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[1]Messerle V. E.,
Dr.Phys.-Math.Sc., Professor, ORCID ID: 0000-0003-4281-1429,
e-mail: ust@physics.kz
[1]Ustimenko A. B.,
Dr.Phys.-Math.Sc., Professor, ORCID ID: 0000-0003-0033-1371,
e-mail: alexanderustimenko@gmail.com
[1]Lavrishchev O.A.,
Cand. Phys.-Math.Sc., Associate Professor, ORCID ID: 0000-0002-5934-8381,
e-mail: lavr@physics.kz
[1]*Nugman M.K.,
Doctoral student, ORCID ID: 0009-0004-3366-5348,
*e-mail: nugmanmarina@gmail.com

[1]Al-Farabi Kazakh National University, Almaty, Kazakhstan

EXERGETIC METHODOLOGY FOR STANDARDIZED PERFORMANCE ASSESSMENT OF PLASMA PROCESSES

Abstract

This article proposes a unified exergetic methodology for comparable, reproducible assessment and subsequent standardization of plasma processes. Based on the Second Law of Thermodynamics, it integrates exergy efficiency (η_{ex}), specific energy consumption (Q_{sp}), exergy ignition cost (EIC), and environmental performance index (EPI) into a formalized KPI-stack. Unlike First Law criteria, the approach accounts for energy quality, irreversibility, and the non-equilibrium nature of plasma, distinguishing chemical, physical, and ionization components and quantifying exergy destruction at individual process stages. The methodology covers plasma ignition, gasification, reforming, and processing of gaseous, liquid, and solid hydrocarbon feedstocks and waste. Measurement, uncertainty assessment, and quality control are aligned with cited metrological requirements; environmental comparisons may incorporate life-cycle assessment. An oil-sludge case study compares conventional combustion at 1100 K with plasma-supported combustion at 1500–2000 K at a fixed process thermal power of 2000 kW. Calculations show differential exergy efficiency increasing from 0.546 to 0.636–0.675 and specific exergy losses decreasing from 18.27 to 14.48 MJ/kg. Environmental performance improves through a higher EPI and lower NO_2 emissions. Beyond thermal disposal, plasma processing produces valuable synthesis gas with total exergy reaching 156.7 MJ. The unified KPI-stack supports technology comparison, operating-mode optimization, and integration into regulatory and technical documentation.

Keywords: plasma processes, exergy analysis, key performance indicators, KPI-stack, energy efficiency, decarbonization, standardization.

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Introduction

The modern energy and industrial policy of most countries, including the Republic of Kazakhstan, is focused on reducing the carbon footprint, increasing energy efficiency, and introducing the Best Available Technologies (BAT) as part of strategies to achieve carbon neutrality [1, 2]. In this context, plasma technologies are considered a promising tool for the deep thermochemical conversion of hydrocarbon raw materials and man-made waste (coal, fuel oil, sludge, biomass, solid household waste) into synthesis gas and other energy-valuable products, while reducing pollutant emissions and the carbon footprint.

Despite the intensive development of plasma technologies and a significant amount of experimental and computational research, there is still no single, unified approach to quantifying their effectiveness in the scientific and engineering literature. Disparate criteria are used for analysis, such as thermal efficiency, the degree of fuel conversion, synthesis gas yield, the rate and stability of ignition, and the specific energy consumption of the plasma torch. The use of various indicators, calculation schemes, and assumptions significantly complicates the comparability of results, limits correct inter-technological comparison, and hinders the formation of a regulatory framework and standards.

Traditional methods of evaluating efficiency, based primarily on the First Law of Thermodynamics, do not adequately describe the physical nature of plasma processes. In particular, they do not take into account the non-equilibrium nature of high-temperature plasma, the structure and magnitude of irreversible losses of available energy, or the redistribution of supplied energy between chemical, physical, and ionization components. As a result, energy indicators do not reflect the quality of energy and do not allow for an objective assessment of the effectiveness of plasma technologies from the perspective of the Second Law of Thermodynamics.

International research in the field of plasma-assisted combustion and plasma gasification shows that the lack of unified exergetic parameters leads to a formal and incomplete comparison of various technological solutions. This circumstance is of particular importance in the context of the transition to BAT and the need to justify technological schemes based on energy, environmental, and resource criteria simultaneously.

In this regard, an urgent scientific and applied task is to develop a universal methodology for quantifying the effectiveness of plasma processes, applicable to various types of fuels, plasma installations, and operating modes. Such a methodology should ensure comparability of results, reproducibility of calculations, and the possibility of integration into regulatory, technical, and standard documents.

In this paper, we hypothesize that the efficiency of plasma processes can be objectively, fully, and reproducibly assessed only on the basis of exergy analysis based on the Second Law of Thermodynamics. The exergetic approach is considered a fundamental basis for the formation of a unified and standardized set of key performance indicators (KPI-stack).

The methodological basis of the study is exergy analysis, upon which a universal measurement and calculation methodology has been developed. This methodology establishes a procedure for quantifying the effectiveness of plasma ignition, gasification, and reforming of hydrocarbon fuels in gas, liquid, and solid phases. Hereafter, all plasma technologies are considered within a single thermodynamic logic, where the key object of analysis is not only the amount of energy supplied but also its quality, determined by exergy.

Equilibrium thermodynamic models are used in this work as a tool for the initial assessment of the limiting characteristics of plasma processes, while non-equilibrium models and experimental diagnostic methods are used to refine and verify calculated data. In this case, exergy analysis acts as a link between model calculations and the actual technological parameters of plasma installations.

The numerical case study presented in this paper is limited to oil sludge. References to coal, biomass, municipal solid waste, and other feedstocks describe the intended applicability range of the methodology and the reviewed literature, rather than the feedstock used in the calculations.

The proposed methodology does not replace existing theoretical and experimental approaches but formalizes and summarizes accumulated global experience, translating it into a unified measurement and calculation protocol suitable for technology comparison and subsequent standardization.

Abbreviations and definitions

Exergy (Ex) – The maximum useful work a system can perform when brought into equilibrium with the environment under given conditions.

Exergetic efficiency coefficient (n_{ex}) – The ratio of the useful exergy of the process products to the total exergy of all input flows.

Specific energy consumption (Q_{sp}) – The amount of energy or exergy supplied per unit of processed raw material or resulting product.

Exergetic ignition cost (EIC, Exergy Ignition Cost) – The total exergy consumed to initiate and stabilize a plasma regime or flame (an integral characteristic of the costs for initiating and stabilizing a plasma regime).

Environmental Performance Index (EPI) – A dimensionless indicator characterizing the environmental effectiveness of a process based on the ratio of actual pollutant concentrations to regulatory values (a generalized environmental metric for comparing different types of feedstocks and technologies).

KPI (Key Performance Indicators) – Quantifiable metrics used to evaluate and compare the effectiveness of technological processes.

KPI-stack – A unified set of interrelated key performance indicators used for the comprehensive performance assessment of plasma processes.

LTE (Local Thermodynamic Equilibrium) – A state in which the temperatures of the different degrees of freedom of particles are considered equal.

CR model (Collisional-Radiative Model) – A kinetic model describing the excitation and ionization of plasma particles, accounting for collisional and radiative processes.

PGM (Plasma Gasification Melting) – A high-temperature process in which waste is converted into energy-rich synthesis gas and inert vitreous slag.

WtV (waste-to-value) – An approach to waste management where waste is treated not as refuse for disposal, but as a valuable resource for creating new products, energy, or raw materials.

BAT – Best Available Techniques (or Technologies).

PFS - Plasma fuel system.

Q – Thermal power.

T – Absolute temperature of the process.

T_0 – Ambient temperature at P0 = 1 atm at 80% relative humidity.

p – Pressure.

P – Installation power in kW.

t – Time to reach the required temperature and measure in h.

m – Mass of fuel in kg.

η_{ex}^{int} – Integral exergy efficiency.

η_{ex}^{dif} – Differential (stream) exergy efficiency.

Materials and methods

Models and Methods for the Exergy-Based Performance Assessment of Plasma Processes

Standardization, as a tool for scaling and commercializing scientific developments, requires the accumulation of comparable data, the identification of universally applicable norms, and the formalization of calculation and measurement procedures. In plasma technologies, thermodynamic assessment is applied in the design of installations (gasifiers, plasma torches, plasma-fuel systems), the optimization of operating modes (temperature, oxidizer/fuel ratio, specific energy consumption), and performance evaluation (energy and exergy indicators, feedstock/waste conversion rates).

The study employs two classes of modeling approaches: equilibrium thermodynamic models (for high-temperature plasma close to LTE) and non-equilibrium kinetic/CR model/state-to-state models (for low-temperature and highly non-equilibrium media), as well as experimental diagnostic methods for model verification and plasma parameter reconstruction.

Data provenance and validation scope. The present study is methodological and computational. The oil-sludge case study combines equilibrium thermodynamic calculations with input data reported in Refs. [4, 34–36]. The origin of each parameter is classified as experimental, rated, literature-derived, assumed, or calculated. The KPI values, including η_{ex}, specific exergy loss, EIC, EPI, and syngas exergy, were calculated using the equations presented below. Verification was performed by comparison with previously published experimental data from Refs. [34–36]. No new independent experimental campaign was conducted within the present study.

The classical approach for describing the plasma gasification of solid waste and biomass is equilibrium thermodynamic modeling based on Gibbs energy minimization (or equilibrium thermodynamic models (Gibbs minimization)) under given conditions, such as T, p, and the elemental composition of the system (n_i) [3–9].

Input data (minimum required for reproducibility):

- Elemental composition of fuel/waste (C/H/O/N/S/Cl + ash/moisture content, if applicable);
- Type and flow rate of the plasma-forming gas/oxidizer;
- Pressure p and temperature range T;
- Steam/air/oxygen/fuel ratios (depending on the problem statement).

Output parameters of the equilibrium model:

- Synthesis gas composition (CO, H_2, CO_2, CH_4, H_2O, N_2, etc.);
- Fraction of condensed phases/slag;
- Integral indicators: heating value of the synthesis gas, gas yield, and temperature regime targets [3–9].

In applied research, equilibrium models are used to calculate synthesis gas composition and energy/exergy indicators for the plasma gasification of MSW [3, 4], to analyze PGM stages (drying, pyrolysis, gasification, melting) in terms of energy and exergy [5], and to optimize operating modes within WtV concepts [7–9].

However, despite the convenience of this approach, there are certain limitations to its application. The equilibrium formulation does not account for kinetics, hydrodynamics, the actual structure of the plasma flare, or the inhomogeneity of temperature and composition fields. The model provides an assessment of the 'ideal' limit of performance.

The main positive aspect of the equilibrium model is its applicability in conjunction with exergy analysis. To transition from 'gas composition' to comparable effectiveness, exergy analysis (the Second Law of Thermodynamics) is used as the primary quantitative tool for assessing energy quality and irreversible losses. Research [5] shows that the 'equilibrium calculation → exergy balance' link allows for the localization of exergy losses by PGM stages and the identification of 'bottlenecks,' the evaluation of the impact of air preheating and the steam/biomass ratio on exergy efficiency [6], and the formulation of engineering-interpretable metrics such as specific synthesis gas yield (Nm^3/kg), cold gas efficiency (%), exergy efficiency, and specific electricity consumption of the plasma torch (kWh/kg) [4–6, 10–12].

For the numerical modeling of the plasma processing of carbon-containing materials in steam/gas/air plasma, the TERRA software package is utilized. It enables equilibrium calculations, evaluation of the influence of operating parameters and feedstock composition, and determination of specific energy consumption and energy efficiency indicators; comparison with experimental data on gas composition confirms the applicability of the thermodynamic approach for the exergetic interpretation of process performance and normalization.

"Non-equilibrium plasma models, such as state-to-state and CR approaches, were reviewed. For the class of plasma technologies where equilibrium assumptions are violated (low-temperature discharges, plasma jets at reduced pressures, hypersonic flows), models that account for the non-equilibrium between translational, vibrational, and electronic degrees of freedom are utilized.

Within the state-to-state approach, each vibrational-electronic level is treated as a separate 'species' with its own number density [16]. CR models describe excitation/ionization kinetics through a system of kinetic equations and are used in conjunction with gas dynamics and radiative transfer, including the calculation of electron and excitation temperatures, level distributions for spectroscopy, and radiation power [17–19]. While physically informative, these methods are computationally expensive and require large datasets of cross-sections and rate coefficients; therefore, in applied energy problems, they are typically used selectively (for diagnostics/verification) or in the form of reduced models [18].

The third methodological approach involves experimental methods and diagnostics (model verification). Spectral methods (OES, LIBS, etc.) are used for the experimental verification of models and the reconstruction of plasma parameters. Based on the spectra of impurity ions/atoms, and utilizing excitation models and CR approximations, particle densities, flows, and sources in the plasma are estimated [20]. LIBS methods, with corrections for matrix effects and self-absorption, are applicable for the analysis of products and particles within the plasma flare [21]. To quantify the gas composition after plasma processing, gas chromatography, mass spectrometry, and IR analyzers are employed [23]. Comparing the measured synthesis gas composition (CO, H_2, CH_4, CO_2, etc.) with the modeled data provides a quantitative assessment of the deviation from equilibrium and serves as a basis for adjusting assumptions and accounting for losses [4, 10–15, 23].

The proposed methodology relies on the KPI-stack concept for plasma processes as a universal exergy-based method. The base set of indicators includes exergy efficiency, specific energy consumption, Exergy Ignition Cost (EIC), and the Environmental Performance Index (EPI), which is linked to pollutant regulations [24].

The exergy balance is formulated by comparing the total exergy of inflows (electrical exergy, and the chemical and physical exergy of the fuel and oxidizer) with the exergy of the products (synthesis gas, melt/slag phase), while accounting for losses (cooling, radiation, etc.).

Thus, the KPI-stack provides a unified performance assessment for various types of fuels (gas, fuel oil, coal, oil sludge, waste) and different plasma technologies (ignition, gasification, reforming), provided that a unified computational protocol and a single input data structure are maintained.

Uncertainty Assessment and Data Quality Requirements

To ensure the reproducibility and suitability of results for standardization, the measurement and calculation procedure must be accompanied by an accuracy assessment and internal quality control. RMG 61-2010 and RMG 76-2014 are used as the regulatory framework for evaluating accuracy, trueness, and precision indicators, as well as for the quality control of quantitative analysis results. For environmental comparability, ISO 14044 approaches may be applied when an LCA (Life Cycle Assessment) interpretation is required [37–39].

The calculated KPI values were verified by comparison with the experimental results reported in Refs. [34–36]. The combined relative uncertainty was estimated at ±6-10%. The main contributions were associated with temperature measurement (±1.5%), gas composition (±3%), electrical power (±1%), and mass measurement (±0.5%).

The KPI Concept for Plasma Technologies

Equilibrium thermodynamic models and exergy analysis form the basis for the primary quantitative assessment of high-temperature plasma processing and gasification [3–15, 26–33]. Non-equilibrium CR/state-to-state approaches are key for low-temperature and specialized plasma regimes, providing a physically correct link between diagnostics and spectroscopy [16–22]. The combined application of models and instrumental methods ensures sufficient data completeness for the reconstruction of process parameters.

Thus, the KPI-stack provides a unified performance assessment for the application of various plasma technologies (ignition, gasification, reforming) in the processing of different fuel types (gas, fuel oil, coal, oil sludge, waste), provided that a unified computational protocol and a single input data structure are maintained.

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Results and discussion

The KPI-stack method is based on the Second Law of Thermodynamics and defines the quantitative efficiency of a plasma process as the ratio of the exergy of the reaction products to the total input exergy:

$$\eta_{ex} = \frac{\sum Ex_{вых} + \sum Ex_{потерь}}{Ex_{вход}} \tag{1}$$

where: ΣEx_{in} – input exergy, including electrical and reaction energy;

ΣEx_{prod} – exergy of products, including the chemical and thermal exergy of the synthesis gas and condensed phases;

ΣEx_{loss} – irreversible losses (radiation, cooling, leakage, etc.).

Calibrated measuring instruments are used for measurements: K-type thermocouples (up to 2500K, accuracy ±0.5%); an optical pyrometer (PIR-1800 or equivalent); gas analyzers (Infracar or equivalent for H_2, CO, CO_2, CH_4, N_2, O_2, H_2S, NO_x, SO_2); wattmeters (up to 200kW, accuracy 1%); analytical balances (0.01g); and the TERRA software package (or equivalent) for thermodynamic exergy calculations. Calculations and comparisons were performed at a process thermal power of 2000kW. Given a lower heating value (LHV) of the oil sludge of 40.2MJ/kg, the calculated fuel consumption is approximately 179.1kg/h.

Exergy of each component:

$$Ex_i = \eta_i \cdot (h_i - h_0) - T_0 \cdot (s_i - s_0) \tag{2}$$

The exergy calculation is based on the specific heat consumption in a combined Carnot cycle using their mean thermodynamic temperatures, a method also known as exergy analysis.

Carnot factor (Carnot coefficient):

$$\tau = 1 - \frac{T_0}{T} \tag{3}$$

Exergy efficiency via the Carnot factor:

$$\eta = 1 - \frac{2T_0}{T + T_0} \tag{4}$$

Exergy efficiency via the Carnot factor:

$$exQ = Q \times \eta \tag{5}$$

where η is the thermal efficiency of the cycle, or the "heat quality" factor.

KPI-stack Indicators:

To ensure a correct comparison between traditional combustion and plasma gasification technologies, the KPI-stack is divided into two functional branches:

I. Full combustion mode, where the target product is the exergy of useful heat.

$$Ex_{use}^{int} = Q_{use} * \tau = Q_{use} * (1 - \frac{T_0}{T}) \quad (6.1)$$

$$Ex_{use}^{dif} = Q_{use} * \tau = \eta * Q * (1 - \frac{T_0}{T}) \quad (6.2)$$

II. Plasma processing mode with synthesis gas production, where the target product is the exergy of the gas.

$$Ex_{gas} = Ex_{gas}^{ch} + Ex_{gas}^{ph} \quad (7)$$

Exergy efficiency is calculated as the ratio of the target product's exergy to the total input exergy of the fuel and electrical energy.

KPI-stack indicators:

Exergy efficiency of the process (for combustion):

$$\eta_{ex} = \frac{Ex_{use}}{Ex_{el} + Ex_{fuel}} \quad (8)$$

Fuel exergy:

$$Ex_{fuel}^{int} = \mathrm{m}_{fuel} \times Q_{fuel} \quad (9.1)$$

$$Ex_{fuel}^{dif} = Q \quad (9.2)$$

Useful heat:

$$Q_{use}^{int} = \eta_{th} * Ex_{fuel} \quad (10.1)$$

$$Q_{use}^{dif} = \eta_{th} * Q \quad (10.2)$$

Total electrical power:

$$P_{el} = P_{aux} + P_{plaz} \quad (11)$$

Electrical input exergy:

$$Ex_{el}^{int} = P_{el} * t * \eta_{th} \quad (12.1)$$

$$Ex_{el}^{dif} = P_{el} \quad (12.2)$$

In the initial calculations, the exergy of the fuel and electrical input was determined in integral form (MJ) for a given operating time. For the analysis of the facility's steady-state operation, the calculation was performed in flow form (kW). A flow-based (power/integral) approach was used in the exergy analysis. The fuel exergy flow is assumed to be equal to the process thermal power (9.2), which is equivalent to the chemical exergy of the fuel burned at a given flow rate. The electrical exergy flow is equal to the consumed electrical power (12.2), since electrical energy is entirely exergetic (with an exergy factor of 1).

Specific energy consumption:

$$Q_{sp}^{int} = \frac{(Ex_{fuel} + Ex_{el} - Ex_{use})}{m} \quad (13)$$

Exergetic Ignition Cost (EIC):

$$EIC^{int} = \frac{Ex_{el}}{m} = \frac{P_{el} * t * \eta_{th} * 3.6}{m} \quad (14)$$

Environmental Performance Index (EPI):

$$EPI = \frac{C_{\text{пдк}}^{\text{воз}}}{C_{\text{факт}}} \times \eta_{ex} \quad (15)$$

where C_{MPC}^{WHO} – is the standardized (regulatory) concentration of the pollutant, and
C_{fact} – is the measured concentration in the emission zone.
For a key pollutant j (e.g., NO_2, SO_2, $PM_{2.5}$):

$$EPI_j = \eta_{ex}^{dif} \times \frac{C_{MPC}^{WHO}}{C_{fact}} \quad (16)$$

Composite index for the aggregate of pollutants::

$$EPI = \sum_j \omega_j \times EPI_j \quad (17)$$

where ω_j are weighting factors (proportional to the impact significance or inversely proportional to the MPC).

The KPI-stack calculation below is presented using the example of oil sludge combustion in a furnace equipped with a PFS compared to combustion without one (hereinafter referred to as traditional combustion). The data is based on research findings [4, 34–36]. The raw data is provided in Table 1, the justification for the selected research temperatures is given in Table 2 [4, 34–36], and the KPI-stack calculation for oil sludge is presented in Table 3.

I. Full combustion mode, where the target product is the exergy of useful heat.

All calculations were performed at a fixed process thermal power of Q = 2000 kW. The electrical power of the plasma torch was Pplaz = 400 kW. Therefore, the value of 2000 kW should not be interpreted as the electrical power of the plasma torch or its power supply system.

Table 1 – Comparative exergy calculation for a single PFS during oil sludge processing

Parameter / Type	Traditional Combustion	PFS -Assisted Gasification	
Fuel combustion temperature, T (K)	1100	1500	2000
Plant efficiency (rated/nominal data), ηth	0,75	0,95	0,95
Plasma torch power, Pplaz (kW)	-	400	400
Furnace ignition power, Paux (kW)	10	-	-
Process thermal power, Q (kW) ≈ MJ/s	2000 ≈ 2		
Mass of processed fuel, mfuel (kg)	10		
Oil sludge flow rate, m˙ (kg/h)	179,1		
Combustion time, t (h)	0,05		
Ambient temperature, T0 (K)	295		
Ambient pressure, p0 (kPa)	101,325		
Fuel heating value, Qfuel (MJ/kg)	40,2		
Input fuel exergy (MJ)	10*40,2=402		
Fuel exergy flow (kW)	2000		

Continuation of Table 1

Net calorific value (LHV) of oil sludge (MJ/kg)	20		
Carnot factor, τ	$1-\frac{295}{1100}=0{,}7318$	$1-\frac{295}{1500}=0{,}8033$	$1-\frac{295}{2000}=0{,}8525$
Exergetic cycle efficiency	$1-\frac{2*295}{1100+295}=0{,}577$	$1-\frac{2*295}{1500+295}=0{,}671$	$1-\frac{2*295}{2000+295}=0{,}743$
Exergetic power (Exergy flow), exQ (kW)	2000*0,577=1154	2000*0,671=1342	2000*0,743=1486
Useful heat from combustion (MJ)	0,75*402=301,5	0,95*402=381,9	0,95*402=381,9
Useful heat rate from combustion (kW)	2000*0,75=1500	2000*0,95=1900	2000*0,95=1900
Exergy of useful heat (MJ)	301,5*0,7318=220,64	381,9*0,8033=306,78	381,9*0,8525=325,57
Useful heat exergy flow, Exuse (kW)	0,75*2000*0,732 =1097,73	0,95*2000*0,8033 =1526,33	0,95*2000*0,8525 =1619,75
Electrical input exergy (kWh)	10кВт*0,05ч*0,75 =0,375 (= 1,35 МДж)	400кВт*0,05ч*0,95 =19 (=68,4 МДж)	400кВт*0,05ч*0,95 =19 (=68,4 МДж)
Electrical input exergy flow (kW)	10	400	400
Exergetic process efficiency	220,64/(1,35+402) =0,547	306,78/(68,4+402) =0,652	325,57/(68,4+402) =0,692
Fuel combustion temperature, T (K)	1097,73/(2000+10) =0,5461	1526,33/(2000+400) =0,6359	1619,75/(2000+400) =0,6749

Note: According to the requirements of the Stockholm Convention and UNEP (United Nations Environment Programme) standards, a temperature of at least 1500 K is required for the complete destruction of organochlorine compounds in oil sludges. The PFS ensures a stable temperature regime above 1700°C (2000 K), which guarantees the environmental safety of the process and exceeds WHO (World Health Organization) international destruction standards.

In this work, two forms of the exergy efficiency coefficient are utilized:

η_{ex}^{int} (cycle efficiency) characterizes the efficiency of a specific processing cycle, accounting for the ignition and stabilization phases; it is applied when calculating the Exergetic Ignition Cost (EIC).

η_{ex}^{dif} (steady-state efficiency) is used to evaluate the facility's performance in a steady-state mode. It is selected as the baseline indicator for the KPI-stack concept, as it ensures comparability, scalability, and reproducibility of results for cross-technology comparisons.

According to the calculations presented in Table 1, the exergetic efficiency of plasma-assisted oil sludge gasification is 16.3% and 28.8% higher than that of traditional methods at 1500 K and 2000 K, respectively. An analysis of the data in Table 1 shows that at the same process thermal power (2000 kW), the transition from traditional combustion to PFS-assisted gasification leads to a significant increase in the exergy of useful heat due to higher process temperatures and improved quality of the input energy.

Despite the increase in electrical consumption when using a plasma torch, the overall exergetic efficiency increases, indicating a reduction in irreversible losses within the system. The results confirm that energy efficiency, as evaluated by the First Law of Thermodynamics, does not reflect the actual quality of the process, whereas exergetic analysis allows for a correct comparison of regimes with different temperature potentials. This justifies the continued use of exergetic indicators within the KPI-stack framework. Based on these initial data, further calculations of integral and flow-based performance indicators are conducted.

Figure 1 presents the dependence of the exergy efficiency on the process temperature. The η_{ex}^{int} characterizes the efficiency of the complete processing cycle, accounting for start-up modes, while η_{ex}^{dif} represents the facility's efficiency in steady-state operation. The divergence of the curves reflects the contribution of transient processes and the exergetic costs for ignition and stabilization.

It follows from Figure 1 that the exergy efficiency increases monotonically with the process temperature for both types of evaluation—integral form and flow form (differential). The gap between the curves reflects the contribution of transient processes associated with the ignition and stabilization of the plasma regime and quantitatively characterizes the additional exergetic load on the system during non-steady-state phases.

The differential exergy efficiency demonstrates a stable temperature dependence and reflects the facility's performance in steady-state mode, making it the preferred baseline indicator for the KPI-stack concept to ensure cross-technology comparison and standardization. The integral efficiency, in turn, remains informative for analyzing operational cycles and calculating the Exergetic Ignition Cost (EIC). This relationship serves as a physically correct link for a primary quantitative assessment and provides the basis for forming a comprehensive KPI-stack through an exergy-based method.

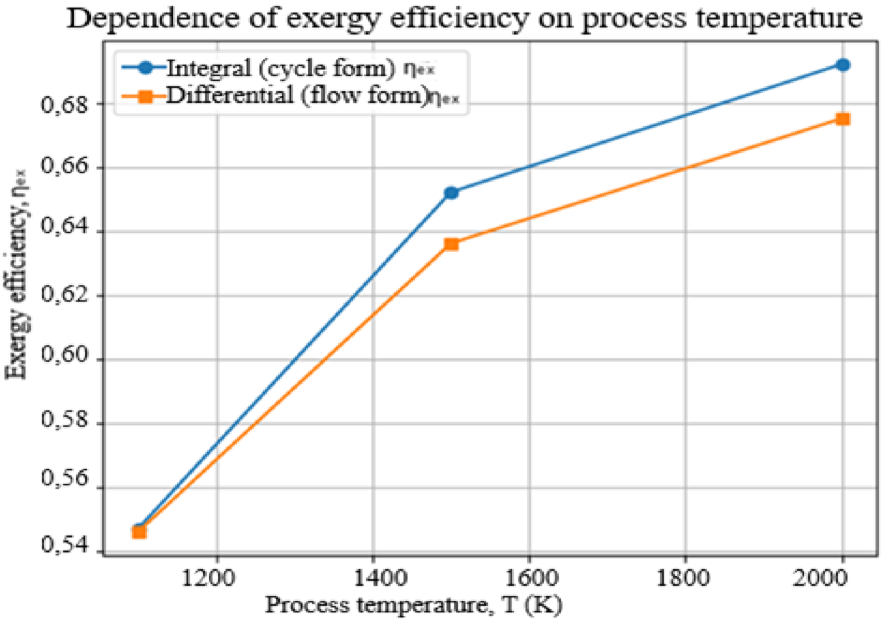

Figure 1 – Dependence of exergy efficiency on temperature.

Table 2 – Variation of gas composition as a function of temperature (T) [4, 10–15, 34–36]

Temperature	Key Process Characteristics
1100 K	Incomplete conversion zone. At this temperature, condensed carbon (C_{cond}) may still be present in the system. The concentration of target components (H_2, CO) has not yet reached its maximum. Minor amounts of methane (CH_4) may be present. Emissions are relatively low, but the process is characterized by high levels of CO (incomplete combustion).
1400 K	Optimal gasification threshold. All carbon is converted into the gas phase. The concentrations of CO and H_2 stabilize at peak values; this serves as the "operating point" for many industrial plasma gasifiers.
1500 K	Stable syngas production. Maximum yield of high-calorific gas is achieved; hazardous impurities (dioxins, furans) are completely destroyed.
2000 K	Excessive energy consumption zone. The gas composition remains virtually unchanged compared to 1500-1600 K; however, specific electrical energy consumption for the process increases significantly. Thermal ionization begins, and atomic fractions start to grow. At a plasma temperature of 2000 K and in the absence of free oxygen, nitrogen remains in an inert state (N_2), preventing the formation of NO_2.

The data in Table 2 demonstrate that an increase in process temperature leads to an equilibrium shift toward the formation of the target components of syngas – hydrogen and carbon monoxide. At a temperature of 1100 K, the process is characterized by incomplete carbon conversion and the potential presence of a solid residue, whereas the range of 1400-1500 K corresponds to a stable steady-state mode of full gasification.

With a further increase in temperature to 2000 K, the gas composition changes insignificantly; however, energy costs increase, indicating the existence of an optimal temperature window in terms of the balance between performance and costs. These results emphasize the need to assess not only the gas composition but also the quality of the energy contained in the products, which is further implemented through the exergy-based method for syngas analysis.

Table 3 – KPI-stack calculation for oil sludge

Indicator Name	Traditional combustion at 1100K	Gasification using PFS at 1500K	Gasification using PFS at 2000K
Measured NO_2 emission concentration: C_{fact} (mcg/m^3)	250	80	60
Specific energy consumption, Qsp (MJ/kg) (13)	$\frac{402 + 1{,}35 - 220{,}64}{10} = 18{,}27$	$\frac{402 + 68{,}4 - 306{,}78}{10} = 16{,}36$	$\frac{402 + 68{,}4 - 325{,}57}{10} = 14{,}48$
Exergetic Ignition Cost, EIC (MJ/kg) (14)	$\frac{13{,}5}{10} = 0{,}135$	$\frac{68{,}4}{10} = 6{,}84$	$\frac{68{,}4}{10} = 6{,}84$
Environmental Performance Index, EPI (16)	$0{,}5461 \times \frac{10}{250} = 0{,}0218$	$0{,}6359 \times \frac{10}{80} = 0{,}0795$	$0{,}6749 \times \frac{10}{60} = 0{,}1125$

Note: According to WHO data, the Maximum Permissible Concentration (MPC) for NO_2 (annual average since 2021) is $C_{MPC}^{WHO} = 10\ mcg/m^3$ [38].

The KPI-stack calculation results (Table 3) demonstrate that plasma-assisted processing of oil sludge is characterized by higher exergy efficiency and lower specific exergetic losses compared to traditional combustion. Despite the increase in the Exergetic Ignition Cost (EIC) associated with the use of a plasmatron, the temperature rise and improvement in energy quality compensate for these costs during the steady-state stage of the process.

The Environmental Performance Index (EPI) also increases when transitioning to plasma modes, indicating an improvement in environmental performance alongside an increase in thermodynamic efficiency. The obtained results confirm the feasibility of using the KPI-stack as an integral tool for the comprehensive energy and environmental assessment of oil sludge processing.

II. Plasma processing mode with synthesis gas production, where the target product is the exergy of the gas.

The plasma mode not only provides thermal energy but also converts a portion of the exergy into a chemically valuable form ($CO+H_2$). Table 4 presents the results of the gas exergy calculations. Calculation of Gas Exergy Ex_{gas}:

- Determine the gas molar flow rate n_{gas} based on flow meter readings and elapsed time.
- For each component H_2, CO, CH_4, CO_2, N_2, determine h_i and s_i, where: n_i - amount of substance for component i (H_2, CO, CH_4 etc.) kmol;
- h_i, s_i - enthalpy (total $_{thermal}$ energy content) and entropy (degree of disorder or randomness) at gas temperature T;
- h_{i0}, s_{i0} - enthalpy and entropy at the standard state;
- ex_i^{ch} - specific chemical exergy of the component.

$$Ex_{gas} = Ex_{gas}^{ph} + Ex_{gas}^{ch} \tag{18}$$

$$\mathrm{Ex}_{gas} = \sum_i n_i\left[\left(h_i - h_{i,0}\right) - T_0\left(s_i - s_{i,0}\right) + \mathrm{ex}_i^{\mathrm{ch}}\right] \tag{19}$$

Table 4 – Syngas exergy calculation

№	Gas component i	Volume Fraction y_i, %	Amount of Substance n_i, kmol	Specific Chemical Exergy ex_i^{ch}, MJ/kmol	Physical Exergy Ex_i^{ph}, MJ	Chemical Exergy $Ex_i^{ch} = n_i \cdot ex_i^{ch}$, MJ	Total Component Exergy $Ex_i = Ex_i^{ph} + Ex_i^{ch}$ МДж	Fraction in Ex_{gas}, %
at T=1100K								
1	H_2	45	0.292	240	2.9	70.0	72.9	50.9
2	CO	40	0.218	275	2.3	60.0	62.3	43.5
3	CH_4	3	0.005	800	0.5	4.0	4.5	3.1
4	CO_2	8	-	~0	0.9	~0	0.9	0.6
5	N_2	4	-	~0	207	~0	2.7	1.9
Total:		100	-	-	9017	134.1	143.17≈143.2	100.0
at T=1500K								
1	H_2	45	0.292	240	5.0	70.1	75.0	50.0
2	CO	40	0.218	275	4.0	60.0	64.0	42.7
3	CH_4	3	0.005	800	0.8	4.0	4.8	3.2
4	CO_2	8	-	~0	1.5	~0	1.5	1.0
5	N_2	4	-	~0	4.7	~0	4.7	3.1
Total:		100	-	-	16.0	134.1	150.0	100.0
at T=2000K								
1	H_2	45	0.292	240	7.1	70.1	77.2	49.2
2	CO	40	0.218	275	5.7	60.0	65.7	41.9
3	CH_4	3	0.005	800	1.1	4.0	5.1	3.3
4	CO_2	8	-	~0	2.1	~0	2.1	1.4
5	N_2	4	-	~0	6.7	~0	6.7	4.3
Total:			100	-	22.6	134.1	156.7	100.0

Notes:
1. Under the condition of constant gas composition, $p \approx p_0$, T_0=295K.
2. The ratio ensures complete gasification without the formation of solid carbon (soot) and achieves the maximum concentration of combustible components (H_2 and CO) in the syngas.
3. Chemical exergy ex_{fuel}^{ch} is determined by the elemental composition of the fuel (C, H, O, S, N) and reference databases (Szargut, JANAF/NASA).
4. For air, chemical exergy is neglected; the physical component is accounted for during preheating $Ex_{ox} \approx 0$.
5. The total relative uncertainty of the result – ± 6-10%. Main components: temperature – ± 1.5%, gas composition – ±3%, power – ±1%, mass – ±0.5%. Verification is performed by comparing calculated η_{ex} values with experimental data from [34-36].
6. The physical exergy of components at 2000K is estimated by scaling the values at 1500K proportionally to ($T-T_0$), assuming a constant gas composition.

The analysis of Table 4 shows that the primary share of syngas exergy is attributed to the chemical exergy of hydrogen and carbon monoxide, while the contribution of physical exergy increases as the process temperature rises. Given a constant gas composition, an increase in temperature leads to a rise in the total syngas exergy due to the enhancement of physical potential, which is particularly evident at 2000K.

This confirms that plasma processing not only provides a thermal effect but also converts a significant portion of the input exergy into a chemically valuable form suitable for subsequent energetic or technological use. This effect represents a fundamental advantage of plasma modes and cannot be identified through analysis based solely on energy indicators of the First Law of Thermodynamics.

Thus, the sequential analysis of the energetic, exergetic, and environmental characteristics of the process confirms the feasibility of applying the exergy-oriented KPI-stack for the objective assessment and optimization of plasma-based oil sludge processing technologies. Furthermore, the possibility of integrating this concept into related fields of thermodynamics is considered.

Alignment of the Methodology with Global Literature

In the majority of reviewed studies, exergetic analysis is performed on a "plant-specific" basis, utilizing diverse sets of indicators without a unified KPI-stack. Moving away from case-by-case analysis, this work proposes a unified methodology featuring a standardized algorithm for measurements, calculations, and reporting, aligned with established standards (ST RK GOST R ISO pro14044) [38].

It should be noted that this methodology places a specific focus on plasma ignition as a distinct phase. While existing research primarily focuses on steady-state gasification and melting, this study distinguishes the plasma ignition/flame stabilization phase as an object of separate quantitative assessment via the EIC (Exergetic Ignition Cost).

This development introduces the KPI-stack for plasma technologies—specifically, the implementation of a parameter set comprising $\eta_{ex}(T)$, $Q_{sp}(T)$, EIC and EPI as a formalized standard. In contrast, existing research typically utilizes combinations such as "Efficiency + Conversion Rate + Q_{sp}." This methodology integrates energy, energy quality, and environmental impact into a single quantitative framework.

The methodology maintains a rigorous link to metrology and measurement uncertainty. To develop and approve a formal standard, it is necessary to define requirements for measuring instruments, logging procedures, total uncertainty assessment, and internal quality control according to RMG 61-2010 and RMG 76-2014 [39–41]—elements that are absent in most scientific publications.

Prospects for Utilizing the KPI-stack Methodology

Based on published international studies, the potential transferability of the KPI-stack to fusion, high-energy physics, and cryogenic systems is discussed conceptually. No dedicated calculations or experimental validation for these sectors were performed in the present study. In the realms of nuclear energy and thermonuclear fusion, exergetic analysis is already actively employed. In [41], it is demonstrated that improper matching of temperature levels between the blanket and the power cycle loops leads to significant exergy destruction; thus, exergetic analysis serves as the primary tool for selecting heat exchange configurations. Through entropy and exergy analysis, the main sources of losses and "bottlenecks" in the thermal schemes of fusion power plants are identified [42].

In [43], a detailed exergetic analysis of individual loops (reactor cooling, power cycle, and heat rejection to the heat sink) was introduced, allowing for the quantitative assessment of exergy destruction along the chain. Furthermore, authors examine the thermodynamic characteristics of D-T (deuterium-tritium) fusion reactions and alternative fuels, including Gibbs free energy and the "spontaneity" of reactions; this effectively represents a thermodynamic (quasi-exergetic) analysis of available energy at the nuclear reaction level [44].

Exergy inflows comprise the thermonuclear power in the blanket, the electrical power supplied to the magnetic system, pumps, and cryogenics. Exergy products include electricity at the busbars, useful low- and medium-potential heat (e.g., for district heating), as well as losses (radiation beyond limits, heat leaks, etc.).Following the example of plasma gasification, exergy efficiency (η_{ex}) is the ratio of useful exergy (electrical energy + useful heat) to the total exergy of inflows and reactions. Specific energy consumption (Q_{sp}) can be interpreted as the specific energy input or auxiliary exergy required for the ignition and maintenance of the thermonuclear plasma (kWh per unit of generated tritium or thermal power). Given that the "quality of energy" in the context of thermonuclear reactors is explicitly discussed in [41], the KPI-stack aligns with these objectives with almost no modifications.

High Energy Physics and Accelerator Complexes

In the field of High Energy Physics (HEP), exergetic analysis is already applied to cryogenic systems and high-temperature superconductors. In [45], it is demonstrated that the exergetic analysis of the LHC (Large Hadron Collider) helium cryosystem allows for a direct link between local losses and the additional power consumption of the refrigeration plant, enabling the optimization of the distribution scheme. Exergetics serves as a tool for optimizing helium liquefaction cycles applicable to superconducting magnets and accelerators [46]. Furthermore, a comprehensive energy and exergy optimization of the HALF (Hefei Advanced Light Facility) synchrotron cryosystem has been performed [48]. Papers on the energy and exergy analysis of cryosystems for High-Temperature Superconducting (HTS) magnets also demonstrate the use of the Second Law of Thermodynamics as the primary efficiency criterion [49]. The review in [50] emphasizes that exergetic analysis is a key tool for evaluating the "energy quality" and sustainability of cryogenic systems.

Thus, the presented methodology is applicable to cryogenic systems, where the objects of study include cryogenic complexes, magnets, RF systems, and detector cooling systems. Exergy inflows consist of the electrical energy from power supply units and the chemical exergy of liquefied gases (He, N_2, Ne, etc.). Exergy products include the maintenance of superconductivity (low temperature as a "high-quality resource"), magnetic field stability, and accelerator operation.

Exergy efficiency (η_{ex}) evaluates what portion of the input exergy is actually used to maintain the required physical conditions and what portion is dissipated as irreversible losses (throttling, Joule losses, heat leaks). Specific energy consumption (Q_{sp}) is defined as the specific energy input per unit of useful "physical work" (e.g., kWh/T·m of magnetic field or kWh/MJ of accumulated beam energy). Formally, the framework is analogous, substituting syngas and MSW with cryogenics and accelerators.

Adaptation of the KPI-stack to Nuclear & HEP

It should be noted that the integration of this methodology is based on four primary indicators applicable to related fields:

Exergy Efficiency (η_{ex}):

- for nuclear systems, this represents the "reactor + power plant" exergy efficiency (the ratio of electrical and useful thermal power to the total exergy of the reaction and auxiliary electricity);
- for high-energy physics accelerators, this represents the exergy efficiency of the cryogenic and magnetic systems (useful "physical exergy" of the experimental conditions / exergy of the input energy).

Specific Energy Consumption ($Q_{sp}(T)$):

- for nuclear systems, this represents the specific energy consumption of the plasma subsystem (heating, confinement, injection) per unit of generated power;
- for high-energy physics accelerators, this represents the kWh per unit of integrated luminosity or accumulated beam energy.

EIC (Exergetic Ignition Cost):

- for nuclear systems, this is the exergetic cost of bringing the reactor/flame/plasma to the operating mode (startup, blanket heating, cryogenic cooldown);
- in high-energy physics, this is the exergetic cost of beam acceleration and bringing the magnetic system to the operating field.

EPI (Environmental Performance Index):

- for nuclear systems, this is a combination of exergy efficiency with indicators of radiation impact, material activation, and thermal discharges;
- for high-energy physics facilities, this represents the link between the η_{ex} of cryogenics and cooling systems and the carbon footprint and energy consumption of the complex.

The review [42–45] confirms that such an approach is not only feasible but also a logical extension of current practices, as exergy is explicitly identified as a key tool for design (an instrument for quantitative analysis).

Conclusions

This work has developed an exergetic methodology and verified its applicability against previously published experimental data for the quantitative assessment of plasma process efficiency, based on the Second Law of Thermodynamics and implemented as a formalized set of indicators: the KPI-stack (η_{ex}, Q_{sp}, EIC, EPI). The proposed approach enables a transition from fragmented energy criteria to a unified, reproducible evaluation system focused on energy quality and the level of irreversible losses.

Calculations have shown that at a fixed process thermal power of 2000kW, the use of a plasma-assisted oil sludge processing mode ensures a steady increase in exergy efficiency compared to traditional combustion. The differential exergy efficiency increases from 0.546 at 1100K to 0.636 at 1500K and reaches 0.675 at 2000 K, which corresponds to an efficiency increase of 16.3% and 23.6%, respectively. A similar trend is observed for the integral exergy efficiency, with values increasing from 0.547 to a range of 0.652-0.692.

Analysis of specific exergy losses showed that increasing the temperature and implementing a plasma torch are accompanied by a reduction in exergy destruction within the system. The Q_{sp} value decreases from 18.27MJ/kg for traditional combustion to 16.36MJ/kg at 1500K and to 14.48MJ/kg at 2000K, indicating a more rational utilization of the fuel's chemical exergy.

It was established that the increase in the Exergetic Ignition Cost (EIC) in plasma modes (up to 6.84MJ/kg compared to 0.135MJ/kg) is local in nature and primarily associated with the ignition and process stabilization phases. In steady-state operation, these costs are offset by the increase in exergetic efficiency and the reduction of total losses, confirming the necessity of separate accounting for startup and steady-state regimes.

The extension of the KPI-stack to fusion and cryogenic systems remains prospective and requires domain-specific definitions, datasets, and independent validation.

Environmental analysis demonstrated that the application of plasma-assisted processing leads to an improvement in the environmental indicators of the process. The Environmental Performance Index (EPI) increases from 0.0218 for traditional combustion to 0.0795 at 1500K and up to 0.1125 at 2000K, which is attributed to a decrease in NO_2 concentration in emissions from 250mcg/m^3 to 80-60mcg/m^3 alongside a simultaneous increase in exergy efficiency.

Furthermore, it was shown that the plasma processing of oil sludge is accompanied by the formation of energy-valuable syngas. The total exergy of the gas increases from 143.2MJ at 1100K to 150.0MJ at 1500K and reaches 156.7MJ at 2000K, with more than 90% of the exergy accounted for by the chemical exergy of hydrogen and carbon monoxide. This indicates the possibility of viewing plasma technologies not only as thermal disposal methods but also as elements of the Waste-to-Value (WtV) concept. Thus, the proposed KPI-stack forms an objective and scalable basis for comparing plasma technologies, optimizing operational modes, and subsequently integrating exergetic criteria into Best Available Techniques (BAT) practices. The results obtained confirm the potential of plasma-assisted processes for enhancing the energy and environmental efficiency of complex hydrocarbon waste processing.

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[1]Мессерле В.Е.,
ф.-м.ғ.д., профессор, ORCID ID: 0000-0003-4281-1429,
e-mail: ust@physics.kz
[1]Устименко А.Б.,
ф.-м.ғ.д., профессор, ORCID ID: 0000-0003-0033-1371,
e-mail: alexanderustimenko@gmail.com
[1]Лаврищев О.А.,
ф.-м.ғ.к., доцент, ORCID ID: 0000-0002-5934-8381,
e-mail: lavr@physics.kz
[1]*Нұғман М.К.,
докторант, ORCID ID: 0009-0004-3366-5348,
*e-mail: nugmanmarina@gmail.com

[1]Әл-Фараби атындағы Қазақ ұлттық университеті, Алматы қ., Қазақстан

ПЛАЗМАЛЫҚ ПРОЦЕСТЕРДІҢ ТИІМДІЛІГІН СТАНДАРТТАЛҒАН БАҒАЛАУҒА АРНАЛҒАН ЭКСЕРГЕТИКАЛЫҚ ӘДІСТЕМЕ

Аңдатпа

Мақалада плазмалық процестердің тиімділігін сандық бағалауға арналған, олардың салыстырмалылығын, қайталанымдылығын және кейіннен стандартталуын қамтамасыз етуге бағытталған бірыңғай эксергетикалық әдістеме ұсынылған. Әзірленген тұжырымдама термодинамиканың екінші заңын қолдануға және эксергетикалық пайдалы әсер коэффициенті (η_{ex}), меншікті энергия шығындары (Q_{sp}), тұтанудың эксергетикалық құны (EIC) және экологиялық индекс (EPI) сияқты негізгі тиімділік көрсеткіштерінің формальды жиынтығын (KPI-stack) қалыптастыруға негізделген. Термодинамиканың бірінші заңына негізделген дәстүрлі энергетикалық критерийлердің энергия сапасын, қайтымсыз шығындар деңгейін және плазмалық процестердің тепе-теңдік емес сипатын көрсетпейтіні дәлелденді, бұл оларды технологияаралық салыстыру және нормалау үшін қолдану мүмкіндігін шектейді. Ұсынылған эксергетикалық тәсіл берілген энергияның химиялық, физикалық және ионизациялық құрамдастар арасында бөлінуін ескеруге, сондай-ақ процестің әртүрлі кезеңдеріндегі эксергияның бұзылуын сандық тұрғыдан бағалауға мүмкіндік береді.

Әдістеме плазмалық тұтануды, газдандыруды, реформингті және көмірсутек шикізаты мен қалдықтарын газ, сұйық және қатты фазаларда қайта өңдеуді қоса алғанда, плазмалық технологиялардың кең ауқымына бейімделген. Жұмыста экологиялық менеджмент және энергия тиімділігі саласындағы қолданыстағы ұлттық және халықаралық стандарттардың талаптарына, сондай-ақ метрологиялық қамтамасыз ету талаптарына сәйкес келетін өлшеу, есептеу және нәтижелердің белгісіздігін бағалау алгоритмі тұжырымдалған. Талдау 1100 K температурадағы дәстүрлі жану режимі және процестің белгіленген 2000 кВт жылу қуаты кезіндегі 1500–2000 K температурадағы плазмалық режимдер үшін жүргізілді. Плазмотронды қолдану дифференциалдық эксергетикалық ПӘК-тің 0,546-дан 0,636–0,675-ке дейін артуына және меншікті эксергетикалық шығындардың 18,27-ден 14,48 МДж/кг-ға дейін төмендеуіне әкелетіні көрсетілген. Сонымен қатар, экологиялық индекстің артуы және шығарындылардағы NO_2 концентрациясының төмендеуі арқылы көрінетін процестің экологиялық сипаттамаларының жақсаруы байқалады. Бұдан бөлек, плазмалық режим жиынтық эксергиясы 156,7 МДж-ға дейін жететін энергетикалық құнды синтез-газдың түзілуін қамтамасыз ететіні анықталды, бұл технологияның функционалдық мүмкіндіктерін қарапайым термиялық кәдеге жарату шеңберінен тыс кеңейтеді. Алынған нәтижелер күрделі көмірсутек қалдықтарын қайта өңдеудің плазмалық технологияларын талдау және оңтайландыру үшін эксергетикалық бағытталған KPI-ларды қолданудың мақсатқа сәйкестігін растайды. Әдістеменің практикалық қолданылуы мұнай шламдарын плазмохимиялық қайта өңдеуге арналған KPI-stack көрсеткіштерін есептеу мысалында көрсетілген. Эксергетикалық көрсеткіштердің бірыңғай жиынтығын енгізу плазмалық технологияларды салыстыруға, жұмыс режимдерін оңтайландыруға және кейіннен әдістемені нормативтік-техникалық құжаттарға интеграциялауға объективті негіз беретіні көрсетілген.

Түйін сөздер: плазмалық процестер, эксергетикалық талдау, негізгі тиімділік көрсеткіштері, KPI-stack, энергия тиімділігі, декарбонизация, стандарттау.

[1]Мессерле В.Е.,
д.ф.-м.н., профессор, ORCID ID: 0000-0003-4281-1429,
e-mail: ust@physics.kz
[1]Устименко А.Б.,
д.ф.-м.н., профессор, ORCID ID: 0000-0003-0033-1371,
e-mail: alexanderustimenko@gmail.com
[1]Лаврищев О.А.,
к.ф.-м.н., доцент, ORCID ID: 0000-0002-5934-8381,
e-mail: lavr@physics.kz
[1]*Нұғман М.К.,
докторант, ORCID ID: 0009-0004-3366-5348,
*e-mail: nugmanmarina@gmail.com

[1]Казахский национальный университет им. аль-Фараби, г. Алматы, Казахстан

ЭКСЕРГЕТИЧЕСКАЯ МЕТОДОЛОГИЯ СТАНДАРТИЗИРОВАННОЙ ОЦЕНКИ ЭФФЕКТИВНОСТИ ПЛАЗМЕННЫХ ПРОЦЕССОВ

Аннотация

В статье предложена унифицированная эксергетическая методика количественной оценки эффективности плазменных процессов, ориентированная на их сопоставимость, воспроизводимость и последующую стандартизацию. Разработанная концепция основана на применении второго закона термодинамики и формировании формализованного набора ключевых показателей эффективности (KPI-stack), включающего эксергетический коэффициент полезного действия (η_{ex}), удельные энергозатраты (Q_{sp}), эксергетическую цену воспламенения (EIC) и экологический индекс (EPI). Показано, что традиционные энергетические критерии, базирующиеся на первом законе термодинамики, не отражают качество энергии, уровень необратимых потерь и неравновесный характер плазменных процессов, что ограничивает их применимость для межтехнологического сравнения и нормирования. Предлагаемый эксергетический подход позволяет учесть распределение подведенной энергии между химической, физической и ионизационной составляющими, а также количественно оценить разрушение эксергии на различных стадиях процесса. Методика адаптирована для широкого класса плазменных технологий, включая плазменное воспламенение, газификацию, реформинг и переработку углеводородного сырья и отходов в газовой, жидкой и твердой фазах. В работе сформулирован алгоритм измерений, расчетов и оценки неопределенности результатов, согласованный с требованиями метрологического обеспечения и действующих национальных и международных стандартов в области экологического менеджмента и энергоэффективности. Анализ выполнен для традиционного сжигания при 1100K и плазменных режимов при 1500-2000K при фиксированной тепловой мощности процесса 2000кВт. Показано, что использование плазмотрона приводит к увеличению дифференциального эксергетического КПД с 0,546 до 0,636-0,675 и снижению удельных эксергетических потерь с 18,27 до 14,48МДж/кг. Одновременно наблюдается улучшение экологических характеристик процесса, выраженное в росте экологического индекса и снижении концентрации NO_2 в выбросах. Дополнительно установлено, что плазменный режим обеспечивает формирование энергетически ценного синтез-газа с суммарной эксергией до 156,7МДж, что расширяет функциональность технологии за пределы простой термической утилизации. Полученные результаты подтверждают целесообразность применения эксергетически ориентированных KPI для анализа и оптимизации плазменных технологий переработки сложных углеводородных отходов. Практическая применимость методики продемонстрирована на примере расчета KPI-stack для плазмохимической переработки нефтешламов. Показано, что введение унифицированного набора эксергетических показателей обеспечивает объективную основу для сравнения плазменных технологий, оптимизации режимов работы и последующей интеграции методики в нормативно-технические документы.

Ключевые слова: плазменные процессы, эксергетический анализ, ключевые показатели эффективности, KPI-stack, энергоэффективность, декарбонизация, стандартизация.