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PROGRESS ON GEL PARTICLES FOR GAS CHANNELING CONTROL IN CO_2 FLOODING RESERVOIRS

Abstract

CO_2 flooding, as a commonly employed enhanced oil recovery (EOR) method today, is characterized by high oil displacement efficiency, environmental friendliness, and economic viability, and has been extensively developed and applied in oil and gas field development. During CO_2 flooding operations, gas channeling frequently occurs within the reservoir due to significant permeability contrasts arising from formation heterogeneity, coupled with the low density and viscosity of CO_2. This phenomenon can adversely affect the normal productivity of oil wells. With the advancement of CO_2 flooding technology, the effective prevention of CO_2 channeling has become crucial for improving oil recovery. Gel particle plugging systems, being economically viable and efficient, exhibit favorable stability, adaptability, and strength, leading to significant applications in oilfield development and demonstrating promising prospects for future development. This paper comprehensively reviews the classification and developmental status of gel particle systems used for channeling control in CO_2 flooding. It introduces the mechanisms of several gel particle types, including preformed particle gel, polymer microspheres, and dispersed particle gel, and examines their current development status both domestically and internationally. Furthermore, future research directions and application prospects are discussed.

Keywords: CO_2 flooding, gel particles, gas channeling plugging materials, improving sweep efficiency.

Introduction

CO_2 flooding is widely employed as an enhanced oil recovery technique. Increased oil production efficiency is achieved by injecting CO_2 into the reservoir, where it reduces crude oil viscosity and improves fluid mobility. Compared to conventional water flooding, CO_2 flooding offers advantages including reduced environmental impact, minimized formation damage, and enhanced economic viability. Furthermore, as a greenhouse gas, Carbon Capture, Utilization and Storage (CCUS) technology can be effectively utilized to reduce greenhouse gas emissions, thereby mitigating the current issue of excessive atmospheric CO_2 levels [1]. However, during CO_2 flooding operations, due to reservoir heterogeneity (such as the presence of high-permeability zones or fractures), CO_2 tends to preferentially flow through high-permeability channels, resulting in gas channeling. This phenomenon leads to reduced displacement efficiency. To enhance gas flooding recovery and ensure effective CO_2 sequestration within the formation, gas channeling control measures must be implemented. Gas channeling control for CO_2 flooding refers to the plugging of deep formation fractures to prevent CO_2 breakthrough [2]. Several methods are widely employed for gas channeling control in CO_2 flooding, including Water-Alternating-Gas injection(WAG), CO_2 foam stabilization, CO_2 thickening method, and polymer gel systems [3–4]. Among these, the WAG process is characterized by operational simplicity, low cost, and minimal contamination. However, downhole monitoring is difficult, and its effectiveness is significantly impacted by subsurface heterogeneity. The CO_2 foam method is noted for its ability to substantially reduce interfacial tension and exhibits synergistic effects with carbon sequestration. Nevertheless, the preparation of foaming agents on-site is challenging, and foam stability is susceptible to degradation under extreme conditions. Viscosified CO_2 injection demonstrates advantages in reducing CO_2 consumption and mitigating leakage risks. However, this approach is associated with high viscosification costs, and potential incompatibility reactions between viscosifiers and subsurface minerals or fluids may cause formation damage [5]. Polymer gel plugging systems are characterized by effective dynamic plugging performance and good controllability. However, tubing tripping operations are required during the injection process, making online injection and retrieval impossible. As a dispersed system, gel particles can be co-injected with gas into the formation, thereby satisfying the requirement for online injection during gas flooding for channeling control [6]. In recent years, the application of gel particles in air-foam flooding and nitrogen flooding for channeling control has gradually increased, and certain plugging effects have been achieved. The potential of gel particles for channeling control in CO_2 flooding is also being explored and demonstrates promising application prospects [7].

Gas channeling control technology utilizing gel particles involves the injection of gel particles into the oil well. These particles are preferentially transported into high-permeability channels or fractures within the formation. Subsequently, physical barriers are formed through particle swelling or accumulation, thereby reducing gas permeability and plugging gas channeling pathways. Consequently, subsequent CO_2 is diverted towards unswept low-permeability zones, leading to an enlarged swept volume and enhanced oil recovery [8]. Gel particles possess a characteristic "deformation-migration-replugging" capability, allowing the plugging location to be dynamically adjusted in response to fluid flow, which enhances their adaptability to heterogeneous formations. This paper describes the current developmental status of gel particle systems. A review of the plugging mechanisms and research progress (both domestic and international) concerning preformed particle gel, polymer microspheres, and dispersed particle gel are presented. Furthermore, future development prospects are discussed. In recent years, significant progress has been made regarding the stability and plugging strength of gel particles. However, for CO_2 flooding applications, improving the acid resistance of gel particles under acidic CO_2 conditions remains a challenge. Future research directions aimed at enhancing plugging effectiveness will continue to focus on improving the stability of gel particles in acidic environments.

Materials and Methods

Progress in gel particle plugging agent used in CO_2 flooding

Preformed particle gel

Preformed particle gel (PPG) is defined as polymer gel particle that have been crosslinked into their final form prior to injection into the formation. It is prepared by dissolving polymers in water, followed by the addition of crosslinkers and additives to form a three-dimensional network gel. Subsequently, this gel is processed into discrete particles through cutting, crushing, drying, and sieving. Dynamic adjustment of channeling pathways within the formation is achieved by PPG through a process involving particle migration, retention, swelling, and plugging. Following injection into the formation, water is absorbed by the particles, causing the polymer chains to extend and the particle volume to expand, thereby functioning to plug the formation [9].

The strength and swelling ratio of the particles can be pre-designed, offering good controllability and strong adaptability to formations. Furthermore, effective performance is also demonstrated under high-temperature and high-pressure reservoir conditions [10]. However, conventional PPG is characterized by relatively large particle sizes, making directional injection into the formation difficult to control. Additionally, a high swelling ratio can lead to limited plugging strength in deep formations. To address these limitations, Zhu et al. proposed a novel approach based on temporary plugging agents (TPA) and conventional PPG [11]. They prepared deformable preformed particle gel (DPPG) using crosslinkers of different molecular weights. The DPPG can function as deformable particle TPA, enabling the selection of high-performance plugging materials. DPPG prepared with lower molecular weight crosslinkers exhibit greater plugging strength and cause less core damage. However, their degradation rate is comparatively slower, requiring a longer time to achieve complete degradation.

Simultaneously, due to prolonged CO_2 flooding, CO_2 inevitably reacts with formation water, resulting in the formation of an acidic environment within the formation. The stability of conventional PPG under acidic and high-temperature conditions, particularly their performance in such harsh environments, is compromised and remains to be improved through further research and development. To enhance acid resistance, Zhou et al. synthesized an acid-resistant preformed particle gel (AR-PPG) using acrylamide (AM), the acid-tolerant monomer dimethyldiallyl ammonium chloride (DMDAAC), and 2-acrylamido-2-methylpropane sulfonic acid (AMPS), among other components [12]. Its swelling behavior, stability, shear resistance, and viscoelastic properties under acidic conditions were experimentally evaluated. Due to the protective effect of the sulfonate group ($-SO_3H$), polymer chain contraction in AR-PPG is minimized, resulting in a more stable structure compared to conventional PPG. Consequently, enhanced shear resistance and acid tolerance are achieved. Aminshahidy et al. employed a free radical combinatorial approach to design and synthesize a novel PPG [13]. The mechanical properties of this PPG were reinforced through the incorporation of graphene nanoplatelets (GNP) and sodium silicate. Results indicated that the network structure of the PPG became more coordinated and denser. Significant improvements in swelling performance and acid resistance were observed for the novel PPG compared to the conventional type. Furthermore, due to the coverage provided by the nanomaterials, direct contact with the aqueous phase is avoided, leading to low pH sensitivity. Experimental testing confirmed that no significant reduction in the swelling capacity of the novel PPG occurred at 80°C. Additionally, to improve the injectivity and acid resistance of preformed particle gel in acidic formations and to address issues related to PPG swelling and stability, CO_2-responsive PPG can also be utilized for gas channeling control during CO_2 flooding. Deng et al. prepared a responsive preformed particle gel (CR-PPG) using N,N'-dimethylacrylamide (DMAA), sodium alginate (SA), along with an organic crosslinker (MBA) and a nanoscale crosslinker (VSNP) [14]. Since CR-PPG is synthesized via the free radical polymerization of VIM, DMAA, and NVP monomers, which contain tertiary amine groups (NR_3), these groups can react with H_2O and CO_2 to form ammonium bicarbonate. This reaction induces the formation of high-density regions within the CR-PPG structure, endowing them with enhanced swelling capacity and strength. Additionally, the VSNP contribute to an increased crosslinking density, resulting in a more stable gel structure. To improve the thermal stability of PPG, Wei et al. synthesized thermally stable PPG (T-PPG) by replacing the crosslinker MBA with thioacetamide (TAA). T-PPG exhibit superior thermal stability compared to conventional MBA-crosslinked PPG (M-PPG) [15]. TAA does not hydrolyze at high temperatures, thereby effectively resisting structural damage caused by elevated temperatures. Experimental results demonstrated that T-PPG remain stable for over 180 days even after being aged at 140°C for 60 hours.

PPG is characterized by favorable swelling capacity, shear resistance, and tolerance to high temperatures and salinity, and have become a significant option for gas channeling control technology. However, the commonly used PPG is typically large-sized, exhibiting rapid swelling rates and high expansion multiples. This results in difficulties associated with their injection into deep complex formations. Consequently, their applicability is primarily limited to super-permeable channels, such as fractures.

Results and Discussion

Polymer Microspheres

Polymer microspheres are defined as spherical particles with dimensions in the micron- or nano-scale, prepared from polymeric materials through chemical or physical methods. These microspheres possess a unique microstructure and favorable deformability. Their shape, resembling that of porous media, facilitates adsorption and aggregation. They can be transported to deep regions within the formation, enabling dynamic plugging of high-permeability channels. Consequently, gas is diverted towards low-permeability zones, achieving gas channeling control and enhanced gas flooding efficiency. This approach effectively addresses the limitations of traditional gel systems, namely their restricted penetration depth and poor long-term stability [16]. Unlike PPG, microspheres exhibit smaller particle sizes, typically within the micron- or nano-scale range. Additionally, superior swelling capacity is demonstrated, and the manufacturing process is comparatively simpler.

Polymer microspheres are widely employed for profile control and plugging in oilfield development due to their favorable characteristics, including excellent water absorbency and elasticity, convenient preparation, simple injection, minimal formation damage, and good environmental compatibility. However, under the acidic conditions prevalent in CO_2 flooding operations, conventional nanospheres are susceptible to degradation, preventing them from providing stable, long-term plugging within the reservoir. To enhance the performance of nanospheres in acidic environments, Ma et al. synthesized an acid-resistant nanosphere (AR-NS) by incorporating the acid-resistant monomer dimethyldiallylammonium chloride (DMDAAC) into conventional nanospheres (NS) [17]. Successful monomer incorporation into the nanospheres was confirmed by Fourier transform infrared (FTIR) spectroscopy analysis. Experimental evaluations further demonstrated that the AR-NS microspheres exhibited significantly superior swelling performance compared to conventional NS in acidic environments. Consequently, the AR-NS microspheres possess enhanced channeling-blocking capacity within low-permeability fractured reservoirs. Meanwhile, Jiang et al. prepared dual-crosslinked nano-polymer microspheres with delayed-swelling properties by introducing the acid-resistant monomer DMDAAC and employing dual-crosslinking technology, enabling effective plugging of deep reservoirs [18]. Zheng et al developed a CO_2-responsive polymer microsphere (CRM) via emulsion polymerization, utilizing polystyrene (PSt) as the core and P(AM-DMA) as the shell [19]. The particle size of CRM microspheres can be increased in response to CO_2 exposure within a certain time frame and subsequently remains stable, avoiding excessive swelling. The swelling capacity is influenced to some extent by temperature and salinity; it is reduced with increasing temperature and salinity, although a degree of salt and temperature tolerance is maintained. Mu et al. synthesized CO_2-sensitive microspheres with an interpenetrating polymer network (IPN) structure through inverse suspension polymerization, based on monomers including polyacrylamide (PAM) and PDMAPMA [20]. Due to the presence of tertiary amine groups, CO_2 responsiveness is imparted, leading to an increase in particle size under acidic conditions. Consequently, favorable injectivity and plugging capability are achieved.

Polymer microspheres are recognized as a significant method for gas channeling control in CO_2 flooding, effectively mitigating gas breakthrough and enhancing oil recovery. Advantages including operational simplicity, favorable swelling capacity, high plugging efficiency, and environmental friendliness are exhibited. Good performance has been observed in large-pore, low-to-moderate permeability reservoirs. However, under extreme conditions, such as high temperature and strong acidity, microsphere failure is prone to occur due to insufficient stability. Long-term, efficient channeling control under these conditions is difficult to achieve. Additionally, the fabrication of thermally stable and responsive microspheres is associated with higher costs and more complex preparation processes.

Dispersed particle gel

Gel is primarily formed by the reaction of partially hydrolyzed polyacrylamide (HPAM) with crosslinkers under controlled temperature conditions, resulting in a three-dimensional network structure with specific strength. Crosslinkers utilized for gel are mainly organic types (such as phenolic resins and polyethyleneimine) or metal ion crosslinkers (e.g., Cr^{3+}, Zr^{4+}). Compared to conventional chemical gel, gel is crosslinked through physical interactions, including van der Waals forces and hydrogen bonding. Consequently, their crosslinking strength is lower, and the network structure can be disrupted by heating or mechanical agitation. Dispersed particle gel (DPG) is defined as spherical particles prepared from bulk gel material through processes involving mechanical shearing and physical rounding [21]. During this process, physical shear is applied to the bulk gel, but the original chemical structure of the gel is not destroyed. After injection into the subsurface, the particles absorb water and swell. Subsequently, accumulation occurs within high-permeability zones.

Due to their physical crosslinking mechanism, aggregated DPG can revert to the bulk gel state. This property enables the formation of an effective seal within the formation. DPG exhibits favorable viscoelastic properties, allowing them to deform and migrate deeply through the reservoir by conforming to pore configurations. Compared to conventional polymers, DPG is minimally affected by subsurface physical forces, such as shear. Consequently, efficient plugging of pores and fractures in high-permeability zones can be achieved through their inherent self-aggregation and swelling behavior. Zhu et al. prepared the dispersed particle gel (DPG) by shearing the bulk gel, which had been synthesized with varying concentrations of polymer and crosslinker [22]. These DPG possessed distinct mechanical properties. A linear relationship was identified between the Young's modulus of the DPG and their plugging efficiency. This finding indicates that the plugging efficiency can be enhanced by optimizing and adjusting the Young's modulus of the bulk gel. Consequently, significant theoretical guidance is provided for the application of DPG in deep fluid diversion and reservoir plugging.

Acid-resistant zirconium gel, chromium gel, and similar systems exhibit an optimal gelation pH range of 3–6, demonstrating good synergistic compatibility with the acidic conditions prevalent in CO_2 flooding for channeling control. However, when exposed to acidic conditions over extended periods, DPG also experiences partial hydrolysis of their three-dimensional crosslinked network, leading to degradation and a reduction in plugging strength. To address this, Ji et al. successfully prepared an anti-CO_2 dispersed particle gel (CR-DPG) for gas channeling control by shearing an organic-inorganic composite bulk gel [23]. Its mechanical strength, gas plugging effectiveness, and viscosity stability under CO_2 conditions were experimentally evaluated. Under CO_2 conditions, the presence of silica particles was found to enhance the mechanical strength of the CR-DPG. The viscosity decreased from 28.3 mPa·s to 20.5 mPa·s, indicating favorable CO_2 tolerance. Furthermore, H^+ ions in the water neutralize the negative surface charge on the particles, promoting aggregation of the CR-DPG and enhancing its stability. Du et al. synthesized a double-network hydrogel composed of crosslinked polyacrylamide (PAAm) and crosslinked sodium alginate (SA) networks [24]. This hydrogel was processed into a DPG suspension. Subsequent modification was performed using potassium methylsilantriolate (PMS) and CO_2, resulting in a novel DPG suspension exhibiting irreversible swelling characteristics. The particle size of the modified DPG suspension was observed to more than double upon swelling. Furthermore, the swelling was irreversible under high-temperature conditions, and a significant improvement in thermal stability was demonstrated. Plugging efficiency was markedly enhanced compared to traditional CO_2-responsive gel. For high-temperature heterogeneous reservoirs with high crude oil viscosity, the improvement of the temperature and salt tolerance of DPG necessitates further research and development. Zhu et al. developed a re-crosslinkable dispersed particle gel (RDPG) [25]. Compared to conventional DPG, re-crosslinking capability was incorporated. Suspensions at specific concentrations demonstrated enhanced high-temperature injectivity and improved thermal stability. At room temperature, significant elasticity was observed, while under elevated temperatures, an extended gelling time was achieved. This characteristic facilitates deep penetration into high-temperature formations. Simultaneously, favorable elasticity and stability were maintained.

Compared to other particulate plugging agents, DPG is characterized by superior injectivity, making them more suitable for deep reservoir conformance control. They are less affected by subsurface physicochemical properties and shear forces, demonstrating effective gas flooding plugging performance. However, limitations are observed regarding the gel strength formed within fractures and pores, where insufficient stability is exhibited. Performance is compromised under extreme conditions due to inadequate long-term stability. Additionally, environmental concerns are posed by metal ions leached from crosslinkers.

Conclusion

CO_2 flooding is widely employed as a conventional enhanced oil recovery method, demonstrating favorable performance in both oil recovery enhancement and environmental benefits. However, challenges such as gas channeling need to be addressed. Through a comprehensive review of literature, the current developmental status and future research directions of gel particle systems are summarized in this work. In recent years, significant advancements have been achieved in the performance engineering of gel particle systems. Nevertheless, field application requires strategic selection based on the respective advantages and limitations of different systems.

(1) PPG is characterized by favorable swelling capacity and resistance to elevated temperatures and acidic environments. However, limitations exist regarding long-term stability and particle size dimensions. The combination of high mechanical strength with rapid swelling rates hinders penetration into deep complex formations. Furthermore, excessive swelling may compromise structural integrity and stability. Consequently, further optimization of synthetic formulations is required, aimed at developing gel particles with controllable swelling kinetics and long-term stability under acidic conditions.

(2) Polymer microspheres in the nano-to-micron size range have demonstrated favorable performance in gas channeling control due to their straightforward manufacturing process, economic viability, and low injection complexity. Future research should prioritize the development of controlled swelling kinetics and targeted delivery mechanisms. Concurrently, enhancement of microsphere stability and tunable degradation rates is required. For CO_2 flooding applications, responsive microspheres exhibit significant effectiveness, necessitating precise regulation of particle size distribution and crosslinking density. This approach will enable dynamic adaptive plugging capabilities.

(3) DPG is characterized by superior injectivity and controllable particle size, demonstrating significant potential for conformance control in deep high-permeability zones. However, the complex physicochemical conditions in deep formations present challenges for conventional DPG, where long-term stability cannot be maintained. Furthermore, field implementation is hindered by the prohibitively high costs of high-performance polymers and additives. Future research should focus on enhancing stability under extreme reservoir conditions, developing effective treatment

methods for residual chemicals post-plugging, and strategically integrating with complementary gas channeling control technologies to achieve synergistic effects.

Future research should prioritize further optimization of particle size and swelling properties to enhance compatibility with formation pore channels, while improving fundamental characteristics such as acid resistance and temperature tolerance through rational modification of internal microstructures. In field applications, customized gel particle plugging systems should be selected according to specific formation conditions, with particular emphasis on combining different plugging agents and technologies. Larger-sized particles are recommended for plugging macro-pores and fractures, while smaller-sized particles combined with gel or surfactants should be employed to fill interstices between larger particles. The synergistic utilization of multiple systems is advised to leverage supramolecular interactions, thereby maximizing gas channeling control efficiency in oil recovery operations and effectively addressing gas breakthrough issues in oilfield operations.

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CO_2 АЙДАУ КЕЗІНДЕ МҰНАЙ ҚАБАТТАРЫНДАҒЫ ГАЗ ШЫҒЫМЫН БАҚЫЛАУҒА АРНАЛҒАН ГЕЛЬ БӨЛШЕКТЕРІН ПАЙДАЛАНУ

Андатпа

Бүгінгі таңда мұнай өндіруді арттырудың кеңінен таралған әдістерінің бірі – көмірқышқыл газымен (CO_2) әсер ету. Бұл әдіс мұнайды ығыстыру тиімділігінің жоғарылығымен, экологиялық қауіпсіздігімен және экономикалық тұрғыдан тиімділігімен ерекшеленеді. CO^2-мен әсер ету технологиясы мұнай-газ кен орындарын игеруде кең қолданыс тапқан. Алайда қабаттың біртекті болмауы, өткізгіштіктің әркелкілігі, CO_2-нің төмен тығыздығы мен тұтқырлығы салдарынан газ шығымы жиі кездеседі. Бұл құбылыс мұнай ұңғымаларының өнімділігіне кері әсер етуі мүмкін. Осыған байланысты газ шығымының алдын алу мұнай өндіру коэффициентін арттыруда маңызды факторға айналуда. Гель бөлшектері негізінде жасалған оқшаулау жүйелері жоғары тұрақтылыққа, бейімделгіштікке және беріктікке ие болып, экономикалық жағынан тиімді шешім ретінде танылуда. Бұл жүйелердің кен орындарын игеруде кеңінен қолданылуы – олардың болашағы зор екенін көрсетеді. Мақалада CO_2-мен әсер ету кезінде газ шығымын бақылауға арналған гель бөлшектері жүйелерінің жіктелуі мен даму жағдайына жан-жақты шолу жасалған. Алдын ала қалыптастырылған бөлшектік гель, полимерлі микросфералар және дисперсті бөлшектік гель (Dispersed Particle Gel) секілді гель түрлерінің әсер ету механизмдері сипатталып, олардың отандық және халықаралық деңгейдегі қазіргі жағдайы қарастырылған. Сонымен қатар, болашақ зерттеу бағыттары мен қолдану мүмкіндіктері талқыланады.

Тірек сөздер: CO_2-мен әсер ету, гель бөлшектері, газ шығымы, оқшаулау материалдары, ығыстыру тиімділігін арттыру.

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ПРИМЕНЕНИЕ ГЕЛЕВЫХ ЧАСТИЦ ДЛЯ КОНТРОЛЯ ГАЗОПРОРЫВА ПРИ CO_2-ЗАВОДНЕНИИ ПЛАСТОВ

Аннотация

Заводнение с использованием диоксида углерода (CO_2), являясь одним из наиболее распространенных методов увеличения нефтеотдачи (МУН) на сегодняшний день, характеризуется высокой эффективностью вытеснения нефти, экологической безопасностью и экономической целесообразностью. Данный метод получил широкое развитие и применение при разработке нефтегазовых месторождений. Однако в процессе CO_2-заводнения из-за значительной неоднородности пласта по проницаемости, а также низкой плотности и вязкости CO_2 часто возникают прорывы газа. Это явление может негативно сказаться на нормальной производительности нефтяных скважин. С развитием технологии CO_2-заводнения эффективное предотвращение прорывов газа стало ключевым фактором повышения коэффициента извлечения нефти. Гелевые частицы как экономически выгодные и эффективные системы обладают высокой стабильностью, адаптивностью и прочностью, что обусловило их широкое применение в разработке месторождений и открыло большие перспективы для дальнейшего использования. В данной статье представлен всесторонний обзор классификации и современного состояния систем на основе гелевых частиц, применяемых для борьбы с прорывами газа при CO_2-заводнении. Рассматриваются механизмы действия нескольких типов гелевых частиц, включая предварительно сформированный частичный гель, полимерные микросферы и диспергированный частичный гель. Анализируется текущий статус их разработки и применения в отечественной и зарубежной практике. Кроме того, обсуждаются будущие направления исследований и перспективы их применения.

Ключевые слова: CO_2-заводнение, гелевые частицы, материалы для изоляции газопрорывов, повышение эффективности вытеснения.

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