev@gmail.com

[1] Казахстанско-Британский технический университет, г. Алматы, 050000, Казахстан
[2] Казахский национальный университет им. аль-Фараби, г. Алматы, 050000, Казахстан

О СТРУКТУРЕ ПУНКТУАЛЬНЫХ ЛИНЕЙНЫХ ПОРЯДКОВ ИЗОМОРФНЫХ НАИМЕНЬШЕМУ ПРЕДЕЛЬНОМУ ОРДИНАЛУ

Аннотация

Алгоритмическая сложность представлений различных структур является объектом значительного интереса в современной научной литературе. Основным инструментом исследования в данном контексте

является сводимость. Это отображение, сохраняющее отношения сигнатуры (такие как отношение эквивалентности, порядка и так далее). Данная работа посвящена исследованию пунктуальных представлений наименьшего предельного ординала относительно примитивно рекурсивной сводимости, обозначим данную структуру через $\mathbf{PR}(\omega)$. В частности, в работе исследуется выполнение свойств структур $\boldsymbol{\Omega}$, состоящей из вычислимых копий ω относительно вычислимой сводимости и $\mathbf{Peq}$, состоящей из пунктуальных отношений эквивалентности относительно примитивно рекурсивной сводимости. Говорим что линейный порядок L сводится к линейному порядку R, если существует всюду определенная функция p такая, что $(x, y) \in L$ тогда и только тогда $(p(x), p(y)) \in R$. Сводимости называют вычислимыми (примитивно рекурсивными), если функция, осуществляющая сводимость, является вычислимой (примитивно рекурсивной). Показано, что степень стандартной копии порядка ω не является наименьшей в $\mathbf{PR}(\omega)$, как это было в $\boldsymbol{\Omega}$. Структура $\mathbf{PR}(\omega)$ не содержит главные и максимальные степени, и данная структура не является плотной. Также приводится пример несравнимой пары с наименьшей верхней гранью.

Ключевые слова: примитивно рекурсивная функция, линейный порядок, примитивно рекурсивная сводимость, пунктуальные представления линейных порядков, самополные порядки.

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[1*]Қоштыбаев Т.Б.,
ф.-м.ғ.к., доцент, ORCID ID: 0009-0004-7344-6801,
e-mail: koshtybayev70@mail.ru
[1]Құткелдиева Э.О.,
пед.ғ.магистрі, ORCID ID: 0000-0002-6754-2280,
e-mail: elzira.kutkeldieva@gmail.com
[2]Жантлеуов К.Қ.,
ф.-м.ғ.к., доцент, ORCID ID: 0009-0001-6658-1165,
e-mail: Kzhantleuov@mail.ru
[2]Жаменкеев Е.К.,
т.ғ.к., қауым.проф. м.а., ORCID ID: 0000-0002-6711-434X ,
e-mail: jamenkeev@mail.ru

[1]Қазақ ұлттық қыздар педагогикалық университеті, 050000, Алматы қ., Қазақстан
[2]Абай атындағы Қазақ ұлттық педагогикалық университеті, 050010, Алматы қ., Қазақстан

КӨЛБЕУ ЖАЗЫҚТЫҚТЫҢ МАТЕМАТИКАЛЫҚ ТЕОРИЯСЫ

Аңдатпа

Көлбеу жазықтықтағы статикалық және динамикалық әсерлердің өзара түрлену заңдылықтары көрсетіліп, жұмсалатын әсерден ұтыс алуға немесе негізгі пайдалы әсерді үнемдеу мүмкіндіктерінің және Жердің тартылысын оңай жеңу жағдайларының математикалық негіздемесі ұсынылған. Бұлар тригонометриялық есептеулер мен динамикалық, статикалық теориялардың негізгі элементтерін қолдану арқылы жүзеге асырылды. Түрлену заңдылықтарына көлбеу жазықтықтың геометриялық өлшемдерінің әсері салыстырмалы түрде бағаланған. Вектор және оны құраушыларының арасындағы байланыстар мен сақталу заңын сипаттайтын математикалық теңдіктер арқылы көлбеу жазықтықтағы статикалық және динамикалық тепе-теңдіктердің орындалу ережелері белгіленген.

Тірек сөздер: тригонометрия, түрлену, көлбеулік бұрышы, вектор құраушысы, үйкеліс, жазықтық.

Кіріспе

Көлбеу жазықтық деп көкжиекке (Жер бетіне) бұрыш жасай орналастырылған тегіс беттік қондырғыны айтады. Ол орын ауыстырулардың статикалық және динамикалық теорияларына сәйкес денелерді жоғары қарай көтеру кезіндегі жұмсалатын күштен ұтыс алуға (немесе күшті үнемдеуге) көмектеседі. Басқаша айтқанда, аталған қондырғы Жердің тартылысын оңай жеңуге мүмкіндік береді. 1586 ж. голландық инженер Симен Стевин және грек ғалымы-инженері Архимед көлбеу жазықтықтың механикалық ұтымдылығын анықтап, оны қарапайым механизмдердің қатарына жатқызған болатын. Бұл жағдай аталған ғалымдардың көп жылғы инженерлік ізденістерінің жемісі десек болады. Көлбеу жазықтықтың теориялық негіздемесі тригонометриялық есептеулер мен статикалық элементтерге байланысты болғанымен, оның тиімділік жағы инженерлік қондырғылардың базалық сипатына да тәуелді екенін білуіміз керек. Көлбеу жазықтықта атқарылатын механикалық жұмысты жеңілдететін немесе механикалық энергия есебімен ғана жұмыс атқаратын және статикалық күштерді түрлендіретін қондырғылардың теориялық құрылымы математикалық есептеулер мен олардың нәтижелерінің дәлдігі мен жүйелілігіне де тәуелді болады.

Материалдар мен әдістер

Мақаланың тақырыбы мен мазмұны қарапайым механизмдерге арналған. Мұнда көлбеу жазықтықтың теориялық негіздемесін құрайтын математикалық аппараттың қолданылуы мен алынған нәтижелердің талқыланулары қарастырылады. Тақырыптың математикалық негізі мен әдісі ретінде тригонометриялық есептеулер, көлбеу жазықтықтағы күштердің динамикалық және статикалық түрлену заңдылықтары алынды.

Негізгі ережелер

Тегіс бетке сүйір бұрыштармен орналасатын жазықтықтағы түрлену механизмдерінің математикалық құрылымын қалыптастырушы элементтерді жүйелеп көрсету идеясы іске асырылады. Түрлену заңдылықтары, көлбеу жазықтықтың геометриялық өлшемдері, ондағы динамикалық және статикалық әсерлердің үйлесімділігі мен байланыс ерекшеліктері жалпылама сипатта қарастырылады.

Әдебиетке шолу

Инженерлік механиканың [1] негізгі тұжырымдамалары мен олардың практикалық қолданыстарының сан-қырлы әдістері талданған. [2] әдебиеттен теориялық механиканың статикалық заңдылықтарына арналған бөлімдерімен танысуға болады жәнемұнда қолданбалы механикаға қатысты тың идеялар мен мысалдар да кеңінен қамтылған. Дененің көлбеу жазықтықтағы қозғалысының теориялық заңдылықтарын, теңдеулерін, әсерлердің өзара түрлену тетіктерін [3–7] дерек көздерден табуға болады. Статикалық есептердің математикалық аппаратына арналған мәліметтер [8–11] әдебиеттерде ұсынылған. Тригонометриялық есептеулердің қолданылу ерекшеліктері және қолданбалы механика, математикалық физика, инженерлік зерттеулер арасындағы өзара байланыстар жан-жақты талданды.

Нәтижелер мен талқылау

Жер бетіне (көкжиекке) α бұрыш жасай орналасқан ұзындығы L метрге тең беті тегіс тақтайшаның (көлбеу жазықтықтың) үстінде массасы m *кг* дене орналасқан болсын. Дененің жағдайы (жай-күйі немесе орнықтылығы) оған бір мезгілде жасалатын бірнеше әсерлердің (күштердің) өзара тепе-теңдікте (баланста) болуы және олардың әрбірінің түрлену (өзгеру) заңдылықтарына байланысты (тәуелді). Әсерлердің түрлену заңдылығы тригонометриялық көрсеткіштер ($\cos\alpha, \sin\alpha$) арқылы іске асырылады және олар жазықтықтың көлбеулік бұрышының (α) $0^o - 90^o$ аралығындағы мәндерінде азайып (немесе көбейіп) отыруын бағамдап (бағалап) отырады. Бағалау нәтижесі коэффициент немесе процент түрінде көрсетіледі. Тақтайшадағы дене бірмезгілде мынадай әсерлердің ықпалында болады: mg –дененің Жерге тартылуы (салмаға); $N = (\cos\alpha)mg$ –тірек (тақтайшаның көтеруі немесе тіреудің салмаққа кері әсері); $F = (\sin\alpha)mg = (\mu\cos\alpha)mg = \mu N$ –дене мен жазықтық арасындағы үйкелістің шамасы. Бұл теңдіктердегі μ –үйкелуші беттердің материалы мен тегістілігіне байланысты болатын үйкеліс коэффициенті: $\mu = tg\alpha < 1$, $\sin\alpha = \mu\cos\alpha$. Ендігі жерде әсерлер арасындағы түрлену процесінің теориялық негіздемесіне тоқталамыз. Тақтайшаны OXY жазықтығында бір ұшы O нүктесінде (координаталар басында) жатқан $\vec{R}$ векторымен (бағытталған кесіндімен) алмастырайық. Вектордың екінші ұшы OXY жазықтығын $0^o - 90^o$ арасындағы доғаны бойлай сағат тіліне қарсы бағытта қозғала алады (доғаның бойында бұрыштық (градустық немесе радиандық) өлшемдегі шкала орналасқан). Вектордың екінші ұшы алғашқыда шкаланың 0^o белгісінде (Жердің бетінде немесе

OX осьінде) тұрған болса, онда ол $30^o,15^o,15^o,30^o$ қадаммен $\alpha = 0^o,30^o,45^o,60^o,90^o$ бұрыштары арқылы жылжып отырады (жазықтықтың Жер бетінен жоғары қарай көтерілуі). $\vec{R}$–дің 90^o–қа сәйкес келетін жағдайы оның OY осьінде тұрғандығын (Жер бетіне тік (перпендикульяр) орналасқандығын) білдіреді. Ал Вектордың $\alpha = 0^o$ жағдайы оның OX осьінде тұрғандығын білдіреді, дәл осы жағдайда осьтегі координаталар (сызықтық немесе метрлік шкала) көмегімен оның ұзындығының L метрге тең екендігі анықталады. Айталық $\vec{R}$ векторы $0^o - 90^o$ арасындағы $\alpha = 0^o,30^o,45^o,60^o,90^o$ бұрыштарының бірінде тұрған болсын ($\vec{R_\alpha}$). Жазықтықтағы вектордың OX және OY осьтерінде құраушылары болатыны белгілі. Вектордың вертикаль (тік) $R_{\alpha y}$ құраушысының мәні L_y, ал оның горизонталь (жазық) $R_{\alpha x}$ құраушысының шамасы L_x болсын. $\vec{R}$ векторының $0^o - 90^o$ аралығындағы жүріп өтетін доғасын радиусы $\vec{R}$–ге тең шеңбердің бір бөлігі немесе ширегі ($\frac{1}{4}$) деп қараймыз. Центрі O нүктесінде орналасқан радиусы $\vec{R}$ шеңбердің теңдеуі $R^2 = x^2 + y^2$ және ол қандай да бір α бұрышта тұрған радиус пен оның x, y құраушыларының арасындағы байланысты іске асырады (немесе радиусты оның құраушылары арқылы анықтауға мүмкіндік береді). Олай болса, бір ұшы O нүктесінде бекітіліп, екінші ұшы α бұрышта тұрған $\vec{R}$ векторының ұзындығы үшін мынадай теңдікті жазуға болады:

$$L^2 = L_x{}^2 + L_y{}^2 \tag{1}$$

Бұл теңдік вектор мен оның құраушыларының арасындағы байланысты реттеп отырады. Тригонометрия теориясында $\vec{R}$ векторының ұзындығы 2-ге тең деп алынады, яғни $L = 2$. Вектор мен оның құраушылыларының $\alpha = 0^o,30^o,45^o,60^o,90^o$ бұрыштарын сәйкес келетін мәндері төмендегі 1-кестеде көрсетілген.

Кесте 1 – Вектор мен оның құраушылыларының $\alpha = 0^o,30^o,45^o,60^o,90^o$ бұрыштарын сәйкес келетін мәндері

	$\alpha = 0^o$	$\alpha = 30^o$	$\alpha = 45^o$	$\alpha = 60^o$	$\alpha = 90^o$
L_x	2	1,733	1,415	1	0
L_y	0	1	1,415	1,733	2
$L^2 = L_x{}^2 + L_y{}^2$	4	4	4	4	4

Бұл кестеден мынадай түрленуді байқау қиын емес: вектордың (таяқшаның) көлбеулік бұрышы артқан сайын оның L_x– горизонтал құраушысының мәні кеміп, L_y– вертикал құраушысының мәні артып жатыр (L_y құраушы L_x–тің кемуі есебінен көбеюде). Дегенмен құраушылар арасында түрлену балансы орындалып тұр, яғни екі құраушының квадраттарының қосындысы вектор ұзындығының квадратына тең ($L^2 = 4$). Құраушылардың мәндерін вектордың ұзындығымен салыстырып беретін немесе құраушылырдың шамаларын вектор ұзындығы арқылы бағалап беретін өрнектерді жазайық:

$$\frac{L_x}{L} = \cos\alpha \quad \text{және} \quad \frac{L_y}{L} = \sin\alpha \tag{2}$$

$$L_x = \left(\cos\alpha\right)L \text{ және } \quad L_y = \left(\sin\alpha\right)L \tag{2A}$$

Сонда (1)-теңдеуден:

$$1=\left(\frac{L_x}{L}\right)^2+\left(\frac{L_y}{L}\right)^2$$

(2)-ні ескерсек

$$\left(\cos\alpha\right)^2+\left(\sin\alpha\right)^2=1 \quad \text{немесе} \quad \cos^2\alpha+\sin^2\alpha=1$$

2 және 3-кестелерде көлбеулік бұрышының әртүрлі мәндері үшін құраушыларды вектор ұзындығы арқылы бағалау (салыстыру) ұсынылған. Бағалау нәтижелері коэффициенттік немесе проценттік көрсеткіштермен берілген.

Кесте 2 – Көлбеулік бұрышының әртүрлі мәндері үшін құраушыларды вектор ұзындығы арқылы бағалау

	$\alpha=0^o$	$\alpha=30^o$	$\alpha=45^o$	$\alpha=60^o$	$\alpha=90^o$
$\cos\alpha=\frac{L_x}{L}$	1 (100 %)	0,87 (87 %)	0,71 (71 %)	0,5 (50 %)	0
$\sin\alpha=\frac{L_y}{L}$	0	0,5 (50 %)	0,71 (71 %)	0,87 (87 %)	1 (100 %)
$\left(\cos\alpha\right)^2+\left(\sin\alpha\right)^2=1$	$1+0$	$0,75+0,25$	$0,50+0,50$	$0,25+0,75$	$0+1$

2-кестеден көріп отырғанымыздай, $\cos\alpha$ көрсеткіші көлбеулік бұрышының белгілі бір мәніне сәйкес келетін L_x құраушының L–мен салыстырғандағы бағасын шығарып берсе, $\sin\alpha$ көрсеткіші сол бұрыштағы L_y құраушының L–ге қатысты бағасын анықтап береді екен. Тақтайшаның көлбеулігі артқан сайын $\cos\alpha$–ның азайып (тақтайшаның OX осінен қарағандағы L_x ұзындығының қысқарып), ал $\sin\alpha$–ның көбейіп (тақтайшаның OY осінен қарағандағы L_y ұзындығының артып) жатқандығын байқаймыз.

Кесте 3 – Көлбеулік бұрышының әртүрлі мәндері үшін құраушыларды вектор ұзындығы арқылы бағалау

	$\alpha=0^o$	$\alpha=30^o$	$\alpha=45^o$	$\alpha=60^o$	$\alpha=90^o$
$L_x=\left(\cos\alpha\right)L$	L	$0,87\ L$	$0,71\ L$	$0,5\ L$	–
$L_y=\left(\sin\alpha\right)L$	–	$0,5\ L$	$0,71\ L$	$0,87$	L

Мысал үшін, тақтайшаның көлбеулігі $\alpha=30^o$ болсын, бұл кезде оның OX осінен қарағандағы L_x ұзындығы негізгі L ұзындығының 87 % құрайды:

$$L_x=\left(\cos\alpha\right)L=|\alpha=30^o|=\cos 30^o L=0,87L=0,87\cdot 2=1,74$$

Ал оның OY осінен қарағандағы L_y ұзындығы L–дің 50 % тең:

$$L_y=\left(\sin\alpha\right)L=|\alpha=30^o|=\sin 30^o L=0,50L=0,50\cdot 2=1$$

Бірақ, екі құраушының квадраттарының қосындысы L –дің квадратына тең:

$$L^2 = L_x{}^2 + L_y{}^2 \quad \rightarrow \quad 2^2 = (1,74)^2 + (1)^2 \quad \rightarrow \quad 4 = 3,03 + 1$$

Вектор және оның құраушылары арасындағы байланыс, құраушылардың өзгеру заңдылығы жайындағы осы баяндалған мәліметтер көлбеу жазықтықта тұрған денеге жасалатын әсерлердің

$$N_\alpha = (\cos\alpha)mg\,, \quad F_\alpha = (\sin\alpha)mg\,, \quad F_\alpha = (\mu\cos\alpha)mg = \mu N_\alpha \qquad (3)$$

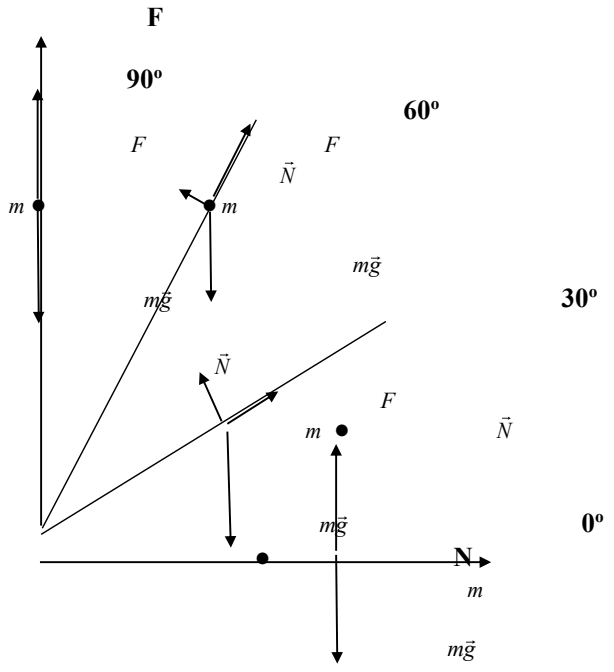
мәндерінің (шамаларының) түрлену заңдылығын түсінуге септігін тигізеді. Бұл өрнектер тіреудің кері көтеруі мен үйкелістің мәндері дененің салмағымен салыстырыла анықталатынын білдіреді (немесе әсерлердің N_α және F_α мәндері mg арқылы бағаланатын болады):

$$\frac{N_\alpha}{mg} = \cos\alpha\,, \qquad \frac{F_\alpha}{mg} = \sin\alpha$$

(3)-гі N_α және F_α шамаларының көлбеулік бұрышына тәуелділік заңдылығы төмендегі 1-суретте және 2, 3-кестелер үлгісінде жасалған 4-кестеде ұсынылған.

Кесте 4 – N_α және F_α шамаларының көлбеулік бұрышына тәуелділік заңдылығы

	$\alpha = 0^o$	$\alpha = 30^o$	$\alpha = 45^o$	$\alpha = 60^o$	$\alpha = 90^o$
$N_\alpha = (\cos\alpha)mg$	$N = mg$	$N = 0,87mg$	$N = 0,71mg$	$N = 0,5mg$	$N = 0$
$F_\alpha = (\sin\alpha)mg$		$F = 0,5mg$	$F = 0,71mg$	$F = 0,87mg$	$F = mg$
$F_\alpha = (\mu\cos\alpha)mg$	$F = \mu mg$				



Сурет 1 – N_α және F_α шамаларының көлбеулік бұрышына тәуелділік заңдылығы

Жоғарыдағы 1-суретте тақтайшаның (көлбеу жазықтықтың) Жер бетінде (OX осінде) тұрғандағы жағдайы $\alpha = 0^o$ сәйкес келеді. Бұл кезде үйкелістің мәні $F = \mu mg$, ал тіреудің шамасы дененің салмағымен бірдей: $N = mg$. Мысалы, дене мен тақтайша арасындағы үйкеліс коэффициентінің мәні $\mu = 0,83$ болсын. Олай болса, үйкелістің мәні дене салмағының $83\,\%$ құрайды:

$$F = \mu mg = |\alpha = 30^o| = 0,83mg$$

Бұл дененің Жер бетіндегі үйкелісі. Әрі қарай тақтайша Жер бетіне $\alpha = 0^o, 30^o, 45^o, 60^o, 90^o$ бұрыштар жасай отырып жоғары қарай көтерілген кезде тірек (тіреу) шамасының азайып, үйкеліс мәндерінің көбейетінін суреттен және 4-кестеден байқауға болады. $\alpha = 90^o$ бұрышта тақтайша Жер бетіне тік (перпендикуляр) орналасады, бұл жағдайда $N = 0$ (тіреу жоқ), ал үйкеліс пен салмақ өзара тең: $F = mg$, яғни дене Жерге қарай еркін құлап түседі. 4-кестеде әсерлердің мәндері арасында сақталу заңының орындалып жатқандығын байқау қиын емес, яғни тіреу шамасының кемуі есебінен үйкелістің артуы іске асып жатыр. Тақтайдың (тіреудің) көлбеулік бұрыштары үшін N_α және F_α шамалары әртүрлі болғанымен, олар төмендегідей шартқа бағынады:

$$\left(mg\right)^2 = {N_\alpha}^2 + {F_\alpha}^2 \qquad (*)$$

Тақтайшаның көлбеулігі $\alpha = 60^o$ жағдайында:

$$\left(mg\right)^2 = \left(N_{60^o}\right)^2 + \left(F_{60^o}\right)^2$$

4-кестедегі N_α және F_α шамалардың $\alpha = 60^o$ мәндерін қолдансақ:

$$\left(mg\right)^2 = \left(0,5mg\right)^2 + \left(0,87mg\right)^2$$

$$\left(mg\right)^2 = \left(0,5^2 + 0,87^2\right)\cdot\left(mg\right)^2$$

$$\left(mg\right)^2 = \left(0,25 + 0,75\right)\cdot\left(mg\right)^2$$

Біз $\alpha = 60^o$ жағдайы үшін (*)-теңдігін дәлелдедік және көлбеулік бұрышының басқа мәндері үшін де орындалатыны ақиқат. Ал егер, көлбеулік бұрышының кез-келген мәні үшін N_α және F_α шамаларын өзара салыстыру қажет болса, онда $F = \mu N$, $\sin\alpha = \mu\cos\alpha$ теңдіктерін қолдану қажет болады. Екінші теңдіктен: $\mu = tg\alpha$. Осыны бірінші теңдікке қойсақ:

$$F_\alpha = \left(tg\alpha\right)N_\alpha \qquad (4)$$

Бұл теңдік көлбеулік бұрышының белгілі бір мәніне сәйкес келетін үйкеліс шамасының бағасын бұрыштың сол мәніндегі тіреудің шамасы арқылы бағалауға мүмкіндік жасайды. Көлбеулік бұрышының тангенсінің мәндері 5-кестеде келтірілген. (4)-ті $\alpha = 30^o, 45^o, 60^o$ мәндері үшін жазайық:

$$F_{30^o} = \left(tg30^o\right)N_{30^o} = 0,58N_{30^o} \qquad (5)$$

$$F_{45^o} = \left(tg45^o\right)N_{45^o} = 1\cdot N_{45^o} \qquad (6)$$

$$F_{60^o} = \left(tg60^o\right)N_{60^o} = 1,73N_{60^o} \qquad (7)$$

Кесте 5 – Көлбеулік бұрышының тангенсінің мәндері

	$\alpha = 0^o$	$\alpha = 30^o$	$\alpha = 45^o$	$\alpha = 60^o$	$\alpha = 90^o$
$tg\alpha$	0	$0,58$ (58%)	1 (100%)	$1,73$ (173%)	
$ctg\alpha$		$1,73$ (173%)	1 (100%)	$0,58$ (58%)	0

(5)-теңдіктен: тақтайша $\alpha = 30^o$ бұрышпен орналасқан кезде үйкелістің мәні тіреудің 58% тең болатынын көруге болады. Бұл тұжырымның ақиқаттылығына көз жеткізу үшін (5)-ке 4-кестеден алынған N_α және F_α шамаларының 30^o-ғы

$$F_{30^o} = 0,5mg \quad \text{және} \quad N_{30^o} = 0,87mg$$

мәндерін қою керек:

$$0,5mg = 0,58 \cdot 0,87mg \;\; 0,5mg = 0,58 \cdot 0,87mg$$

осыдан

$$\frac{0,5}{0,87} = 0,58$$

(6)-теңдіктен: тақтайша $\alpha = 45^o$ бұрышпен орналасқан кезде үйкеліс пен тіреудің мәндері бірдей болады. Шынында да, (6)-ға 4-кестеден алынған

$$F_{45^o} = 0,71mg\,, \qquad N_{45^o} = 0,71mg$$

мәндерді қоятын болсақ, онда

$$0,71mg = 1 \cdot 0,71mg$$

Осы теңдіктен:

$$\frac{0,71}{0,71} = 1$$

(7)-теңдіктен тақтайша $\alpha = 60^o$ бұрышпен орналасқан кезде үйкелістің мәні тіреудің мәнінен 73 % артық болады екен. Бұл тұжырымның ақиқаттылығына көз жеткізу үшін (7)-ге 4-кестеден алынған N_α және F_α шамаларының 60^o-ы

$$F_{60^o} = 0,87mg \quad \text{және} \quad N_{60^o} = 0,5mg$$

мәндерін қоямыз:

$$0,87mg = 1,73 \cdot 0,5mg$$

осыдан

$$\frac{0,87}{0,5} = 1,73$$

Көлбеулік бұрышының әрбір мәндері үшін тіреудің шамасын үйкелістің мәндері арқылы да бағалауға болады, яғни (4)-тен:

$$N_\alpha = \left(ctg\alpha\right) F_\alpha \qquad (8)$$

Көлбеулік бұрышының котангенсінің мәндері 5-кестеде ұсынылған. (8)-ді $\alpha = 30^o, 45^o, 60^o$ мәндері үшін жазайық:

$$N_{30^o} = \left(ctg30^o\right) F_{30^o} = 1,73F_{30^o} \quad (9)$$

$$N_{45^o} = \left(ctg45^o\right) F_{45^o} = 1 \cdot F_{45^o} \quad (10)$$

$$N_{60^o} = \left(ctg60^o\right) F_{60^o} = 0,58F_{60^o} \quad (11)$$

(9)-теңдіктен: тақтайша $\alpha = 30^o$ бұрышпен орналасқан кездегі тіреудің шамасы үйкелістің мәнінен 73 % артық болады. Бұл тұжырымның ақиқаттылығына көз жеткізу үшін (9)-ға 4-кестеден алынған N_α және F_α шамаларының 30^o-ы

$$F_{30^o} = 0,5mg \; F_{30^o} = 0,5mg \quad \text{және} \quad N_{30^o} = 0,87mg$$

мәндерін қойсақ:

$$0,87mg = 1,73 \cdot 0,5mg$$

Осы өрнектен:

$$\frac{0,87}{0,5} = 1,73$$

(10)-теңдіктен тақтайша $\alpha = 45^o$ бұрышпен орналасқан кезде үйкеліс пен тіреудің мәндері бірдей болатындығын көруге болады. Шынында да, (10)-ға 4-кестеден алынған

$$F_{45^o} = 0,71mg \quad \text{және} \quad N_{45^o} = 0,71mg$$

мәндерді қоятын болсақ, онда:

$$0,71mg = 1 \cdot 0,71mg$$

осыдан

$$\frac{0,71}{0,71} = 1$$

(11)-теңдіктен: тақтайша $\alpha = 60^o$ бұрышпен орналасқан кезде тіреудің мәні үйкелістің 58 % болатынын көруге болады. Бұл тұжырымның ақиқаттылығына көз жеткізу үшін (11)-ге 4-кестеден алынған N_α және F_α шамаларының 60^o-ы

$$F_{60^o} = 0,87mg \quad \text{және} \quad N_{60^o} = 0,5mg$$

мәндерін қоямыз:

$$0,5mg = 0,58 \cdot 0,87mg$$

Осыдан

$$\frac{0,5}{0,87} = 0,58$$

Көлбеу жазықтық және оның теориялық негіздемесінің практикалық (іс–жүзінде) қолданылу аясы. Көлбеу жазықтық қарапайым механизмдер қатарына жататын болғадықтан ол жүкті жоғары көтеріп шығару үшін жұмсалатын күшті үнемдеуге көмектеседі, яғни дененің салмағынан аз болатын күшпен жүктің тік (вертикаль) бағыттағы орын ауыстыруын іске асыра алады. Мақалада ұсынылған есептеулер осы жағдайдың орындалу (іске асу) теориясы болып табылады. Олай болса, осы мақалада көрсетілген теорияны көлбеу жазықтықтағы күшті үнемдеу теориясы деп атаса да болады екен. Теориядағы ұсынылған заңдылықтар мен

тұжырымдамалардың практикалық (іс-жүзіндегі) қолданылу аясының мысалдары ретінде екі жазық бетті қосатын көлбеу бетшені (пандус), теңіз көліктері мен ұшақтарға көтеріліп түскенде қолданылатын жылжымалы баспалдақтарды (траптар) алуға болады. 1300 ж. басталған қайта өрлеу кезеңінен бүгінгі күнге дейінгі инженерлік қондырғыларда қолданылып жүрген көлбеу жазықтықтар адамзат өркениеті үшін түрлі дәуірлерді бастан кешірді. Механикалық күштердің динамикасы қарапайым механизмдер ретінде қарастырылып, жүкті қаншалықты биік көтеру мәселесін шешумен айналысты. Осындай ізденістердің нәтижесінде механикалық жұмыс атқару концепциясы пайда болды. Египеттік тұрғындар көлбеу жазықтықтардың рампа деп аталатын түрін храмдар мен пирамида құрылыстарында пайдаланды. Көлбеу жазықтықтардың қазіргі заманғы қолданылу жағдайларына тоқталар болсақ, олардың қатарына төмендегі инженерлік қондырғыларды жатқызуға болады:

- гидравликалық көтергіш (домкрат) ішіндегі көбеу жазықтық бойымен қозғалатын поршенге қысым түсіру арқылы жүкті оңай көтеруге болады;
- көлбеу конвейерлік лента арқылы жүтерді жоғары көтеріп, төмен түсіруге болады;
- тұрғын үйлердің еңкіш шатырлары қарлар мен сулардың жиналып ұзақ тұрып қалмауын болдармау үшін қолданылады;
- көлік жүретін трассалардың көлбеу болуы сулардың жиналып қалып көлшіктердің пайда болуына жол бермейді.

Қорытынды

Көлбеу жазықтықта тұрған денеге жасалатын әсерлердің көлбеулік бұрышына тәуелділік заңдылықтары арқылы әсерлердің өзара түрлену механизміне математикалық талдау жасалды. Тригонометриялық түрлендірулер мен векторлық талдау элементтерін қолдану арқылы статикалық әсерлер дене салмағымен салыстырыла бағаланды. Бағалау нәтижелері графикалық кескіндеме сурет және бірнеше кестелер арқылы көрсетілді. Сақталу заңын сипаттайтын математикалық теңдіктер арқылы көлбеу жазықтықтағы статикалық және динамикалық тепе-теңдіктердің ережелері тағайындалып, олардың жұмыс ортасы анықталды. Көлбеу жазықтық және оның теориялық негіздемесінің практикалық (іс-жүзінде) қолданылу аясын көрсететін қазіргі заманғы қарапайым инженерлік қондырғыларға жекелей тоқталып, олардың өзіндік ерекшеліктері көрсетілді. Мақаланың зерттеу мақсаттары толығымен іске асты деп санауға болады.

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[1]*Koshtybayev T.,
Can.Phys.-Math.Sc., Associate Professor, ORCID ID: 0009-0004-7344-6801,
e-mail: koshtybayev70@mail.ru
[1]Kutkeldiyeva E.,
M.Ped.Sc., ORCID ID: 0000-0002-6754-2280,
e-mail: elzira.kutkeldieva@gmail.com
[2]Kzhantleuov K.,
Can.Phys.-Math.Sc., Associate Professor, ORCID ID: 0009-0001-6658-1165,
e-mail: Kzhantleuov@mail.ru,
[2]Zhamenkeev E.
Can.Tech.Sc., Acting Associate professor, ORCID ID: 0000-0002-6711-434X,
e-mail: jamenkeev@mail.ru

[1]Kazakh National Women's Pedagogical University, 050000,
Almaty, Kazakhstan
[2]Abai Kazakh National Pedagogical University,050010,
Almaty, Kazakhstan

MATHEMATICAL THEORY OF THE INCLINED PLANE

Abstract

The laws of mutual transformation of statistical and dynamic effects on an inclined plane are shown, a mathematical justification is given for obtaining a gain from the action or the possibility of saving the main useful action and facilitating the actions of Gravity. All the above statements are carried out using the basic elements of the theories of dynamics, statics and trigonometric calculations. The influence of the geometric dimensions of the inclined plane on the transformation of actions is estimated. The mechanism of statistical and dynamic equilibrium of actions on an inclined plane is substantiated through mathematical expressions of the conservation law and the relationship between the components of the vector.

Key words: transformations, tilt angle, vector component, friction, plane.

[1]*Қоштыбаев Т.Б.,
к.ф.-м.н., доцент, ORCID ID: 0009-0004-7344-6801,
*e-mail: koshtybayev70@mail.ru
[1]Құткелдиева Э.О.,
магистр пед. н., ORCID ID: 0000-0002-6754-2280,
e-mail: elzira.kutkeldieva@gmail.com
[2]Жантлеуов К.Қ.,
к.ф.-м.н., доцент, ORCID ID: 0009-0001-6658-1165,
e-mail: Kzhantleuov@mail.ru
[2]Жаменкеев Е.К.,
к.т.н., и.о. ассоц. проф., ORCID ID: 0000-0002-6711-434X,
e-mail: jamenkeev@mail.ru

[1]Казахский национальный женский педагогичесий университет,
050000, г. Алматы, Казахстан
[2]Казахский национальный педагогический университет имени Абая,
050010, г. Алматы, Казахстаны

МАТЕМАТИЧЕСКАЯ ТЕОРИЯ НАКЛОННОЙ ПЛОСКОСТИ

Аннотация

Показаны законы взаимного преобразования статистических и динамических воздействий на наклонной плоскости, приведено математическое обоснование получения выигрыша от действия или возможности экономии основного полезного действия и облегчения действий земного притяжения. Все вышесказанные утверждения осуществляются с помощью основных элементов теорий динамики, статики и тригонометрических вычислений. Оценены влияния геометрических размеров наклонной плоскости на преобразование действий. Обоснован механизм статистического и динамического равновесия действий на наклонной плоскости через математические выражения закона сохранения и связи между составляющими вектора.

Ключевые слова: преобразования, угол наклона, составляющая вектора, трение, плоскость

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[1,2*]Гаранин Ю.А.,
докторант, ORCID ID: 0000-0002-0759-4329, *e-mail: jorge.r2448@gmail.com
[1]Шакирзянов Р.И.,
PhD, ORCID ID: 0000-0001-9908-3034, e-mail: halfraf@mail.ru
[1,2]Козловский А.Л.,
PhD, ORCID ID: 0000-0001-8832-7443, e-mail: kozlovskiy.a@inp.kz
[1,2]Шлимас Д.И.,
PhD, ORCID ID: 0000-0003-2454-7177, e-mail: shlimas@mail.ru
[1,2]Боргеков Д.Б.,
PhD, ORCID ID: 0000-0002-9727-0511, e-mail: borgekov@mail.com

[1]Евразийский национальный университет им. Л.Н. Гумилева, 010000, г. Астана, Казахстан
[2]Астанинский филиал Института ядерной физики, 010000, г. Астана, Казахстан

СИНТЕЗ МНОГОКОМПОНЕНТНЫХ КЕРАМИК ZRO_2:WO_3:AL_2O_3:MGO

Аннотация

В данной работе был исследован фазовый состав и микроструктура многокомпонентных керамик ZrO_2:WO_3:Al_2O_3:MgO в зависимости от концентрации компонентов. Определены зависимости между концентрацией элементов в исходной шихте и фазовым составом, объемной усадкой, плотностью и микроструктурой синтезированных образцов. Методом рамановской спектроскопии установлено, что добавление к исходной матрице ZrO_2:WO_3 смеси Al_2O_3:MgO не приводит к образованию твердого раствора ZrO_2:WO_3:Al_2O_3:MgO. С увеличением содержания Al_2O_3:MgO происходит увеличение объемной усадки и плотности, что может быть связано с образованием жидкой фазы системы WO_3:Al_2O_3 при температуре 1450 °C и, как следствие, более эффективной миграции пор и дефектов к поверхности. Анализ СЭМ-изображений поперечных сечений полученных образцов показал, что все образцы обладают развитой морфологией с различными формами зерен.

Ключевые слова: многокомпонентные керамики, твердофазный синтез, жаропрочные материалы, ZrO_2:WO_3:Al_2O_3:MgO.

Введение

Несмотря на интенсивное развитие современного керамического материаловедения, проблемы, связанные с износом и долговечностью использования деталей, работающих в условиях

высоких температур, остаются актуальными [1, 2]. Благодаря своим превосходным свойствам (рекордная для оксидных керамик вязкость разрушения, высокие показатели износостойкости и прочности на изгиб, а также низкий коэффициент трения и высокая температура плавления) диоксид циркония (ZrO_2) является перспективным материалом для использования в качестве матрицы жаропрочных и износостойких керамик [3, 4]. В то же время высокая температура спекания и мартенситный переход тетрагональной фазы ZrO_2 (t – ZrO_2) в моноклинную (m – ZrO_2) при температуре 1000 ^{0}C требуют дальнейшего совершенствования данного типа керамик. Одним из перспективных материалов для понижения температуры спекания может оказаться оксид вольфрама (WO_3). WO_3 нашел применение при производстве топливных элементов, суперконденсаторов, элементов в фотокатализе и водородной энергетике [5–7]. Благодаря высокой стабильности при температурах до 1600 ^{0}C и относительно высокой твердости (8,5–9 по шкале Мооса) WO_3 подходит для армирования ZrO_2. Из анализа фазовых диаграмм WO_3 с другими оксидными соединениями установлено, что добавление Al_2O_3 способствует образованию эвтектики с температурой плавления в диапазоне 1200–1300 ^{0}C [8], что дополнительно позволит понизить температуру спекания образцов. Добавление Al_2O_3 к матрице ZrO_2 позволит минимизировать фактор распространения трещин, возникающих при эксплуатации изделий в условиях высоких температур, его зерна за счет больших значений твердости (9,5–9 по шкале Мооса) способствуют диссипации энергии распространяющейся трещины в результате ее отклонения от начального направления [9]. Однако добавление оксидов вольфрама и алюминия не решает проблему со стабилизацией тетрагональной фазы оксида циркония. Для решения данной проблемы прибегают к легированию ZrO_2 такими оксидами, как CeO_2, Y_2O_3, CaO и MgO [10–12]. Среди перечисленных оксидных соединений MgO обладает наивысшей температурой плавления (2852 ^{0}C), а также образует с Al_2O_3 шпинель $MgAl_2O_4$, которая обладает хорошими механическими свойствами.

На данный момент нет информации о фазовом составе и микроструктуре многокомпонентных керамик ZrO_2:WO_3:Al_2O_3:MgO. Решение данной проблемы методами численного моделирования является весьма трудоемкой задачей, в связи с чем необходимо получить сведения о фазовом составе и микроструктуре многокомпонентных керамик ZrO_2:WO_3:Al_2O_3:MgO экспериментальным методом.

Методы и материалы

Синтез многокомпонентных керамик проводился методом твердофазного спекания из оксидов металлов ZrO_2, Al_2O_3, WO_3, MgO. За основу была взята смесь ZrO_2:WO_3 с соотношением 1:1. Для подготовки исходной шихты смешивали ZrO_2:WO_3 и Al_2O_3:MgO с различными концентрациями, представленными в таблице 1. Перед твердофазным спеканием исходная смесь в нужных пропорциях гомогенизировалась в планетарной мельнице Pulverisette 6 в режиме: 250 об/мин в течение 30 мин. Из полученных шихт подготавливали пресс-порошки путем добавления 1 масс. % поливинилового спирта (пластификатора). Для этого исходные порошки смешивали на магнитной мешалке с водным раствором пластификатора. Затем суспензия высушивалась до получения сухого сыпучего порошка. Для получения образцов для твердофазного спекания полученные пресс-порошки прессовались с использованием стальной пресс-формы из нержавеющей стали при приложенном давлении 200 МПа в течение 10 секунд. Полученные образцы имели форму таблетки с диаметром 12,1 мм и толщиной 1–1,8 мм. Спекание проводилось при температуре 1500 °C в течение 5 часов в муфельной печи Nabertherm LHT 08/18 в воздушной атмосфере с остыванием камеры в естественных условиях до комнатной температуры в течение 24 часов.

Таблица 1 – Состав экспериментальных образцов

№ образца	Массовая доля ZrO_2, %	Массовая доля WO_3, %	Массовая доля Al_2O_3, %	Массовая доля MgO, %
1	50	50	–	–
2	–	–	50	50
3	47,5	47,5	2,5	2,5
4	45	45	5	5
5	42,5	42,5	7,5	7,5
6	40	40	10	10
7	37,5	37,5	12,5	12,5

Объемная усадка полученных образцов измерялась по формуле $(1 – V_{\text{после спекания}}/V_{\text{до спекания}})\cdot 100\%$ путем измерения геометрических размеров таблеток до спекания и после. Рентгеновские дифрактограммы регистрировались с помощью дифрактометра Rigaku SmartLab при комнатной температуре. В качестве источника рентгеновского излучения использовалась медная трубка Cu-Kα (λ = 1.5406 Å). Съемка дифрактограммы производилась в геометрии Брегга-Брентано (θ-θ скан) с шагом 0.01° и скоростью 3°/мин. Анализ дифрактограмм выполнялся с помощью софта DifracEva V.4.2.1. Уточнение фазового состава проводилось методом рамановской спектроскопии. Спектры комбинационного рассеивания регистрировались с помощью рамановского микроскопа EnSpectr на длине волны лазерного излучения 582 нм. Поперечные сечения синтезированных образцов исследовались методом сканирующей электронной микроскопии (СЭМ) на сканирующем электронном микроскопе Hitachi tabletop TM 3030.

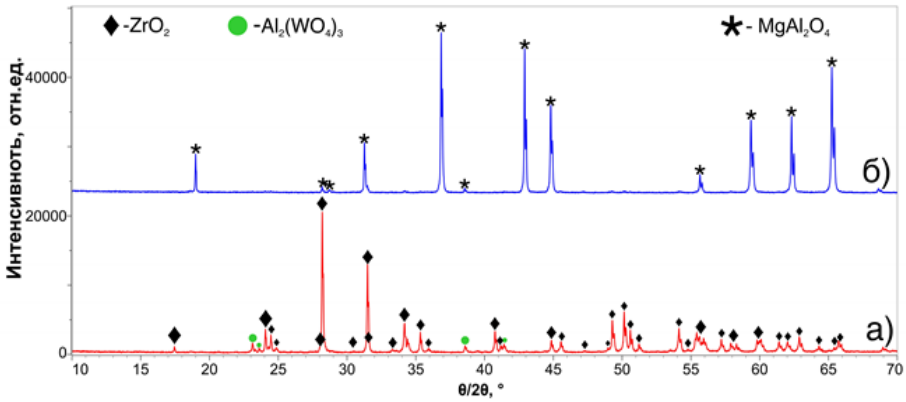
Основные положения

На данный момент времени нет данных о фазовом составе и микроструктуре многокомпонентных керамик ZrO_2:WO_3:Al_2O_3:MgO. В то же время известно, что свойства керамик во многом зависят от фазового состава и микроструктуры образцов. Применение численных методов моделирования для прогнозирования структурных параметров является весьма трудоемкой задачей, в связи с чем необходимо получить данную информацию экспериментальным путем. В данной работе впервые был проведен эксперимент по синтезу и определению зависимостей между составом экспериментальных образцов керамик ZrO_2:WO_3:Al_2O_3:MgO в зависимости от состава.

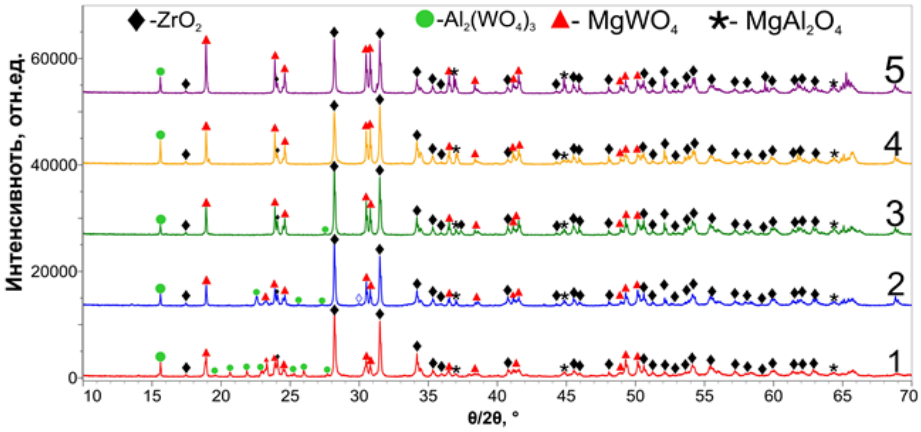
Результаты и обсуждения

На рисунке 1 (стр. 117) представлены рентгеновские дифрактограммы полученных образцов. На рисунке 1(а) представлены дифрактограммы ZrO_2:WO_3 и Al_2O_3:MgO керамик. ZrO_2:WO_3 керамика характеризуется преимущественным содержанием моноклинной фазы диоксида циркония (PDF 01-070-2491, пр. гр. P21/c), а также незначительным содержанием в образце фазы $Al_2(WO_4)_3$ (PDF 00-024-1101, пр. гр. Pnca). Наличие фазы $Al_2(WO_4)_3$ в исходном образце можно объяснить тем, что из-за низкой точки плавления (1254 ^{0}C) и образования эвтектики между Al_2O_3 и WO_3 произошла диффузия атомов алюминия из тигля в керамику. Al_2O_3:MgO керамика характеризуется исключительно фазой $MgAl_2O_4$ (PDF 01-073-1959, пр. гр. Fd-3m).

Образцы № 3–7 характеризуются многофазной структурой с преимущественным содержанием m – ZrO_2. В образце № 3 при добавлении 5 масс. % Al_2O_3:MgO наблюдается незначительное содержание тетрагонального диоксида циркония (PDF 01-078-5751, пр. гр. P42/nmc), стабилизированного MgO. Между тем с ростом содержания Al_2O_3:MgO фаза t – ZrO_2 пропадает вследствие образования более реактивной фазы $MgWO_4$ (PDF 00-027-0789, пр. гр. P2/a).



а)



б)

Рисунок 1 – Рентгеновские дифрактограммы керамик ZrO_2:WO_3:Al_2O_3:MgO, где а(а)) образец № 1, а(б)) образец № 2, б. 1) образец № 3, б(2)) образец № 4, б(3)) образец № 5, б(4)) образец № 6, б(5)) образец № 7

На рисунке 2 (стр. 118) представлены рамановские спектры синтезированных образцов ZrO_2:WO_3:Al_2O_3:MgO с разными концентрациями Al_2O_3 и MgO. При анализе спектров керамики ZrO_2:WO_3 были обнаружены моды, характерные для моноклинной фазы оксида циркония (178, 190, 222, 306, 333, 347, 382, 475, 501, 537, 557, 615, 637 $см^{-1}$) [13], а также мода при 1049 $см^{-1}$, относящаяся к соединению $Al_2(WO_4)_3$ [14]. Как уже упоминалось ранее, данное соединение могло образоваться в результате взаимодействия материала тигля с порошком при отжиге. Пики при 210, 306, 403, 669,724 и 765 $см^{-1}$ на рамановских спектрах порошка Al_2O_3:MgO указывают на наличие фазы $MgAl_2O_4$ [15, 16]. При добавлении 2,5 масс.% Al_2O_3 и 2,5 масс % MgO к ZrO_2:WO_3 помимо моноклинной фазы оксида циркония появляется также тетрагональная фаза оксида циркония с характерными пиками при 152, 267, 292 и 418 $см^{-1}$ [17] и фаза $MgWO_4$ с модами при 798 и 913 $см^{-1}$ [18]. Дальнейшее повышение содержания Al_2O_3 до 5 масс. % и MgO 5 масс. % приводит к появлению пиков при 709 и 800 $см^{-1}$, которые могут указывать на наличие WO_3 в полученном порошке [19]. При концентрации Al_2O_3-MgO, равной 15%, пики, относящиеся к соединениям $MgAl_2O_4$ и $MgWO_4$, становятся более интенсивными. Из полученных данных следует, что образцы обладают многофазной структурой. Образование стабилизированной тетрагональной фазы оксида циркония наблюдается только для образца № 3. Данный факт можно объяснить тем, что с увеличением содержания MgO происходит об-

разование энергетически более выгодной фазы $MgWO_4$ с энтальпией образования в пределах 69–71 кДж мол$^{-1}$ [20], в то время как энтальпия образования тетрагональной фазы циркония в результате стабилизации MgO -36 кДж мол$^{-1}$ [21].

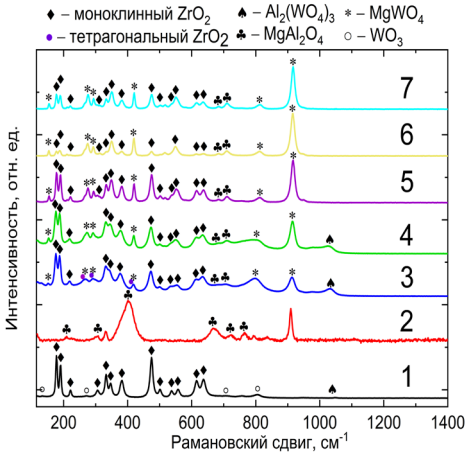


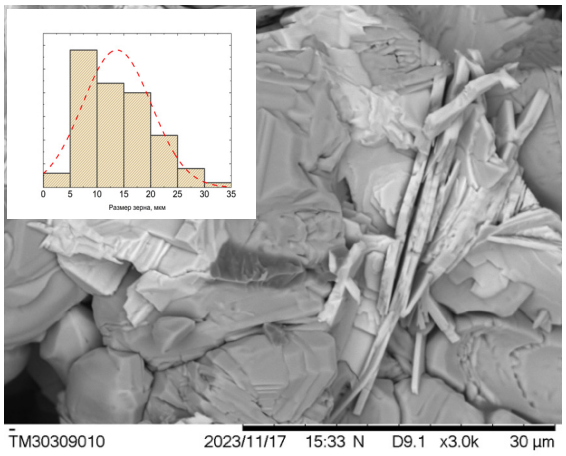
Рисунок 2 – Рамановские спектры керамик ZrO_2:WO_3:Al_2O_3:MgO

В таблице 2 представлены значения объемной усадки и плотности в зависимости от состава синтезированных образцов. Из представленных данных видно, что с увеличением концентрации Al_2O_3:MgO наблюдается увеличение значений как объемной усадки, так и плотности. Одной из причин данного эффекта может быть образование жидкой фазы Al_2O_3:WO_3 при температуре 1450 ^{0}C и, как следствие, более эффективном процессе миграции пор к поверхности.

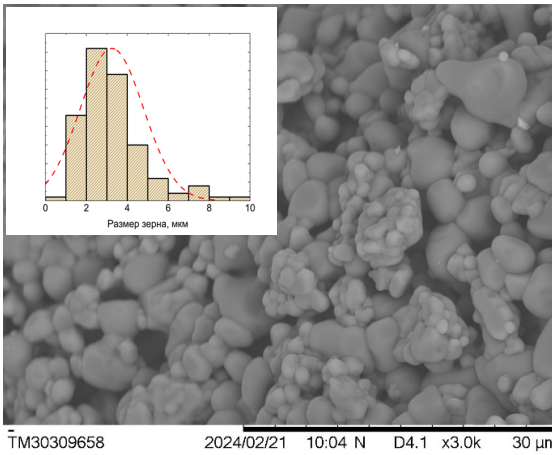
Таблица 2 – Фазовый состав, объемная усадка и плотность синтезированных образцов $(ZrO_2)_x$:$(WO_3)_x$:$(Al_2O_3)_x$:$(MgO)_x$

№ образца	Фаза	Объемная усадка, %	Плотность, г/см3
1	m-ZrO_2 $Al_2(WO_4)_3$	32.3	2.92
2	$MgAl_2O_4$	33	2,50
3	m-ZrO_2 t-ZrO_2 $MgWO_4$ $Al_2(WO_4)_3$	34.7	3,10
4	m-ZrO_2 $MgWO_4$ $Al_2(WO_4)_3$ WO_3	34.1	3,79
5	m-ZrO_2 $MgWO_4$ $Al_2(WO_4)_3$ $MgAl_2O_4$	33.1	3.92
6	m-ZrO_2 $MgWO_4$ $Al_2(WO_4)_3$ $MgAl_2O_4$	54	3,90
7	m-ZrO_2 $MgWO_4$ $Al_2(WO_4)_3$ $MgAl_2O_4$	32.3	4,19

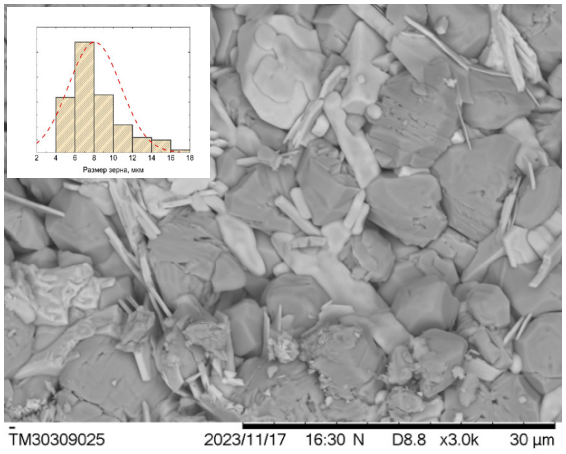
На рисунке 3 представлены СЭМ-изображения поперечных сечений синтезированных образцов в зависимости от концентрации Al_2O_3 и MgO. При добавлении смеси Al_2O_3:MgO к исходной матрице наблюдается образование структуры с большим набором зерен с разной морфологией поверхности, что согласуется с результатами рамановской спектроскопии.



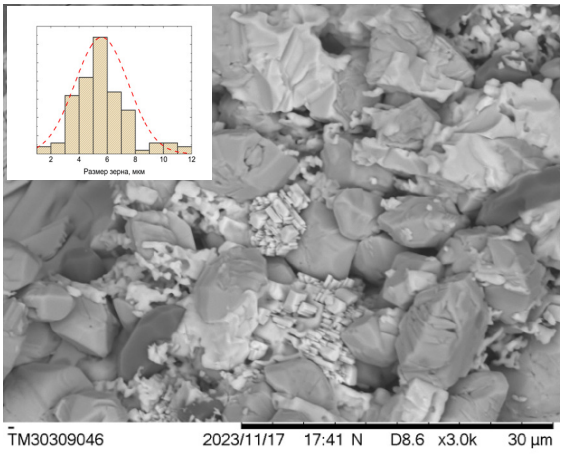
а)



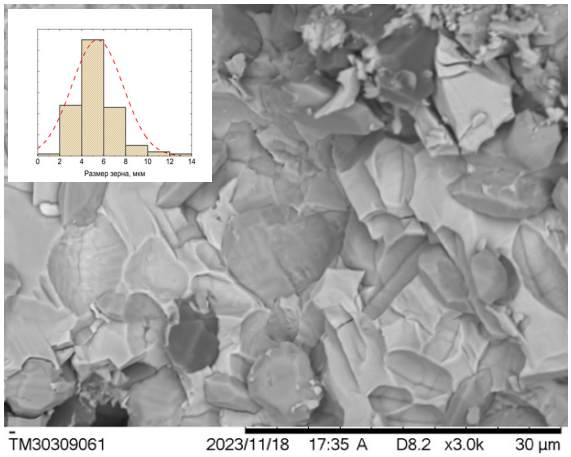
б)



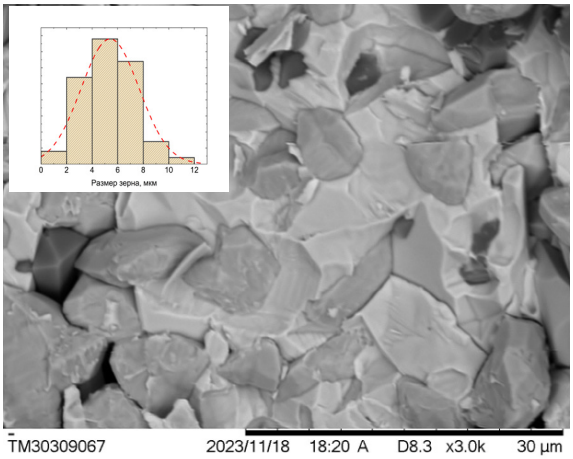
в)



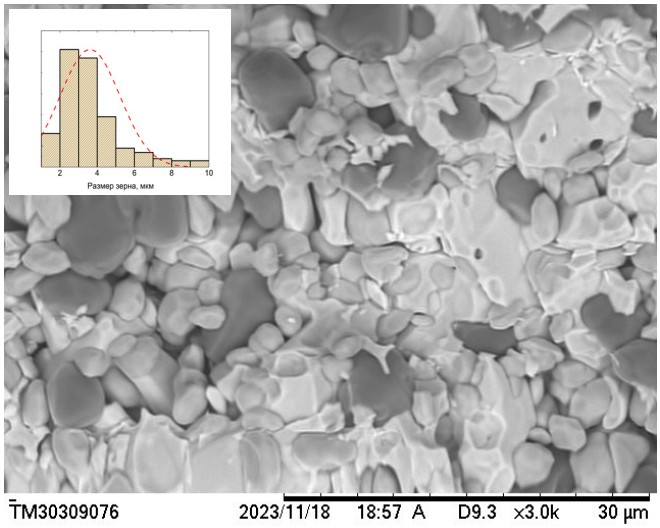
г)



д)



е)



ж)

Рисунок 3 – СЭМ-изображения поперечных сечений и распределение размеров зерен керамик ZrO_2:WO_3:Al_2O_3:MgO, где а) образец № 1, б) образец № 2, в) образец № 3, г) образец № 4, д) образец № 5, е) образец № 6, ж) образец № 7

Из СЭМ-изображений видно, что с увеличением содержания в составе Al_2O_3 и MgO происходит уменьшение среднего размера зерна, что приводит к увеличению значений плотности синтезированных образцов. Как видно из рисунка 3, средний размер зерна уменьшается с ≈ 15 микрон до ≈ 4 микрон при увеличении содержания смеси Al_2O_3:MgO. Уменьшение размера можно частично объяснить тем, что при увеличении в составе шихты порошковой смеси Al_2O_3:MgO частицы ZrO_2 распределяются так, что не могут достаточно взаимодействовать между собой и не способны «спаиваться» во время процесса спекания. Также можно предположить, что WO_3 и фазы, содержащие вольфрам, неравномерно распределяются между частицами ZrO_2 и $MgAl_2O_4$. По этой причине при образовании жидкой фазы не происходит и ее равномерного распределения по всему объему образца и тем самым не оказывает эффекта «спаивания».

Заключение

В работе было исследовано влияние концентрации смеси Al_2O_3:MgO в матрице ZrO_2:WO_3. Установлено, что вне зависимости от концентрации Al_2O_3:MgO образования твердофазного раствора замещения ZrO_2:WO_3:Al_2O_3:MgO не происходит. Фазовый анализ, выполненный методом рамановской спектроскопии, показал, что полученные керамики, в зависимости от состава включают в себя фазы m-ZrO_2, $MgAl_2O_4$, $MgWO_4$, $Al_2(WO_4)_3$, t-ZrO_2. За исключением образца № 3 стабилизации t – ZrO_2 в образцах не наблюдается из-за образования более «реактивной» фазы $MgWO_4$ и, как следствие, недостатка MgO для образования твердого раствора $Zr_{1-x}Mg_xO_2$. Все образовавшиеся фазы обладают температурой плавления в диапазоне 1400–2400 ^{0}C, вследствие чего можно утверждать, что полученные образцы имеют высокую жаропрочность. С увеличением концентрации смеси происходит увеличение значений объемной усадки и плотности синтезированных керамик за счет уменьшения среднего размера зерна. Анализ СЭМ-изображений поперечных сечений показал, что все синтезированные образцы обладают выраженной морфологией поверхности.

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[1,2]Гаранин Ю.А.,
докторант, ORCID ID: 0000-0002-0759-4329, *e-mail: jorge.r2448@gmail.com
[1]Шакирзянов Р.И.,
PhD, ORCID ID: 0000-0001-9908-3034, e-mail: halfraf@mail.ru
[1,2]Козловский А.Л.,
PhD, ORCID ID: 0000-0001-8832-7443, e-mail: kozlovskiy.a@inp.kz
[1,2]Шлимас Д.И.,
PhD, ORCID ID: 0000-0003-2454-7177, e-mail: shlimas@mail.ru
[1,2]Боргеков Д.Б.,
PhD, ORCID ID: 0000-0002-9727-0511, e-mail: borgekov@mail.com

[1]Л.Н. Гумилев атындағы Еуразия ұлттық университеті, 010000, Астана қ., Қазақстан
[2]Ядролық физика институтының Астаналық филиалы, 010000, Астана қ., Қазақстан

ZRO_2:WO_3:AL_2O_3:MGO КӨП КОМПОНЕНТТІ КЕРАМИКА СИНТЕЗІ

Аңдатпа

Бұл жұмыста компоненттердің концентрациясына байланысты ZrO_2:WO3:Al_2O_3:MgO көп компонентті керамикаларының фазалық құрамы мен микроқұрылымы зерттелді. Бастапқы шихтадағы элементтердің концентрациясы мен фазалық құрамы, көлемдік шөгуі, синтезделген үлгілердің тығыздығы мен микроқұрылымы арасындағы тәуелділіктер анықталды. Раман спектроскопиясы арқылы бастапқы ZrO_2:WO_3 матрицасына Al_2O_3:MgO қоспасын қосу ZrO_2:WO_3:Al_2O_3:MgO қатты ерітіндісінің пайда болуына әкелмейтіні анықталды. Al_2O_3:MgO мөлшерінің жоғарылауымен көлемдік шөгу мен тығыздықтың жоғарылауы байқалады, бұл WO_3:Al_2O_3 жүйесінің сұйық фазасының 1450 °C температурада пайда болуымен және тері тесігі мен ақаулардың бетіне тиімдірек қоныс аударуымен байланысты болуы мүмкін. Алынған үлгілердің көлденең қималарының СЭМ суреттерін талдау барлық үлгілердің дәннің әртүрлі формалары бар дамыған морфологиясы бар екенін көрсетті.

Тірек сөздер: көп компонентті керамика, қатты фазалы синтез, ыстыққа төзімді материалдар, ZrO_2:WO_3:Al_2O_3:MgO.

[1,2]Garanin YU.A.,
Doctoral student, ORCID ID: 0000-0002-0759-4329, *e-mail: jorge.r2448@gmail.com
[1]Shakirzyanov R.I.,
PhD, ORCID ID: 0000-0001-9908-3034, e-mail: halfraf@mail.ru
[1,2]Kozlovskiy A.L.,
PhD, ORCID ID: 0000-0001-8832-7443, e-mail: kozlovskiy.a@inp.kz
[1,2]Shlimas D.I.,
PhD, ORCID ID: 0000-0003-2454-7177, e-mail: shlimas@mail.ru
[1,2]Borgekov D.B.,
PhD, ORCID ID: 0000-0002-9727-0511, e-mail: borgekov@mail.com

[1]L.N. Gumilyov Eurasian National University, 010000, Astana, Kazakhstan
[2]Astana Branch of the Institute of Nuclear Physics,010000, Astana, Kazakhstan

SYNTHESIS OF MULTICOMPONENT ZRO_2:WO3:AL_2O_3:MGO CERAMICS

Abstract

In this work, the phase composition and microstructure of multicomponent ZrO_2:WO_3:Al_2O_3:MgO ceramics were studied depending on the concentration of the components. The dependences between the concentration of elements in the initial charge and the phase composition, volume shrinkage, density and microstructure of synthesized samples are determined. It was found by Raman spectroscopy that the addition of an Al_2O_3:MgO mixture to the initial ZrO_2:WO_3 matrix does not lead to the formation of a ZrO_2:WO_3:Al_2O_3:MgO solid solution. With an increase in the content of Al_2O_3:MgO, there is an increase in volumetric shrinkage and density, which may be associated with the formation of the liquid phase of the WO_3:Al_2O_3 system at a temperature of 1450 °C and, as a result, more efficient migration of pores and defects to the surface. The analysis of the SEM images of the cross sections of the obtained samples showed that all samples have a developed morphology with different grain shapes.

Key words: multicomponent ceramics, solid-phase synthesis, heat-resistant materials, ZrO_2:WO_3:Al_2O_3:MgO.

UDC 620.3
IRSTI 29.19.22

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[1]Amirbekova G.S.,
Doctoral student, ORCID ID:0009-0001-3774-0120, e-mail: gulzhanatt95@gmail.com
[1*]Tolepov ZH.K.,
PhD, ORCID ID:0000-0001-7895-0434, *e-mail: mr.tolepov@mail.ru
[1]Guseinov N.,
ORCID ID: 0000-0003-4804-5323, e-mail: solar_neo@mail.ru
[1]Tulegenova M.A.,
PhD, ORCID ID: 0000-0002-6413-4302, e-mail: malika.tulegenova@bk.ru
[2]Kuanyshbekov T.,
PhD, ORCID ID: 0000-0002-2236-3678, e-mail: kuanyshbekov_17@mail.ru
[3]Arynbek Y.,
ORCID ID: 0000-0002-6942-8211, e-mail: yersultan@jinr.ru

[1]Al-Farabi Kazakh National University, 050040, Almaty, Kazakhstan
[2]National Scientific Laboratory of Collective Use S. Amonzholov East Kazakhstan University, 070002, Ust-Kamenogorsk, Kazakhstan
[3]Laboratory of Neutron Physics, Joint Institute for Nuclear Research, Dubna, Russia

THE EFFECT OF PLASMA SURFACE TREATMENT ON THE STRUCTURE OF THE LEAD SULFIDE FILM

Abstract

In this work, the effect of the substrate surface on the formation of structured lead sulfide films is studied. For this purpose, the surface of single-crystalline silicon (100) was subjected to plasma treatment in a glow discharge in an argon atmosphere, at a working pressure of 1 Pa and a potential difference across the electrodes of 2 kV. Lead sulfide films were obtained on treated and untreated single-crystalline silicon surfaces by chemical deposition from an aqueous solution of lead nitrate, thiourea and sodium hydroxide at a temperature of 70°C for 30 minutes. The surface morphology, elemental composition, and crystal structure were studied by scanning electron microscopy, energy dispersive analysis, and X-ray diffraction, respectively. As a result, the films deposited on pretreated substrates have a distinctly different surface structure compared to films deposited on untreated substrates. Under the same synthesis conditions, the growth of crystals on the treated surface occurred predominantly along certain lines and were grouped into individual particles, while on the untreated surface a continuous film was formed. Thus, through plasma treatment, crystal growth can be controlled to create nanostructures.

Key words: Lead sulfide films, plasma treatment, chemical bath deposition, morphology, elemental composition, structure.

Introduction

PbS thin films are widely used in optoelectronics and sensors as materials for IR detectors, optical switches, efficient solar radiation conversion devices, chemical sensors, temperature sensors, photodetectors that operate in the infrared wavelength range and photoresistors, temperature-sensitive sensors, detectors in the infrared range of the spectrum [1–6]. Lead sulfide, a narrow-band semiconductor, which is the basic thermoelectric materials in the temperature range of 300-950 K and this material is also a promising material in semiconductor optoelectronics for the creation of injection lasers [7–10]. In this group, lead sulfide (PbS), which is a narrow-band semiconductor (≈ 0.41 eV at room temperature), is widely used in many fields, such as Pb^{2+} ion-selective sensors, in

micro and optoelectronics, nanotechnology [11–12], in photometric switches [13]. Unlike all other semiconductors, the temperature band gap coefficient in PbS is positive [14]. Of all the currently used methods for producing PbS, the method of chemical precipitation from solutions is of the greatest interest [15]. This method makes it possible to obtain thin films of metal chalcogenides, which provides great opportunities for the synthesis of new compounds. The study of the properties of the obtained films is the main task, since this is the main criterion of the material. Lead sulfide is one of the most promising materials for use in the infrared field. Therefore, the synthesis of semiconductor PbS films from aqueous solutions is of great interest [16–18].

Plasma treatment is a method of modifying the surface of a substrate that uses plasma to affect the structure of vegetation on this substrate. Plasma is an ionized gas consisting of charged particles (ions and electrons) [19]. Plasma treatment can affect the structure of lead sulfide in several ways, for example, by changing the surface of the substrate, the morphology can be changed. Plasma can change the shape and size of lead sulfide particles. This can lead to an increase in the surface area of the material, which can improve its characteristics [20]. Plasma surface treatment can lead to defects in the structure of lead sulfide. These defects can affect its electrical and optical properties [21–22].

Materials and methods

The substrate of monocrystalline silicon (100) was subjected to plasma treatment in a glow discharge in an argon atmosphere for t = 5 minutes at a discharge voltage U = 2 kV and a current strength equal to I = 0.5 mA.

Thin films of lead sulfide were produced by precipitation from an aqueous solution in a chemical bath on silicon substrates purified in alcohol. During the experiment, deionized water was used in solutions. First: Pb $(NO_3)_2$ (lead nitrate) 25 ml 0.18 M (1.525 g), NaOH (sodium hydroxide) 75 ml 0.38 M (1.162 g), the solutions were mixed with a magnetic mixer for 120 minutes in a 150 ml glass. CH_4N_2S (thiourea) 50 ml of 0.11 M (0.398 g) was added to this solution [23]. The formula for the chemical reaction will be as follows:

$$Pb(NO_3)_2 + 2NaOH + CH_4N_2S \longrightarrow H_2O + PbS + CH_4N_2O + 2NaNO_3 \quad (1)$$

Then the silicon substrates cleaned by ultrasound were immersed in a glass in a vertical direction. The temperature of the bath was maintained at 70°C. At the end, the resulting structures were washed with deionized water. The substrate was placed in the solution for 30 minutes, resulting in homogeneous thin films of gray color.

The morphology and elemental composition were studied by electron microscopy and energy dispersive analysis using an FEI Quanta 200i installation.

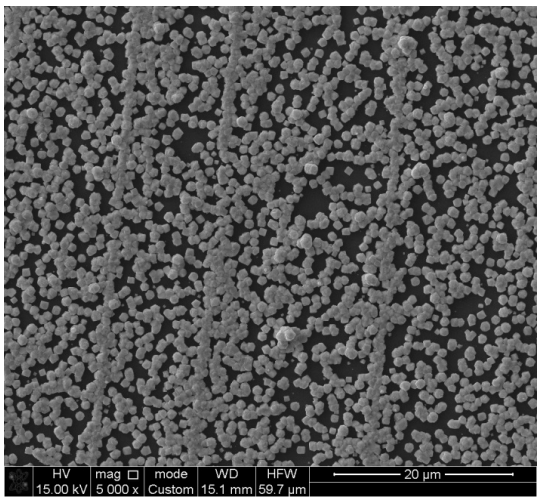
The structure of the resulting films was studied by X-ray diffraction (XRD) using a Rigaku MiniFlex installation. The wavelength corresponds to the excitation of the copper atom on the line. The scanning speed was deg/min, the angles varied in the range of 10° - 90°.

Main provision

It was revealed that preliminary plasma treatment of the substrate surface affects the growth of PbS crystals, that is, it allows preserving the individuality of the particles.

Results and discussion

Figure 1 shows the images of a scanning electron microscope and the elemental composition of the films obtained, 1 (a) – the morphology of the film obtained on the treated surface 1 (b) – the morphology of the film obtained on the untreated surface. 1 (c) and 1 (d) are the corresponding elemental composition of the obtained films



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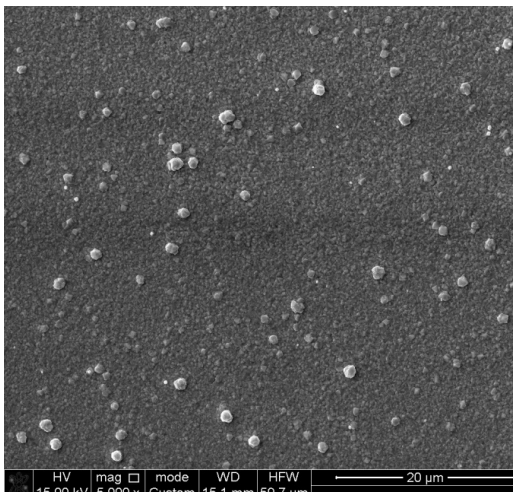

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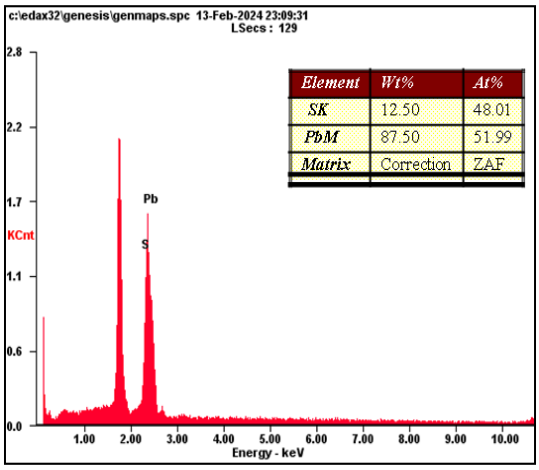

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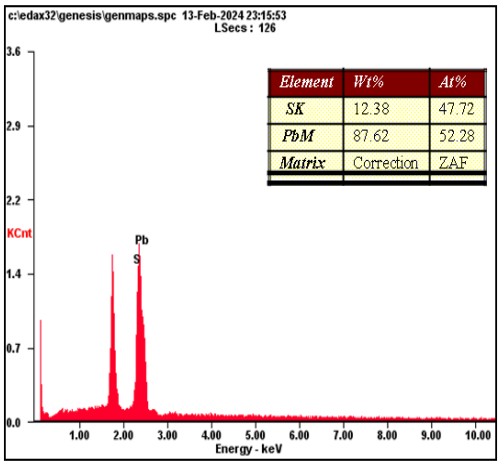

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Figure 1– (a) – morphology structure and (c) – energy-dispersion analysis of PbS obtained on a treated substrate, (b) – morphology structure and (d) – energy-dispersion analysis of PbS obtained on an untreated substrate

Using a scanning electron microscope (SEM), a sample of lead sulfide (PbS) was magnified 5000 times. The accelerating voltage of the electron beam was 15 kV, the beam current was 10 nA, the working distance, i.e. the distance between the electron gun and the sample was 15.1 mm. From the results obtained using a scanning electron microscope, it follows that the plasma-treated surface promotes crystal growth while maintaining the individuality of the particles and mainly along certain lines, while a continuous film is formed on the untreated surface. Figure 1(a) shows the results of a scanning electron microscope (SEM) study of the morphology of lead sulfide (PbS) produced on a plasma-treated surface. The purpose of the study was to study the effect of plasma treatment on the structure and properties of PbS films. It was found that plasma treatment leads to a change in the morphology of PbS films. On a plasma-treated substrate, the PbS film is more uniform and has a smoother surface. The sizes of the resulting particles are approximately uniform and average 500 nm, and also had the shape of cubic crystallites. This texture was found in all studied samples. The texture and morphology of films grown on a silicon surface depends on the time and deposition rate, on the pH level, temperature, but also, as it turns out, on the substrate surface. Preliminary plasma treatment

of the substrate apparently leads to an uneven charge distribution on the silicon surface, associated with the crystalline structure of the surface. This helps preserve the individuality of the particles.

To determine the elemental composition of PbS material samples, the energy dispersive spectroscopy (EDS) method with an energy of 20 keV was used. The results of determining the chemical composition and atomic content of the elements Pb and S in the film are presented in the figure. 1(c) and 1(d). The figure clearly shows the presence of Pb and S peaks in the energy dispersive spectroscopy of the samples. Energy dispersive analysis shows that the sample is composed of lead (Pb) and sulfur (S). The Pb/S ratio is 1:1, which corresponds to the stoichiometric composition of lead sulfide (PbS). Based on the data obtained, it can be concluded that the material under study is lead sulfide (PbS). Peaks in the energy-dispersive spectrum correspond to the energy that is emitted by atoms when electrons transition to lower energy levels.

When conducting energy dispersive analysis, it was found that as a result of plasma treatment, the peak corresponding to lead sulfide (PbS) was lower than the peak of the silicon (Si) substrate. At the same time, in the substrate untreated with plasma, the PbS peak was higher than the Si peak. This corresponds to the fact that after treatment the silicon surface had a larger area. In addition, after treatment, a decrease in the atomic fraction of lead by 1 at.% was revealed.

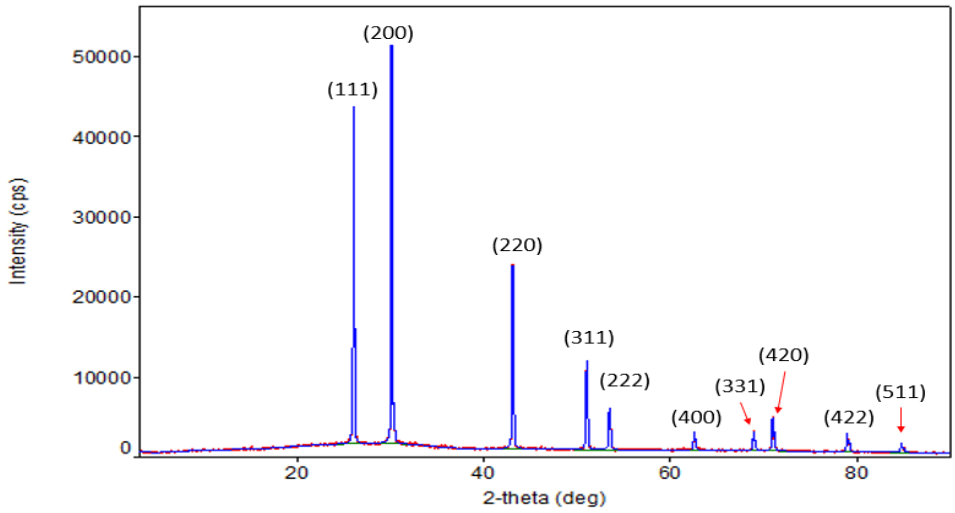

Figure 2 – X-ray diffraction of the PbS film

From X-ray diffraction analysis, peaks corresponding to the plane indices (111), (200), (220), (311), (222), (400), (331), (420), (422) and (511) were identified at angles 2θ 26.10°, 43.22°, 51.20° and 53.62°, respectively. It follows from the diffract gram that the film has a face-centered cubic structure and corresponds to the Fm-3m spatial group. The determination of the lattice parameters is carried out by fulfilling the Bragg's law [24].

$$2d_{hkl}\sin 2\theta = m\lambda \tag{2}$$

Where, d_{hkl} – interplant distance, θ – sliding angle, that is, the angle between the reflecting plane and the incident beam, λ – the wavelength of the X-ray radiation ($\lambda(Cu_{K\alpha}) = 1,5418\ \AA$) and m – the order of reflection and has a positive integer, for cubic symmetry is determined by:

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}} \tag{3}$$

Where, a – the lattice constant, h,k,l – plane indexes. The lattice constant was calculated, and it is 5.93 A. The results of X-ray diffraction analysis correspond to world literature data.

Conclusion

In this study, the morphology and elemental composition of PbS films obtained on surfaces pretreated and untreated by plasma were studied using scanning electron microscope (SEM) and energy dispersive spectroscopy. Preliminary plasma treatment of the substrate surface leads to a change in the morphology of PbS films. The PbS film obtained on the treated substrate is more uniform in size and has an average size of 500 nm, as well as a shape in the form of cubic crystallites. Thus, we can conclude that treating the surface of single-crystalline silicon in a glow discharge plasma promotes the growth of crystals on this surface individually and predominantly along certain lines, while a continuous film is formed on the untreated surface. This indicates that crystal growth can be controlled using plasma treatment to create nanostructures.

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[1]Әмірбекова Г.С.,
докторант, ORCID ID:0009-0001-3774-0120,
e-mail: gulzhanatt95@gmail.com
[1]*Төлепов Ж.Қ.,
PhD, ORCID ID:0000-0001-7895-0434, *e-mail: mr.tolepov@mail.ru
[1]Гусейнов Н.,
ORCID ID: 0000-0003-4804-5323, e-mail: solar_neo@mail.ru
[1]Төлегенова М.А.,
PhD, ORCID ID:0000-0002-6413-4302, e-mail: malika.tulegenova@bk.ru
[2]Қуанышбеков Т.,
PhD, ORCID ID:0000-0002-2236-3678, e-mail: kuanyshbekov_17@mail.ru
[3]Арынбек Е.,
ORCID ID: 0000-0002-6942-8211, e-mail: yersultan@jinr.ru

[1]әл-Фараби атындағы Қазақ ұлттық университеті, 050040, Алматы қ., Қазақстан
[2]С. Аманжолов атындағы Шығыс Қазақстан университетінің Ұжымдық қолданыстағы ұлттық ғылыми зертханасы, 070002, Өскемен қ., Қазақстан
[3]Біріккен ядролық зерттеулер институтының Нейтрондық физика зертханасы, Дубна қ., Ресей

ПЛАЗМАЛЫҚ БЕТТІ ӨҢДЕУДІҢ ҚОРҒАСЫН СУЛЬФИДІНІҢ ПЛЕНКА ҚҰРЫЛЫМЫНА ӘСЕРІ

Аңдатпа

Бірегей қасиеттеріне байланысты қорғасын сульфиді (PbS) қазіргі уақытта әлемнің көптеген жетекші зертханаларында зерттелетін материал. Мұндай қасиеттерге құрылымдық модификация арқылы оптикалық және электронды қасиеттер жатады. Бұл жұмыста субстрат бетінің қорғасын сульфидінің құрылымдық пленкаларының түзілуіне әсері зерттеледі. Ол үшін монокристалды кремнийдің (100) беті аргон атмосферасында солғын разрядта, 1 Па жұмыс қысымында және 2 кВ электродтардағы потенциалдар айырмасында плазмалық өңдеуден өтті. Қорғасын сульфидінің пленкалары 30 минут ішінде 70°С температурада қорғасын нитраты, тиомочевина және натрий гидроксидінің сулы ерітіндісінен химиялық тұндыру әдісімен монокристалды кремнийдің өңделген және өңделмеген беттеріне алынды. Сәйкесінше сканерлейтін электронды микроскопия, энергия диперсиялық талдау және рентгендік құрылымдық талдау әдістерімен беттік морфология, элементтік құрам және кристалдық құрылым зерттелді. Нәтижесінде, алдынала өңделген субстраттардағы алынған пленкалар өңделмеген субстраттарға тұндырылған пленкалармен салыстырғанда айқын беткі құрылымға ие. Бірдей синтез жағдайында өңделген беттегі кристалдардың өсуі, негізінен белгілі бір сызықтар бойымен жүрді және жеке бөлшектерге топтастырылды, ал өңделмеген бетте біртұтас пленка пайда болды. Осылайша, наноқұрылымдарды құру үшін плазмалық өңдеу арқылы кристалдардың өсуін бақылауға болады.

Тірек сөздер: қорғасын сульфидінің пленкалары, плазмалық өңдеу, химиялық ваннадағы сулы ерітіндіден тұндыру, морфология, элементтік құрамы, құрылымы.

[1]Амирбекова Г.С.,
докторант, ORCID ID: 0009-0001-3774-0120,
e-mail: gulzhanatt95@gmail.com
[1]Толепов Ж.К.,
PhD, ORCID ID: 0000-0001-7895-0434, *e-mail: mr.tolepov@mail.ru
[1]Гусейнов Н.,
ORCID ID: 0000-0003-4804-5323, e-mail: solar_neo@mail.ru
[1]Тулегенова М.А.,
PhD, ORCID ID: 0000-0002-6413-4302, e-mail: malika.tulegenova@bk.ru
[2]Куанышбеков Т.,
PhD, ORCID ID: 0000-0002-2236-3678, e-mail: kuanyshbekov_17@mail.ru
[3]Арынбек Е.,
ORCID ID: 0000-0002-6942-8211, e-mail: yersultan@jinr.ru

[1]Казахский национальный университет им. аль-Фараби, 050040, г. Алматы, Казахстан
[2]Национальная научная лаборатория коллективного пользования Восточно-Казахстанского университета им. С. Аманжолова, 070002, г. Усть-Каменогорск, Казахстан
[3]Лаборатория нейтронной физики объединенного института ядерных исследований, г. Дубна, Россия

ВЛИЯНИЕ ПЛАЗМЕННОЙ ОБРАБОТКИ ПОВЕРХНОСТИ НА СТРУКТУРУ ПЛЕНКИ СУЛЬФИДА СВИНЦА

Аннотация

Благодаря своим уникальным свойствам сульфид свинца (PbS) является материалом, который в настоящее время изучается во многих ведущих лабораториях мира. К таким свойствам можно отнести оптические и электронные свойства за счет структурных модификаций. В данной работе изучается влияние поверхности подложки на формирование структурированных пленок сульфида свинца. Для этого поверхность монокристаллического кремния (100) подвергалась плазменной обработке в тлеющем разряде в атмосфере аргона, при рабочем давлении 1 Па и разности потенциалов на электродах 2 кВ. Пленки сульфида свинца были получены на обработанные и необработанные поверхности монокристаллического кремния методом химического осаждения из водного раствора нитрата свинца, тиомочевины и гидрооксида натрия при температуре 70 °C в течение 30 минут. Были изучены морфология поверхности, элементный состав и кристаллическая структура методами сканирующей электронной микроскопии, энергодисперсионного анализа и рентгеноструктурного анализа соответственно. В результате полученные пленки на предварительно обработанные подложки имеют явную отличительную поверхностную структуру по сравнению с пленками, осажденными на необработанные подложки. При одинаковых условиях синтеза рост кристаллов на обработанной поверхности происходил преимущественно вдоль определенных линий и сгруппированы в отдельные частицы, тогда как на необработанной поверхности формировалась сплошная пленка. Таким образом, путем плазменной обработки можно контролировать рост кристаллов для создания наноструктур.

Ключевые слова: пленки сульфида свинца, плазменная обработка, осаждения из водного раствора в химической ванне, морфология, элементный состав, структура.

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[1,2,3*]Гаранин Ю.А.
докторант, ORCID ID: 0000-0002-0759-4329,
*e-mail: jorge.r2448@gmail.com

[1]Евразийский национальный университет им. Л.Н. Гумилева, 010000, г. Астана, Казахстан
[2]Астанинский филиал института ядерной физики, 010000, г. Астана, Казахстан
[3]ТОО «Kazakhstan Advanced Science Research Center», 050000, г. Алматы, Казахстан

ВЛИЯНИЕ ВЫБОРА ИСХОДНОГО МАТЕРИАЛА НА ФАЗОВЫЙ СОСТАВ И ФАЗОВУЮ СТАБИЛЬНОСТЬ ЧАСТИЦ ZRO_2, СИНТЕЗИРОВАННЫХ ГИДРОТЕРМАЛЬНЫМ МЕТОДОМ

Аннотация

В данной работе был исследован фазовый состав, микроструктура и фазовая стабильность образцов диоксида циркония, полученных методом гидротермального синтеза из разных исходных материалов. Установлено, что при использовании в качестве исходного материала $ZrOCl_2 \cdot 8H_2O$ образуются частицы диоксида циркония с содержанием моноклинной и тетрагональной (кубической) фазы, в то же время при использовании в качестве исходного материала $ZrO(NO_3)_2 \cdot 2H_2O$ в образцах идентифицирована только моноклинная фаза. Размеры ОКР, рассчитанные с применением уравнения Шеррера, находятся в диапазоне от 9 до 40 нм. Анализ СЭМ-изображений экспериментальных образцов показал, что наночастицы образуют конгломераты с размерами в несколько микрон. Исследование фазовой стабильности t, c – ZrO_2 фазы от температурного воздействия показало, что t, c – ZrO_2 является метастабильной фазой с размерами ОКР до отжига 10 нм. При повышении температуры отжига происходит постепенная трансформация метастабильной t, c – ZrO_2 в моноклинную, вследствие протекания процессов изменения поверхностной энергии и разрастания частиц, а также спекания конгломератов в более крупные монолитные частицы.

Ключевые слова: ZrO_2, гидротермальный синтез, фазовый состав, фазовая стабильность.

Введение

Керамика из диоксида циркония (ZrO_2) является важным материалом в ядерной энергетике, при производстве твердотопливных оксидных элементов и жаропрочных покрытий [1–3]. ZrO_2 характеризуется высокой коррозионной стойкостью, тугоплавкостью и износостойкостью [4–6]. Диоксид циркония имеет три различные кристаллические структуры при разных температурах: моноклинную (m – ZrO_2, 1175 ^{0}C), тетрагональную (t – ZrO_2, 1175 – 2370 ^{0}C) и кубическую (c – ZrO_2, 2370 – 2680 ^{0}C) [7]. При производстве керамик на основе диоксида циркония очень важен фазовый состав. Так, c – ZrO_2 обладает высокой кислородной ионной проводимостью и химической стабильностью, что делает ее подходящей для применения в качестве датчиков кислорода, твердооксидных топливных элементов и каталитических систем [8]. t – ZrO_2, в свою очередь, обладает самыми лучшими функциональными свойствами (износостойкость, коррозионная стойкость, прочность на изгиб), что очень важно для защитных покрытий в различных отраслях [9, 10].

В настоящее время нано- и микрочастицы ZrO_2 получают с помощью золь-гель метода, химического соосаждения, метода распылительного пиролиза и др. [11–13]. Используя методы, перечисленные выше, можно получать частицы размером от десятков нанометров до нескольких микрометров. Между тем данные технологии синтеза обладают существенными недостатками, такими как: медленная скорость реакции, сложный и трудоемкий процесс, высокое

потребление энергии [14]. Перспективным методом получения наночастиц диоксида циркония является гидротермальный синтез. Данный метод основывается на мягком химическом синтезе частиц из раствора в водной среде при температуре больше 100 ^{0}C и давлении больше 1 атм. Процесс проходит в автоклаве, изготовленном из инертных материалов (чаще всего нержавеющая сталь или тефлон). Основные преимущества гидротермального синтеза: высокая степень смешения реагентов, относительно мягкие условия синтеза, процесс проходит в один этап. Варьируя минерализаторы и кислотность среды, температуру и давление в реакторе, а также продолжительность синтеза, можно изменять форму, размер и фазовый состав частиц.

Несмотря на достаточно большое количество статей, посвященных гидротермальному синтезу частиц ZrO_2 [11–14], термическая стабильность тетрагональной (кубической) фазы ZrO_2 достаточно не изучена.

Методы и материалы

Частицы ZrO_2 были получены методом гидротермального синтеза в стальном автоклаве с тефлоновым реактором объемом 25 мл. Для синтеза частиц ZrO_2 использовали два типа материала-прекурсора. В первом случае использовали 17,5 мл 0,1 моль/л раствора цирконил-хлорид октагидрата ($ZrOCl_2 \cdot 8H_2O$) с дистиллированной водой, а во втором – 17,5 мл 0,1 моль/л раствора циркония (4) оксонитрат дигидрат ($ZrO(NO_3)_2 \cdot 2H_2O$). С целью предотвращения образования конгломератов из более мелких частиц в обоих случаях в раствор добавляли 0,14 г PEG6000. В качестве минерализатора для повышения pH среды до 9 в раствор вводили 5 мл NaOH с концентрацией 10 моль/л. Автоклав был заполнен на 90% от объема для оптимального протекания процессов синтеза. Полученный раствор подвергался гидротермальной обработке в течение 12 часов при температуре 180 ^{0}C. В результате протекания процесса гидротермального синтеза был получен белый порошок, который несколько раз центрифугировался в дистиллированной воде и этиловом спирте, после чего сушился при температуре 60 ^{0}C.

Рентгенофазовый анализ был проведен методом рентгеновской дифракции на дифрактометре Bruker D8-advance с Cu-K_α излучением. Размер области когерентного рассеяния (ОКР) был рассчитан для рефлексов (111) моноклинной фазы и (101) тетрагональной ((111) кубической) фазы ZrO_2, которые были предварительно аппроксимированы, используя функцию Псевдо – Войда, с помощью уравнения Шеррера [15]:

$$d_{XRD} = \frac{0{,}9\lambda}{\beta cos\theta}, \quad (1)$$

где β – ширина на полувысоте (FWHM) для рефлексов (111) моноклинной фазы и (101) тетрагональной ((111) кубической) фазы ZrO_2; 0,9 – коэффициент, учитывающий форму частиц.

Расчет доли моноклинной фазы в экспериментальных образцах проводили с использованием уравнения [16]:

$$X_m = \frac{I_m(\bar{1}11)+I_m(111)}{I_m(\bar{1}11)+I_m(111)+I_t(101)}, \quad (2)$$

где I_m, I_t – интенсивности рефлексов на дифрактограмме.

Изображения морфологии поверхности были получены на сканирующем электронном микроскопе (СЭМ) Thermo Scientific Phenom ProX G6 Desktop SEM. Распределение частиц ZrO_2 по размерам было получено с помощью анализатора частиц ANALYSETTE NanoTec. Перед исследованием образцы диспергировались в дионизованной воде и подвергались обработке в ультразвуковой ванне в течение 30 минут. Отжиг экспериментальных образцов проводился в муфельной печи Nabertherm LHT 08/18 при температуре от 100 до 800 ^{0}C со скоростью нагрева 10 ^{0}C/мин. в течение двух часов при каждой температуре.

Основные положения

Свойства керамики на основе ZrO_2 во многом зависят от фазового состава. Используя гидротермальный метод синтеза частиц ZrO_2, возможно получать низкотемпературную тетрагональную (кубическую) фазу. Между тем стабильность t, c – ZrO_2 фазы при температурном воздействии достаточно не изучена.

Результаты

Методом рентгеновской дифракции был исследован фазовый состав частиц ZrO_2, полученных из разных исходных материалов. Из рисунка 1 видно, что, несмотря на одинаковые параметры синтеза, фазовый состав полученных частиц существенно отличается. Частицы ZrO_2, полученные из $ZrO(NO_3)_2 \cdot 2H_2O$, обладают исключительно m – ZrO_2 (PDF 00-065-0687) пространственная группа P21/a(14). В образцах, полученных с использованием в качестве стартового материала $ZrOCl_2 \cdot 8H_2O$, содержится фаза m – ZrO_2, а также t – ZrO_2 (PDF 00-050-1089) пространственная группа P42/nmc(137) или c – (PDF 01-071-6425) пространственная группа Fm-3m (225). Из-за похожей структуры у t – ZrO_2 и c – ZrO_2 [17] методом рентгеновской дифракции тяжело достоверно определить, какая из фаз, помимо m – ZrO_2, присутствует в образце, полученном из $ZrOCl_2 \cdot 8H_2O$.

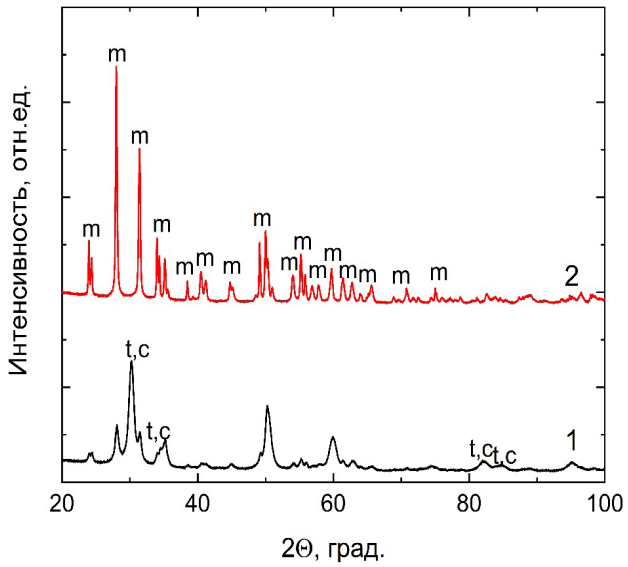


Рисунок 1 – Дифрактограммы исходных частиц ZrO_2, полученных методом гидротермального синтеза из: 1) $ZrOCl_2 \cdot 8H_2O$ и 2) $ZrO(NO_3)_2 \cdot 2H_2O$

Размеры области когерентного рассеяния (ОКР), рассчитанные с помощью уравнения Шеррера (1), а также содеражние t, c – ZrO_2 рассчитанные по формуле (2), представлены в таблице 1. Из представленных данных видно, что размер ОКР для ZrO_2, полученного из $ZrOCl_2 \cdot 8H_2O$, не превышает 20 нм, а для частиц, полученных из $ZrO(NO_3)_2 \cdot 2H_2O$, составляет более 30 нм. Можно предположить, что отсутствие t, c – ZrO_2 в образце, полученном из $ZrO(NO_3)_2 \cdot 2H_2O$, связано с размерным фактором синтезированных частиц. Известно, что для получения тетрагональной фазы диоксида циркония при комнатной температуре необходимо,

чтобы размер частиц не превышал 10–20 нм [18], что связано с минимизацией поверхностной энергии для наночастиц. Цирконил хлорид обладает более низкой степенью гидролиза, которая взаимосвязана с более высокой степенью диссоциации гидрохлорных соединений по сравнению с нитратными [19]. В результате при использовании $ZrO(NO_3)_2 \cdot 2H_2O$ в качестве стартового материала за время синтеза наночастицы успевают сконгломерировать, образовать более крупные частицы и совершить t (c) → m фазовый переход.

Таблица 1 – Размер ОКР и содержание тетрагональной фазы частиц ZrO_2 полученных методом гидротермального синтеза из разных стартовых материалов.

Материал-прекурсор	t – ZrO_2 ОКР, нм	m – ZrO_2 ОКР, нм	Содержание t – фазы, %
$ZrOCl_2 \cdot 8H_2O$	9,43	13,96	63,2
$ZrO(NO_3)_2 \cdot 2H_2O$	-	36,00	0

На рисунке 2 приведены СЭМ-изображения исходных частиц ZrO_2. Анализ изображений СЭМ показал, что вне зависимости от используемого стартового материала для гидротермального синтеза частиц ZrO_2 наночастицы диоксида циркония под действием электростатических и Ван дер Вальсовых сил конгломерируют в большие частицы размером в несколько микрон, что также подтверждается публикациями других авторов [20, 21].

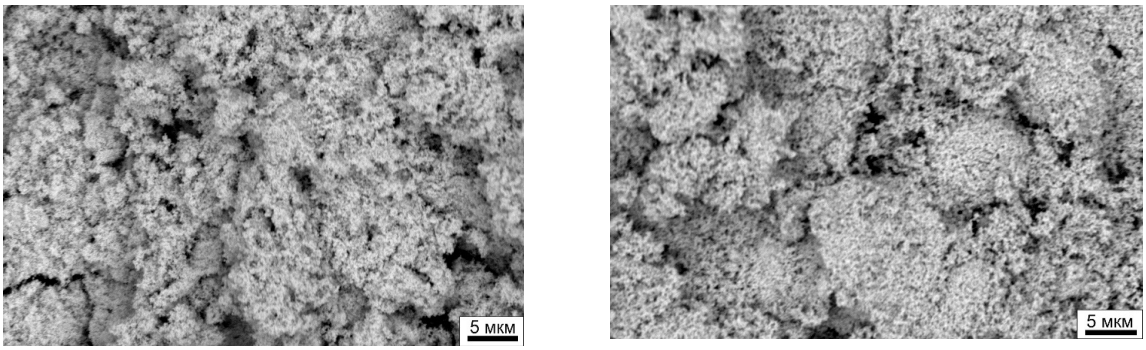
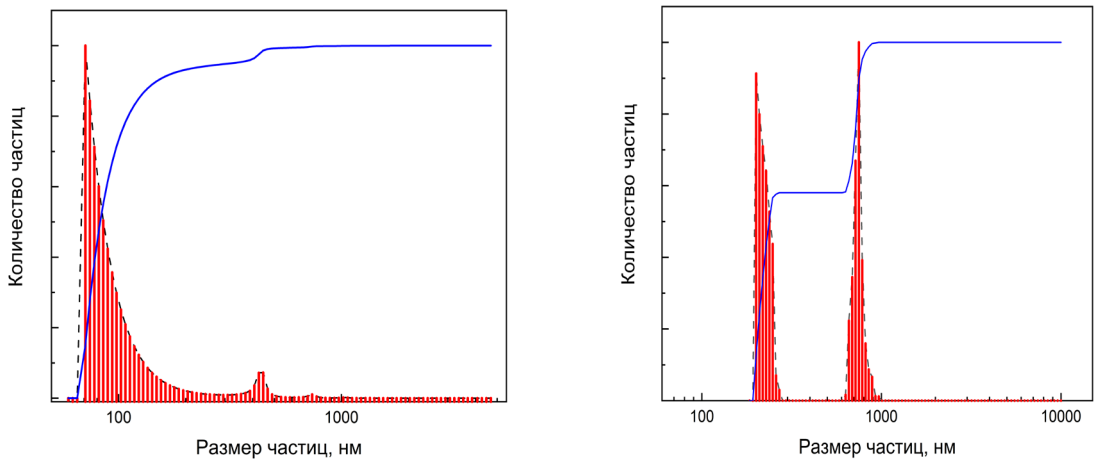


Рисунок 2 – СЭМ-изображения исходных частиц ZrO_2, полученных из:
а) $ZrOCl_2 \cdot 8H_2O$ и б) $ZrO(NO_3)_2 \cdot 2H_2O$ методом гидротермального синтеза

Методом лазерной оптической дифракции были исследованы размеры частиц ZrO_2, полученных из разных исходных материалов. Из рисунка 3 (а) следует, что при использовании для гидротермального синтеза $ZrOCl_2 \cdot 8H_2O$ получаются частицы в диапазоне от 70 до 1200 нм, максимум которого находится при ≈100 нм. В то же время при использовании $ZrO(NO_3)_2 \cdot 2H_2O$ (рисунок 3(б)) для гидротермального синтеза частиц ZrO_2 максимумы распределения находятся при ≈200 нм и ≈1000 нм. Данные лазерной оптической дифракции подтверждают предположение, что более мелкие частицы образуют конгломераты. Стоит отметить, что при исследовании размера частиц методом лазерной оптической дифракции невозможно однозначно утверждать, что полученные значения соответствуют реальному размеру частиц. Это связано с тем, что наночастицы, несмотря на обработку ультразвуком, достаточно интенсивно конгломерируют.



а) б)

Рисунок 3 – Распределение по размерам частиц ZrO_2, полученных из:
а) $ZrOCl_2 \cdot 8H_2O$ и б) $ZrO(NO_3)_2 \cdot 2H_2O$

Для дальнейших исследований изменения фазового состава от температурного воздействия были выбраны частицы диоксида циркония, полученные из $ZrOCl_2 \cdot 8H_2O$. На рисунке 4 представленны дифрактограммы частиц ZrO_2 после термического отжига при различных температурах. Из представленных данных видно, что с увеличением температуры отжига происходит уменьшение интенсивности рефлексов, характерных для тетрагонального диоксида циркония, и увеличение интенсивности рефлексов, характерных для моноклинной фазы диоксида циркония. Фазовый состав образцов после термического отжига, рассчитанный по уравнению (2), представлен в таблице 2 (стр. 135). С ростом температуры отжига наблюдается значительное уменьшение доли тетрагональной фазы диоксида циркония, что объясняется процессами фазового перехода в результате спекания частиц и, как следствие, увеличения их размеров.

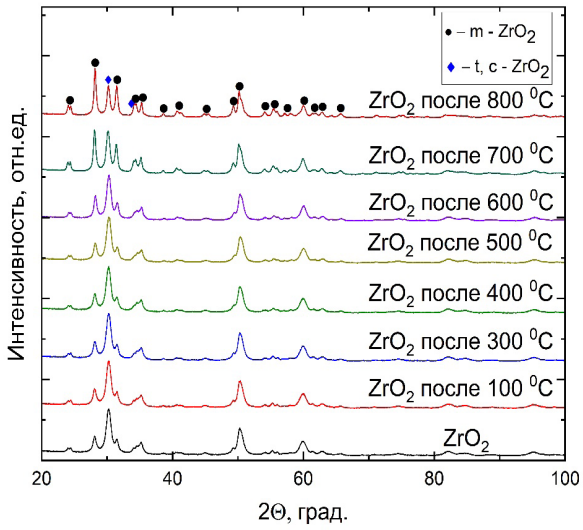


Рисунок 4 – Дифрактограммы частиц ZrO_2, полученных из $ZrOCl_2 \cdot 8H_2O$ после отжига при температурах от 100 до 800 ^0C

На рисунке 5 представлена зависимость изменения размеров ОКР для рефлекса (111) m – ZrO_2 и (101) t – ZrO_2 (или (111) c – ZrO_2) от температуры отжига. Стоит отметить, что при расчете ОКР не учитывалось возможное возникновение деформационных искажений, возникающих при отжиге. С ростом температуры отжига происходит постепенное увеличение значений ОКР для рефлекса (101) t – ZrO_2 (или (111) c – ZrO_2). Сопоставив данные рентгенофазового анализа (таблица 2) и рассчитанных параметров ОКР, можно утверждать, что под воздействием температуры наблюдается разрастание частиц вследствие протекания процессов, обуславливающих изменение поверхностной энергии.

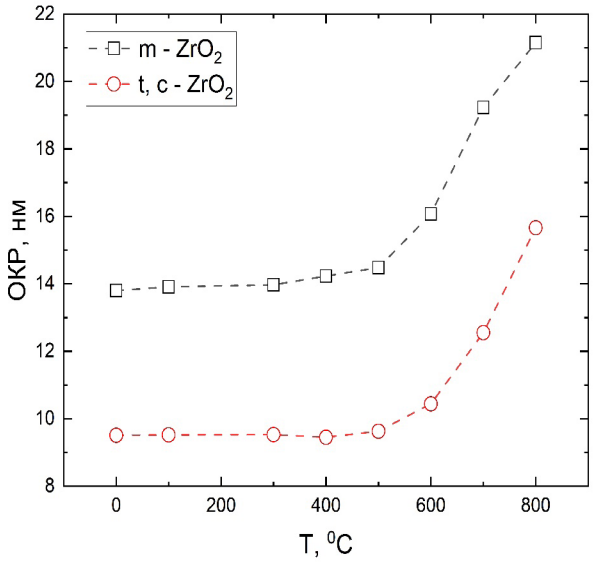


Рисунок 5 – Зависимость размера ОКР частиц ZrO_2 от температуры отжига

На рисунке 6 (стр. 136) представлено СЭМ-изображение частиц ZrO_2 после отжига при температуре 800 ^{0}C. Образец представляет собой частицы с двумя видами морфологии поверхности. Первый вид частиц – это большие частицы неправильной формы размером от 3 до 15 мкм и второй – конгломераты частиц размером меньше 3 мкм.

Таблица 2 – фазовый состав частиц ZrO_2 после отжига при температурах в диапазоне 100–800 ^{0}C

T, ^{0}C	t, ч.	m – фаза, %	t – фаза, %
0	2	36,8	63,2
100		36,5	63,5
300		36,9	63,1
400		37,2	62,8
500		38,2	61,8
600		44,9	55,1
700		62,2	37,8
800		72,2	27,8

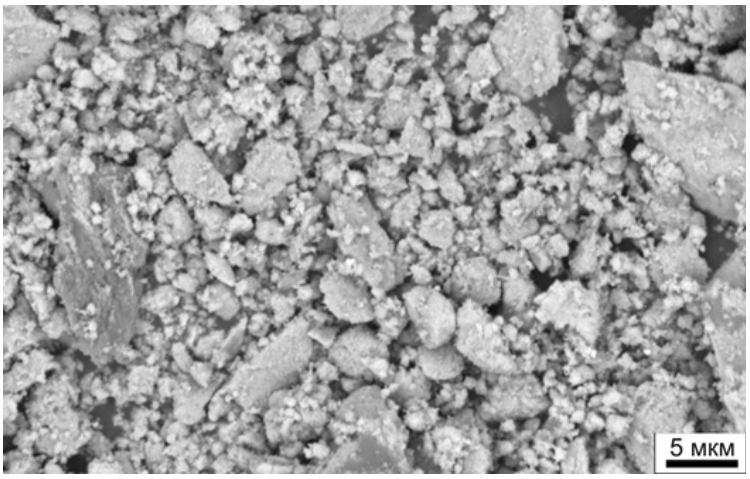


Рисунок 6 – СЭМ-изображения частиц ZrO_2
после отжига при Т = 800 ^{0}С

Для более детального уточнения размера частиц после после отжига использовали лазерную оптическую дифракцию. На рисунке 7 представлены данные распределения по размерам частиц ZrO_2 после отжига при Т = 800 ^{0}С. На графике можно выделить три области. Первая – конгломераты частиц в диапазоне размеров 0,1–10 мкм. Вторая – частицы размером от 10 до 70 мкм, и третья – частицы размером от 70 до 150 мкм. Можно предположить, что первая область в большей степени характеризует конгломераты наночастиц, а также конгломераты, которые под действием высокой температуры спеклись в монолитные частицы размером 5–10 мкм. Наличие второй и третьей области можно частично объяснить тем, что различная плотность «насыпки» порошка, а также наличие воздушных пор приводят к неравномерности протекания процессов спекания при отжиге, что в итоге обуславливает неравномерность роста частиц. Результаты СЭМ и лазерной оптической дифракции подтверждают наличие процессов спекания и разрастания зерен, что в результате приводит к уменьшению поверхностной энергии частиц и, как следствие, к фазовому переходу t (c) → m.

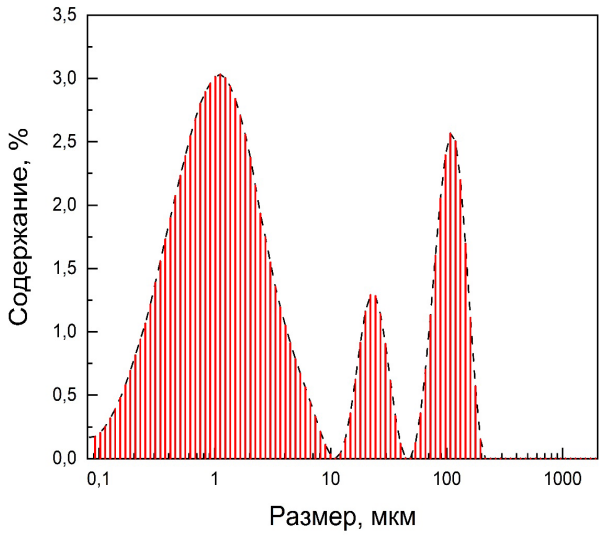


Рисунок 7 – Данные распределения по размерам частиц ZrO_2
после отжига при Т = 800 ^{0}С

Заключение

В данной работе исследован фазовый состав частиц ZrO_2 в зависимости от используемого стартового материала. Установлено, что образцы частиц ZrO_2, полученные методом гидротермального синтеза в течение 12 часов при температуре 180 ^{0}C из исходного материала $ZrO(NO_3)_2 \cdot 2H_2O$, обладают исключительно моноклинной фазой. В то же время при использовании в качестве исходного материала $ZrOCl_2 \cdot 8H_2O$ при тех же условиях синтеза в образцах наблюдается фаза t, c – ZrO_2. Появление высокотемпературной фазы диоксида циркония в образце обусловлено размерным фактором, благодаря чему возможно существование данной фазы при комнатной температуре. Дальнейший анализ стабильности t, c – ZrO_2 фазы при температурном воздействии показал, что в результате разрастания частиц и протекания процессов спекания конгломератов наночастиц в более крупные однородные частицы происходит фазовая трансформация метастабильной t, c – ZrO_2 в m – ZrO_2. Размеры ОКР, рассчитанные с помощью уравнения Шеррера для рефлексов (111) m – ZrO_2 и (101) t – ZrO_2 (или (111) c – ZrO_2), показывают постепенное увеличение минимального размера частиц с ростом температуры отжига. СЭМ-изображение частиц ZrO_2 и данные распределения частиц, полученные методом лазерной оптической дифракции, после отжига при температуре 800 ^{0}C, подтверждают протекание процессов спекания и образования крупных частиц размером от 10 до 150 мкм. Таким образом, методом гидротермального синтеза при заданных условиях синтеза оптимальным исходным материалом является $ZrOCl_2 \cdot 8H_2O$. При использовании $ZrOCl_2 \cdot 8H_2O$ образуются наночастицы ZrO_2 с преимущественным содержанием метастабильной фазы t, c – ZrO_2. Фазовый состав частиц ZrO_2, согласно таблице 2, стабилен в диапазоне температур 100–500 ^{0}C.

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[1,2,3*]ГАРАНИН Ю.А.,
докторант, ORCID ID: 0000-0002-0759-4329,
*e-mail: jorge.r2448@gmail.com

[1]Л.Н. Гумилев атындағы Еуразия ұлттық университеті, 010000, Астана қ., Қазақстан
[2]Ядролық физика институтының Астаналық филиалы, 010000, Астана қ., Қазақстан
[3]«Kazakhstan Advanced Science Research Center» ЖШС, 050000 Алматы қ., Қазақстан

ГИДРОТЕРМИЯЛЫҚ ӘДІСПЕН СИНТЕЗДЕЛГЕН ZRO_2 БӨЛШЕКТЕРІНІҢ ФАЗАЛЫҚ ҚҰРАМЫ МЕН ФАЗАЛЫҚ ТҰРАҚТЫЛЫҒЫНА БАСТАПҚЫ МАТЕРИАЛДЫ ТАҢДАУДЫҢ ӘСЕРІ

Аңдатпа

Бұл жұмыста әртүрлі бастапқы материалдардан гидротермиялық синтез әдісімен алынған цирконий диоксиді үлгілерінің фазалық құрамы, микрокұрылымы және фазалық тұрақтылығы зерттелді. $ZrOCl_2 \cdot 8H_2O$ бастапқы материал ретінде пайдаланылған кезде құрамында моноклиникалық және тетрагональды (текше) фазалы цирконий бөлшектері түзілетіні анықталды, сонымен қатар $ZrO(NO_3)_2 \cdot 2H_2O$ бастапқы материал ретінде пайдаланылған кезде үлгілерде тек моноклиникалық фаза анықталды. Шеррер теңдеуін қолдану арқылы есептелген КША өлшемдері 9-дан 40 нм-ге дейін. Эксперименттік үлгілердің СЭМ-суреттерін талдау нанобөлшектердің өлшемдері бірнеше микрон болатын конгломераттар түзетінін көрсетті. Температуралық әсерден t, c – ZrO_2 фазасының фазалық тұрақтылығын зерттеу t, c – ZrO_2 10 нм күйдіруге дейін КША өлшемдері бар метастабильді фаза екенін көрсетті. Күйдіру температурасының жоғарылауымен метастабильді тетрагональды (текше) ZrO_2 фазасының моноклинге біртіндеп өзгеруі, беткі энергияны азайту және бөлшектердің көбеюі, сондай-ақ конгломераттардың үлкен монолитті бөлшектерге агломерациялануы нәтижесінде жүреді.

Тірек сөздер: ZrO_2, гидротермиялық синтез, фазалық құрам, фазалық тұрақтылық.

[1,2,3*]Garanin YU.A.,
Doctoral student, ORCID ID: 0000-0002-0759-4329,
*e-mail: jorge.r2448@gmail.com.

[1]L.N. Gumilyov Eurasian National University, 010000, Astana, Kazakhstan
[2]Astana Branch of the Institute of Nuclear Physics,010000, Astana, Kazakhstan
[3]«Kazakhstan Advanced Science Research Center» LLP, 050000, Almaty, Kazakhstan

THE EFFECT OF THE CHOICE OF THE STARTING MATERIAL ON THE PHASE COMPOSITION AND PHASE STABILITY OF ZRO_2 PARTICLES SYNTHESIZED BY THE HYDROTHERMAL METHOD

Abstract

In this work, the phase composition, microstructure and phase stability of zirconium dioxide samples obtained by hydrothermal synthesis from various starting materials were investigated. It was found that when using $ZrOCl_2 \cdot 8H_2O$ as a starting material, zirconium dioxide particles containing monoclinic and tetragonal (cubic) phases are formed, at the same time, when using $ZrO(NO_3)_2 \cdot 2H_2O$ as a starting material, only the monoclinic phase was identified in the samples. The CSR dimensions calculated using the Scherrer equation are in the range from 9 to 40 nm. Analysis of SEM images of experimental samples showed that nanoparticles form conglomerates with sizes of several microns. A study of the phase stability of the t, c – ZrO2 phase from temperature exposure showed that t, c – ZrO2 is a metastable phase with CSR sizes up to annealing of 10 nm. With an increase in the annealing temperature, the metastable tetragonal (cubic) phase of ZrO_2 gradually transforms into a monoclinic one, due to the processes of minimizing surface energy and particle proliferation, as well as sintering conglomerates into larger monolithic particles.

Key words: ZrO_2, hydrothermal synthesis, phase composition, phase stability.

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[1,2]*Utelbayev B.T.,
Master of Business Administration, ORCID ID: 0009-0007-9874-4401,
*e-mail: b_utelbayev@kbtu.kz
[1,3]Azhigali A.S.,
Master of Business Administration, ORCID ID: 0009-0000-0620-7158,
e-mail: a_azhigali@kbtu.kz
[1,4]Amangeldin A.G.,
Master of Business Administration, ORCID ID: 0009-0007-4697-7254,
e-mail: a_amangeldin@kbtu.kz

[1]Kazakh-British Technical University, 050000, Almaty, Kazakhstan
[2]SLB (ex. Schlumberger), Angola
[3]"Samsung Electronics Central Eurasia" LLP, 050000, Almaty, Kazakhstan
[4]"Beineu – Shymkent Gas Pipeline" LLP, 050000, Almaty, Kazakhstan

ENVIRONMENTAL SUSTAINABILITY IN CROSS-BORDER ENERGY TRADE: THE CASE OF THE KAZAKHSTAN – CHINA PIPELINE

Abstract

The article delves into the nuanced realm of environmental sustainability in the context of the Kazakhstan-China pipeline – a crucial conduit for oil and gas resources spanning borders. Rigorous methodologies, including Geographic Information System (GIS) mapping and community engagement, unveil the environmental challenges intrinsic to cross-border energy projects. From habitat disruption and pollution to the potential for oil spills, the negative impacts demand strategic mitigation. The article advocates for a multifaceted approach, recommending the incorporation of advanced technologies, strategic route planning, and diversified energy sources. Emphasizing community engagement, transparency, and international cooperation, the proposed sustainable practices aim to balance the imperatives of economic growth with ecological preservation. As the world grapples with increasing energy demands, the Kazakhstan-China pipeline stands as a poignant case study, prompting a collective reevaluation of our approach to global energy trade. Through proactive measures and collaborative efforts, it is possible to navigate the delicate equilibrium between energy security and environmental stewardship, fostering a future where sustainable practices underscore the foundation of cross-border energy endeavors.

Key words: Kazakhstan-China pipeline, oil and gas resources, energy, environment, sustainability.

Introduction

In the dynamic landscape of global energy trade, the interconnection between economic development and environmental responsibility stands as a critical junction. One obvious illustration of this delicate balance is found in the Kazakhstan-China pipeline, a vital conduit for the transportation of oil and gas resources across borders. As nations seek to meet their energy demands, the environmental implications of such cross-border ventures cannot be overlooked. This article delves into the environmental sustainability aspects of the Kazakhstan-China Pipeline, overviewing the intricacies of its impact on ecosystems and proposing innovative solutions for the transportation of energy resources in a more sustainable manner.

The Kazakhstan-China pipeline represents a link in the energy cooperation between two nations – Kazakhstan and China. Stretching over thousands of kilometers, this network of pipelines facilitates the flow of oil and gas resources, fostering economic collaboration between the resource-rich Central Asian nation and the energy-hungry giant of the East. The pipeline not only embodies the interdependence of nations in the global energy market but also poses a myriad of environmental challenges that demand a careful consideration.

As the Kazakhstan-China pipeline winds its way through diverse terrains, from the expansive steppes of Kazakhstan to the mountainous landscapes of China, it leaves an indelible mark on the environment. The extraction, transportation, and processing of oil and gas resources are intrinsically linked to ecological disturbances, ranging from habitat disruption and soil degradation to air and water pollution. Furthermore, the potential for oil spills or gas leaks along the pipeline route poses a looming threat to biodiversity and human communities alike.

In the face of these environmental challenges, the imperative for sustainable practices in cross-border energy trade becomes evident. The Kazakhstan-China pipeline presents a unique opportunity to redefine the narrative surrounding the transportation of vital energy resources. By incorporating eco-friendly technologies, implementing environmental regulations, and encouraging international cooperation, it is possible to mitigate the adverse effects and pave the way for a more sustainable energy future.

The following article aims to comprehensively analyze the environmental sustainability aspects of the Kazakhstan-China pipeline, shedding light on both the challenges and opportunities it presents. Subsequent sections will delve into specific environmental implications, explore existing efforts to address these concerns, and propose innovative solutions for fostering a more sustainable approach to cross-border energy trade. Through navigating the web of both economic growth and environmental responsibility, the Kazakhstan-China pipeline serves as a microcosm of the global energy dilemma. By critically examining its environmental footprint and advocating for sustainable practices, it is possible to highlight a path towards a harmonious coexistence between energy demands and ecological preservation.

Main Provisions
Literature Review

The intersection of environmental sustainability and cross-border energy trade has garnered significant attention in scholarly circles, reflecting the growing global concern for balancing economic progress with ecological responsibility. The literature surrounding this complex interplay provides valuable insights into the challenges faced by nations engaged in cross-border energy trade and offers potential solutions to mitigate the environmental impact. This review provides some key themes and findings from existing research, clarifying the broader context and specific nuances of the environmental sustainability discourse, with a focus on the Kazakhstan-China pipeline.

1. Cross-Border Energy Trade and Environmental Concerns

As the global demand for energy continues to surge, nations increasingly turn to cross-border energy trade to secure their supply. However, this transition is not without environmental

ramifications [1, 2]. There are environmental externalities associated with cross-border energy transportation, emphasizing the need for comprehensive assessments that go beyond economic considerations [3, 4, 5]. The Kazakhstan-China pipeline, as a case in point, exemplifies the challenges posed by traversing diverse ecosystems and raises questions about the long-term ecological consequences [6, 7, 8].

2. Environmental Impact Assessment along Cross-Border Pipelines

The assessment of environmental impacts along cross-border pipelines has become a focal point in academic research [9, 10, 11, 12]. It was conducted a comprehensive environmental impact assessment of oil and gas pipelines, including those traversing international boundaries [13, 14]. Their findings underscored the need for stringent regulations, advanced technologies, and international cooperation to minimize adverse effects. It aligns with the concerns surrounding the Kazakhstan-China pipeline, where the varied topography and ecosystems demand a nuanced approach to environmental impact assessment [15, 16].

3. Technological Innovations for Sustainable Energy Transportation

Advancements in technology play a pivotal role in shaping the environmental sustainability of cross-border energy trade [17, 18]. The researchers have explored the application of innovative technologies, such as leak detection systems and eco-friendly materials for pipelines, as means to reduce environmental risks [19, 20, 21]. Integrating such technologies into the infrastructure of the Kazakhstan-China pipeline could be instrumental in preventing and addressing potential environmental incidents [22, 23].

4. Regulatory Frameworks and International Cooperation

The establishment of robust regulatory frameworks and the promotion of international cooperation emerge as critical factors in ensuring the environmental sustainability of cross-border energy projects [24]. In their examination of global energy governance, some scholars have emphasized the role of regulatory bodies in harmonizing environmental standards. The Kazakhstan-China pipeline, spanning two nations, underscores the necessity for collaborative governance to address shared environmental concerns effectively [25, 26].

5. Case Studies: Lessons from Cross-Border Energy Projects

Examining case studies provides valuable lessons for understanding the features of environmental sustainability in cross-border energy trade. The experiences of other pipelines, such as the Baku-Tbilisi-Ceyhan pipeline or the Nord Stream pipeline, offer insights into successful strategies and potential pitfalls [27]. Drawing parallels and distinctions between these cases and the Kazakhstan-China pipeline can inform best practices and innovative solutions tailored to the specific challenges of each project [28].

6. The Role of Stakeholders in Promoting Sustainability

Stakeholder engagement emerges as a key determinant in the success of sustainable practices along cross-border energy routes [28]. It was explored the role of stakeholders, including governments, industry players, and local communities, in influencing the environmental outcomes of energy projects [29]. Understanding the diverse interests and concerns of stakeholders along the Kazakhstan-China pipeline is essential for crafting inclusive and effective sustainability initiatives [30].

The literature has reviewed here underscores the multifaceted nature of environmental sustainability in cross-border energy trade. As the world grapples with the imperative to meet energy demands while safeguarding the environment, the Kazakhstan-China pipeline stands as a pivotal case study. By building upon the insights from existing research, policymakers, industry leaders, and environmental advocates can collaboratively work towards sustainable solutions that balance economic prosperity with an ecological preservation.

Methodology

There are many effective methods to analyze a sustainability of the pipeline. One of the most qualified tools is the application of Geographic Information System (GIS) mapping to assess and

visualize the environmental sustainability of the Kazakhstan-China Pipeline [31]. GIS as a powerful tool for spatial analysis can be employed to integrate diverse datasets and provide a comprehensive spatial context for understanding an ecological impact along the pipeline route. It consists of six major stages [32].

The first step involves the collection and compilation of relevant GIS data. This includes topographical maps, land use data, ecological features, and any available environmental monitoring data along the Kazakhstan-China Pipeline route. By assembling a rich dataset, the GIS analysis will be able to capture the complexity of the landscape and identify key environmental indicators.

The second step examines an environmental impact along the pipeline route. Various environmental parameters, such as soil quality, air and water quality, and biodiversity, will be geographically referenced and analyzed. This spatial perspective will highlight areas of potential environmental stress, helping to pinpoint regions that require specific attention in terms of mitigation strategies.

The third step identifies high-risk areas, which may include ecologically sensitive zones, water bodies, or regions prone to soil erosion. The GIS analysis will provide a visual representation of the areas, which are the most vulnerable to environmental disturbances, guiding decision-makers in the prioritization of mitigation efforts.

The fourth step includes a scenario modeling to be employed to simulate the potential outcomes of different mitigation strategies. This proactive approach allows for the exploration of various scenarios, such as the implementation of eco-friendly technologies or the establishment of buffer zones around environmentally sensitive areas. Through GIS-based modeling, the effectiveness of these strategies in minimizing the environmental impact can be assessed before implementation.

The fifth step ensures the accessibility of GIS maps to the public. Transparent communication is vital for building trust and fostering collaboration among stakeholders. The GIS maps, illustrating environmental data and potential mitigation strategies, will be made accessible through online platforms, allowing stakeholders, including local communities, to engage with and contribute to the decision-making process.

The final step involves a continuous monitoring of environmental changes. By implementing a system for regular updates and incorporating real-time data, the GIS analysis can adapt to evolving environmental conditions. This iterative approach ensures that environmental sustainability measures remain relevant and effective throughout the lifecycle of the Kazakhstan-China pipeline.

Based on a format of this tool, it is possible to conduct a brief GIS mapping to see the impact of the pipeline on the environment.

Results

Considering the statistics and reports from the official site of the Kazakhstan-China pipeline, it was prepared the list of environmental indicators, which was carefully analyzed. See Table 1 below.

Table 1 – Environmental Indicators of the Kazakhstan-China Pipeline (source: made by the authors)

Location	Soil quality		Air quality		Water quality		Biodiversity index	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Atasu-Alashankou	High	Medium	Medium	Medium	Good	Medium	High	Medium
Kenkiyak-Kumkol	High	High	Medium	Medium	Good	Good	High	High

Considering the results of Table 1 it is seen that the construction and operation of pipelines can have several negative impacts on various environmental indicators. While advancements in technology and regulatory frameworks aim to minimize these impacts, challenges persist.

First, a construction of pipeline often requires clearing land, leading to habitat disruption and fragmentation. It can affect local flora and fauna, especially in ecologically sensitive areas.

Second, this is a soil disturbance as excavation and installation activities can disturb the soil, leading to erosion and soil compaction. It can result in changes to soil structure, nutrient composition, and water retention capacity.

Third, pipeline construction and maintenance activities can introduce pollutants into nearby water bodies. Accidental spills, leaks, or improper disposal of construction materials can contaminate rivers, streams, and groundwater, affecting aquatic ecosystems and water quality.

Fourth, construction activities, particularly those involving heavy machinery, can release pollutants into the air. Dust, particulate matter, and emissions from machinery contribute to air pollution, potentially impacting local air quality.

Fifth, the pipeline's operational activities generate noise and vibrations, which can disturb wildlife, affecting their behavior and communication. This disruption can be particularly impactful in areas with sensitive or endangered species.

Sixth, one of the major concerns associated with oil pipelines is the risk of spills. Accidental releases of oil can lead to extensive environmental damage, affecting soil, water, and wildlife. Cleanup efforts may not fully restore the affected ecosystems.

Seventh, the extraction, transportation, and combustion of fossil fuels, which pipelines facilitate, contribute to greenhouse gas emissions. This situation contributes to global climate change and associated environmental impacts.

Further, pipeline can impact local communities and populations, affecting their traditional lands, livelihoods, and access to resources. Disruptions to cultural practices and potential conflicts over land use may arise.

In addition, the associated infrastructure can alter the visual landscape, particularly in pristine or scenic areas. This alteration may affect the aesthetic value of the environment and impact tourism. In this regard, the presence of any pipeline can lead to long-term changes in land use, restricting certain activities or altering land accessibility. It can have cascading effects on local economies and lifestyles.

It is essential to note that the severity of these impacts can vary based on factors such as pipeline design, construction practices, regulatory oversight, and the sensitivity of the local environment. Mitigation measures and adherence to environmental regulations are crucial for minimizing the negative effects of pipelines on the environment.

Conclusion

The analysis of the Kazakhstan-China pipeline has brought to light various environmental challenges inherent in cross-border energy projects. From habitat disruption and soil disturbance to potential water and air pollution, the negative impacts underscore the importance of a meticulous approach to environmental management. The risk of oil spills and the potential long-term consequences of greenhouse gas emissions further emphasize the complex web of challenges faced in the pursuit of energy security.

The methodologies proposed for assessing environmental sustainability, whether through advanced tools like Geographic Information System (GIS) mapping or simpler approaches like field observations and stakeholder engagement, provide valuable insights. GIS mapping, with its spatial analysis capabilities, offers a nuanced understanding of environmental indicators and aids in the identification of high-risk areas. On the other hand, simpler methods involving community workshops and data collection from key stakeholders contribute to a more accessible and inclusive decision-making process.

The negative impacts associated with pipelines, including habitat disruption, pollution, and the potential for oil spills, cannot be ignored. However, it is imperative to recognize that proactive mitigation strategies can significantly alleviate these concerns. Rigorous environmental impact

assessments, the implementation of advanced technologies for leak detection, and adherence to stringent regulatory frameworks are paramount in minimizing the ecological footprint of cross-border energy projects.

Therefore, some recommendations were generated towards introducing sustainable practices by the Kazakhstan-China pipeline.

First, the project needs to embrace state-of-the-art technologies, such as advanced leak detection systems and environmentally friendly materials for pipeline construction. These technologies can enhance the safety and reliability of the pipeline while minimizing environmental risks.

Second, it is possible to conduct thorough environmental impact assessments during the planning phase, considering diverse ecosystems, sensitive habitats, and areas prone to ecological stress. Strategic route planning can help avoid or minimize the disruption of critical environmental zones.

Third, the pipeline can foster an active engagement with local communities and Indigenous populations. Their insights and traditional knowledge can contribute to more sustainable project planning, ensuring that the pipeline respects cultural practices and minimizes negative impacts on local livelihoods.

Fourth, it should establish a robust system for continuous monitoring of environmental indicators along the pipeline route. Transparency in sharing monitoring data with the public and relevant stakeholders ensures accountability and builds trust.

Fifth, the Kazakhstan-China pipeline can encourage a diversified approach to energy sources, including investments in renewable energy. It can reduce dependence on fossil fuels, mitigate greenhouse gas emissions, and contribute to a more sustainable and resilient energy future.

Finally, the project should promote international cooperation and the development of standardized environmental regulations for cross-border energy projects. Harmonizing standards ensures that environmental protection is prioritized uniformly across borders.

In conclusion, the journey towards environmental sustainability in cross-border energy trade is challenging but navigable. The Kazakhstan-China pipeline serves as a microcosm of the global energy dilemma, urging us to reevaluate practices, prioritize innovation, and forge partnerships that transcend national boundaries. By embracing sustainable practices, incorporating advanced technologies, and fostering collaboration, we can pave the way for a future where the transportation of oil and gas resources harmonizes with the preservation of our planet's ecological integrity. The choices made today will resonate far into the future, shaping the legacy of our commitment to a sustainable and resilient world.

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[1,2]*Утельбаев Б.Т.,
Іскерлік әкімшілендіру магистрі, ORCID ID: 0009-0007-9874-4401,
*e-mail: b_utelbayev@kbtu.kz
[1,3]Әжіғали Ә.С.,
Іскерлік әкімшілендіру магистрі, ORCID ID: 0009-0000-0620-7158,
e-mail: a_azhigali@kbtu.kz
[1,4]Амангельдин А.Ғ.,
Іскерлік әкімшілендіру магистрі, ORCID ID: 0009-0007-4697-7254,
e-mail: a_amangeldin@kbtu.kz

[1]Қазақстан-Британ техникалық университеті, 050000, Алматы қ., Қазақстан
[2]SLB («Шлюмберже»), Ангола
[3]«Samsung Electronics Central Eurasia» ЖШС, 050000, Алматы қ., Қазақстан
[4]«Бейнеу – Шымкент Газ Құбыры» ЖШС, 050000, Алматы қ., Қазақстан

ТРАНСШЕКАРАЛЫҚ ЭНЕРГИЯ САУДАСЫНДАҒЫ ЭКОЛОГИЯЛЫҚ ТҰРАҚТЫЛЫҚ: ҚАЗАҚСТАН – ҚЫТАЙ ҚҰБЫРЫНЫҢ МЫСАЛЫ

Аңдатпа

Мақалада Қазақстан-Қытай мұнай құбыры контекстіндегі экологиялық тұрақтылықтың нюансты саласы – шекараларды қамтитын мұнай мен газ ресурстары үшін шешуші арна қарастырылады. Географиялық ақпараттық жүйені (ГАЖ) картаға түсіруді және қоғамдастықтың қатысуын қоса алғанда, қатаң әдістемелер трансшекаралық энергетикалық жобаларға тән экологиялық қиындықтарды айқындайды. Тіршілік ету ортасының бұзылуы мен ластануынан мұнай төгілу ықтималдығына дейінгі жағымсыз әсерлер стратегиялық тұрғыда азайтуды талап етеді. Мақалада озық технологияларды, стратегиялық бағыттарды жоспарлау және әртараптандырылған энергия көздерін енгізу ұсынылып, көп қырлы көзқарастар жақталады. Қоғамдастықтың қатысуын, ашықтықты және халықаралық ынтымақтастықты баса көрсете отырып, ұсынылып отырған тұрақты тәжірибелер экономикалық өсу императивтері мен экологияны сақтауды теңестіруге бағытталған. Әлем энергияға сұраныстың артуымен күресіп жатқан кезде, Қазақстан-Қытай құбыры жаһандық энергетикалық саудаға деген көзқарасымызды ұжымдық түрде қайта бағалауға түрткі болатын маңызды мысал. Белсенді шаралар мен бірлескен күш-жігер арқылы энергетикалық қауіпсіздік пен қоршаған ортаны басқару арасындағы тепе-теңдікті қалпына келтіруге болады, бұл тұрақты тәжірибе трансшекаралық энергетикалық күш-жігердің негізін құрайтын болашақты қамтамасыз етеді.

Тірек сөздер: Қазақстан-Қытай құбыры, мұнай және газ ресурстары, энергетика, экология, тұрақтылық.

[1,2]*Утельбаев Б.Т.,
магистр бизнес-администрирования, ORCID ID: 0009-0007-9874-4401,
*e-mail: b_utelbayev@kbtu.kz
[1,3]Ажигали А.С.,
магистр бизнес-администрирования, ORCID ID: 0009-0000-0620-7158,
e-mail: a_azhigali@kbtu.kz
[1,4]Амангельдин А.Г.,
магистр бизнес-администрирования, ORCID ID: 0009-0007-4697-7254,
e-mail: a_amangeldin@kbtu.kz

[1]Казахстанско-Британский технический университет, 050000, г. Алматы, Казахстан
[2]Компания «SLB» («Шлюмберже»), Ангола
[3]ТОО «Samsung Electronics Central Eurasia»,050000, г. Алматы, Казахстан
[4]ТОО «Газопровод Бейнеу – Шымкент», 050000, г. Алматы, Казахстан

ЭКОЛОГИЧЕСКАЯ УСТОЙЧИВОСТЬ В ТРАНСГРАНИЧНОЙ ТОРГОВЛЕ ЭНЕРГОНОСИТЕЛЯМИ: НА ПРИМЕРЕ НЕФТЕГАЗОПРОВОДА КАЗАХСТАН – КИТАЙ

Аннотация

Данная статья рассматривает нюансы экологической устойчивости на фоне Казахстанско-Китайского трубопровода – критически важного канала для перевозки нефти и газа через границы. Тщательные методологии, включая картографирование с использованием ГИС и взаимодействие с местным населением, раскрывают экологические вызовы, свойственные проектам по пересечению границ. От разрушения среды обитания и загрязнения до потенциала утечек нефти – данные негативные последствия требуют стратегического смягчения. Статья рекомендует многогранный подход, предлагая внедрение передовых технологий, стратегическое планирование маршрута и диверсификацию источников энергии. С акцентом на взаимодействие с местным населением, прозрачность и международное сотрудничество предлагаемые устойчивые практики направлены на баланс между неотложными задачами экономического роста и экологическим сохранением. Пока мир борется с растущими потребностями в энергии, Казахстанско-Китайский трубопровод служит заметным кейсом, провоцируя коллективное переосмысление нашего подхода к глобальной энергетической торговле. Через проактивные меры и совместные усилия становится возможным сбалансировать хрупкое равновесие между энергетической безопасностью и экологическим управлением, создавая будущее, где устойчивые практики лежат в основе международных энергетических усилий.

Ключевые слова: Казахстанско-Китайский трубопровод, нефтегазовые ресурсы, энергия, окружающая среда, устойчивость.

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[1]Pan Shilong,
master's student, e-mail: 14777697739@qq.com
[1]*Kang Wanli,
PhD, Professor,*e-mail: kangwanli@126.com
[1]Jiang Haizhuang,
doctoral student, e-mail: 2737353467@qq.com
[1]Zhang Junyi,
master's student, e-mail: 1506074112@qq.com
[1]Li Haocong,
master's student, e-mail: 1244243374@qq.com
[1,2]Sarsenbekuly B.,
PhD, associate professor, ORCID ID: 0000-0002-8145-0542,
e-mail: b.sarsenbekuly@kbtu.kz
[1]Yang Hongbin,
PhD, associate professor, e-mail: yhb0810@126.com

[1]School of Petroleum Engineering, China University of Petroleum (East China),
Qingdao 266580, P.R. China.
[2]School of Energy and Oil and Gas Industry, Kazakh-British Technical University,
050000, Almaty, Kazakhstan

APPLICATION PROGRESS OF INSITU POLYMER GEL IN OILFIELD CONFORMANCE CONTROL TREATMENT

Abstract

Many oilfields around the world are using enhanced oil recovery methods to maximize oil production. Long-term water flooding processes have led to water channeling in mature reservoirs, which is a severe problem in oilfields. Polymer gel is widely used as a plugging agent to reduce water production. Previously, the conventional polymer gel is extensively used for blocking the thief zones, but the performance of conventional polymer gel is not satisfactory in high salinity and high temperature conditions due to rapid syneresis and thermal degradation. The amphiphilic polymer is taking much attention for polymer gel formulation because they are more salt resistant in low concentration compared to high concentration conventional HPAM polymer. In this paper, the crosslinking mechanism of insitu polymer gel is reviewed. The related difficulties and development prospects of polymer gels are presented. It provides a basis for the application of polymer gel in oilfield conformance control treatment. This will help researchers to develop polymer gels to improve oil recovery under economic conditions to meet the requirements of oilfields.

Key words: insitu polymer gel, amphiphilic polymer, crosslinking mechanism, high salinity, high temperature.

Introduction

Excessive water production in mature reservoirs is a major concern recently. During the water flooding, water overflows in the heterogeneous reservoirs, cause mineral dissolution. The production water together with hydrocarbon is undesirable by product, the total produced water consists of the formation and the injected water during the flooding, that increases production cost for proper disposal of produced water that affects overall project economics. According to the recent statistical analysis, 40 billion dollars per year is spent on the treatment of unwanted water. Therefore, proper, stable and economical treatment is needed for the disposal of this produced water [1–4].

Weak gels are very effective when they cross-linked under the reservoir condition as a plugging agent and for the fluid diversion conformance improvement. The gel treatment is a function of placement and size of the gel slug. The most important restrictions as discussed is a slow gelatin rate, effectiveness of pH, low retention, high mobility of the gallant, effective water diversity, stability of gel and effect of temperature and salinity [5].

The insitu gel system consists of hydrolyzed poly-acrylamide (HPAM) named as conventional polymer, that consist of hydroxyl group. Due to thermal hydrolysis under high salinity and high temperature, some of the amide groups ($–CONH_2$) on polymer backbone convert to carboxylate groups that crosslink under excessive brine, resulting in syneresis or precipitation of polymer gel, which is not very useful for high salinity and temperature application. HPAM is a straight-chain polymer that has acrylamide (AM) molecule as monomer, hydrolysis of conventional polymer increases with the increase of temperature and as a result, the amount of polyacrylic acid increases in the backbone, which is sensitive to hardness. The hydrolysis degree determines the properties of these monomers. If the hydrolysis is less, polymer will not be water-soluble and if the degree of hydrolysis is too large, its properties will be more sensitive to salinity and hardness [6, 7]. Polymer gels are unstable above a certain temperature and salinity limit. Efforts are made to increase the upper salinity and temperature limit. Crosslinkers, such as metallic, organic and inorganic commonly used for viscosity enhancement. Polymer gel can form three dimensional network structure that traps water and thus will increase the viscosity of water by ionic or covalent bond depends on the type of crosslinkers and polymer selected, as the ionic and covalent bond have different structure so that the stability. Covalent bond usually formed with the organic crosslinkers has high thermodynamically stable, at elevated temperature as compared to ionic bond [8, 9].

Crosslinking mechanism of insitu polymer gels

A lot of progress has been done in polymer gel technology, some new kind of materials synthesized that makes polymer gel technology beneficial as a permeability reduction in the heterogeneous reservoir. The Reservoirs between the temperature ranges greater than 80˚C, conventional polymer system was not so effective for excessive water treatment, the addition of temperature resistance monomer like, N-vinyl pyrrolidon (NVP) and 2-acrylamido-2-methylpropane sulfonic acid (AMPS) can enhance the temperature resistance ability of a polymer gel, on the other hand for harsh reservoirs there is a great progress for insitu polymer gel formulated by the addition of surfactant, nano materials with the polymer and crosslinker, named as nano composite gels, which gives better performance in the harsh reservoir condition, but it's an expensive technology [10, 11].

The double crosslinking techniques also used recently to enhance the effectiveness of insitu polymer gel for high temperature conditions. The conventional polymer HPAM has two functional groups amide and carboxylate that react with crosslinker to form polymer gel with high mechanical strength, but the concentration for conventional polymer used is too high and due to high viscosity one group of the polymer is reacted with the cross linker and other groups remain unreacted due to which strength of polymer gel is not so good that's why concept double crosslinking will introduced so that both groups of the polymer will react with cross linkers, the result showed that the double crosslinked polymer gel system can easily to inject in the deep reservoir and have high temperature and salt resultant [12].

Due to unsatisfactory performance of conventional polymer the modified functional polymer also used recently to formulate polymer gel for high temperature and high salinity reservoirs, like amphiphilic polymer, hydrophobic associative polymer (HAP), salt-resistant comb-type acrylamide polymers (KYPAM), and AMPS/AM copolymer are used, their chemical structure is shown in Figure 1 **(p. 161)** [13, 14].

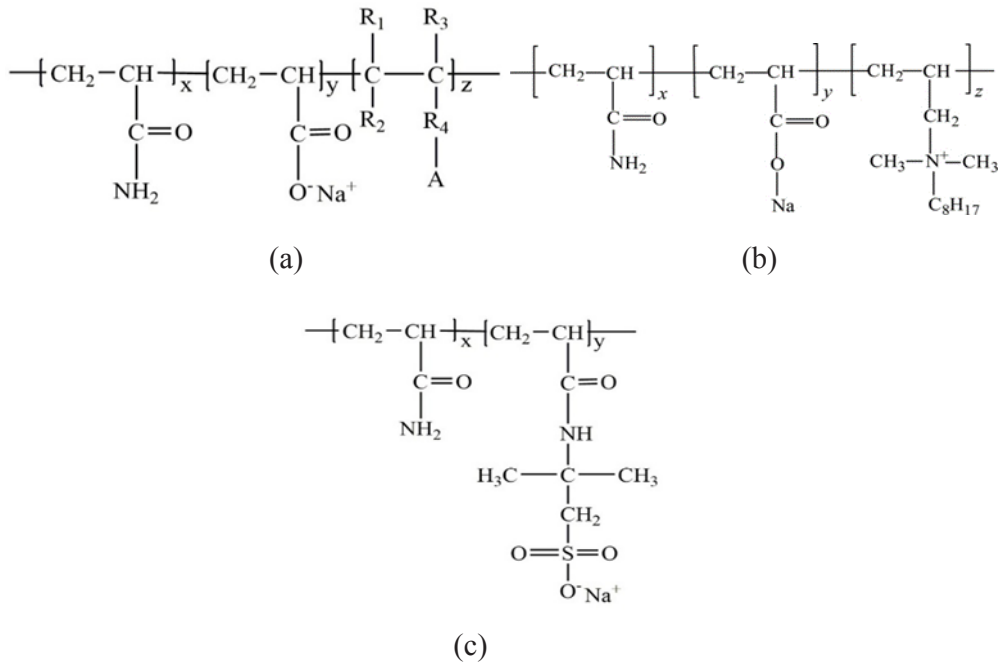

Figure 1 – Chemical structure of recently used polymer for gel formulation (a) KYPAM (b) AMPS/AM copolymer (c) HAP

The HAP has good performance but there is a difference of gelation time and gel strength in dynamic and static experiments. Dynamic experiment means the sand pack core flooding experiment and static method mean the most commonly used bottle test method. The double crosslinking system of Crl/WPF crosslinked with conventional polymer gives extremely high temperature and high salinity resistant polymer gel. Associative polymer gel under high salinity and Temperature have good performance in laboratory and the oil field [15, 16].

For the high temperature reservoir, the performance of inorganic cross-linked polymer gel is unsatisfactory. However, the organic crosslinker has better performance for high temperature reservoir condition but the crosslinking reaction is too fast at elevated temperature. To avoid the problem of low gelation time some retardant and delaying agent can be used to enhance the gelation time of organic crosslinkers [17, 18]. For the metallic cross linker like Cr^{3+}, Al^{3+} and Zr^{4+} etc. the gelation time is also very low even less than 2 hours at the temperature greater than 90˚C, the gelation time of HPAM/Cr^{3+} is extended by sodium lactate [19]. However, it is difficult to set the criteria between high temperature and higher temperature, the different researcher gives the different criteria for the temperature ranges for organic and inorganic cross linkers.

However, there are no suitable criteria found for temperature ranges of high temperature reservoirs but usually in enhanced oil recovery (EOR) process the reservoir with temperature greater than 80˚C is considered as high temperature reservoir and the reservoir with temperature greater than 120˚C is consider extremely high temperature reservoir, and the reservoir with temperature ranges in between 60˚C to 80˚C will consider low temperature reservoirs [20].

During the process of water flooding the produced water from the production well is unnecessary, because of this the water flooding is not so much effective. Therefore, the conformance control treatment method is required to increase the effectiveness of water flooding and decrease the unnecessary water production. Weak gels are most widely used as a conformance control treatment and their performance is very satisfactory and to decrease the unwanted water production.

For in-depth fluid diversion in the heterogeneous reservoir, week gel is used because their viscosity is very low before injection, so they can easily inject in large volume into the deep formation

to block the thief zones of the heterogeneous reservoirs. Secondly, weak gels are very effective under the condition of high salinity and high temperature. Some weak gels have low gelation time but they are very effective, it is difficult to inject this kind of gels in the deep formation, some delaying agent is always required to increase the gelation time so that they can be injected into the deep formation.

For insitu gel, the gellant is prepared at the surface by mixing the different chemicals like polymer, cross linker, and other additives to form a gellant solution. After the formulation of gallant solution, the gallant is injected into the target reservoir and the gel will form under the reservoir conditions after the specific gelling time.

The performance of insitu polymer gel is effected by many factors like degradation of gallant when injected into the reservoir by the pump, the condition of the formation water like some kind of gel will not perform well in the high salinity formation water, the temperature of the reservoir, pH and chemical composition. The first time the insitu gel system was applied in 1970, for in-depth conformance control insitu gel system is used previously [21]. In Figure 2 shown the formulation of insitu polymer gel system.

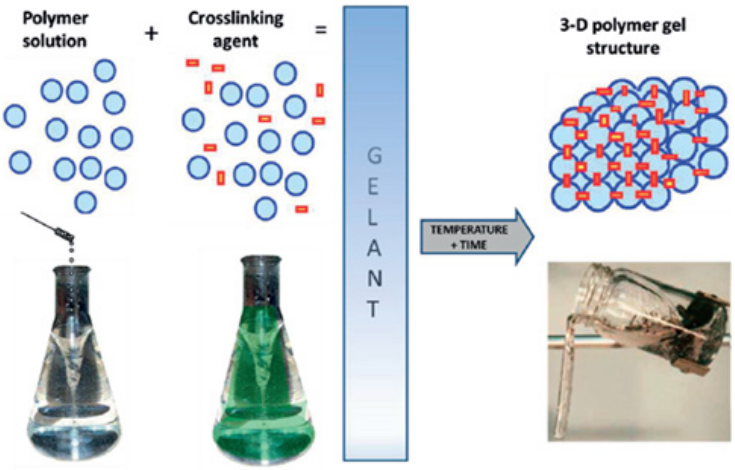

Figure 2 – Formulation of insitu polymer gel

During the polymer gel operation, for the most part, either by diverting fluid flow from high permeability, low permeability zones, insitu polymer gel have been used for water shut off and profile modification across injection and production well, as shown in Figure 3, after formation of gel the flow part of the fluid is diverting to the low permeability layer [22].

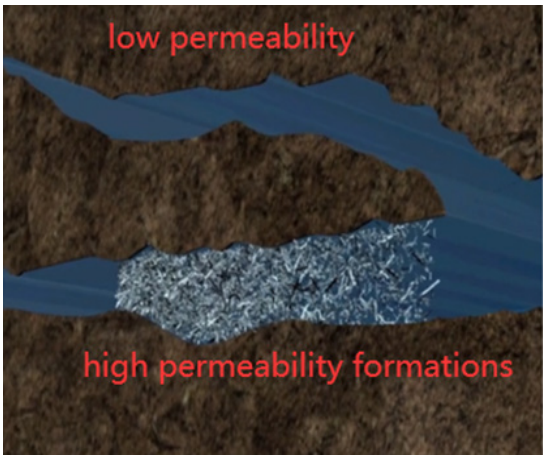

Figure 3 – Plugging of thief zones with polymer gel

Weak gels have low gellant viscosity before forming the three dimensional polymer gel, actually the weak gels are portion of the bulk gel system, these gels are effective in the wide range of salinity and temperature and they can be injected in the deep reservoirs to plug the high permeability region in the subsequent water flooding, but some of the weak gel has very low gelation time, such kind of gels are very effective with delaying agent.

The bulk gel used previously have some drawbacks such has their plugging radius is very insignificant, and because of this their injection is not effective, due to this reason they have poor plugging rate and fluid diversion properties. So, the weak gel is preferred because of their low viscosity they can easily penetrate into fractured and high permeability reservoirs and gives better plugging properties. Weak gels are multifunctional they can be used as oil displacement agent [23, 24]

Gel formulations

For gel formulation, polymer play a vital role, a different type of polymers are used for the gel formulation have benefits and draw backs according to the condition of the reservoirs. So, it is important to choose a polymer that has better performance under high salt and temperature conditions. For gel formulation, various polymers have been studied such as HPAM, HAP, and salt tolerant KYPAM polymer.

Development of salt and temperature resistant polymer

Many developments take place for the synthesization of salt and temperature resistant polymers. Amphiphilic polymers are a new class of polymers that have been synthesized by the addition of a small number of hydrophobic groups into the HPAM molecular chain. These polymers are generally utilized in different fields in oil field development. At the point when the concentration of the amphiphilic polymer is higher than the critical association concentration, the hydrophobic group is for the most part made of inter molecular association, developing a spatial network structure. Due to the association between the hydrophobic groups, the amphiphilic polymer has good temperature resistance, salt resistance and mechanical shear resistance in aqueous solution compared with the partially hydrolyzed polyacrylamide, amphiphilic polymers are unique in relation to the established water-soluble polymers as in the measure of hydrophobic monomers suitable for making physical relationship with one another is low [25, 26].

Despite the fact that their molecular weight is high, but still, they depend on excessive hydrophobic collaborations between various polymer chains for the thickness impacts. The hydrophobic groups interrelate and form an intermolecular polymer network in the aqueous solution as shown in Figure 4 [27].

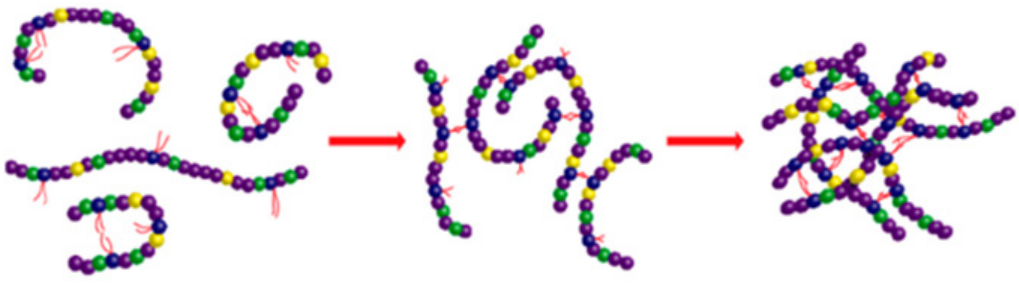

Figure 4 – Association process of amphiphilic polymers

If the visualization of the network structure of polymer is taken randomly it will exhibit the network similar to the gel, indicating a viscoelastic property, but with the passage of time flow occurs due to the Brownian movement breaks the end-gather relationship for a short duration of time before the other association of same group on a similar chain. These polymers have not been tried for conformance control treatment, yet the lab results demonstrate that with some specific crosslinkers,

they can be utilized for particular water-shutoff applications. Progressively more research is required to utilize this hypothesis. In this thesis, the purpose is to change the current profile of the main agent and make full utilization of the amphiphilic polymer.

Types of crosslinkers

Inorganic crosslinkers

Wide range of inorganic crosslinkers is used previously, formed strong polymer gel. The different kinds of cross-linker prompt to divergences in the rheological properties, salt, and temperature resistance. Gels synthesized with metallic cross-linker such as Cr^{3+}, Al^{3+} or Zr^{4+} has inferior stability at high temperature and their small gelation time avoids appropriate placement in deep high temperature reservoirs, however with a delayed gelation mechanism their gelation time can be enhanced and, this kind of cross linkers can be used for deep conformance control treatment, Al crosslinker has low gelation time and is suitable for low temperature but by chelating the aluminum with citrate, its gelation time can be enhanced [28].

The chromium cross-linked with polyacrylamide polymer to complexion of Cr ions with carboxylate groups on the polymer chain, this cross linker also shows the syneresis problem under the high salinity and high temperature condition and not thermally stable. Others type are polyacrylamide/ Cr^{3+} carboxylate system and Xanthan/Cr^{3+} system. Titanium crosslinker has also been developed due to the bad environmental impact of some metallic crosslinkers. The inorganic crosslinkers linked through ionic bonding among the negatively charged carboxylate groups on the polymer chain and multivalent cation. Inorganic cross-linked polymer gel usually used at low temperature (<70˚C) reservoirs, since high temperature and high salinity will be the reason for syneresis of inorganic polymer gel [29,30].

Organic crosslinkers

There has been an enduring demand within the oil industry to develop active conformance improvement polymer gel technologies by using the organic chemical crosslinking agents that would impart carbon-carbon-bond chemical crosslinking between the gel polymer molecules [31]. This would avoid the use of metal crosslinking agents, and would outcome in remarkably strong and stable polymer gels. These gels are suitable for high temperature application (>70˚C). Organic cross-linked polymer gel results in the formation of a covalent bond between amide group of polymer and crosslinker which can form a good temperature resistance gel [32].

For example, the commonly used organically cross-linked polymer-gel technologies developed are based on, hydroquinone (HQ), hexamethylene (HMTA), organic chromium, phenol formaldehyde chemistries. The organic cross linker of phenol/formaldehyde is used widely but due to the high content of its toxicity, that limit its use. There is a covalent bond formation among organic crosslinkers and the amide group of the polymer and stabilize under high salinity and high temperature conditions.

Polymer gel application in China

The conformance control treatment technology has been applied on site since the 1950s and has a history of nearly 40 years. In most of the oil fields currently developed, water flooding is a conventional means of enhancing oil recovery. However, after some long-term water injection in some old oil fields, the water content of the oilfield has reached a limit. At the same time, due to the heterogeneity of the reservoir, the distribution of remaining oil is relatively more dispersed, but in the local but relatively concentrated. According to statistics, the current average oil recovery rate in China is about 29.8%. However, due to technical means and economic factors, a large part of crude oil is still stuck in the stratum. Therefore, it is urgent to explore various new technical means for underground complex areas, carrying out reasonable research on enhanced oil recovery to meet the demand for oil in daily production [33, 34].

In the 1970s, the successful application of polymer weak gels to reduce produced water made the petroleum industry very interested in this technology. Injecting polymer gel into the wellbore can

effectively block the formation in the near-well zone, thereby reducing the water yield of the well. After the 1990s, along with the continuous updating of technology, polymer weak gels are gradually used in the deep migration of reservoirs, mainly for reservoirs with serious reservoir heterogeneity. In addition, they are often used for cracks and large an oil layer with a very poor permeability in the tunnel or layer. This method can not only block the large pores and high permeability layers in the reservoir but also improve the oil-water mobility ratio in the layer. Compared with pure polymer flooding, this system uses a low polymer concentration and is more applicable [35].

The TP-910 conformance control treatment technology researched by the Petroleum Exploration and Development Research Institute has been widely used in oil fields such as Liaohe, Shengli, and Henan, and also seen obvious effects in Bohai Oil Company. During this period, various research units have successively developed PIA series conformance control treatment technology, BD-861 conformance control treatment technology, and three-phase foam. Since the 1990s, oil wells in the eastern oil fields of China have entered a period of high water cut, and the technology of conformance control treatment and water shutoff has been fully developed. As a particle-moving conformance control treatment agent for blocking large holes, it has been widely used in oil fields such as Shengli, Jianghan and Zhongyuan due to its low cost and easy operation. At the same time, polymer gel conformance control treatment and water shutoff technology have also been fully developed [36, 37].

Recently the major oil fields in the country (including Shengli, Liaohe, Dagang, Zhongyuan, Yumen, Daqing, Jilin, North China, Xinjiang, Qinghai, Jianghan and other oil fields) have carried out water injection well conformance control treatment and production well water shutoff work with water injection wells as the unit. Daqing Oilfield has carried out comprehensive management of “stable oil control and water control” with the main content of “regulating water, increasing production and extracting liquid” in the Saraji oil area, and achieved remarkable results. The conformance control treatment and water shutoff technology have been widely used in China [38].

Problems associated with insitu polymer gel during conformance control treatment

Although polymer gel treatment is widely used technique for conformance control there are still many problems that affect the performance of polymer gel which limits its use in the oilfields operations. Some of the major problems related to the polymer gel are given below.

Mechanical degradation

When an external force act on the polymer solution its structure is destroyed this phenomenon is called shear degradation. As many water shuts off polymers have a high molecular weight due to which they have high viscosity when this polymer mix with a cross linker that makes its injection difficult [39].

The pump will induce the mechanical force on a gellant solution, caused the mechanical degradation of polymer structure and may affect its performance. HPAM named as the conventional polymer used most commonly but their viscosity is declining with an increase of mechanical force and limits its use under the influence of high mechanical force.

Chemical degradation and precipitation

During the precipitation, solid particles will be deposited on the surface of polymer solution. The formation water contains many divalent cations like Ca^{2+} and $Mg^{2+}$when the carboxylate group of hydrolyzed polymer is interacting with these divalent cations, with the increase of these carboxylate groups the solubility of these cations will decrease and precipitation occurs due to which polymer is unavailable for polymer gel formulation [40].

Syneresis

Extraction of water from the polymer gel under the influence of high temperature, salinity, divalent cations is called syneresis, due to this the polymer gel structure is decompose with the passage of time, numerous polymer gel system has this issue as appeared in Figure 5 (p. 156) [41]. Syneresis is described by a decrease in volume, ejection of water and stickiness loses. Conceivable causes are polymer hydrolysis, excessive cross linkage, NaCl and divalent cations.

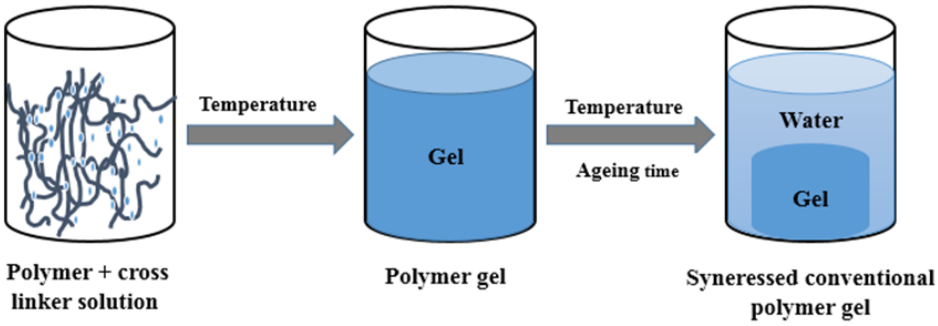

Figure 5 – Syneresis of conventional polymer gel in high salinity and temperature and reservoirs

Polymer gel with syneresis may involve 5% of the initial gel volume. Under high temperature conditions, conventional polymers (HPAM) hydrolyze to acrylate groups, which gives more sites for crosslinking and conceivable syneresis. In the formation water concentration of divalent cations is higher that cause the reason for over crosslinking as compared to metal crosslinker injection. Even with low syneresis (%), the polymer gel is still effective for the permeability reduction applications. For matrix applications, it is not so significant but for fractured reservoirs, it is very important [42].

Future development of polymer gels

In recent years, reservoir exploitation has developed towards deeper wells. At the same time, great progress has been made in polymer gel research, but there are still deficiencies. In order to meet the requirements of reservoir consistency control treatment to improve oil recovery, it is necessary to improve the performance of polymer gel, which can start from the following points:

(1) Strengthen and improve the existing process, use polymers with good temperature and salt resistance to improve the deficiencies of the system.

(2) By controlling the gelling time and strength of the polymer gel, the polymer gel is gelled in the deep part of the core, and the deep consistency control treatment of the oilfield is realized.

(3) Synergist is added to the polymer gel system to reduce the cost by reducing the amount of polymer gel.

(4) In order to make up for the shortcomings of poor stability and shear resistance of a single polymer gel system, the polymer gel system is combined with inorganic particles, polymer microspheres, surfactants and other systems to achieve the complementary advantages of each system.

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[1]Пан Шилон,
магистрант, e-mail: 14777697739@qq.com
[1]*Кан Ванли,
PhD, профессор, *e-mail: kangwanli@126.com
[1]Дзиян Хайджуан,
докторант, e-mail: 2737353467@qq.com
[1]Джан Дзюни,
магистрант, e-mail: 1506074112@qq.com
[1]Ли Хаоцон,
магистрант, e-mail: 1244243374@qq.com
[1,2]Сарсенбекұлы Б.,
PhD, қауым. проф., ORCID ID: 0000-0002-8145-0542,
e-mail: b.sarsenbekuly@kbtu.kz
[1]Ян Хонбин,
PhD, қауым. проф., e-mail: yhb0810@126.com

[1]Мұнай инженерлік мектебі, Қытай мұнай университеті (Шығыс Қытай),
266580, Циндао қ., ҚХР
[2]Энергетика және мұнай-газ индустриясы мектебі, Қазақстан-Британ техникалық
университеті, 050000, Алматы қ., Қазақстан

МҰНАЙ КЕН ОРЫНДАРЫНДАҒЫ ҚАБЫЛДАУ ПРОФИЛІН БАҚЫЛАУ ҮШІН ПОЛИМЕРЛІ ГЕЛДЕРДІ ҚОЛДАНУДАҒЫ ПРОГРЕСС

Аңдатпа

Дүние жүзіндегі көптеген мұнай кен орындарында мұнай өндіруді барынша арттыру үшін мұнай өндірудің жетілдірілген әдістері қолданылады. Ұзақ мерзімді су басу процестері судың жетілген қабаттарға қайта бағытталуына әкеліп соқты, бұл мұнай кен орындарындағы күрделі мәселе. Полимерлі гель сұйықтықтың жоғалуын азайту үшін бітеу агенті ретінде кеңінен қолданылады. Бұрын қарапайым полимерлі гель абсорбция аймақтарын блоктау үшін кеңінен қолданылған, бірақ тез синерезс және термиялық ыдырау салдарынан қарапайым полимерлі гельдің тиімділігі жоғары тұздылық пен жоғары температура жағдайында қанағаттанарлық емес. Амфифилді полимерлер полимер гельдерін жасауда басты назарға алынады, өйткені олар әдеттегі жоғары концентрациядағы ГПАМ полимерімен салыстырғанда төмен концентрацияда және тұзға төзімді. Бұл мақалада полимерлі гельді өзара байланыстыру механизмі қарастырылады. Осыған байланысты қиындықтар және полимер гельдердің даму перспективалары ұсынылған. Бұл мұнай кен орындарының қабылдау профилін бақылауда полимер гельді қолданудың негізін құрайды. Бұл зерттеушілерге мұнай кен орындарының талаптарына сәйкес келетін экономикалық жағдайларда мұнайды жақсарту үшін полимер гельдерін жасауға көмектеседі.

Тірек сөздер: полимер гелі, амфифильді полимер, тігілу механизмі, жоғары тұздылық, жоғары температура.

[1]Пан Шилон,
магистрант, e-mail: 14777697739@qq.com
[1]*Кан Ванли,
PhD, профессор, *e-mail: kangwanli@126.com
[1]Дзиян Хайджуан,
докторант, e-mail: 2737353467@qq.com
[1]Джан Дзюни,
магистрант, e-mail: 1506074112@qq.com
[1]Ли Хаоцон,
магистрант, e-mail: 1244243374@qq.com
[1,2]Сарсенбекұлы Б.,
PhD, ассоц. проф., ORCID ID: 0000-0002-8145-0542,
e-mail: b.sarsenbekuly@kbtu.kz,
[1]Ян Хонбин,
PhD, ассоц. проф., e-mail: yhb0810@126.com

[1]Школа нефтяной инженерии, Китайский университет нефти (Восточный Китай), Циндао 266580, КНР
[2]Школа энергетики и нефтегазовой индустрии, Казахстанско-Британский технический университет, 050000, г. Алматы, Казахстан

ПРОГРЕСС В ПРИМЕНЕНИИ ПОЛИМЕРНОГО ГЕЛЯ ДЛЯ РЕГУЛИРОВАНИЯ ПРОФИЛЯ ПРИЕМИСТОСТИ НЕФТЯНЫХ МЕСТОРОЖДЕНИЙ

Аннотация

Многие нефтяные месторождения по всему миру используют методы повышения нефтеотдачи для максимизации добычи нефти. Длительные процессы заводнения привели к перенаправлению воды в зрелые пласты, что является серьезной проблемой на нефтяных месторождениях. Полимерный гель широко используется в качестве закупоривающего агента для снижения водоотдачи. Ранее обычный полимерный гель широко использовался для блокировки зон поглощения, но эффективность обычного полимерного геля не является удовлетворительной в условиях высокой солености и высоких температур из-за быстрого синерезиса и термического разложения. Амфифильным полимерам уделяется большое внимание при разработке полимерных гелей, поскольку они более устойчивы к соли при низкой концентрации по сравнению с обычным полимером ГПАМ с высокой концентрацией. В этой статье рассматривается механизм сшивания полимерного геля. Представлены связанные с этим трудности и перспективы развития полимерных гелей. Это обеспечивает основу для применения полимерного геля при проведении регулирования профиля приемистости нефтяных месторождений. Это поможет исследователям разработать полимерные гели для повышения нефтеотдачи в экономических условиях, отвечающих требованиям нефтяных месторождений.

Ключевые слова: полимерный гель, амфифильный полимер, механизм сшивки, высокая соленость, высокая температура.

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[1]Алимов Ф.Б.,
магистр юридических наук, ORCID ID: 0009-0003-5899-7632,
e-mail: f.alimov@qg.kz

[1]ТОО «НТЦ «Казахгаз», 010000, г. Астана, Казахстан

ПЕРСПЕКТИВЫ РАЗВИТИЯ ТРУБОПРОВОДНОГО ТРАНСПОРТА ГАЗА

Аннотация

В связи с мировыми тенденциями развития зеленой энергетики, а также с развитием добычи газа на территории Республики Казахстан вопросы газификации страны, транспорта газа до потребителя становятся особо актуальными. В статье проведен исторический экскурс по транспорту газа, сравнительный анализ различных видов транспорта газа, преимущества трубопроводного транспорта газа, а также обзор развития газовой отрасли в целом и в частности вопросов газификации, транспорта газа на примере акционерного общества «Интергаз Центральная Азия», которое является национальным оператором по магистральным газопроводам Республики Казахстан. Рассмотрены вопросы газификации страны, в частности северных регионов и г. Астаны. Также проведен анализ и выявлены перспективы развития газовой отрасли и газовых компаний в Казахстане. Согласно дорожной карте газификации страны особое внимание уделяется газификации северных и центральных регионов страны, где поэтапно рассматривается обеспечение газом населенных пунктов вдоль трассы газопровода «Сарыарка». Приведена статистика работы филиалов АО «Интергаз Центральная Азия», участков, которые обслуживает каждый филиал. В завершение даны рекомендации по эффективному использованию газовых ресурсов страны и постепенному переходу к «чистой» энергетике.

Ключевые слова: трубопроводный транспорт газа, газификация, магистральный газопровод, инженерно-технический центр, «зеленая» энергетика.

Введение

Газ и нефть человечество начало использовать более 6000 лет до нашей эры. Когда имеется потребность в газе и нефти, появляется необходимость их транспортирования до потребителей. Историками нефтегазовой отрасли и археологами установлено наличие древних нефтегазовых промыслов в районах цивилизации, а именно в Междуречье, между Тигром и Евфратом еще за 6000 лет до нашей эры. Добыча осуществлялась поверхностным методом, и продукция направлялась по реке Евфрат к городам Ур, Иди. Для добытой нефти использовались специальные наливные сосуды из глины. Нефть использовалась для строительных целей, отопления и освещения, а также в медицинских и военных целях. Максимальный объем таких примитивных танкеров составляла до 5 т. В Киевской Руси на Таманском полуострове для перевозки нефти использовались специальные сосуды – амфоры, которые вывозились византийскими кораблями. Впервые в мире именно византийцы использовали нефть в качестве супероружия раннего средневековья, так называемый греческий огонь. После изменения политической ситуации в раннем средневековье, а именно падение Византийской империи привело к упадку таманских нефтепромыслов. Позднее открытие новых залежей нефти и газа в Закавказье сделало основным поставщиком нефти и газа уже этот район, точнее район Баку и его окрестности. Для транспортировки продукции этого района использовались караваны верблюдов. Сама продукция перевозилась в кожаных мешках. В связи с тем, что тарифы перевозки нефти железнодорожным путем были достаточно высокими, стали подумывать об альтернативных путях перевозки нефти. Первый в мире нефтепровод появился в США именно по этой при-

чине. Идея транспортировки нефти, газа или других жидкостей применялась намного ранее. Впервые китайцы за 5000 лет до нашей эры соорудили водопровод из бамбука для транспортировки воды на рисовые поля. Также китайцами были использованы бамбуковые трубопроводы для транспортировки газа к печам с целью выпаривания солей. Еще три тысячи лет назад китайцы впервые в мире бурили скважины для добычи солей, используя механический метод. Так как соль добывалась в виде рассола, для его выпаривания требовалось топливо. В качестве топлива как раз использовался газ из бамбукового трубопровода. Для отвода жидкостей и сточных вод строились глиняные трубопроводы. Например, в древнеиндийском городе Мохенджо-Даро 5000 лет назад; в Древнем Египте для этих целей использовались деревянные, медные и свинцовые трубы; в Киосском дворце на острове Крит за 2000 лет до нашей эры для этих целей использовались терракотовые трубы. В древнеримской цивилизации для водоснабжения использовались свинцовые трубопроводы для подачи питьевой воды населению и снабжения водой общественных бань. Иногда длина этих трубопроводов достигала до 91 км. В Древней Руси в XI в. был построен водопровод из деревянных труб для подачи воды в Новгород из реки Волхов. Для подъема воды на определенную высоту начали использовать дополнительные устройства. Например, в XVII в. в Москве использовали водопровод, который имел дополнительный механизм – водоподъемную машину, аналог современных насосов и компрессоров в газонефтепроводах.

Основные положения

Основными положениями настоящей работы является анализ существующей системы транспорта газа в Республике Казахстан, имеющихся проблем в этой области и путей их решения. Пути решения проблем рассмотрены на примере компании, занимающейся вопросами транспортировки газа. Актуальность данного исследования заключается в решении существенных проблем транспортировки газа, а также газификации северных и центральных регионов страны, что указано в дорожной карте.

Проблемы и перспективы. По сравнению с другими видами транспорта для перевозки газа, нефти и нефтепродуктов преимущество имеет трубопроводный транспорт. Первое преимущество заключается в удобстве прокладки самого трубопровода в тех участках, где нет доступа водному, автомобильному транспорту, например болотистые места, высокогорные участки, подводные, подземные переходы. Другое преимущество заключается в низкой себестоимости перевозимой продукции, тогда как на водном и железнодорожном транспорте стоимость перевозки газа, нефти и нефтепродуктов достаточно высокая. В связи с тем что к трубопроводному транспорту, особенно к газопроводам, предъявляются высокие требования по герметичности, обеспечивается сохранность качества перевозимой продукции. Нет опасности испарения легких компонентов углеводородов. Такие высокие требования по герметичности характерны для магистральных газопроводов и нефтепроводов. Перевозка газа, нефти и нефтепродуктов газонефтепроводами требует минимальных капиталовложений при сооружении. При перевозке углеводородов газонефтепроводами имеется возможность максимальной автоматизации процессов, контроля за утечками, давлением и т.п., что может полностью исключить отрицательное влияние на окружающую среду. Трубопроводный транспорт газа, нефти и нефтепродуктов также не лишен недостатков. Основным недостатком такого вида транспорта считается узкая направленность эксплуатации газонефтепроводов.

Всевозможные проблемы и перспективы трубопроводного транспорта – то, что в настоящее время волнует профессионалов нефтегазовой отрасли. Для решения возможных проблем в нашей стране разработаны и реализуются в настоящее время несколько проектов по сооружению систем трубопроводного транспорта, которые позволили бы расширить перечень решаемых задач в нефтегазовой отрасли. Девяностые-двухтысячные годы были наиболее труд-

ными в истории нефтегазовой отрасли Казахстана [1]. Практическое отсутствие или очень низкая скорость работ по поиску и разведке новых углеводородных залежей, бурению новых поисковых, разведочных и эксплуатационных скважин, по модернизации морально и физически устаревшей материально-технической базы препятствовали добыче фактических объемов и экспорту углеводородного сырья [2]. Также отставала от модернизации и система трубопроводного транспорта углеводородов. Для улучшения работ в этом направлении деятельность в области трубопроводного транспорта углеводородов определяется и регулируется на законодательном уровне самим государством. В нашей стране имеются регламенты алгоритма прокладки составных частей трубопроводного транспорта как на суше, так и во внутренних морских водах.

Материалы и методы

Вопрос развития газовой промышленности и газификации регионов – одна из важных сфер в повестке дня нашей страны (рисунок 1). На сегодня уровень газификации страны составляет порядка 47,4%. Более 1300 населенных пунктов имеют доступ к газу. Ежегодно из республиканского бюджета для газификации страны выделяется порядка 13 млрд тенге.

По сравнению с другими регионами из-за ограниченных технических возможностей не охваченными в полной мере газификацией оставались регионы северной и центральной части страны.

Разработанная Генеральная схема газификации Республики Казахстан на срок до 2030 г. приведена на рисунке 1.

Рисунок 1 – Генеральная схема газификации страны

Благодаря 5-й социальной инициативе Главы государства решается вопрос газификации г. Астаны, Карагандинской и Акмолинской областей. В этих регионах местными акиматами областей и акиматом г. Астаны разработаны дорожные карты строительства инфраструктуры по газификации с учетом сроков строительства всех узлов магистрального газопровода и строительства региональных сетей в каждой из перечисленных областей и г. Астаны. Согласно дорожным картам, первый этап по маршруту запланированного газопровода охватит 171 населенный пункт вдоль трассы газопровода и должен обеспечить порядка 2,7 млн человек газом (рисунок 2, стр. 164).

По составленной дорожной карте для жителей г. Астаны первостепенная задача – обеспечение газом жилых массивов Коктал-1,2, Железнодорожный, Юго-Восток, как правой, так и левой стороны, а также переход на газ ТЭЦ-1,2,3.

Рисунок 2 – Газификация г. Астаны, Карагандинской и Акмолинской областей

Рисунок 3 – Схема газификации г. Астаны до 2030 г.

Результаты и обсуждение

Развитие газовых компаний в Казахстане. В данной статье хотелось бы показать развитие газовой отрасли нашей страны на примере АО «Интергаз Центральная Азия», которое было создано в июле 1997 г. Его задачей является осуществление эксплуатации и технического обслуживания всей внутренней газотранспортной системы Республики Казахстан.

Компания является дочерней компанией АО «Национальная компания «QazaqGaz» и представляет его интересы в области магистральной транспортировки природного газа. АО «НК «QazaqGaz» признано основной газовой компанией нашей страны и представляет интересы Республики Казахстан как на внутреннем, так и на внешнем газовом рынке.

Начиная с июля 2018 г. АО «Интергаз Центральная Азия» имеет статус национального оператора по магистральным газопроводам согласно Постановлению Правительства Республики Казахстан.

Компания осуществляет внутреннюю транспортировку и транзит природного газа по территории страны по магистральным газопроводам, общая протяженность которых составляет 20 612,63 тыс. км. Из них 7007,32 км магистрального газопровода относятся к сторонним организациям, которым компания оказывает услуги по техническому обслуживанию, 2790,71 км участка газопроводов являются отводами.

Во владении компании имеется 32 компрессорные станции, посредством которых осуществляется транспортировка газа, на этих компрессорных станциях установлено 319 ГПА, в том числе на договорной основе эксплуатируются компрессорная станция – 1 «Бозой», компрессорные станции «Туркестан», «Караозек», «Коркыт Ата».

Компания эксплуатирует три подземных хранилища газа. Наиболее крупным из которых является подземное хранилище газа Бозойское, объем хранения газа примерно равен 4 000 000 тыс. м^3. Бозойское ПХГ расположено в Актюбинской области. Следующее подземное хранилище газа – Полторацкое, расположено в Туркестанской области, объем хранения составляет 350 000 тыс. м^3. Третье хранилище – Акыртобинское с объемом хранения 300 000 тыс. м^3, расположено в Жамбылской области.

Компания имеет несколько производственных филиалов – управление магистральных газопроводов. Филиалы предназначены для эксплуатации региональных участков газотранспортной системы. В составе компании имеются следующие производственные филиалы:

- управление магистральным газопроводом «Уральск»: обслуживает магистральный газопровод Оренбург – Новопсков, магистральный газопровод «Союз», магистральный газопровод Средняя Азия – Центр с лупингами, магистральный газопровод Карачаганак – Уральск;
- управление магистральным газопроводом «Актобе»: обслуживает магистральный газопровод Бухара – Урал, газопровод Жанажол – Октябрьск – Актобе с лупингами, магистральный газопровод «Жанажол-КС-13», магистральный газопровод Бейнеу – Бозой – Шымкент, магистральный газопровод «Кожасай-КС-12»;
- управление магистральным газопроводом «Атырау»: обслуживает магистральный газопровод Макат – Северный Кавказ, магистральный газопровод Средняя Азия – Центр с лупингами;
- управление магистральным газопроводом «Актау»: обслуживает магистральный газопровод Средняя Азия – Центр, магистральный газопровод Окарем – Бейнеу с лупингами, магистральный газопровод Бейнеу – Бозой – Шымкент, магистральный газопровод Узень – Жетыбай – Актау;
- управление магистральным газопроводом «Костанай»: обслуживает магистральный газопровод Бухара – Урал, магистральный газопровод Карталы – Рудный – Костанай;
- управление магистральным газопроводом «Караганда»: обслуживает магистральный газопровод «Сарыарка».
- управление магистральным газопроводом «Кызылорда»: обслуживает магистральный газопровод Бейнеу – Бозой – Шымкент, магистральный газопровод «Сарыарка»;
- управление магистральным газопроводом «Шымкент»: обслуживает магистральный газопровод Бухарский газоносный район – Ташкент – Бишкек – Алматы, магистральный газопровод Газли – Шымкент, магистральный газопровод Казахстан – Китай, Бейнеу – Бозой – Шымкент;

◆ управление магистральным газопроводом «Тараз»: обслуживает магистральный газопровод Бухарский газоносный район – Ташкент – Бишкек – Алматы, компрессорную станцию «Амангельды-КС-5», магистральный газопровод Казахстан – Китай;

◆ управление магистральным газопроводом «Алматы»: обслуживает магистральный газопровод Бухарский газоносный район – Ташкент – Бишкек – Алматы, магистральный газопровод Алматы – Байсерке – Талгар, магистральный газопровод Казахстан – Китай, магистральный газопровод Байсерке – Капшагай, магистральный газопровод Алматы – Талдыкорган;

Также в состав компании входят два центра:

◆ инженерно-технический центр – является отраслевым диагностическим центром по обслуживанию всех узлов магистральных газопроводов страны, а именно линейной части, компрессорных станций, газораспределительных станций, подземных хранилищ газа газотранспортной системы. Центр создан в 1996 г. Специалисты центра постоянно повышают свои навыки, прошли обучение и аттестованы по различным видам неразрушающего контроля в лучших учебных центрах страны и за ее пределами. Центр имеет все необходимые разрешительные документы для выполнения работ по технической диагностике оборудования производственных объектов и имеет в своем распоряжении передовое оборудование мировых производителей, что позволяет качественно и в срок выполнять пусконаладочные и диагностические работы на объектах газотранспортной системы РК;

◆ научно-технический центр – единственное профильное учебное учреждение, которое предназначено для проведения подготовки, переподготовки, повышения квалификации работников и специалистов, занимающихся транспортировкой природного газа и эксплуатацией магистральных газопроводов.

Заключение

Выводы и рекомендации. Использование природного газа имеет особую роль в распределении мирового топливного баланса и занимает второе место после нефти. В связи с развитием технологий, предполагающих наименьшее загрязнение окружающей среды, начинает развиваться газовая отрасль мира ускоренными темпами. Это также связано с бурным развитием рынка сжиженного газа и мировыми тенденциями, связанными с углеродной нейтральностью, декарбонизацией и чистой энергетикой. Возможен резкий рост потребления газа, и есть предположение, что доля углеводородного газообразного топлива в мировом энергобалансе может достигать около 30%. В результате этого предположения мировые эксперты характеризуют предстоящий период развития энергетики как эпоху метана. Для Республики Казахстан природный газ также становится все более перспективным энергоносителем. Разведанные и оцененные запасы газа на настоящее время составляют около 3,9 трлн м^3. Если учитывать новые открытия на шельфе Каспия, то они достигают 6–8 трлн м^3. При этом особенностью разведанных запасов газа в Республике Казахстан является то, что практически на всех месторождениях добыча газа ведется попутно с добычей нефти и конденсата. Поэтому активное освоение этих месторождений и резкий рост объемов добычи нефти в последние годы диктуют необходимость утилизации увеличивающихся объемов добываемого попутного газа. С учетом вышесказанного ожидается, что развитие газовой отрасли страны может идти в ускоренном режиме, с большей газификацией отдаленных и не обеспеченных газом регионов, также будут развиваться вопросы, связанные с транспортировкой газа во все эти регионы [3].

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[1]Alimov F.B.,
Master of Laws, ORCID ID: 0009-0003-5899-7632,
e-mail: f.alimov@qg.kz

[1]LLP «STC «QazaqGaz», 010000, Astana, Kazakhstan

PROSPECTS FOR THE DEVELOPMENT OF PIPELINE GAS TRANSPORT

Abstract

In connection with the global trends in the development of green energy, as well as with the development of gas production in the territory of the Republic of Kazakhstan, the issues of gasification of the country, gas transportation to the consumer are becoming particularly relevant. The article provides a historical overview of gas transport, a comparative analysis of various types of gas transport, the advantages of pipeline gas transport, as well as an overview of the development of the gas industry in general and in particular, issues of gasification, gas transport on the example of the National operator of main gas pipelines JSC "Intergas Central Asia". The issues of gasification of the country, in particular, the northern regions and Astana, were considered. The analysis and prospects for the development of the gas industry and gas companies in Kazakhstan were also carried out. According to the Roadmap for the country's gasification, special attention is paid to the gasification of the northern and central regions of the country, where the provision of gas to settlements along the Saryarka gas pipeline route is being considered in stages. The statistics of the branches of JSC "Intergas Central Asia", the sites that each branch serves, are given. In conclusion, recommendations are given on the effective use of the country's gas resources and a gradual transition to "clean" energy.

Key words: gas pipeline transport, gasification, main gas pipeline, engineering, and technical center, "Green" energy.

[1]Алимов Ф.Б.,
заң ғылымдарының магистрі, ORCID ID: 0009-0003-5899-7632,
e-mail: f.alimov@qg.kz

[1]«Қазақгаз» ҒЗО» ЖШС, 010000, Астана қ., Казақстан

ГАЗДЫ ҚҰБЫР АРҚЫЛЫ ТАСЫМАЛДАУДЫ ДАМЫТУ ПЕРСПЕКТИВАЛАРЫ

Аңдатпа

Жасыл энергетиканы дамытудың әлемдік үрдістеріне, сондай-ақ Қазақстан Республикасының аумағында газ өндіруді дамытуға байланысты елді газдандыру, тұтынушыға дейін газ тасымалдау мәселелері аса өзекті болып отыр. Мақалада газ көлігі бойынша тарихи экскурсия, газ көлігінің әртүрлі түрлеріне салыстырмалы талдау, газ құбыры көлігінің артықшылықтары, сондай-ақ Қазақстан Республикасының магистральдық газ құбырлары бойынша ұлттық операторы «Интергаз Орталық Азия» акционерлік қоғамының мысалында газдандыру, газ көлігі мәселелеріне жалпы газ саласының дамуына шолу жасалды. Елді, атап айтқанда, солтүстік өңірлер мен Астананы газдандыру мәселелері қаралды. Сондай-ақ Қазақстанда газ саласы мен газ компанияларына талдау жасалып, олардың даму перспективалары анықталды. Елді газдандырудың Жол картасына сәйкес «Сарыарқа» газ құбыры трассасының бойындағы елді мекендерді газбен қамтамасыз ету кезең-кезеңімен қаралатын елдің солтүстік және орталық өңірлерін газдандыруға ерекше назар аударылады. «Интергаз Орталық Азия» АҚ филиалдарының жұмыс статистикасы, әрбір филиалға қызмет көрсететін учаскелер ұсынылған. Соңында еліміздің газ ресурстарын тиімді пайдалану және «таза» энергетикаға біртіндеп көшу бойынша ұсыныстар берілді.

Тірек сөздер: газ құбыры көлігі, газдандыру, магистральдық газ құбыры, инженерлік-техникалық орталық, «жасыл» энергетика.

ЭКОНОМИКА ЖӘНЕ БИЗНЕС
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[1]*Atakoziyeva Y.Y.,
Master's student, Researcher, ORCID ID: 0009-0006-4761-3893
*e-mail: atakozieva@gmail.com
[2]Moldakhmetova S.K.,
Master's student, Researcher, ORCID ID: 0009-0000-1212-8595
[3]Khonai A.,
Master's student, Researcher, ORCID ID: 0009-0000-8619-2813
e-mail: kcharman@cam-ed.com
[4]Charman K.P.,
PhD, Professor, ORCID ID: 0009-0004-3204-3010
e-mail: kcharman@cam-ed.com

[1]Haileybury Almaty Non-Profit JSC, 050044, Almaty, Kazakhstan
[2]Infocus.Europe s.r.o, Kiev, Ukraine
[3]Sole Trader Korkem Exclusives, Almaty, Kazakhstan
[4]CamEd Business School, 1, 20211, Phnom Penh, Cambodia

USING INTERCULTURAL COMMUNICATIVE COMPETENCE DIMENSIONS IN MANAGING MULTICULTURAL TEAM PERFORMANCE

Abstract

This article provides the relevance and effectiveness of intercultural communication competence for managing multicultural teams within Kazakhstan-based international companies. This research seeks to assess project managers and team members' knowledge, attitudes and skills related to intercultural communication competence. Byram's model of intercultural communication competence will be utilized with its emphasis on cultural knowledge and attitudes. This study's significance lies in its focus on cross-cultural management and communication in diverse work environments, using quantitative survey research methodologies conducted among project managers and team members in Kazakhstan international companies. The purpose is to investigate whether project managers and team members from multinational companies in Kazakhstan, operating in diverse cultural settings, possess the ability to identify elements of cross-cultural communicative competence while overseeing their teams and supervising the performance of their subordinates. Data analysis offers insights into intercultural communication competence knowledge, attitudes and skills within their specific context. These findings contribute to existing knowledge on intercultural communication competence and its application in managing multicultural teams, emphasizing the significance of cultural knowledge, positive attitudes toward diversity and effective communication skills for achieving successful project results. Furthermore, the results can provide practical implications for project managers and organizations looking to enhance their intercultural communication competence.

Key words: Project Management, Culture, Communication, Intercultural Communicative Competence.

Introduction

Project managers and senior leaders must possess intercultural competency to manage multicultural teams in today's globalized business environment successfully. Cultural exchange is becoming an increasing trend due to political issues driving people from one country to another and represents an invaluable opportunity for workers to learn from one another, share knowledge, develop new skills and advance in their fields. For such experiences to be fruitful, both project managers and staff members must accept and respect those with differing cultural backgrounds.

Studies conducted in previous years demonstrated the importance of understanding the perspective of the receiver for effective communication. Communication skills are also considered crucial to project managers working on multicultural teams. This paper highlights that professionals with developed intercultural communication abilities possess good knowledge and are aware of cultural differences. Their goal should be to use this expertise when engaging people from diverse language and cultural backgrounds.

This study will assess the effectiveness of intercultural communication for managing multicultural team performance by focusing on three components of Byram's model of intercultural communication competence – knowledge and attitudes – which provide insights into its efficacy in doing so. They demonstrate the significance of adopting positive attitudes toward cultural diversity while mastering effective communication techniques.

Today's global business world places greater demand on project managers and senior leaders to have experience managing cross-cultural communications and dealing with diversity within their teams. At present, as political issues drive people from their home countries and into other nations, cultural and experience sharing has become a worldwide trend. Working communities offer ample opportunities to learn, share knowledge, and develop new abilities within their field. To ensure a productive exchange of experiences and maintain healthy working relationships, project managers and their employees must accept people from diverse cultural backgrounds and communicate in ways which demonstrate respect for diversity.

Objectives

The objective of this study is to investigate whether project managers and team members from multinational companies in Kazakhstan, operating in diverse cultural settings, possess the ability to identify elements of cross-cultural communicative competence while overseeing their teams and supervising the performance of their subordinates. Additionally, the study aims to determine whether these individuals exhibit an inclusive and open approach by integrating intercultural communicative competence knowledge and skills into their leadership styles. The research inquiries in this investigation will be categorized based on the key dimensions of intercultural communicative competence:

Intercultural Communication Competence Knowledge and Awareness

1. Do team members in the project area have knowledge about key elements and fundamental ideas of Intercultural Communicative competence?

Attitudes to Intercultural Communication/ Motivation

2. What attitudes do they reflect towards implementing intercultural communication competence dimensions when communicating and managing the workflow of their teams and subordinates? Do they believe it is necessary to consider cultural differences in their working environment when assigning work and building communications?

Intercultural Communication Competence Skills

Do project team members use intercultural communication competence skills when communicating with their subordinates or resolving conflict situations? If yes, what are the most common intercultural contexts they mention? If not, what are the boundaries towards using these skills?

Main Provisions

Susana Schulz and Rosabel Rodig-Vila's Intercultural Communication Competence as a Key Competence for Global and Multicultural Organizations published in Intercultural Education (2016) explores the concept and significance of Intercultural Communication Competence [15]. They emphasize its significance as essential for individuals, organizations and societies in today's globalized society. The authors explore various models for intercultural communication competence, including Byram's Model. Aksana Kvalchuk's article entitled, "The Role of Intercultural Communicative Competence in Enhancing Cross-Cultural Management Effectiveness," published in Human Resource Management Review in 2019, examines the crucial role played by intercultural communication competence, in enhancing effective cross-cultural management effectiveness [8]. This article describes the challenges associated with cross-cultural management, such as differences in communication styles and values, as well as practical suggestions to assist managers and employees develop intercultural competency. The author emphasizes cultural sensitivity, adaptability, awareness and suggests that cultivating Intercultural communication competence requires continual learning, reflection and practice. Garcia-Lorca & Rubio-Andrada (2010) present a framework to conceptualize the relationship between intercultural team performance and intercultural communication competency [12]. They maintain that intercultural communication competence plays a significant role in intercultural team performance, thus organizations looking to become successful in multicultural environments must understand and develop this competency.

Brief Overview of the Theoretical Model

Byram's Intercultural Competence Model is a well-recognized framework of theory applied in research relating to cross-cultural communication, intercultural education and related areas. The model comprises five components – attitudes, knowledge and skills, language use and discourse. Byram (1997) asserts that intercultural competency refers to being able to effectively interact and communicate across cultures by appreciating cultural differences while adapting easily in unfamiliar cultural environments [1].

Attitude is one of the key components of intercultural competency. This involves being open-minded and curious about other cultures while showing care and consideration towards them. Knowledge is the cognitive component of intercultural competency and includes comprehending cultural similarities and differences as well as becoming aware of one's personal biases. Intercultural competence is an indispensable skill that involves being able to navigate and communicate in cross-cultural environments. Discourse provides another dimension - being able to analyze and interpret how values and norms are communicated across cultural divides through language is crucial in this respect. Byram's Model has been widely utilized by various studies related to language learning, intercultural training and study abroad programs. Deardorff (2006) used Byram's model to identify intercultural competence as an outcome of internationalization within US institutions of higher education; Huang and Van der Zee used Byram's Model to assess impact of study abroad programs on intercultural attitudes while O'Dowd (2003 p3) utilized it to study computer-mediated communication's role in language acquisition and intercultural competency using Byram's Model; finally Risager (2007) proposed an innovative transnational language and culture pedagogy using Byram's Model as its source [5].

Byram's Intercultural Competency Model provides a framework to understand and develop intercultural communication abilities. Its five components – attitudes, knowledge, skills and language – have been extensively used in cross-cultural research studies as well as many field applications of its application in different contexts.

Intercultural project management can be achieved using two frameworks: Byram's model of Intercultural Communicative Competence and Project Management Body of Knowledge.

Byram's Model of Intercultural Communication and PMBOK Concepts

Project managers can better navigate intercultural projects by drawing upon Byram's model and the PMBOK for guidance [11]. Byram's model can help project managers to understand cultural

differences that might impede project outcomes while the PMBOK helps plan, organize, control, and achieve specific project goals – for instance through using its project communication management knowledge area in planning communications strategies that account for cultural differences or reflecting upon own cultural biases and assumptions by using Byram's critical cultural awareness competency.

Byram's Model of Intercultural Communicative Competence provides a framework for building intercultural communications skills and attitudes necessary for effective cross-cultural dialogue. This model comprises interdependent components:

1. Knowledge: Recognizing cultural differences and similarities, including values, beliefs and customs from various cultures as well as communication styles between them.
2. Skills: Gain practical skills that enable you to understand and interact with people of various cultural backgrounds, including listening actively, empathizing with one another and adapting your communication style accordingly.
3. Attitudes: Exhibit an openness and curiosity towards other cultures. Assess and challenge any biases or assumptions you might hold within yourself about other peoples or societies.

By applying Byram's model to intercultural project management processes, project managers will be able to enhance their ability to collaborate effectively with multiple stakeholders – such as recognizing cultural differences and adapting communications strategies – while creating an inclusive project environment. The Project Management Body of Knowledge or PMBOK, provides an exhaustive guide to project management. Used alongside Byram's model, this standard guide from the Project Management Institute serves as a definitive reference [11]. The PMBOK recognizes communication as a critical component of project success. Communication encompasses transmitting, receiving and interpreting information at all stages of a project's life cycle – this means its importance is essential for stakeholder engagement, project performance measurement, risk mitigation strategies and issue resolution.

Materials and Methods

Research Design

This study encompassed three key research questions that pertain to the dimensions of Intercultural Communicative Competence, namely knowledge, attitudes, and skills.

To address these research questions, a mixed research design was chosen as research method for this project, allowing for the utilization of multiple research tools to investigate the study's problem.

To address the first question, a quantitative questionnaire will be administered to project managers and senior leaders in various organizations dealing with culturally diverse employees. The questionnaire will consist of different sections covering various aspects related to intercultural communicative competence. The questionnaire will also incorporate questions related to Hofstede's cultural dimensions model and topics like stereotyping and discrimination to assess participants' knowledge of intercultural communication competence.

To primarily address the second and third questions, interviews will be conducted with representatives from the sample group. This qualitative approach will enable the analysis of the main intercultural communication challenges faced by project managers and team members.

Population and Sampling

Population for this study is defined as international organizations, businesses that involve international project groups, employees to whom this study might become beneficial. Understanding of cultural dimensions and its potential impact on team performance will help the population to build and reconsider business strategies that they use within their teams and organizations in terms of improving internal communications and business processes.

Sample group is represented by questionnaire and interview respondents. Main goal is to reach and collect responses from employees and team members of international organizations who work for a long period of time in multicultural environments interacting in different projects.

The sample group for this research paper comprised a selection of Kazakhstani international companies operating across diverse industries. Employees of the following companies took part in the questionnaire and interview for this study: Haileybury Almaty, KPMG, the American Consulate, Homecredit Bank, the British Consulate, and Suleyman Demirel University.

Instrumentation

To address all research questions, a two-step investigation method comprising a questionnaire and semi-structured interview is essential. Each instrument will target specific questions to gather information relevant to the research. To ensure content validity, utilizing existing questionnaires is preferred. After extensive literature review, it was observed that most works focus on human resources. Researchers conducted agreement analysis to select questions for the questionnaire, ensuring it measures intended aspects. Five main models were analyzed to inform the construction of project management-based questionnaires, with some questions adapted from these studies.

"Developing Intercultural Communicative Competence through a Virtual Exchange Program" by Dorothy Chun. This study explores the use of virtual exchange programs to develop intercultural communicative competence and highlights the key communication components involved in successful intercultural communication [2]. Research review of "Assessing the impact of cross-cultural communication competence on expatriate business operations in multinational corporations of a Sub-Saharan African context" by James Baba Abugre and Yaw A. Debrah examines the impact of cross-cultural communication competence and importance of cultural awareness, empathy, and communication skills in developing intercultural competence on expatriates work outcomes [6]. And "Assessing Intercultural Competence in Higher Education: Existing Research and Future Directions" by Darla K. Deardorff provides an overview of the current research on intercultural competence assessment and highlights the importance of communication skills and intercultural sensitivity in developing intercultural competence [5]. "Intercultural Competence: A Review of Existing Concepts, Frameworks and Models" by Katrin Voltmer and Christina A. Victoroff examines the different conceptualizations of intercultural competence and highlights the key communication components involved in effective intercultural communication [17].

The development of the intercultural communication questionnaire for project management research drew from various resources, including the Project Management Body of Knowledge (PMBOK) and PM Process Chart. Particularly, the communications management section of the PMBOK provided insights into how intercultural communication impacts project success. Additionally, the PM Process Chart proved useful in formulating questions related to specific project execution stages. By leveraging established project management frameworks, the research questionnaire gathered comprehensive data on intercultural communication abilities and experiences among project managers and team members. The questionnaire consists of 18 questions, with six related to different areas of Byram's model, divided into three sections, using a 5-point Likert scale for responses. For the third research question, interview questions were prepared for participants willing to discuss intercultural communication cases from their work experiences. Conducted semi-structuredly, the interviews aim to elicit full, open-ended answers, with the potential for follow-up questions based on participant responses. Recordings of the interviews will be transcribed and analyzed to provide valuable insights for both researchers and readers who may relate to the described cases.

Analysis Plan

Triangulation Method

Using multiple sources of data is a way to verify the findings and reduce the possibility of errors, biases, or inconsistencies. In this research project investigators chose to use both questionnaire and interview methods to collect data from project managers and team members. By using both methods, it's possible to obtain a more comprehensive understanding of the intercultural communication skills and experiences of the participants. By combining quantitative and qualitative methods, researchers could compare and contrast the data, identify discrepancies or inconsistencies, and develop a more nuanced and nuanced analysis of the intercultural communication experiences of project managers and team members.

SPSS Method

In this research project on intercultural communication in project management, the researchers will use the Statistical Package for the Social Sciences method to analyze the data collected from the questionnaire. The SPSS method is a widely used statistical analysis software that allows researchers to perform a range of analyses on the data, including descriptive statistics, inferential statistics, and multivariate analysis.

The semi-structured interviews will be conducted, recorded, and transcribed. Descriptive statistics and visual aids will be used to analyze the data, identifying general patterns and trends in respondents' intercultural communication competence knowledge, attitudes, and skills. Thematic analysis will be used to identify common themes related to intercultural communication competence knowledge, attitudes, and skills for each level based on the interview data.

Results and Discussion

Data Analysis

The data analysis for this study was conducted using IBM SPSS 25.0 software package. Firstly, a frequency distribution table was generated to examine the demographic characteristics of the participants.

To assess the normality of the Likert-scale scores used in the study, the Shapiro-Wilk test was employed. Given that the sample size was less than 50, it was determined that the scores exhibited a normal distribution, as indicated by a p-value greater than 0.05.

Furthermore, the reliability of the Likert-type questions was evaluated using the Cronbach's Alpha coefficient.

Survey Findings

This section of the research focused on the examination of participants' involvement and the investigation of various aspects related to Intercultural Communicative Competence. Specifically, the study examined participants' knowledge level concerning the fundamental concepts and key elements of intercultural communication competence, their attitudes towards incorporating intercultural communication competence dimensions into their communication and team management practices, as well as the projected utilization of intercultural communication competence skills by team members during communication with subordinates and conflict resolution situations.

The findings pertaining to these areas were rigorously analyzed, and comprehensive interpretations of the results were provided. The objective was to gain a deep understanding of the participants' perspectives and behaviors regarding intercultural communication competence. The outcomes aimed to uncover insights into their comprehension of intercultural communication competence, their willingness to implement intercultural communication competence dimensions in their communication and team management practices, and the potential utilization of intercultural communication competence skills within their teams.

By delving into these dimensions, the research aimed to provide valuable insights for enhancing intercultural communication practices within the context under investigation, highlighting potential areas for growth and improvement.

Findings on Participants' Work Experience and Team Members

This section presents the findings related to the work experience of the participants and their corresponding team members. The provided table presents data concerning the total number of years of working experience and the total count of team members associated with each participant. The mean value of total years of seniority was computed as 6 years, with a minimum of less than one year and a maximum of 26 years. The approximate average number of team members who participated in the survey for each project was found to be 8 individuals. The range of team members varied, with a minimum of 2 people and a maximum of 25 people.

Table 1 – Years of working experience of respondents

	N	Minimum	Maximum	Mean	Std. Deviation
Total years of working experience:	30	0	26	6.57	6.574
The approximate number of team members in project:	29	2	25	8.07	5.196
Valid N (listwise)	29				

Findings of the respondents experiences in international community

This chart shows us a percentage of respondents' total work experience in the international community.

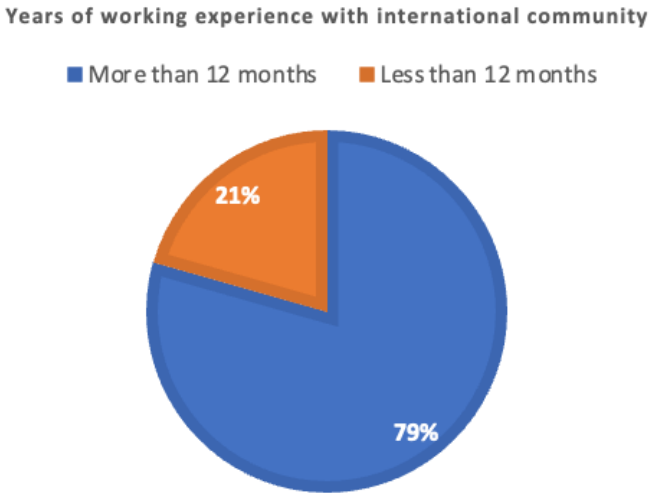

Figure 1 – Years of working experience with international community

Respondents have been working in international communities for more than 12 months. Only 21% have less than 12 months of work experience.

Test of Normality

A test of normality was conducted using the Shapiro-Wilk test to assess the normal distribution of the data. The resulting test statistic yielded a value of 0.445. According to the Shapiro-Wilk test interpretation, when the p-value exceeds 0.05, it indicates that the data follows a normal distribution. Consequently, this allows for the application of subsequent analyses such as regression and correlation.

The table below represents the data regarding the status of the respondents' knowledge and awareness of intercultural communication competence dimensions. The presented tabular data provides insights into the respondents' level of familiarity with the crucial components and fundamental concepts pertaining to the dimensions of Intercultural Communicative Competence. The obtained result yields a p-value of 3.177, or according to the Likert-scale interpretation, falls within the neutral range. This implies that a substantial portion of the respondents do not possess comprehensive knowledge (i.e., a complete understanding) of the key elements and fundamental ideas underpinning intercultural communication competence dimensions. However, it is noteworthy that they are not entirely uninformed either, indicating a moderate level of awareness.

Table 2 – Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Icc_awareness	30	1.83	4.33	3.1778	.61109
Valid N (listwise)	30				

Findings regarding respondents' attitudes toward the implementation of intercultural communication competence dimensions in their communication and team management practices

The tabular data presented offers valuable insights into the attitudes of the respondents regarding the incorporation of intercultural communication competence dimensions within their communication and team management endeavors. The resulting p-value of 3.533, as per the Likert-scale interpretation, indicates a predominantly positive stance among the majority of respondents. This suggests that they possess favorable attitudes towards the implementation of intercultural communication competence dimensions when engaging in communication activities and overseeing the workflow of their respective teams.

Table 3 – Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
attitude	30	2.50	4.83	3.5333	.49789
Valid N (listwise)	30				

The findings pertaining to the utilization of intercultural communication competence skills by respondents during communication with subordinates and conflict resolution situations . The presented table provides an overview of the responses to questions concerning the utilization of intercultural communication competence skills. The calculated result of 3.7, or the corresponding positive interpretation based on the Likert Scale, indicates that a significant majority of the respondents demonstrate the use of ICC skills when engaging in communication with their teammates or resolving conflicts.

Table 4 – Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
skill	30	2.83	4.83	3.7556	.50236
Valid N (listwise)	30				

Regression Analysis

A regression analysis was conducted to examine the hypothesis that the total years of experience would significantly predict Intercultural Communicative Competence dimensions. The results of the analysis yielded the following coefficients: intercultural communication competence awareness Table 1 (0.242), intercultural communication competence skill Table 2 (0.641), and intercultural communication competence attitude Table 3 (0.300), in relation to the total years of experience.

To evaluate the hypothesis, an Anova test was performed. If the resulting p-value is greater than 0.05, it indicates that the hypothesis should be rejected. In this case, all of the obtained p-values are greater than 0.05. Therefore, it can be concluded that there is no significant prediction of intercultural communication competence dimensions by total years of experience.

Ho: There will be significant prediction intercultural communication competence dimensions by total years of experience.

Ha: There will be no significant prediction of intercultural communication competence dimensions by total years of experience.

Table 5 – Regression Analysis

ANOVA[a] Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.275	1	.275	1.114	.300[b]
	Residual	6.914	28	.247		
	Total	7.189	29			

a. Dependent Variable: attitude
b. Predictors: (Constant), Total years of working experience: 30

Table 6 – Regression Analysis

ANOVA[a] Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.527	1	.527	1.431	.242[b]
	Residual	10.303	28	.368		
	Total	10.830	29			

a. Dependent Variable: awareness
b. Predictors: (Constant), Total years of working experience: 29

Table 7 – Regression Analysis

ANOVAa Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.058	1	.058	.223	.641b
	Residual	7.261	28	.259		
	Total	7.319	29			

a. Dependent Variable: skill
b. Predictors: (Constant), Total years of working experience: 30

Correlation Analysis

In this section, a correlation analysis was conducted to investigate the relationship between years of working with the intercultural community and Intercultural Communicative Competence dimensions. The null hypothesis (Ho) posited that there would be a positive correlation between these two variables, while the alternative hypothesis (Ha) suggested the absence of a positive correlation.

The obtained p-values from the correlation analysis were 0.09, 0.05, and 0.09 for the respective intercultural communication competence dimensions. These p-values indicate a relatively low correlation between years of working with the intercultural community and the intercultural communication competence dimensions under investigation.

It should be noted that a p-value of 0.05 is commonly used as the threshold for determining statistical significance. In this case, all three p-values exceeded this threshold, suggesting that the

observed correlations are not statistically significant. Consequently, the results suggest a weak or negligible relationship between the years of working with the intercultural community and the intercultural communication competence dimensions being examined.

Table 8 – Correlations

		Years of working experience with international community:	skill	awareness	attitude
Years of working experience with international community:	Pearson Correlation	1	.090	.055	.091
	Sig. (2-tailed)		.636	.771	.633
	N	30	30	30	30
skill	Pearson Correlation	.090	1	.468**	.700**
	Sig. (2-tailed)	.636		.009	<.001
	N	30	30	30	30
awareness	Pearson Correlation	.055	.468**	1	.650**
	Sig. (2-tailed)	.771	.009		<.001
	N	30	30	30	30
attitude	Pearson Correlation	.091	.700**	.650**	1
	Sig. (2-tailed)	.633	<.001	<.001	
	N	30	30	30	30
**. Correlation is significant at the 0.01 level (2-tailed).					

Interview results

Findings of No. 1 interview:

Participants were interviewed three times regarding their perspectives on intercultural communication skills in managing multicultural teams. In the first interview, one participant emphasized the necessity of these skills for organizations operating across borders. They illustrated how adapting communication styles and understanding cultural norms contributes to strong relationships with local partners. Participants acknowledged that cultural differences can cause friction within teams. Lack of representation and disparate salaries between international and local employees were cited as reasons for inconsistent skill application.

Findings of No. 2 interview:

In the second interview, the participant underscored the significance of intercultural capabilities when working with individuals from diverse backgrounds and achieving goals. They shared examples of how adaptability and cultural knowledge affected communication with team members from the United States and another country. The team's knowledge of Russian culture helped prevent a dispute that could have hindered project completion. Lack of interest and knowledge about other cultures were identified as primary obstacles to consistently applying Intercultural Communication Competencies.

Findings of No. 3 interview:

In the third interview, the participant discussed the value of intercultural skills in organizing inclusive multicultural events. They shared a scenario where pictures and open dialogue helped overcome communication challenges with a team member from a different cultural background. Participants revealed conflicts among team members with differing cultural backgrounds, adversely impacting project timelines and morale. Conflicts were resolved through meetings, active listening sessions, and finding common ground. Language barriers, lack of cultural understanding, and biases were major challenges to consistent skill application.

Discussion of interview findings

Interviews demonstrated the significance of intercultural skills for managing multicultural teams and achieving project success. Participants consistently stressed understanding cultural norms, adapting communication styles, encouraging open dialogue, and addressing challenges such as lack of knowledge, prejudices, language barriers, and disparities within teams, which require training or awareness to overcome.

Analysis of the interviews provides qualitative insights into the application of intercultural communication competence in managing multicultural teams. Several recurring themes emerged through inductive methods.

Intercultural Communication: All participants recognized the importance of intercultural skills for project completion and building relationships among culturally diverse team members. They emphasized respect, understanding, and adapting communication styles based on cultural preferences.

Participants demonstrated how intercultural competency skills led to successful project outcomes, such as adjusting communication styles and using visual aids according to cultural norms.

Communication Challenges: While conflicts between team members of different cultures were rare, participants acknowledged the risk of miscommunication due to cultural differences. They emphasized the significance of curiosity and knowledge about other cultures to overcome communication barriers.

Language barriers, biases, and lack of cultural awareness were identified as primary obstacles to consistent use of intercultural communication competencies. Participants suggested cultural exchanges and training programs as solutions to address these challenges.

Key Findings:

a) Intercultural communication skills are vital for leading multicultural teams, fostering strong relationships, avoiding conflict, and meeting project objectives.

b) Acknowledging and adjusting to cultural considerations positively influences communication, enabling adaptability and forming bonds with teammates from diverse backgrounds.

c) Conflict resolution is facilitated by intercultural communication skills, emphasizing finding common ground, active listening, and open discussions.

d) Complications in applying intercultural communication competence skills include an absence of diversity within teams, salary disparities, lacking knowledge and interest, biases, and language barriers. Solutions include promoting diversity, addressing salary disparities, fostering a learning culture, providing language support, and cultural training.

Conclusion

In conclusion, the presented findings offer valuable insights into the respondents' level of familiarity, attitudes, and utilization of Intercultural Communicative Competence dimensions. The analysis of the tabular data indicates that a substantial portion of the participants do not possess comprehensive knowledge of the key elements and fundamental ideas underlying intercultural communication competence dimensions. However, it is important to note that they do exhibit a moderate level of awareness.

Furthermore, the data reveals that the majority of respondents hold positive attitudes towards the incorporation of intercultural communication competence dimensions in their communication and team management endeavors. This suggests that they recognize the value and importance of intercultural communication competence in their interactions and workflow.

Additionally, the findings indicate that a significant majority of the participants demonstrate the use of intercultural communication competence skills when engaging in communication with their teammates or resolving conflicts. This highlights the practical application and relevance of intercultural communication competence in their day-to-day activities.

Overall, these findings contribute to the understanding of the respondents' familiarity, attitudes, and utilization of intercultural communication competence dimensions. They provide insights into the current state of intercultural communication competence awareness and implementation among the participants, offering a basis for further research and potential interventions in promoting intercultural competence and effective communication within diverse teams and contexts.

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[1]*Атакозиева Е.Е.,
магистр, ғылыми қызметкер, ORCID ID: 0009-0006-4761-3893
*e-mail: atakozieva@gmail.com
[2]Молдахметова С.К.,
магистр, ғылыми қызметкер, ORCID ID: 0009-0000-1212-8595
[3]Хонай А.,
магистр, ғылыми қызметкер, ORCID ID: 0009-0000-8619-2813
e-mail: kcharman@cam-ed.com
[4]Charman K.P.,
PhD, профессор, ORCID ID: 0009-0004-3204-3010
e-mail: kcharman@cam-ed.com

[1]Haileybury Almaty АҚ, 0500044, Алматы қ., Қазақстан
[2]Infocus.Europe s.r.o, Киев қ., Украина
[3]ЖК Korkem Exclusives, Алматы қ., Қазақстан
[4]CamEd Business School, Пномпень қ., Камбоджа

КӨПМӘДЕНИЕТТІ ҰЖЫМНЫҢ ЖҰМЫСЫН БАСҚАРУ ҮШІН МӘДЕНИЕТАРАЛЫҚ КОММУНИКАТИВТІ ҚҰЗЫРЕТТІЛІК ӨЛШЕМДЕРІН ҚОЛДАНУ

Аңдатпа

Берілген мақалада жобаларды басқару саласындағы халықаралық компаниялардағы көпмәдениетті ұжымдарды басқару үшін мәдениетаралық коммуникациялық құзыреттіліктің (ICC) өзектілігі мен тиімділігін қамтамасыз етеді. Бұл зерттеудің мақсаты жоба менеджерлері мен топ мүшелерінің мәдениетаралық коммуникациялық құзыреттілікке (ICC) қатысты білімдерін, көзқарастарын және дағдыларын бағалауға бағытталған, ол үшін Байрамның ICC моделі мәдени білімдер мен көзқарастарға баса назар аудара отырып пайдаланылады. Бұл зерттеудің маңыздылығы оның қазақстандық халықаралық компаниялардағы жоба менеджерлері мен топ мүшелері арасында жүргізілген сандық сауалнамалық зерттеу әдістемелерін пайдалана отырып, әртүрлі жұмыс ортасында мәдениетаралық басқару мен коммуникацияға бағытталғандығында. Деректерді талдау олардың нақты контекстінде ICC біліміне, көзқарастарына және дағдыларына түсінік береді. Бұл нәтижелер жобаның сәтті нәтижелеріне қол жеткізу үшін мәдени білімнің, әртүрлілікке оң көзқарастың және тиімді коммуникациялық дағдылардың маңыздылығын атап көрсете отырып, мәдениетаралық коммуникация құзыреттілігі (МКС) және оны көпмәдениетті ұжымдарды басқаруда қолдану туралы бар білімге ықпал етеді. Сонымен қатар нәтижелер жоба менеджерлері мен ұйымдар үшін олардың мәдениетаралық коммуникация құзыреттілігін арттыруға практикалық әсер ете алады.

Тірек сөздер: жобаларды басқару, мәдениет, коммуникация, мәдениетаралық коммуникативті құзыреттілік.

[1]*Атакозиева Е.Е.,
магистр, научный сотрудник, ORCID ID: 0009-0006-4761-3893
*e-mail: atakozieva@gmail.com
[2]Молдахметова С.К.,
магистр, научный сотрудник, ORCID ID: 0009-0000-1212-8595
[3]Хонай А.,
магистр, научный сотрудник, ORCID ID: 0009-0000-8619-2813
e-mail: kcharman@cam-ed.com
[4]Charman K.P.,
PhD, профессор, ORCID ID: 0009-0004-3204-3010
e-mail: kcharman@cam-ed.com

[1]Haileybury Almaty АҚ, 0500044, г. Алматы, Казахстан
[2]Infocus.Europe s.r.o, г. Киев, Украина
[3]ЖК Korkem Exclusives, г. Алматы, Казахстан
[4]CamEd Business School, г. Пномпень, Камбоджа

ИСПОЛЬЗОВАНИЕ ИЗМЕРЕНИЙ МЕЖКУЛЬТУРНОЙ КОММУНИКАТИВНОЙ КОМПЕТЕНТНОСТИ В УПРАВЛЕНИИ РАБОТОЙ МУЛЬТИКУЛЬТУРНОЙ КОМАНДЫ

Аннотация

В данной статье представлена актуальность и эффективность компетенции межкультурной коммуникации для управления мультикультурными командами в казахстанских международных компаниях. Целью данного исследования является оценка знаний, отношений и навыков менеджеров проектов и членов команд, связанных с компетентностью в межкультурном общении. Модель межкультурной коммуникативной компетентности Байрама будет использоваться с акцентом на культурные знания и отношения. Значимость этого исследования заключается в том, что оно сосредоточено на межкультурном управлении и общении в различных рабочих средах с использованием методологий количественного опроса, проводимого среди менеджеров проектов и членов команд в казахстанских международных компаниях. Цель состоит в том, чтобы выяснить, обладают ли менеджеры проектов и члены команд транснациональных компаний в Казахстане, работающих в различных культурных средах, способностью выявлять элементы межкультурной коммуникативной компетентности при наблюдении за своими командами и работе своих подчиненных. Анализ данных дает представление о знаниях, отношениях и навыках межкультурной коммуникации в их конкретном контексте. Эти результаты дополняют существующие знания о компетентности межкультурного общения и их применении в управлении мультикультурными командами, подчеркивая важность культурных знаний, позитивного отношения к разнообразию и эффективных коммуникативных навыков для достижения успешных результатов проекта. Кроме того, результаты могут иметь практическое значение для менеджеров проектов и организаций, стремящихся повысить свою компетентность в межкультурном общении.

Ключевые слова: управление проектами, культура, коммуникация, межкультурная коммуникативная компетентность.

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[1]*Bolatbek B.,
ORCID ID: 0009-0004-2725-7137
e-mail: botagoz.bolatbekkyzy@gmail.com
[2]Saydaliev Hayot Berk,
ORCID ID: 0000-0002-4231-2366
e-mail: h.saydaliev@tsue.uz

[1]Narxoz University, Almaty, Kazakhstan
[2]Institute for Macroeconomic and Regional Studies under
Cabinet of Ministries of the Republic of Uzbekistan, Tashkent, Uzbekistan

CARBON EMISSIONS IN AGRICULTURAL GROWTH: A COMPREHENSIVE ANALYSIS OF FACTORS INFLUENCING ORGANIC CROP PRODUCTION IN KAZAKHSTAN

Abstract

The article examines the problem of carbon emissions into the atmosphere caused by agricultural activities. She analyzes various aspects of the problem, including the impact of fertilizer use, tillage, and animal husbandry on carbon emissions. The article examines modern methods and technologies that can reduce agriculture's carbon footprint and improve its environmental sustainability. The authors also discuss the role of renewable energy, effective waste management and sustainable practices in agriculture to reduce its contribution to climate change. This study is anticipated to make significant contributions to both recent literature and policymaking in Kazakhstan across several dimensions. Economic regression analysis was conducted using the panel data models such as Random Effects and Fixed Effects, and two econometric models were assessed. The findings of this study shed light on the intricate relationship between carbon emissions and key determinants within the agricultural sector of Kazakhstan. By employing a comprehensive regression model, incorporating various variables such as oilseed imports and exports, investments in the green economy, fertilizer usage, arable land, and economic indicators, this research delves into the nuanced dynamics influencing carbon emissions.

Key words: agriculture, carbon emission, crop production, agro-industrial complex, sustainable development.

Introduction

Global climate change is a pressing concern attributed to elevated levels of greenhouse gases (GHGs) in the atmosphere, primarily driven by human-induced activities like the burning of fossil fuels and the clearing of forests (Raihan et al., 2021; Wan Mohd Jaafar, 2020). The ongoing rise in carbon dioxide (CO_2) emissions is anticipated to yield significant repercussions for the Earth's climate system, leading to potentially disastrous outcomes that will impact various sectors of society (Raihan et al., 2019; Begum et al., 2020). Hence, the global emphasis on curbing carbon dioxide (CO_2) emissions and enhancing environmental conditions has intensified, aiming for sustainable development and the alleviation of adverse consequences associated with climate change (Begum et al., 2015; Raihan et al., 2022).

The Paris Agreement, a multilateral environmental accord negotiated under the United Nations Framework Convention on Climate Change (UNFCCC), aims to enhance the collective global effort in addressing challenges related to climate change within the context of sustainable development. Nevertheless, Kazakhstan, being the largest landlocked country globally with abundant natural resources, holds a significant position as one of the leading exporters of oil and gas (Wang et al.,

2019). Kazakhstan's pursuit of emission reduction holds paramount importance, and the country's endorsement of the Paris Agreement signifies a noteworthy advancement for this nation heavily reliant on fossil fuels. Kazakhstan has pledged to achieve an unconditional goal of reducing greenhouse gas (GHG) emissions by 15% and a conditional target of a 25% GHG emission reduction by 2030, relative to the levels observed in 1990, as outlined in the Paris Agreement. Simultaneously, Kazakhstan grapples with significant environmental challenges (Wang et al., 2019).

Cities host the majority of the global population and contribute to more than 70% of worldwide CO_2 emissions (Sharifi, 2021). This proportion is anticipated to rise further with ongoing urbanization trends (Sharifi, 2021: Gasimli et al., 2019). However, urbanization is recognized as a pivotal element in economic growth and structural development (Gasimli et al., 2019). Consequently, Kazakhstan's national '2050' growth strategy places urbanization as one of its cornerstones (Seitz, 2021). In 2020, urban areas and cities constituted 57.67% of Kazakhstan's total population, experiencing an annual urban population growth of 1.5% (World Development Indicators, 2022). The United Nations Department of Economic and Social Affairs (DESA) estimates that Kazakhstan's urbanization levels, both past and projected by 2050, surpass the average for Asia overall and particularly for Central Asia (The Astana Times, 2021). DESA predicts a 69.1% urbanization rate in Kazakhstan by 2050, with seven out of ten people expected to reside in cities by that time (The Astana Times, 2021). Kazakhstan's cities are regarded as focal points for economic activity and prosperity (Seitz, 2021). Urbanization, driven by migration from rural areas to cities, opens up opportunities for employment, education, healthcare, transportation, telecommunications, and other public services (Zhend and Walsh, 2019). Consequently, urbanization leads to an increased demand for energy, resulting in carbon emissions (Zheng and Walsh, 2019).

According to Zhu and Peng (2012), urbanization manifests three significant effects on CO_2 emissions: first, elevated residential and industrial energy consumption; second, increased energy utilization by the construction industry for infrastructure improvement, transportation, and residential structures; and third, deforestation for urban development. Additionally, the heightened use of household appliances (e.g., air conditioning, water heaters) significantly contributes to increased electricity consumption and, consequently, a rise in CO_2 emissions (Zhu and Peng, 2012). Rapid urbanization poses a threat to sustainable development, as it escalates both energy consumption and environmental degradation (Gasimli et al., 2019; Seitz, 2021; Zhu and Peng, 2012). Therefore, it becomes imperative to investigate the correlation between urbanization and CO_2 emissions for the sake of sustainable development in Kazakhstan.

A comprehensive grasp of Kazakhstan's susceptibility to climate change is gaining heightened significance for policymakers striving to navigate the delicate equilibrium between initiatives aimed at mitigating climate change and fostering sustainable development. Managing the trade-off between pollution and development stands out as the most challenging aspect of simultaneously pursuing these dual objectives. Consequently, the conundrum revolves around whether sustainable growth and enhanced environmental quality, particularly in terms of emission reduction, can coexist as mutually inclusive goals. A pivotal inquiry arises concerning how Kazakhstan can effectively diminish CO_2 emissions, and addressing this query involves an examination of the primary sources of CO_2 emissions in the country.

This study is anticipated to make significant contributions to both recent literature and policymaking in Kazakhstan across several dimensions. Firstly, it addresses a noticeable gap in existing academic literature by conducting a thorough econometric analysis to investigate the connection between CO_2 emissions and their determinants in Kazakhstan. The outcomes have the potential to offer novel insights to an international audience regarding the intricacies of environmental factors and their sustainable management. Secondly, the research is positioned as an advancement over prior studies, utilizing innovative econometric methodologies and incorporating new drivers associated with CO_2 emissions specific to Kazakhstan, aspects often overlooked in earlier research.

Main provisions

A distinctive aspect of this study lies in the estimation of the impact of agriculture and forests on Kazakhstan's environment, representing a pioneering effort to reveal the influences of agricultural productivity and forested area on CO_2 emissions in the context of Kazakhstan. This research sheds light on the unique role played by agriculture and forestry in emission reduction, a facet frequently neglected in investigations into the determinants of CO_2 emissions.

Literature Review

The link between economic growth and energy use has been investigated in detail in a variety of studies applying different types of econometric methodologies. For example, Begum et al. (2020) find that the economic growth and energy use bears a positive impact on carbon emission employing ARDL and DOLS methods for yearly data spanning from 1970 to 2009. Adebayo (2020) implemented FMOLS and DOLS estimators using the data from 1971 to 2016 and document that economic growth exhibit the positive impact on carbon emission in Mexico.

Odugbesan and Adebayo (2019) identified a correlation between economic growth, energy consumption, and CO_2 emissions in Nigeria based on annual data from 1981 to 2016, employing ARDL, FMOLS, and DOLS methodologies. Vo et al. (2018) similarly found a positive association between CO_2 emissions, economic growth, and energy usage in ASEAN countries using FMOLS and DOLS techniques with data spanning from 1971 to 2014. Teng et al. (2020) observed a similar trend in OECD nations, reporting that economic growth and energy consumption contribute to CO_2 emissions. Shaari et al. (2017) utilized the ARDL model to demonstrate a positive relationship between energy consumption and CO_2 emissions in OIC countries.

In recent years, there has been extensive research on the relationship between urbanization and CO_2 emissions. Zhang et al. (2019) investigated this relationship in Malaysia using ARDL, FMOLS, and DOLS techniques on data spanning from 1960 to 2018, revealing a positive association between economic growth, urbanization, and CO_2 emissions. Adebayo and Kalmaz (2020) analyzed Egypt's data from 1971 to 2014, employing ARDL, FMOLS, and DOLS methods, and found a similar positive connection between economic growth, energy consumption, urbanization, and CO_2 emissions. Nondo and Kahsai (2018) utilized the ARDL methodology to study South Africa's data from 1970 to 2016, uncovering positive impacts of economic growth, energy intensity, and urbanization on CO_2 emissions. Kirikkaleli and Kalmaz (2017) observed comparable positive influences of economic growth, energy consumption, and urbanization on CO_2 emissions in Turkey from 1960 to 2016, employing FMOLS and DOLS methods. Usman et al. (2019) investigated India's data from 1971 to 2014 using the ARDL estimator, finding that economic growth and energy usage contribute to CO_2 emissions. Liu and Bae (2018) revealed the positive effects of economic growth, energy consumption, and urbanization on CO_2 emissions in China from 1970 to 2015 using the ARDL method. Ahmed et al. (2020) reported that economic growth, energy use, and urbanization lead to CO_2 emissions in Indonesia, utilizing an ARDL estimator on data spanning from 1971 to 2014. Islam et al. (2015) demonstrated the positive effects of economic growth, energy use, and urbanization on CO_2 emissions in Bangladesh using the ARDL approach and data from 1970 to 2009. Raihan et al. (2021) found that economic growth and urbanization contribute to CO_2 emissions in Argentina based on time series data from 1990 to 2019, employing DOLS, FMOLS, and CCR methods.

Hasanov et al. (2016) demonstrated that economic growth has a continuously increasing effect on CO_2 emissions over the long term in Kazakhstan, using DOLS, FMOLS, and CCR cointegration methods on data from 1992 to 2013. Akbota and Baek (2018) applied the ARDL approach to Kazakhstan's data from 1980 to 2011, indicating that both economic growth and energy usage contribute to CO_2 emissions. Additionally, Zhang (2017) found that economic growth and urbanization positively influence CO_2 emissions in Kazakhstan and four other Central Asian countries from 1992 to 2013, employing Panel FMOLS, DOLS, and OLS techniques. Zhang et al. (2019) reported that

economic growth and energy usage lead to increased CO_2 emissions in 50 developing countries, including Kazakhstan, using FMOLS estimator on yearly data from 1995 to 2017. Adeneye et al. (2020) highlighted the positive impacts of economic growth and energy usage on CO_2 emissions in a panel of 42 Asian countries, including Kazakhstan, utilizing FMOLS and DOLS methods on data from 2000 to 2014. Rasoulinezhad and Saboori (2018) discovered similar positive effects of economic growth and fossil fuel energy consumption on CO_2 emissions in the Commonwealth of Independent States, which includes Kazakhstan, from 1992 to 2015, using DOLS and FMOLS methods. Raihan and Tuspekova (2021) revealed the positive effects of economic growth and fossil fuel energy usage on CO_2 emissions in Kazakhstan from 1996 to 2018, employing DOLS, FMOLS, and CCR methods. However, existing environmental studies have primarily focused on CO_2 emissions resulting from economic activities and energy consumption, neglecting the roles of urbanization, agriculture, and deforestation in shaping environmental quality, especially in Kazakhstan. Hence, this study aims to address this research gap by examining the dynamic effects of economic growth, energy usage, urbanization, agricultural productivity, and forested area on CO_2 emissions in Kazakhstan.

Method and Results

Carbon emissions were designated as the dependent variable for the purpose of studying their impact on organic agriculture. This choice stems from the anticipated transition to carbon neutrality in Kazakhstan by 2060. The study focuses on coal emissions in rural areas.

Due to the rapid expansion of the agricultural economy, the environmental conditions have deteriorated, resulting in an increased volume of carbon emissions. The accumulation of these emissions contributes to the greenhouse effect, subsequently intensifying global warming. In 2020, carbon emissions from the agricultural sector in Kazakhstan reached 40.72 million tons. This substantial amount underscores the critical importance of conducting a comprehensive study on the factors influencing carbon emissions within the agricultural sector, given its strategic implications.

While other potential determinant factors exist in the literature, the factors selected for inclusion in Table 1 were prioritized based on their relevance to the specific context of Kazakhstan and their documented significance in previous research. Additionally, data availability and feasibility considerations also played a role in determining the final selection of determinant factors. Overall, the chosen factors provide a robust framework for analyzing carbon emissions in Kazakhstan's agricultural sector and offer valuable insights for policymakers and stakeholders aiming to address climate change and promote sustainable agriculture.

Numerous scientists have undertaken extensive research on carbon emissions in agriculture (Akbota and Baek, 2018; Hasanov et al, 2016). Coal emissions are predominantly correlated with factors such as economic growth, energy intensity, energy structure, and labor productivity. Some researchers emphasize the significance of urbanization, financial potential, and energy structure using alternative models, considering carbon emissions in agriculture as a pivotal driving force. Consequently, for the analysis of carbon emissions, the research model incorporates factors such as the import and export of oilseeds, the volume of investments directed towards a green economy, the application of mineral and organic fertilizers, the oilseeds acreage, the gross regional product, and the price index of oilseeds. The precise formula for the research model is outlined below:

$$CO_{2_{it}} = \alpha_i + \beta_1 OIMP_{it} + \beta_2 OEXP_{it} + \beta_3 GEINV_{it} + \beta_4 MFER_{it} + \beta_5 OFER_{it} + \beta_6 ASO_{it} + \beta_7 TRP_{it} + \beta_8 OPIND_{it} + e_{it}$$

Here's the continuation of the refined version with the inclusion of the formula:
CO_2 – carbon emission (tons);
OIMPit – import of oilseeds (tons);
OEXPit – export of oilseeds (tons);
GEINVit – investment in the green economy (thousand tenge);

MFERit – mineral fertilizers (thousand tons);
OFERit – organic fertilizers (thousand tons);
ASOit – arable land of oilseeds (thousand hectares);
TRPit – gross regional product (%);
OPINDit – price index of oilseeds (%).

Oilseed imports and exports (OIMPit and OEXPit) play a significant role in shaping carbon emissions within the agricultural sector. The volume of oilseed imports reflects the demand for agricultural inputs, while exports represent the extent of agricultural production destined for external markets. High levels of oilseed exports may indicate intensive agricultural activities, potentially leading to increased carbon emissions due to factors such as transportation and land use changes.

Investment in green economy initiatives, such as renewable energy technologies and sustainable agriculture practices (GEINVit), can influence carbon emissions in the agricultural sector. Higher levels of investment in the green economy may lead to the adoption of cleaner production methods and technologies, resulting in reduced carbon emissions from agricultural activities.

The use of fertilizers, both mineral and organic, is a crucial determinant of carbon emissions in agriculture (MFERit and OFERit). While fertilizers enhance soil fertility and crop yields, they can also contribute to carbon emissions through processes such as fertilizer production, application, and decomposition. The distinction between mineral and organic fertilizers is essential, as organic fertilizers tend to have lower carbon footprints and may promote soil health and carbon sequestration.

The availability of arable land dedicated to oilseed cultivation is a key determinant of agricultural carbon emissions (ASOit). Expansion of oilseed cultivation may lead to land-use changes, including deforestation or conversion of grasslands, which can result in significant carbon emissions and loss of biodiversity. Sustainable land management practices and land-use planning are essential for mitigating the environmental impacts of agricultural expansion.

Economic indicators such as gross regional product and price index of oilseeds reflect the economic activity and market dynamics within the agricultural sector (TRPit and OPINDit). Changes in economic conditions and market prices can influence production practices and investment decisions, thereby impacting carbon emissions. Understanding the relationship between economic factors and carbon emissions is crucial for designing effective policies to promote sustainable agricultural development.

Results and Discussion

Economic regression analysis was conducted using the panel data models such as Random Effects and Fixed Effects, and two econometric models were assessed. Table 1 presents the results of the analysis, evaluating two econometric models through the application of random and constant effects methods. The study's primary contribution lies in its revelation of the impactful relationship between the use of organic fertilizers and the yield of organic crop production, highlighting the importance of sustainable practices. The findings emphasize the need for implementing renewable energy technologies in agriculture to reduce the sector's carbon footprint. The study recommends a shift from excessive reliance on chemical fertilizers and pesticides to the adoption of organic fertilizers and biological pest control, promoting soil fertility and cleaner environmental conditions during agricultural production.

Table 1 (p. 188) displays the comprehensive regression model, showcasing results from both the random effect model (RE) and the fixed effect model (FE). In the second row of the table, the significance level of 1% is observed for the oilseed exports (OEXP) ratio, indicating a random effect (RE) of 0.000749 (first column) and a constant effect (FE) of 0.000703 (second column). This implies a substantiated connection between carbon emissions in agriculture and the export of oilseeds. Excessive carbon emissions directly influence exports, a noteworthy finding considering Kazakhstan's role as a significant exporter in organic crop production. Hence, the export market emerges as a pivotal driving force.

Table 1 – Relationship between Carbon Emissions (CO_2) and Key Determinants in agriculture

VARIABLES	RE (1) coe	FE (2) coe	FE (3) coe
OIMP	0.000355	0.000301	0.000301
	(0.000679)	(0.000674)	(0.000674)
OEXP	-0.000749***	-0.000703***	-0.000703***
	(9.11e-05)	(8.85e-05)	(8.85e-05)
GEINV	3.63e-08	1.88e-08	1.88e-08
	(1.18e-07)	(1.17e-07)	(1.17e-07)
MFER	-0.527**	-0.490**	-0.490**
	(0.228)	(0.227)	(0.227)
OFER	0.00574	0.00152	0.00152
	(0.0471)	(0.0465)	(0.0465)
ASO	0.0569**	0.0568**	0.0568**
	(0.0245)	(0.0226)	(0.0226)
TRP	0.0515	0.0557	0.0557
	(0.141)	(0.140)	(0.140)
TRPSQ	3.59e-05	1.36e-05	1.36e-05
	(0.00108)	(0.00107)	(0.00107)
OPIND	-0.154	-0.0845	-0.0845
	(0.102)	(0.0943)	(0.0943)
Constant	37.68***	31.93**	31.93**
	(8.537)	(13.79)	(13.79)
Observations	90	90	90
R-squared	0.571		
Number of regions in the data set	18	18	18

Note: Compiled by the author using the STATA batch program, employing calculated data.

Table 1 displays the comprehensive regression model, showcasing results from both the random effect model (RE) and the fixed effect model (FE). In the second row of the table, the significance level of 1% is observed for the oilseed exports (OEXP) ratio, indicating a random effect (RE) of 0.000749 (first column) and a constant effect (FE) of 0.000703 (second column). This implies a substantiated connection between carbon emissions in agriculture and the export of oilseeds. Excessive carbon emissions directly influence exports, a noteworthy finding considering Kazakhstan's role as a significant exporter in organic crop production. Hence, the export market emerges as a pivotal driving force.

Examining the eighth row of Table 1, the Kuznets hypothesis regarding the relationship between carbon dioxide emissions and the square of the gross regional product (TRPSQ) was investigated. The existing Kuznets environmental curve model was extended by incorporating additional variables to provide a more precise assessment of the interplay between economic prosperity and environmental impact. It was affirmed that, according to the analysis, no significant connection exists between the specified indicators. The study utilized panel data from Kazakhstan's regions spanning 2017–2021, employing a regression model to investigate organic crop production. The primary findings of the

research indicate a substantiated relationship, demonstrating that the utilization of organic fertilizers significantly impacts the yield of organic crop production.

The research reveals that carbon emissions in agriculture exert a significant influence on the environmentally sustainable growth of organic crop production. Consequently, the study advocates for the implementation of renewable energy-consuming technologies in agricultural machinery as a means to mitigate the carbon footprint of agriculture. Notably, the primary contributors to carbon emissions in agriculture were identified as the excessive use of chemical fertilizers and pesticides. In light of these findings, the study recommends leveraging the advantages of organic fertilizers and biological pest control to reduce reliance on chemical fertilizers. This approach not only enhances soil fertility but also promotes cleaner environmental conditions during the production of agricultural products. Recent research underscores the significance of considering rural education standards to enhance awareness regarding the environmental impact of non-renewable energy, chemical usage, and agricultural biomass management. In the context of agricultural biomass, there is a call to encourage farmers to adopt biomass as a bioenergy source. This not only serves to reduce agricultural costs but also contributes to environmental cleanliness. The reliance on chemicals in rural areas adversely affects soil fertility, leading to diminished crop yields. Furthermore, the introduction of high biotechnological crop varieties, resistant to pest attacks, is deemed essential. This approach eliminates the need for chemical sprays among farmers, promoting sustainable and eco-friendly agricultural practices.

These initiatives offer a means to conserve crucial resources, mitigating issues like reduced soil fertility and land degradation. Additionally, to boost crop production, it becomes imperative to introduce high-yielding, early-maturing, and heat-resistant crop varieties. Furthermore, this study identifies potential future research areas, specifically in the management of agricultural biomass for bioenergy production, aimed at curbing carbon emissions in agriculture.

The findings of this study have significant implications for policy development in Kazakhstan, particularly in the context of the nation's commitment to transition to carbon neutrality by 2060 and its participation in international agreements such as the Paris Agreement. By elucidating the factors influencing carbon emissions within the agricultural sector and highlighting the importance of sustainable practices, this research provides valuable insights for shaping policies aimed at achieving environmental sustainability goals.

First and foremost, the study underscores the critical role of organic fertilizers in mitigating carbon emissions and promoting environmentally sustainable agriculture. Policy measures aimed at incentivizing the adoption of organic fertilizers and discouraging the excessive use of chemical-based fertilizers and pesticides can play a crucial role in reducing the agricultural sector's carbon footprint. Kazakhstan could consider implementing subsidy programs or providing technical assistance to farmers to facilitate the transition to organic farming practices. Additionally, stringent regulations and enforcement mechanisms may be necessary to curb the indiscriminate use of chemical inputs and promote sustainable agricultural practices.

Furthermore, the correlation between carbon emissions and oilseed exports highlights the interconnectedness of economic activities and environmental sustainability. Policymakers in Kazakhstan need to consider the environmental implications of trade policies and ensure that economic growth is pursued in a manner that is compatible with environmental conservation goals. Measures such as incorporating environmental impact assessments into trade agreements and promoting sustainable agricultural exports can help strike a balance between economic development and environmental protection.

In the context of the Paris Agreement, Kazakhstan's participation necessitates a concerted effort to align domestic policies with the goals and commitments outlined in the agreement. The findings of this study provide valuable insights for Kazakhstan to enhance its Nationally Determined Contributions (NDCs) and strengthen its climate action plans, particularly in the agricultural sector. By prioritizing measures to reduce carbon emissions from agriculture, such as promoting organic farming practices, enhancing energy efficiency in agricultural machinery, and investing in renewable

energy technologies, Kazakhstan can demonstrate its commitment to achieving the objectives of the Paris Agreement.

Moreover, the study's identification of potential future research areas, such as the management of agricultural biomass for bioenergy production, underscores the importance of innovation and technological advancements in addressing climate change challenges. Kazakhstan could invest in research and development initiatives aimed at exploring the potential of biomass as a renewable energy source and developing high-yielding, climate-resilient crop varieties. By fostering innovation and supporting the adoption of sustainable agricultural practices, Kazakhstan can position itself as a leader in climate-smart agriculture and contribute to global efforts to combat climate change.

The findings of this study shed light on the intricate relationship between carbon emissions and key determinants within the agricultural sector of Kazakhstan. By employing a comprehensive regression model, incorporating various variables such as oilseed imports and exports, investments in the green economy, fertilizer usage, arable land, and economic indicators, this research delves into the nuanced dynamics influencing carbon emissions.

One of the significant findings of this study is the substantial impact of organic fertilizers on the yield of organic crop production. This highlights the importance of sustainable practices in agriculture, particularly in mitigating carbon emissions. The results underscore the necessity of transitioning from conventional chemical-based fertilizers and pesticides to organic alternatives, which not only enhance soil fertility but also contribute to cleaner environmental conditions during agricultural production. This finding aligns with recent trends emphasizing the adoption of eco-friendly agricultural practices worldwide.

Furthermore, the study reveals a notable correlation between carbon emissions and oilseed exports. The analysis suggests that excessive carbon emissions directly influence exports, indicating a complex interplay between economic activities and environmental sustainability. Given Kazakhstan's significant role as an exporter in organic crop production, these findings have strategic implications for policymakers and stakeholders, emphasizing the importance of incorporating environmental considerations into trade and economic policies.

Moreover, the investigation into the Kuznets hypothesis regarding the relationship between carbon dioxide emissions and economic prosperity yields interesting insights. Contrary to expectations, the analysis does not find a significant connection between carbon emissions and the square of the gross regional product. This underscores the need for a nuanced understanding of the relationship between economic growth and environmental impact, suggesting that other factors may influence carbon emissions within the agricultural sector.

The study also identifies several potential avenues for future research. Specifically, the management of agricultural biomass for bioenergy production emerges as a promising area for further investigation. By exploring the potential of biomass as a renewable energy source, future studies can contribute to reducing carbon emissions in agriculture while addressing energy security concerns. Additionally, the introduction of high biotechnological crop varieties resistant to pest attacks holds promise for promoting sustainable and eco-friendly agricultural practices, further mitigating the reliance on chemical inputs.

In conclusion, this study underscores the critical importance of addressing carbon emissions within the agricultural sector to achieve environmental sustainability goals. By elucidating the complex relationships between various determinants and carbon emissions, this research provides valuable insights for policymakers, stakeholders, and researchers striving to promote sustainable agricultural practices and mitigate the sector's carbon footprint. Ultimately, the findings and recommendations presented in this study contribute to the ongoing discourse on sustainable agriculture and environmental conservation.

Conclusion

In conclusion, this study offers valuable insights into the intricate relationship between carbon emissions and key determinants within Kazakhstan's agricultural sector, with implications for policy

development and environmental sustainability efforts. By employing a comprehensive regression model and analyzing panel data spanning from 2017 to 2021, this research provides robust evidence regarding the factors influencing carbon emissions in agriculture.

The econometric analysis, based on a dataset comprising 90 observations across various regions of Kazakhstan, reveals several key findings. Notably, the study finds a significant correlation between oilseed exports and carbon emissions, with a coefficient of -0.000749 in the random effects model and -0.000703 in the fixed effects model, both statistically significant at the 1% level. This highlights the impact of economic activities, particularly trade, on carbon emissions within the agricultural sector.

Furthermore, the study identifies organic fertilizers as a critical determinant of carbon emissions, with a coefficient of 0.00152 in the fixed effects model, although not statistically significant. However, the coefficient for mineral fertilizers is statistically significant, indicating a negative relationship between their usage and carbon emissions (-0.490 in the fixed effects model, significant at the 5% level). This underscores the importance of promoting sustainable agricultural practices, such as the adoption of organic fertilizers, to mitigate carbon emissions and enhance environmental sustainability.

Additionally, the analysis does not find a significant relationship between carbon emissions and the square of the gross regional product, contrary to the expectations based on the Kuznets hypothesis. This suggests that other factors, such as technological advancements and policy interventions, may play a more significant role in influencing carbon emissions within the agricultural sector.

In light of these findings, policymakers in Kazakhstan are urged to prioritize measures aimed at promoting sustainable agriculture and reducing the sector's carbon footprint. This includes incentivizing the adoption of organic farming practices, enhancing energy efficiency in agricultural operations, and investing in renewable energy technologies. Moreover, aligning trade policies with environmental conservation goals and strengthening international cooperation, particularly within the framework of the Paris Agreement, are essential steps towards achieving carbon neutrality by 2060 and contributing to global efforts to combat climate change.

In conclusion, this study underscores the importance of addressing carbon emissions in agriculture as part of broader efforts to promote environmental sustainability and achieve climate goals. By leveraging the insights gleaned from econometric analysis and adopting evidence-based policy interventions, Kazakhstan can pave the way for a greener, more sustainable agricultural sector while fulfilling its commitments to international climate agreements.

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[1]*Болатбек Б.,
ORCID ID: 0009-0004-2725-7137
e-mail: botagoz.bolatbekkyzy@gmail.com
[2]Сайдалиев Хайот Берк,
ORCID ID: 0000-0002-4231-2366
e-mail: h.saydaliev@tsue.uz

[1]Нархоз университеті, Алматы қ., Қазақстан
[2]Өзбекстан Республикасы Министрлер кабинеті жанындағы Макроэкономикалық және аймақтық зерттеулер институты, Ташкент қ., Өзбекстан

АУЫЛ ШАРУАШЫЛЫҒЫ ӨСІМІНДЕГІ КӨМІРТЕК ШЫҒАРЫНДЫЛАРЫ: ҚАЗАҚСТАНДАҒЫ ОРГАНИКАЛЫҚ ӨСІМДІК ШАРУАШЫЛЫҒЫНА ӘСЕР ЕТЕТІН ФАКТОРЛАРДЫ КЕШЕНДІ ТАЛДАУ

Аңдатпа

Мақалада ауылшаруашылық қызметі нәтижесінде атмосфераға көміртегі шығарындылары мәселесі қарастырылады. Ол мәселенің әртүрлі аспектілерін, соның ішінде тыңайтқыштарды пайдалану, топырақ өңдеу және мал шаруашылығының көміртегі шығарындыларына әсерін талдайды. Мақалада ауыл шаруашылығының көміртегі ізін азайтатын және оның экологиялық тұрақтылығын жақсартатын

заманауи әдістер мен технологиялар қарастырылады. Сондай-ақ авторлар жаңартылатын энергияның рөлін, қалдықтарды тиімді басқаруды және оның климаттың өзгеруіне ықпалын азайту үшін ауыл шаруашылығындағы тұрақты тәжірибелерді талқылайды. Бұл зерттеу соңғы әдебиеттерге де, Қазақстандағы саясаттың дамуына да бірнеше жағынан елеулі үлес қосады деп күтілуде. Экономикалық регрессиялық талдау кездейсоқ әсерлер және тіркелген әсерлер сияқты панельдік деректер үлгілері арқылы жүргізілді және екі эконометрикалық модель бағаланды. Бұл зерттеудің нәтижелері көміртегі шығарындылары мен Қазақстанның ауыл шаруашылығы секторын қозғайтын негізгі факторлар арасындағы күрделі байланыстарды ашады. Майлы дақылдардың импорты мен экспорты, жасыл экономика инвестициялары, тыңайтқыштарды пайдалану, егістік жерлер және экономикалық көрсеткіштер сияқты әртүрлі айнымалыларды қамтитын кешенді регрессиялық модельді пайдалана отырып, бұл зерттеу көміртегі шығарындыларына әсер ететін нәзік динамикаға тереңірек үңіледі.

Тірек сөздер: ауыл шаруашылығы, көміртегі шығарындылары, өсімдік шаруашылығы, агроөнеркәсіптік кешен, тұрақты даму.

[1]*Болатбек Б.,
ORCID ID: 0009-0004-2725-7137
e-mail: botagoz.bolatbekkyzy@gmail.com
[2]Сайдалиев Хайот Берк,
ORCID ID: 0000-0002-4231-2366
e-mail: h.saydaliev@tsue.uz

[1]Университет Нархоз, г. Алматы, Казахстан
[2]Институт макроэкономических и региональных исследований
при Кабинете Министров Республики Узбекистан, г. Ташкент, Узбекистан

ВЫБРОСЫ УГЛЕРОДА ПРИ РОСТЕ СЕЛЬСКОГО ХОЗЯЙСТВА: КОМПЛЕКСНЫЙ АНАЛИЗ ФАКТОРОВ, ВЛИЯЮЩИХ НА ПРОИЗВОДСТВО ОРГАНИЧЕСКИХ СЕЛЬСКОХОЗЯЙСТВЕННЫХ КУЛЬТУР В КАЗАХСТАНЕ

Аннотация

Статья исследует проблему выбросов углерода в атмосферу, обусловленную деятельностью сельского хозяйства. Она анализирует различные аспекты данной проблемы, включая влияние использования удобрений, обработки почвы и разведения животных на уровень выбросов углерода. В статье рассматриваются современные методы и технологии, которые могут снизить углеродные следы сельского хозяйства и улучшить его экологическую устойчивость. Авторы также обсуждают роль возобновляемых источников энергии, эффективного управления отходами и применения устойчивых практик в сельском хозяйстве для снижения его вклада в изменение климата. Ожидается, что это исследование внесет значительный вклад как в новейшую литературу, так и в разработку политики в Казахстане по нескольким направлениям. Экономический регрессионный анализ проводился с использованием моделей панельных данных, таких как случайные эффекты и фиксированные эффекты, и были оценены две эконометрические модели. Результаты этого исследования проливают свет на сложную взаимосвязь между выбросами углерода и ключевыми факторами, определяющими сельскохозяйственный сектор Казахстана. Используя комплексную регрессионную модель, включающую различные переменные, такие как импорт и экспорт масличных культур, инвестиции в зеленую экономику, использование удобрений, пахотные земли и экономические показатели, это исследование углубляется в тонкую динамику, влияющую на выбросы углерода.

Ключевые слова: сельское хозяйство, выбросы углерода, растениеводство, агропромышленный комплекс, устойчивое развитие.

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[1]Kuanyshkyzy Zh.,
ORCID ID: 0009-0005-7316-5097
e-mail: z_kuanyshkyzy@kbtu.kz

[1]Kazakh-British Technical University, 050040, Almaty, Kazakhstan

THE USE OF ALTERNATIVE SOURCES OF ENERGY IN KAZAKHSTAN

Abstract

The main aim of this research was to discover and analyze the opportunities of Kazakhstan in establishing RSE. There were used the research methods like primary data collection through interviewing and secondary data collection though analysis and discussion of existing works. The crucial research results were revealed in terms that Kazakhstan has all the good chances in sustaining the RSE within its territory, however, there were recognized some governmental, financial, political and operational barriers. Nevertheless, most of the results follow the pattern that in foreseeable future, Kazakhstan might become one of the leading countries in utilizing the RSE. The contribution of the study is vital, due to the reason that this research highlights the common issues and offers the available solutions to them according to new and already existed discoveries. There is a necessity in further research, like more detailed strategies in establishing the RSE facilities and operational structures. Also, huge need in organizing the research and activities related to educational aspects that would allow to increase the intellectual resources for this sphere specifically.

Key words: alternative energy sources, energy balance, Kazakhstan, green opportunities in Kazakh energy sector.

Introduction

Every country is unique. The shift from fossil fuel to renewable energy sources is more challenging for some than for others, and Kazakhstan, which has vast hydrocarbon reserves, is an example of such a country. As a result, this transformation has created and will continue to create issues for oil producing countries in general, and for Kazakhstan in particular. Due to the scarcity of these natural resources, negative externalities that are appearing through utilization of fossil fuels, increasing costs and modern necessity to obtain innovative methods of energy production the topic of using alternative sources of energy becomes even more relevant. In the world, there are cases of developed countries using the RES in an efficient way, it took lots of time for them to achieve this kind of results and it is an optimal opportunity for Kazakhstan to look over these examples and create their own decisions regarding the features and specific characteristics of the country. Therefore, this article focuses explicitly on the opportunities and variations that Kazakhstan has and could handle in the future.

When discussing the topic of this article, it is vital to emphasize its significance. And this significance is supported by the following factors:

- The oil era is unavoidably coming to an end. If effective adaptation measures are not launched immediately, the Kazakh economy would face huge challenges.
- Kazakhstan, the world's ninth largest country, offers enormous potential for the development of renewable energy sources, particularly wind and solar.
- Another important incentive for rapid action in the discussed sector is the country's increasing environmental deterioration.

- The country has accepted international commitments, such as the Kyoto Protocol and the Paris Agreement.
- Raising public awareness of environmental issues in the country and throughout the world.

Research objectives of this research are related to deeply understanding the alternative energy industry's current state, its foreseeable opportunities and expectations that were held based on the data from the secondary research/ literature review.

- Will Kazakhstan be able to transfer to renewable sources of energy in the foreseeable future?
- What are the potential implications of this transfer?
- What are the ways for this transfer?

This paper is designed as follows: Section 1 describes the abstract and introductory part of the research that highlights the relevance and urgency of the topic; Section 2 contains literature review where range of perspectives of different authors were revealed in their statistics, discussions and analyses; Section 3 explains the methodology of the research and the results with discussions that were presented in statement forms, tables and recommendations; Section 4 shares the conclusion and acknowledgement parts of overall article; Section 5 presents the references of all sources that were used in this work.

Main provisions

Even though various studies have been conducted, there is a scarcity of prior study on this issue. This study aims to address that gap by capturing broad patterns and dependencies, as well as developing appropriate adaptation techniques targeted at mitigating any negative outcomes.

Literature review

Generally, much research have highlighted the natural dominance and advantages of the territory, that allows to adapt range of RSE panels and facilities. According the results of Defect and Diffusion Forum within a topic of Renewable energy potential of Kazakhstan, it was mentioned that Kazakhstan has a big land making it an ideal location for renewable energy generation. Most of the terrain is suitable for solar energy harvesting, as well as a wide region with strong wind speeds, which has a significant potential for producing adequate wind energy. Wind turbines offer a significant potential for energy generation in areas like Jungar Gates and the Chylyk Corridor. Due to a lack of water, the area between Balkhash Lake and the Aral Sea in Kazakhstan is sparsely inhabited. Simultaneously, this location receives a lot of sunlight. It is feasible to capture a big amount of solar energy if it has several solar panel arrays [9]. That information is supported in many scientific notes and considered to be major advantage that keep the trust in Kazakh RSE prosperity.

The benefits of renewable energy preserve long-term global economic production while minimizing the usage of conventional energy. The five main sources of renewable energy are sun, wind, geothermal, biomass, and hydropower. In contrast to traditional energy sources, renewable energy is abundant, safe, and clean. Many people believe that renewable energy may alleviate energy security issues and lower emissions as it is a carbon-free energy source. In order to achieve the global emission reduction target of 50% by 2050, renewable energy is essential to sustain in our cluster [13]. The scientific article named "Role of economic growth, renewable energy, and technological innovation to achieve environmental sustainability in Kazakhstan" have shared such ideas, that crucially support this article to great extent. In that manner the analysis of existing works allows us to maintain the trustworthy research with range of justifications and discussion points.

Through brainstorming processes, analysis of the available data related to the topic, there were some ideas that had been discussed earlier with an addition of a new glance at it. There are shared opinions on the barriers on entering and establishing the alternative sources of energy on a regular basis in Kazakhstan, which is presented in a work named "A review of current energy systems and green energy potential in Kazakhstan". Low power pricing, inefficient technologies with poor

regulatory and legal frameworks, and a high-risk business climate are all obstacles to development of the alternative sources of energy is the insight that is shared in research [6].

Also, the summarizing idea from the International Journal of Energy Economics and Policy correlates with final findings and conclusions of this article, in which it is assumed that Kazakhstan has tremendous potential for alternative energy development. Even if there is a relatively low percentage of overall energy output and the existing capabilities of RSE plants are not completely exploited there. The correlation with this journal's notes is significant in determining the actuality of the research. The conclusion that is supported by many specialists is mentioned there also [7].

Within the statistically interesting article named "Future development of price instruments of state support for the use of renewable energy sources in Kazakhstan", there was precisely analyzed and described the financial perspective of the energy cluster. It is one of the important factors that is having to be taken into consideration, while exploring the issue of RSE. For instance, with the purpose of choosing renewable energy projects, Kazakhstan has instituted an auction bidding procedure. The set tariffs that were in effect up until 2018 were replaced by this method, which at first made it possible to establish the Republic of Kazakhstan's renewable energy industry. The primary goals of implementing the auction process are to provide competitive market rates for energy produced by RES facilities and to identify the most successful RES projects [10].

Moreover, the negative push factors were discovered within the energy cluster case. The article "Energy Security Strategy in Kazakhstan: Environmental Security and Renewable Energy Sources" had deep discussions related to the core issue that is making all countries all over the world to search the clean energy sources. The progressive depletion of resources and equipment deterioration is another difficulty Kazakhstan will have to deal with in the next decades. This may cause challenges in the fuel and energy balance, which may eventually result in an energy crisis and a restriction on the export of gas and oil. This problem is linked to dwindling financial resources, insufficient capability, and a lack of energy independence. Ensuring the state's energy security is one way to solve this issue, and it is a major area of interest for scholars both domestically and internationally [11].

The idea of the green economy also helped to advance the use of renewable energy sources. It has set forth several goals that the government and society must accomplish, including the increasing production and use of renewable energy, even if it is only a concept and not a law. Such idea was described in work called "Energy security in Kazakhstan: The consumers' perspective", that declares about the energy cluster from being seen though different lenses and different perspectives. The relation and the participation rate of the citizens in supporting the establishment of RSE in contrast appeared to be even more significant than the governmental participation. The reasons of societal impact were taken, and the main consumer rates also have shown the influence over this cluster, due to the reason that exactly the householders are controlling these sources by invisible hands [12].

Kazakhstan, as Central Asia's largest country, has a lot of solar energy potential, each year 1300–1800 kWh of solar radiation per square meter are produced and solar energy has a 2.5 billion kWh yearly potential, according to estimations. The territories of southeast Kazakhstan depict the Aral Sea basin, Almaty, and Fort Shevchenko (on the Caspian Sea shore) are the key point locations, where the highest flow of solar energy have been noticed for sustaining there the solar panels [2]. Moreover, Kazakhstan can generate up to 760 GW of wind energy at a reasonable cost in the Atyrau Region and a strip west of Nur-Sultan that encompasses the Kostanay, Akmola, and Karagandy regions. Wind is the most powerful source of energy in the former region, notably near Fort Shevchenko, and it may be less expensive than the gas fired electricity that predominates there, moreover, Diungarian Gates on the Xinjiang border, is one of the most potential wind energy development areas too [3].

Additionally, it is important to mention that Kazakhstan is a strong agrarian economy, cultivating a wide range of crops and producing considerable volumes of agricultural waste. One possible solution is to convert these undesirable and leftover residual amounts into bioenergy for cooking, heating, and electricity generation. The integration of renewable energy into energy balance is regarded to be the most important factor in ensuring the implementation of Kazakhstan's Green Economy program [1].

Methodology and data

Firstly, there were eight primary interviews conducted. Interview respondents are specialists, people, who's professions are tightly related to the energy production industry and their answers were considered as expert opinions. Each respondent gave personal and expanded answer to questions, that helped to create the result board.

Secondly, secondary data sources from the internet were actively used. The websites/online sources that were used for secondary data research are credible and all have the time actuality for the past 10 years, they are available in the reference part.

Additionally, the analysis tools like SWOT and Porter's Diamond model were used for deep understanding of the data and filtering it in categories.

- Information gathering through the relevant literature review.
- Interviews with experts in this field of knowledge, market players, government officials and representatives of academia.
- Analyzing the collected information and drawing conclusions.
- To minimize the risk of bias, the information gathered was cross checked where possible. Clarification calls were made when necessary.
- The analytical part was initially discussed with experts, market players, government officials and academia representatives.

Results and Discussion

The analysis of primary and secondary data was done in this part. The data from the primary interviews from eight different experts were analyzed contextually and presented in bullet points. Secondary data sources were paraphrased, analyzed and used actively in discussion parts. Both of the sources of information were correlated together to build the SWOT analysis table and Porter Diamond model. Additionally, the research recommendations were shared below the analyzed work.

Table 1 – SWOT analysis of RSE in Kazakhstan

SWOT analysis of RSE in Kazakhstan	
Strengths: ◆ Presence of large and free territories ◆ Available human capital ◆ The support of current energy sources from natural resources ◆ Experience of other developed countries	Weaknesses: ◆ Systematic errors, the structure of organizations, which are not well established ◆ Corruption ◆ High rate of returns on foreign investment
Opportunities: ◆ Construction of an energy infrastructure aimed at achieving regional self sufficiency ◆ The best available technologies and practices for converting energy sources ◆ Entering the top countries in alternative energy sources	Threats: ◆ Dependance on foreign financing ◆ Unskilled and unqualified labor force ◆ Uncertainty in department regulations

Porter Diamond Model:

Chance:

- Alternative sources of energy in Kazakhstan

Firm strategy, structure and rivalry:

- Presence of department for extraction alternative sources of energy
- Foreign invested organizations

- Research and development
- Experience of advanced developed countries

Factor conditions:

- Huge stocks of renewable natural resources
- Available foreign and both domestic investments
- Human capital

Demand conditions:

- Dependance on non renewable resources
- Growing population
- Necessity in larger amounts of electricity
- Regions with limited energy sources
- Green energy demand

Related and supporting industries:

- World organizations
- United Nations ESCAP
- The Green Finance & Development Center
- Eurasian Research Institute

Government:

- Regulation of monopolistic oil extraction companies
- Subsidiaries for alternative sources of energy
- 2050 plan of sustaining green energy

Interview results:

- Renewables can have negative effects on the environment as well.
- There are serious issues with the integration of renewable energy generation projects into the country's energy system.
- Energy losses in power grids are enormous. There is an urgent need to decrease them.
- Risks of investments in RES projects are high.
- Kazakhstan is at the beginning of this process. So, there is no need to repeat mistakes made by other countries or cases. Just to follow paths, which already proved to be successful. Examples: most efficient solar panels or the system of carbon emissions trading.
- Lack of government support. Government institutions do not properly facilitate and support the development of renewables in the country, although there is no shortage of official declarations and international commitments.
- The legal and especially regulatory framework requires substantial improvements. For example, still there is no established system of carbon emissions trading or measures to support microgeneration.
- High costs of RES projects. Financing of RES projects is most often provided by development banks.
- Low electricity tariffs. This is a government policy.
- Prices on energy from renewables are still expensive for the majority of the population though they are declining.

According to the interim results of the interview, there was an understanding that RES is the new direction for Kazakhstan to follow, but there are barriers like finances, mindset of population, and the old methods of energy production that take control over most of the activities of the country within the market.

The secondary database research built an understanding that Kazakhstan has already functioning power stations and producing the energy source from wind specifically. However, most of them are not functioning on a wide range and they are short in financing, therefore, some technical difficulties take longer to be solved, as there are not enough specialists, who deal with RES stations and also the repairing process itself is expensive to conduct for small ownership companies, therefore, topic of RES in Kazakhstan is not widely and loudly expanded nowadays, except for electric vehicles that are entering the market with upward moving tendency.

Recommendations:

- Increasing public awareness remains the main path towards the transition to the renewable source of energy. The respondents repeatedly addressed this issue.
- Strengthening the legal and regulatory framework.
- Increasing government support, including financial incentives.
- Studying the experience and technologies of developed countries and adopting the most successful examples in the country.
- Strengthening our own educational and R&D spheres for the successful development of RES projects.
- Due attention to be paid to energy efficiency and energy conservation measures.

Conclusion

Renewables are a great chance for Kazakhstan in development perspectives. Therefore, the country can and shall develop alternative sources of energy using available means and creating the needed ones. Difficult environmental situation, international obligations taken by the government of Kazakhstan and the global energy transition make this path unavoidable. According to the main results of conducted interviews, the legislative, social and financial aspects of energy cluster need to be adjusted in firsthand. By sustaining the structure and system, this cluster would be better to monitor and evaluate. Unfortunately, by using the SWOT analysis and Porter Diamond model there were revealed barriers of monopolistic control of the sphere, scarcity of intellectual human resources and social non acceptance by citizens that slow down the processes of establishing the RSE. However, the strategy that would consider all these aspects is possible to solve the appearing barriers and issues, but this article did not present the great strategy yet, only the recommendations and discussions. And it is the largest limitation of the research, as the exact and frankly stated strategy is missing out. There is a lack of precise solutions toward the identified problems, as most of the research was dedicated to analysis and recognition of data, but not solving and updating. For further research purposes the study of RSE strategies that were used by developed countries is a good choice. That research would be more practical and compare/ contrast style, which would give more information and push factors for upward movement in the energy cluster of Kazakhstan.

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[1]Қуанышқызы Ж.,
ORCID ID: 0009-0005-7316-5097
e-mail: z_kuanyshkyzy@kbtu.kz

[1]Қазақстан-Британ техникалық университеті, 050040, Алматы қ., Қазақстан

ҚАЗАҚСТАНДАҒЫ БАЛАМАЛЫ ЭНЕРГИЯ КӨЗДЕРІНІҢ ПАЙДАЛАНЫЛУЫ

Аңдатпа

Бұл зерттеудің негізгі мақсаты ЖЭК белгілеудегі Қазақстанның мүмкіндіктерін анықтау және талдау болды. Сұхбат арқылы бастапқы деректерді жинау және бар жұмыстарды талдау және талқылау арқылы қосымша деректерді жинау сияқты зерттеу әдістері қолданылды. Зерттеудің ең маңызды нәтижелері Қазақстанның өз аумағында ЖЭК-ті орнатуға жақсы мүмкіндігі бар екендігі анықталды, алайда кейбір үкіметтік, қаржылық, саяси және операциялық кедергілер анықталды. Осыған қарамастан, нәтижелердің басым бөлігі болашақта Қазақстанның ЖЭК-ті пайдалану бойынша жетекші елдердің біріне айналуы мүмкін екенін көрсетті. Зерттеудің үлесі өте маңызды, өйткені ол жалпы мәселелерді айқындап, жаңа және өткен зерттеулерге сәйкес қол жетімді шешімдерді ұсынады. ЖЭК нысандары мен операциялық құрылымдарын орнатуда егжей-тегжейлі стратегиялар сияқты қосымша зерттеулерге қажеттілік бар. Сондай-ақ осы сала үшін зияткерлік ресурстарды ұлғайтуға мүмкіндік беретін білім беру аспектілерімен байланысты зерттеулер мен іс-шараларды ұйымдастыру керек.

Тірек сөздер: энергияның баламалы көздері, энергетикалық теңгерім, Қазақстан, қазақстандық энергетиканың «жасыл» мүмкіндіктері.

[1]Куанышкызы Ж.,
ORCID ID: 0009-0005-7316-5097
e-mail: z_kuanyshkyzy@kbtu.kz

[1]Казахстанско-Британский технический университет, 050040, г. Алматы, Казахстан

ИСПОЛЬЗОВАНИЕ АЛЬТЕРНАТИВНЫХ ИСТОЧНИКОВ ЭНЕРГИИ В КАЗАХСТАНЕ

Аннотация

Основная цель данного исследования заключалась в выявлении и анализе возможностей Казахстана в установлениях ВИЭ. Использовались такие методы исследования, как сбор первичных данных посредством интервьюирования и сбор вторичных данных посредством анализа и обсуждения существующих работ. Самые важные результаты исследования были выявлены в том контексте, что Казахстан имеет хорошие шансы для поддержания ВИЭ на своей территории, однако были выявлены некоторые правительственные, финансовые, политические и операционные барьеры. Тем не менее большая часть результатов соответствует модели, согласно которой в обозримом будущем Казахстан может стать одной из ведущих стран по использованию ВИЭ. Вклад исследования имеет весомое значение, поскольку оно подчеркивает распространенные проблемы и предлагает доступные решения для них в соответствии с новыми и существующими исследованиями. Имеется необходимость в дальнейших исследованиях, таких как более детальные стратегии создания объектов и операционных структур ВИЭ. Также присутствует огромная потребность в организации исследований и мероприятий, связанных с образовательными аспектами, которые позволили бы увеличить интеллектуальные ресурсы именно для этой сферы.

Ключевые слова: альтернативные источники энергии, энергетический баланс, Казахстан, «зеленые» возможности казахстанской энергетики.

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[1,2]*Mamyrova D.N.,
Bachelor, ORCID ID: 0009-0004-5355-3351
*e-mail: mamyrova.darina@gmail.com

[1]Kazakh-British Technical University, 050000, Almaty, Kazakhstan
[2]University of London, Senate House, Malet Street, WC1E 7HU, London, United Kingdom

CEREMONIAL SPENDING AND HOUSEHOLD DEBT

Abstract

This paper examines the relationship between ceremonial spending and household debt in Kazakhstan. More precisely, it investigates the impact of various household characteristics on the volume of ceremonial expenditure and explores the association between ceremonial spending and the incidence of household debt. The effect of a set of household characteristics on ceremonial spending is assessed using a log-linear regression, treating ceremonial expenditure as log per capita values, and using an ordered probit regression, treating ceremonial spending as a share from total household spending. The effect of ceremonial expenditure, as well as household characteristics, on household incidence of debt is then assessed using probit estimation. The study found that the household characteristics associated with age – the age of the head of the household and the mean age within it – influence the volume of ceremonial expenditure. Other factors affecting ceremonial spending were found to be the number of children and the number of elderly people in the household. Furthermore, household debt in Kazakhstan was found to be heavily influenced by the number of children in the household as well. This study contributes to future extensive empirical research on ceremonial spending in Kazakhstan, providing a base for empirical analysis.

Key words: ceremonial spending, household debt, Consumer loans, household income, Kazakhstani family.

Introduction

The primary goal of this paper is to build understanding of the ceremonial spending patterns of households in Kazakhstan. High level of debt is a significant problem for a Kazakhstani family; recent negative economic shocks showed that households' high indebtedness has serious socio-political implications and could lead to unrest. Recently, a bill on bankruptcy of physical persons was passed, and whether ceremonial spending contributes to household debt is a socially and economically significant question which this paper aims to address. The anecdotal evidence suggests that a lot of celebrations and festivities, such as weddings, are organized on credit. However, there is no official data to support or refute this claim.

The data used in the analysis came from a country-wide household survey, where respondents answered detailed questions on their indebtedness and spending patterns. The effect of household characteristics on spending on celebrations is estimated both in a log-linear regression and in a probit model, ceremonial spending volumes being considered as absolute values and as shares from total spending respectively. Then, the hypothesized relationship between ceremonial spending, as well as other household characteristics, and household debt is estimated using probit regression.

Main provisions

The issue of high indebtedness across the population of Kazakhstan is being addressed in governmental legislation. The volume of unsecured consumer loans, typically provided by microcredit organizations, has increased by 28% YoY (Forbes, 2024). According to official data,

84% of Kazakhstan's adult population are in debt, this figure increasing at a rapid pace. The amount of debt overdue by more than 90 days is about 1.4 trillion tenge; that is, 1.7 million people cannot pay off their debts on time (Radio Azattyq, 2023).

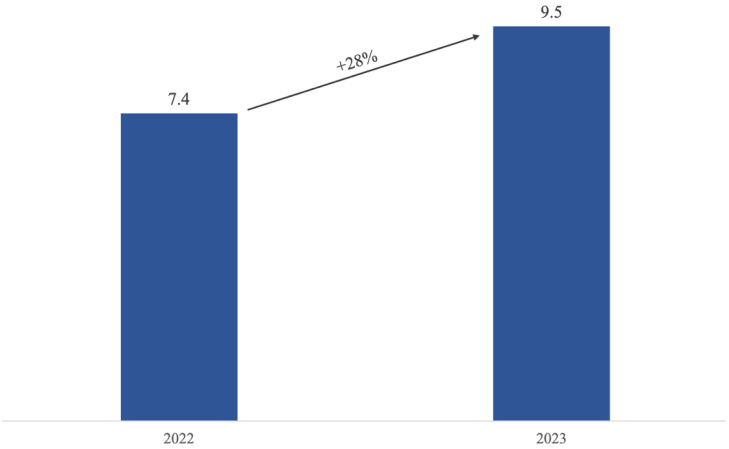

Figure 1 – The Volume of Unsecured Consumer Loans in Kazakhstan, trillions tenge

As of the bill on the bankruptcy of physical persons, since March 3 of 2023, more than 77 thousand applications have been filed.

Consumer loans, in their essence, are crucial to financial markets; one of the true concerns is the purposes to which Kazakhstani residents direct their borrowed money, as well as whether certain purposes have a more significant impact on the current level of debt.

Literature review

The literature review was formed by anchoring this research within a broader landscape of academic discourse on the effect of ceremonial spending on household debt in the context of diverse social, economic, and cultural backgrounds.

Banerjee and Duflo (2006) use household survey data from 13 countries to document the economic lives of the poor population, including their consumption and spending patterns, revealing anomalous choices. The paper makes the key insight that ceremonial spending is a crucial part of budget for many poor households, thus demonstrating that expenditure on festivities plays a large role in forming their debt. Although the authors do not employ regression analysis, the aspects of household survey data that yield most representative results can be highlighted.

Chen and Zhang (2012) also study the correlation between social spending and the level of financial freedom that individuals in China possess, extending the analysis onto the child population's health statuses. They outline that the effects of ceremonial spending are more significant for the poor population rather than those who are financially comfortable due to the fiscal burden being considerably higher. This is a valuable insight for this research, as a parallel can be drawn with ceremonial spending in Kazakhstan; household debt is closely tied with the economic status of said household, thus the effect of ceremonial expenditure is likely more significant for indebted households.

Bloch, Rao and Desai (2004) look at wedding celebrations in rural India or, to be more precise, the determinants of the expenditure on them. More specifically, they investigate the social aspect of it and how "peer pressure" and people's need for validation lead to them engaging in conspicuous consumption. Evidently, the same concept likely holds in both Kazakhstan.

This research is essentially built upon Aldashev (2019), who provides empirical evidence that having access to bank loans leads to Kyrgyzstani households spending more on festivities. In addition, households with higher ceremonial spending levels are more likely to suffer from debt. In other words, higher borrowing leads to higher ceremonial spending, and higher ceremonial spending, in its turn, leads to higher borrowing. The empirical model in this research is inspired by Aldashev, therefore employs a similar framework for the ceremonial spending and household debt patterns in Kazakhstan, providing the opportunity for comparison between the two socially, economically and culturally similar countries.

Materials and methods

Empirical Model

The volume of ceremonial expenditure of a given household depends on a variety of household characteristics (Aldashev, 2019). Empirically, it can be specified in the following way:

$$CS_i = \alpha_0 + \alpha_1 X_i + \epsilon_i$$

Where is the volume of household ceremonial spending, are household characteristics and is the error term satisfying OLS assumptions.

Household debt is then treated as a dummy variable, which takes value 1 if a given household has active debt and 0 if it does not. The debt is specified as a function of household ceremonial spending and household characteristics in a probit model as follows:

$$P(D_i = 1) = \Phi(z_i) = \Phi(\beta_0 + \beta_1 CS_i + \beta_2 X_i + \epsilon_i)$$

$$z_i = \beta_0 + \beta_1 CS_i + \beta_2 X_i + \epsilon_i$$

Where D_i is demand for borrowing, CS_i is the log ceremonial expenditure, X_i is other household characteristics, and ϵ_i is the error term which satisfies OLS assumptions. Assume that $\Phi(z_i)$ follows Normal distribution.

Although the households' volumes of debt, as well as their ability to repay it, are significant to the relationship being analyzed, such data is unavailable. Nevertheless, the incidence of debt is a useful metric as well, as it could mean that a household's spending exceeds its income.

Data and Stylized Facts

The data used in the empirical analysis was obtained from a country-wide household survey – "On the influence of traditions, culture and history on economic results in Kazakhstan" – carried out by the "Public Opinion" Research Institute. The data was collected by the institute specifically in the framework of this project and is hence not yet available to the general public.

The data presents responses from 969 households, fairly evenly distributed across the country. The figure below represents the geographical distribution of the households participating in the survey, presenting evidence of the sample's randomity.

The information taken from the survey includes dummies on debt, which indicated whether a household took out a loan in the past 12 months, whether the household spent on ceremonies within the same time frame and if so, what was the volume of that expenditure. The household characteristics used in analysis were household income, the mean age in the household, the nationality, age and level of education of the head of the household, the share of females, the number of children and elderly people, as well as region and type of residence.

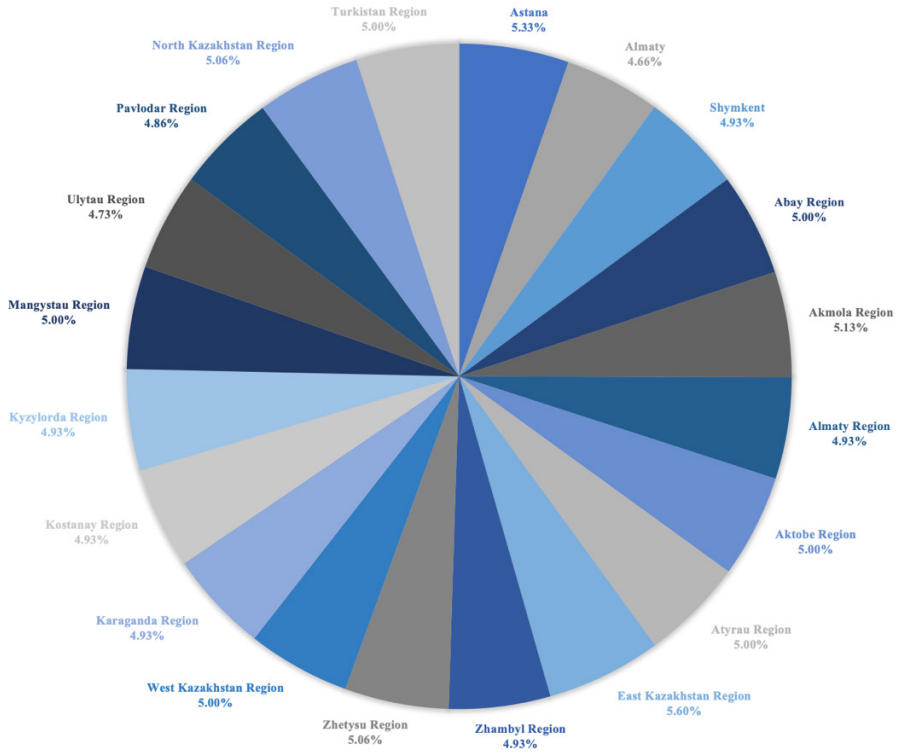

Figure 2 – Geographical Distribution of Households

Upon primary data analysis, it was found that an average Kazakhstani resident spends on average 1,012,429 tenge on celebrations annually. Ceremonies account for 30% to 40% of households' total spending monthly on average. The mean ceremonial spending per capita is 78,184 tenge. The survey also provided data on how much each of the most common types of celebrations contributed to household ceremonial spending. The table below summarizes how much households spent on each of the celebrations and rituals in the past 12 months.

Table 1 – Descriptive Statistics on Ceremonial Spending

Celebration	Mean	Median	Standard Deviation	Minimum	Maximum	N of non-missing values
Weddings from the bride's side (Uzatu Toys)	1,746,786	1,000,000	1,567,681	60,000	6,000,000	28
Weddings from the groom's side (Uilenu Toys)	1,680,466	1,600,000	1,706,485	500	7,000,000	44
Housewarmings and celebrations associated with the purchase of a new car	1,044,477	333,500	1,395,396	20,000	5,000,000	44
Anniversaries	834,342	300,000	1,885,366	10,000	1,500,000	131
Funerals	820,000	500,000	1,276,822	20,000	8,000,000	38
Celebrations associated with childbirth	523,118	300,000	609,248	15,000	3,000,000	85

Gifts given and received on each of these occasions also contribute to household ceremonial spending. The table below summarizes how much money was given to households in gifts or as a gesture of support from their guests.

Table 2 – Descriptive Statistics on Gifts Received on Ceremonies

Celebration	Mean	Median	Standard Deviation	Minimum	Maximum	N of non-missing values
Anniversaries	919,882	200,000	2,952,896	10,000	2,000,000	131
Funerals	1,019,655	600,000	1,345,398	100,000	7,000,000	84
Weddings from the groom's side (Uilenu Toys)	926,618	940,000	853,542	10,000	3,500,000	100
Weddings from the bride's side (Uzatu Toys)	730,790	500,000	593,105	10,000	1,500,000	59
Celebrations associated with childbirth	361,797	225,000	372,131	10,000	1,500,000	151
Housewarmings and celebrations associated with the purchase of a new car	258,158	100,000	411,020	10,000	2,000,000	89

As of household debt, 30% of households in Kazakhstan have taken out a loan in the previous 12 months, meaning that they have active debt. 66% of households took out their loans in commercial banks, and 17% – in microcredit organizations. 10% of households are in debt to a private person, and roughly 4% owe to pawnshops and the Agriculture Financial Support Fund.

For the regression analysis, a set of household characteristics, including yearly household income, was formed, where each of them will serve as independent variables with a hypothesized relationship with ceremonial spending. Given that ceremonial spending and income are given on household levels, they were transformed into per capita values. Additionally, per capita ceremonial spending and per capita household income are taken as natural logarithms to approximate their distribution to that of Normal distribution.

Per capita log household income

The higher the income of the household, the higher are the financial resources that could be directed towards spending on rituals. Hence, a positive relationship between household income and ceremonial spending is expected. The maximum value of log per capita household income is 16.706, meaning that the maximum tenge value of per capita household yearly income is approximately 17,999,958 tenge. Similarly, the minimum value of log per capita household income is 12.388, meaning that the minimum tenge value of per capita household yearly income is approximately 239,999.

The age of the head of household and the mean age in the household

Apart from nationality, there are also likely differences associated with spending patterns across generations. For this reason, age is considered and separated into two variables – the age of the head of the household, who is likely to make major decisions associated with spending, and the mean age of all members of the household. The mean age in an average Kazakhstani household is 39.7 years, whereas the age of an average head of a Kazakhstani household is 50 years.

The level of education of the head of the household

In another hypothesis, a more educated head of a family will spend less on ceremonies. Education is divided into three categories, specified as dummy variables – secondary education, professional secondary education and higher education. The head of the household is then considered low-skilled,

medium-skilled and high-skilled respectively. 47% of all heads of households considered in the analysis are medium-skilled, 40% are high-skilled and 13% are low-skilled.

Numbers of children and elderly people in the household

A direct theoretical correlation cannot be drawn between the presence of children or elderly people in the household, except for the possibility that the presence of elderly people could influence ceremonial spending due to the age component mentioned above. Nevertheless, these variables are still beneficial to include in analysis for the purpose of checking if there is, in fact, some sort of relationship. Household members aged under 18 are considered children and members aged over 65 are considered elderly. There are households without children and elderly people present in the sample; the maximum number of children in one household is 5, whereas that of elderly is 2.

Share of females in the household

This variable is included for the purpose of discovering whether gender has an impact on ceremonial spending. The mean share of females in households is 0.5; there are household composed of males only, as well as females only.

Residence

In this sample, there are two types of household residence – city and village. Due to the obvious economic, industrial and social differences between them, there is potential for a correlation with the volume of ceremonial spending; thus, this variable is included as a dummy. 32% of households in the sample reside in cities while 68% live in villages.

Region

There are likely to be economic differences between the different regions of Kazakhstan that could influence household spending patterns and what portion of income is directed towards rituals and ceremonies. This variable is included as a dummy as well. The geographical distribution of households interviewed in the survey is fairly uniform; the region with the most respondents is East Kazakhstan, while Almaty presents the fewest number of households in the dataset.

Although the households' levels of financial literacy would be of interest, such data is unavailable.

Results and discussion

Table 3 below provides the regression results corresponding the effect of household characteristics on ceremonial spending, specified by the empirical equation:

$$CS_i = \alpha_0 + \alpha_1 X_i + \epsilon_i$$

Dummy variables of regions were omitted from this summary and onward due to irrelevance to the models.

Table 3 – The Effect of Household Characteristics on Ceremonial Spending

Dependent Variable: Log per capita ceremonial spending			
Variable	Coefficient	Standard error	Significance
Log per capita income	0.20	0.19	
Share of females	0.15	0.55	
Number of children	0.09	0.15	
Number of elderly people	-0.42	0.18	**
Household mean age	0.05	0.02	***

Continuation of table 3

Head of the household age	-0.03	0.01	***
Head of the household medium-skilled	0.09	0.35	
Head of the household high-skilled	0.04	0.36	
Household resides in a city	-0.27	0.30	
F			1.89
R2			0.28
N			152

* – significant at = 0.1
** – significant at = 0.05
*** – significant at = 0.01

From the regression results, there are three significant variables in the model – the number of elderly people in the household, the mean age in the household and the age of the head of the household. Specifically, the number of elderly people and the age of the head of the household are negatively correlated with the volume of ceremonial expenditure. The reason for this is most likely a social one; a possible explanation could be that younger people are more psychologically inclined towards status spending.

Log per capita income does indeed have a positive effect on ceremonial spending; however it is not significant. The gender composition of households, the number of children in them, the levels of education of heads of households and the type of residence are not significant to this model either.

There are only 152 observations in this regression because a large portion of the respondents preferred not to give a specific number for their ceremonial expenditure or struggled to recall it. Hence, the next regression presents the effect of household characteristics on the share of ceremonial spending out of the total household spending. This part of the survey was obligatory; thus, there is no issue with the number of observations. Since the question was given in the form of several answer options (i.e., if the share of ceremonial spending out of total spending was under 10%, under 20%, etc.), I use ordered probit. The regression results are summarized in Table 4.

Table 4 – The Effect of Household Characteristics on the Share of Ceremonial Spending from Total Spending

Dependent Variable: Share of ceremonial spending out of total spending			
Variable	Coefficient	Standard Error	Significance
Share of females	-0.15	0.12	
Number of children	-0.09	0.03	***
Number of elderly people	-0.18	0.06	***
Household mean age	-0.00	0.00	

Continuation of table 4

Head of the household age	0.00	0.00	
Head of the household low-skilled	0.00	0.12	
Head of the household medium-skilled	-0.05	0.08	
Household resides in a city	0.13	0.09	
LR chi2(27)			182.14
Log likelihood			-1723.40
N			946

* – significant at = 0.1
** – significant at = 0.05
*** – significant at = 0.01

With this approach, there are two variables significant to the model – the number of children and the number of elderly people in a household. The number of children likely has a strong effect on the volume of ceremonial spending due to those resources that could have been spent on festivities being instead directed towards those expenses that bringing up children requires. As of the number of elderly people, the previously mentioned negative correlation holds.

Table 5 below provides the regression results for the effect of ceremonial spending on household debt, specified by the empirical equation:

$$P(D_i = 1) = \Phi(z_i) = \Phi(\beta_0 + \beta_1 CS_i + \beta_2 X_i + \epsilon_i)$$

$$z_i = \beta_0 + \beta_1 CS_i + \beta_2 X_i + \epsilon_i$$

Table 5 – The Effect of Ceremonial Spending on Household Debt

Dependent Variable: Incidence of debt			
Variable	Coefficient	Standard Error	Significance
Log per capita ceremonial spending	0.10	0.09	
Log per capita income	0.02	0.19	
Share of females	-0.81	0.57	
Number of children	0.39	0.16	**
Number of elderly people	-0.18	0.22	
Household mean age	0.01	0.02	
Head of the household age	0.00	0.02	

Continuation of table 5

Head of the household low-skilled	-0.44	0.40	
Head of the household medium-skilled	-0.06	0.30	
Household resides in a city	-0.25	0.31	
LR chi2(27)			28.57
Log likelihood			-84.85
N			144

* – significant at = 0.1
** – significant at = 0.05
*** – significant at = 0.01

Per capita ceremonial spending has no significant effect on the incidence of debt, and the only significant variable in this model is the number of children. In other words, the more children a Kazakhstani family has, the likelier it is that said family is indebted, which is due to the increased spending that emerges with childbirth. In 2023, 1.3 trillion tenge in social payments for families with more than 4 children was being directed to 2.6 million households, the former value increasing by 40% YoY (Vecher.kz, 2023). According to the empirical results above, the growing number of consumer loans being issued could be in a statistically significant positive correlation with the growing number of large families.

One of the potential explanations for the lack of relationship between ceremonial spending and household debt is issues with the data – a portion of respondents preferred not to answer the question if they had active debt, thus generating missing values in the debt variable and a smaller number of observations than could be needed for better estimates. Naturally, it is also possible that households in Kazakhstan organize festivities using their savings, and ceremonial expenditure has no sufficient impact on households' indebtedness, the latter rather being attributed to other socio-economic factors.

Conclusion

When analyzing the effect of household characteristics on log per capita ceremonial spending, we see that the factors associated with age – the mean age in the household, the age of the head of the household and the number of elderly people – are significant to the model, indicating that age has a strong effect on decision-making on ceremonial expenditure. According to the empirical results, older people are less inclined towards status spending than younger Kazakhstanis. When ceremonial spending was taken as a share of total spending in an ordered probit regression, another highly significant variable was observed, that being the number of children, also having a negative effect coefficient. One possible explanation to this is that the expenses associated with childbirth and taking care of children in general likely triggers changes in households' spending patterns.

As of household debt, the only variable having a significant effect on its incidence was found to be the number of children. As mentioned above, families with more children likely spend more and thus their likelihood of borrowing is higher. No significant correlation between ceremonial spending and household debt was observed. It could be possible that Kazakhstani households finance their festivities using their savings and the high levels of indebtedness come from other socio-economic factors; yet, given that this is the first study on ceremonial spending and household debt in the context of Kazakhstan, a foundation is laid for future extensive empirical research to be built upon for the better understanding of status spending patterns and their significance to economic wellbeing.

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[1,2]*Мамырова Д.Н.,
бакалавр, ORCID ID: 0009-0004-5355-3351
e-mail: mamyrova.darina@gmail.com

[1]Қазақстан-Британ техникалық университеті, 050000, Алматы қ., Қазақстан
[2]Лондон университеті, WC1E 7HU, Лондон қ., Ұлыбритания

САЛТАНАТТЫ ШЫҒЫНДАР ЖӘНЕ ҮЙ ШАРУАШЫЛЫҒЫНЫҢ ҚАРЫЗЫ

Аңдатпа

Бұл жұмыс Қазақстандағы салтанатты шығындар мен үй шаруашылықтары қарызының арасындағы байланысты қарастырады. Дәлірек айтсақ, әртүрлі тұрмыстық сипаттамалардың салтанатты шығындардың көлеміне әсерін зерттейді және салтанатты шығындар мен үй шаруашылығы қарызының пайда болуы арасындағы байланысты зерттейді. Үй шаруашылығы сипаттамалары жиынтығының салтанатты шығындарға әсері лог-сызықтық регрессия арқылы бағаланады, салтанатты шығындарды жан басына шаққандағы капитал мәндері ретінде қарастырады және реттелген пробит регрессиясын пайдалана отырып, салтанатты шығындарды үй шаруашылығының жалпы шығындарының үлесі ретінде қарастырады. Салтанатты шығындардың, сондай-ақ үй шаруашылығы сипаттамаларының үй шаруашылығы қарыздарының жиілігіне әсері кейін пробиттік бағалау арқылы бағаланады. Зерттеу көрсеткендей, жасқа байланысты үй шаруашылығының ерекшеліктері – үй шаруашылығы басшысының жасы және ондағы орташа жас – салтанатты шығындардың көлеміне әсер етеді. Үй шаруашылығындағы балалар мен қарт адамдардың саны салтанатты шығындарға әсер ететін басқа факторлар екендігі анықталды. Сонымен қатар, Қазақстандағы үй шаруашылықтарының қарызына үй шаруашылығындағы балалар саны да қатты әсер ететіні анықталды. Бұл зерттеу эмпирикалық талдау үшін негіз бола отырып, Қазақстандағы салтанатты шығындар бойынша болашақтағы ауқымды эмпирикалық зерттеулерге үлес қосады.

Тірек сөздер: салтанатты шығыстар, үй шаруашылығының қарызы, тұтыну несиелері, жеке табыс, қазақ отбасы.

[1,2]*Мамырова Д.Н.,
бакалавр, ORCID ID: 0009-0004-5355-3351
e-mail: mamyrova.darina@gmail.com

[1]Казахстанско-Британский технический университет, 050000, г. Алматы, Казахстан
[2]Лондонский университет, WC1E 7HU, г. Лондон, Великобритания

ЦЕРЕМОНИАЛЬНЫЕ РАСХОДЫ И ДОЛГ ДОМОХОЗЯЙСТВ

Аннотация

В данной статье рассматривается взаимосвязь между церемониальными расходами и долгом домохозяйств в Казахстане. Исследование направлено на анализ влияния различных характеристик домохозяйств на объем церемониальных расходов и связи между церемониальными расходами и наличием долга домохозяйств. Влияние набора характеристик домохозяйства на церемониальные расходы оценивается с помощью лог-линейной регрессии, рассматривающей церемониальные расходы как логарифмические значения на душу населения, и с использованием упорядоченной пробит-регрессии, рассматривающей церемониальные расходы как долю от общих расходов домохозяйства. Влияние церемониальных расходов, а также характеристик домохозяйства на наличие долга затем оценивается с использованием пробит-регрессии. Исследование показало, что на объем церемониальных расходов влияют характеристики домохозяйства, связанные с возрастом – возраст главы домохозяйства и средний возраст внутри него. Другими факторами, влияющими на церемониальные расходы, оказались количество детей и количество пожилых людей в семье. Кроме того, было обнаружено, что долг домохозяйств в Казахстане зависит от количества детей в домохозяйстве. Данное исследование предоставляет основу для будущих эмпирических исследований церемониальных расходов в Казахстане.

Ключевые слова: церемониальные расходы, долг домохозяйств, потребительские кредиты, доходы населения, казахстанская семья.

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ЖУРНАЛЫНДА ЖАРИЯЛАНАТЫН МАҚАЛАЛАРДЫ РӘСІМДЕУГЕ ҚОЙЫЛАТЫН ТАЛАПТАР

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Соңында «Әдебиеттер тізімі (References)» жазылады. Мәтіндегі әдеби сілтемелер төртбұрышты жақшада ұсынылады [1]. Әдебиеттер тізімі МЕМСТ-ке сәйкес екі рет рәсімделеді. Тізім мақаланың негізгі мәтініне толық сәйкес келіп, мақалада аталған (тек аталған) барлық жұмыстарды қамтуы керек. Әрі қарай, дәл осы сілтемелер жалпы қабылданған ағылшын транслитерациясында жазылады.

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