

Research Progress on Formation Drag Reducers for Pressure Reduction and Injection Enhancement in Oil Production

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Abstract: With the rapid increase in the exploitation of oil and gas resources, conventional oil and gas resources in most oil and gas fields in China are being depleted at an accelerating pace, and research on the exploitation of unconventional oil and gas resources has become a crucial approach to safeguarding national energy security. China is endowed with abundant low-permeability reservoir resources with great application potential, yet their exploitation is fraught with considerable challenges. Water injection into the formation is a routine practice during the exploitation of low-permeability reservoirs to maintain formation pressure and improve oil recovery efficiency. However, most low-permeability oilfields currently suffer from problems such as high water injection pressure and a high proportion of insufficient injection, which prevents the establishment of effective displacement in oil-water wells and lead to a sharp drop in formation pressure, consequently driving up the exploitation costs of low-permeability reservoirs. The application of suitable formation drag reducers for oil production in the exploitation process of low-permeability reservoirs can significantly reduce water injection pressure and enhance oil recovery efficiency. This paper aims to summarize and sort out the action mechanisms of pressure reduction and injection enhancement, the types of drag reducers, and the current research status of pressure reduction and injection enhancement. Furthermore, it proposes the development directions of drag reducers in the field of pressure reduction and injection enhancement, providing a certain technical reference for improving the exploitation efficiency of low-permeability oilfields.

Keywords: Low-permeability Oilfield; Drag Reducer; Pressure Reduction and Injection Enhancement; Water Injection Method.

1. Introduction

In recent years, with the gradual depletion of conventional oil and gas resources in China, the exploitation of unconventional oil and gas resources represented by low-permeability reservoirs has attracted extensive research and attention. Nevertheless, as the exploitation depth of low-permeability reservoirs continues to increase, problems such as high water injection pressure and a high proportion of insufficient injection have emerged one after another, which result in the failure to establish effective displacement in oil-water wells, a sharp drop in formation pressure, and a significant rise in exploitation costs[1,2]. The fundamental causes of high water injection pressure are twofold: first, the pore throats of low-permeability reservoirs are tiny, leading to a high proportion of water film thickness in the pores, a substantial reduction in effective seepage channels, and a great loss of permeability caused by the boundary layer[3]; second, residual oil in the formation and reinjected oily wastewater make oil droplets adhere to the surface of pore throats, and the Jamin effect leads to high displacement pressure, blockage of seepage channels, and a high permeability damage rate[4]. Current research shows that even if high-pressure water injection is effective in the exploitation of low-permeability reservoirs, problems such as low formation water absorption capacity, slow energy diffusion of water injection wells, rapid decline in formation pressure, and poor response of oil wells still exist[5,6]. Therefore, long-term high-pressure water injection is not advisable, and reasonable measures must be taken to reduce injection pressure. Exploring water injection pressure

reduction and injection enhancement methods for low-permeability reservoirs is the key to improving their development effect.

To address the problem of reduced seepage capacity caused by water film and residual oil blockage during the exploitation of low-permeability reservoirs, on the basis of meeting the requirements of pressure reduction and injection enhancement for oilfield water wells, the development of new formation drag reducers for oil production, the improvement of the utilization efficiency of water injection wells, and the clarification of the drag reduction mechanism of drag reducers can effectively save oil production costs and create economic and environmental benefits[7]. This paper intends to summarize and sort out the principles of pressure reduction and injection enhancement for low-permeability reservoirs, the types of drag reducers, and the current research status of pressure reduction and injection enhancement. In addition, it puts forward the development directions of drag reducers in pressure reduction and injection enhancement, providing a certain technical reference for improving the exploitation efficiency of low-permeability oilfields.

2. Mechanisms of Pressure Reduction and Injection Enhancement Technology

With the increasing attention and research on the exploitation and utilization of low-permeability reservoirs, an increasing number of formation drag reducer materials have been developed. At present, the widely used formation drag reducers mainly include surfactant-based, acidic liquid-based,

and nanomaterial-based types[8]. Different drag reducer materials achieve pressure reduction and injection enhancement through distinct specific mechanisms, but in general, the core approaches of pressure reduction and injection enhancement lie in three aspects: improving the interfacial properties of fluids, expanding the physical channels of fluids, and altering the surface properties of rock formations[9,10]. Usually, the three mechanisms coexist when drag reducers are applied for pressure reduction and injection enhancement in low-permeability reservoirs.

2.1. Improving the Interfacial Properties of Fluids

The exploitation of low-permeability reservoirs is significantly more difficult than that of conventional reservoirs, mainly because the cores of low-permeability reservoirs are dense with small pore throat radii. When crude oil flows through micro-pores and throats, the capillary resistance is significantly enhanced, which in turn triggers the Jamin effect, leading to a substantial increase in fluid seepage resistance and a decrease in oil displacement efficiency[11]. In response to the above problems, improving the interfacial properties of fluids is an effective measure to achieve pressure reduction and injection enhancement. During the exploitation of low-permeability reservoirs, the optimal addition of suitable surfactant-based drag reducers can significantly reduce the oil-water interfacial tension in the reservoir, leading to a sharp decrease in capillary resistance. Oil droplets can flow more smoothly through pore throats, thus effectively alleviating the phenomenon of oil droplet blockage (as shown in Figure.1), and ultimately achieving the goals of reducing water injection pressure and improving oil displacement efficiency.

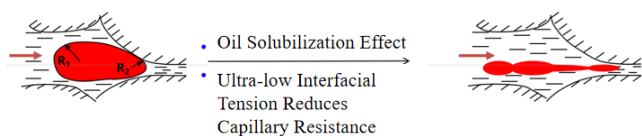


Figure 1. Schematic diagram of reducing oil-water interfacial tension by improving fluid interfacial properties

2.2. Expanding the Physical Channels of Fluids

The insufficient physical fluid channels in the formation of low-permeability reservoirs are the fundamental reasons for high water injection pressure and low water injection volume. Therefore, in addition to improving the interfacial properties of fluids, expanding the physical channels of fluids is also an effective measure for pressure reduction and injection enhancement. In the early stage of low-permeability reservoir exploitation, the injection of acidic liquid-based drag reducers such as hydrochloric acid, ammonium bifluoride, and boric acid into the formation can modify the reservoir structure, reduce formation resistance, and improve oil and gas exploitation efficiency[12]. After being injected into the formation, acidic liquids can, on the one hand, dissolve soluble substances such as carbonates and sulfates in the formation, remove formation blockage, broaden and increase the pore throat structure, and reduce the resistance during oil displacement; on the other hand, when acidic liquids come into contact with the formation oil flow, they can also undergo physical and chemical reactions with it, shorten the length of crude oil molecular chains, reduce the viscosity and surface tension of oil flow, and significantly decrease the flow

resistance of oil flow[13].

2.3. Altering the Surface Properties of Rock Formations

Current research has also found that the wettability characteristics of formation rocks have a significant impact on oil displacement efficiency during the oil displacement process in low-permeability reservoirs, and the appropriate regulation of rock formation surface properties is also an effective measure to achieve pressure reduction and injection enhancement. Altering the surface properties of rock formations is mainly realized by dispersing nanomaterial-based drag reducers in a dispersion medium and injecting them into the formation, which form a nano-adsorption layer on the surface of rock pores. Utilizing the excellent hydrophobic properties of the materials, the wettability of rocks is changed, the water film in the pores is thinned, the effective pore size is expanded, and the flow resistance of water during water injection and oil displacement is effectively reduced[14]. The coating formed by nanomaterial-based drag reducers on the surface of formation rocks can also effectively isolate the contact between water and rock formations and reduce the hydration expansion phenomenon between water and clay particles[15]. This effect improves the permeability of the formation, thereby increasing the water injection volume and reducing the pumping pressure at the same time. In addition, when nanomaterials are adsorbed on the surface of rock formations, the formed water-repellent layer can prevent injected water from approaching the surface of pore throats, producing a water flow slip effect, which further significantly reduces the water phase flow resistance[16].

3. Types of Drag Reducers

3.1. Surfactant-based Drag Reducers

At present, surfactant-based drag reducers are mainly divided into four categories: cationic, anionic, amphoteric ionic, and non-ionic[17]. Cationic surfactants, represented by cetyltrimethylammonium chloride (CTAC), exhibit excellent performance in reducing fluid resistance, but they also have high toxicity and cause severe pollution to the reservoir[18]. Anionic surfactants, represented by sodium dodecyl sulfate (AS), show an excellent drag reduction effect, but their poor salt tolerance limits their application range[19]. Amphoteric ionic surfactants, represented by trimethylamine oleamide (ZA), have certain biodegradable characteristics and relatively low toxicity, but the available types are limited[20]. Non-ionic surfactants, represented by oleic acid dimethylamine oxide (ODMAO), have low biological toxicity and good biodegradability, and can enhance their tolerance in salt solutions, but their application range is restricted due to the high cost[21]. The development of new and high-efficiency surfactants has always been a key approach for oilfields to improve displacement and recovery efficiency. In recent years, research has found that the non-ionic surfactant alcohol ether glycoside has a better drag reduction effect, lower cost, and better environmental friendliness. Alcohol ether glycoside can significantly reduce the oil-water interfacial tension to the level of 10^{-3} mN/m[22]. The low interfacial tension helps to reduce the flow resistance of water in the reservoir, thereby improving water displacement efficiency. Alcohol ether glycoside drag reducers can also prevent the expansion and dispersion of

water-sensitive rocks, protect the reservoir structure, and avoid reservoir damage caused by water injection[23].

3.2. Acidic liquid-based Drag Reducers

In the exploitation of low-permeability reservoirs, the injection of acidic liquids can significantly expand the formation fluid channels, achieving pressure reduction, injection enhancement, and improved oil recovery efficiency. At present, the widely used acidic liquids mainly include four categories: inorganic strong acids, organic acids, retarded acids, and modified acids[24]. Inorganic strong acids, represented by hydrochloric acid (HCl), hydrofluoric acid (HF), and mud acid (HCl+HF), are suitable for carbonate and sandstone formations. They feature fast reaction, strong corrosion, and a significant effect of pressure reduction and injection enhancement, but cause severe corrosion to metal equipment and pipelines[25]. Organic acids, represented by formic acid, acetic acid, and citric acid, are suitable for high-temperature formations, sensitive formations and other environments. They have low corrosivity but slow reaction, large dosage, and high cost[26]. Retarded acids, represented by fluoroboric acid, phosphoric acid, and polybasic acids, are suitable for low-permeability sandstones and deep formations. They have a controllable reaction rate and can penetrate deep into the formation[27]. Modified acids, represented by gelled acid, cross-linked acid, foam acid, and emulsified acid, are suitable for high-temperature, low-pressure, and water-sensitive formations. They have the characteristics of low filtration loss, slow reaction, and easy flowback[28]. With the increasing requirements for pressure reduction and injection enhancement in low-permeability reservoirs, single acidic liquid-based drag reducers can no longer meet the production needs, and the application and research of composite acid systems have attracted increasing attention. In view of the characteristics of low-permeability reservoirs such as high clay content, easy blockage, and high starting pressure, retarded acid systems or composite acid systems should be prioritized for acidic liquid-based formation drag reducers to achieve deep plugging removal and long-term stable injection[29].

3.3. Nanomaterial-based Drag Reducers

Nanomaterials have attracted extensive attention and research in the development of formation drag reducers for low-permeability reservoirs due to their large specific surface area and high surface activity. At present, the widely used nanomaterial-based drag reducers mainly include nano-silicon dioxide (SiO_2), metal oxide nanoparticles, carbon-based nanomaterials, and new two-dimensional nanomaterials [30]. Among them, nano-silicon dioxide (SiO_2) materials are the most widely used, with the advantages of low cost, long validity period, low reactivity with the formation, and low tendency to cause secondary damage. However, they have poor stability and high dispersion requirements, and the particle size must be strictly controlled to match the pore throats[31]. Metal oxide nanoparticles, represented by aluminum oxide (Al_2O_3), iron oxide ($\text{Fe}_2\text{O}_3/\text{Fe}_3\text{O}_4$), zinc oxide (ZnO), and magnesium oxide (MgO), have the advantages of strong wettability modification ability, high mechanical strength, and the ability to reduce crude oil viscosity. However, they have high cost, are prone to agglomeration, and tend to accumulate at the injection point, leading to pore blockage[32]. Carbon-based nanomaterials, represented by carbon nanotubes (CNT),

biomass carbon nanoparticles, and graphene, have the advantages of environmental friendliness, good oil-water interfacial tension reduction effect, and good stability. However, they have unstable performance, poor injectivity, and high preparation cost[33]. New two-dimensional nanomaterials, represented by black phosphorus (BP) nanosheets and molybdenum disulfide (MoS_2) nanosheets, have the advantages of low interfacial free energy, strong adsorptivity, and good modifiability. However, they have excessively high cost, poor long-term stability, and immature technology[34]. At present, nanomaterial-based drag reducers are usually not used alone, but mainly compounded with high molecular polymers to form nano-composite drag reducers, which integrate the advantages of nanomaterials and high molecular polymers[35] and make up for their respective deficiencies at the same time, achieving high-efficiency pressure reduction and injection enhancement effects in low-permeability reservoirs through synergistic effects.

4. Current Research Status of Pressure Reduction and Injection Enhancement Technology

In the water injection operation of low-permeability reservoirs, the insufficient water injection volume may be caused by the reduced formation water absorption capacity due to blockage or the poor permeability of the formation itself, which makes the water injection process difficult. To improve the exploitation efficiency of low-permeability reservoirs, suitable drag reducers should be selected targetedly to solve the problems of high water injection pressure and insufficient water injection volume. The current research status of pressure reduction and injection enhancement of different types of formation drag reducers is as follows.

4.1. Current Research Status of Surfactant-Based Drag Reducers for Pressure Reduction and Injection Enhancements

Surfactant-based drag reducers are the most widely used and mature materials for pressure reduction and injection enhancement in the exploitation of low-permeability reservoirs at present. However, under the harsh conditions of low-permeability reservoirs, they still face some challenges, such as performance failure under high shear stress and compatibility problems with other additives (e.g., stabilizers). Therefore, the selection and development of surfactant-based drag reducer materials, as well as the in-depth exploration of the influencing factors and mechanisms of drag reduction effect, are in urgent need of further research and improvement. Mohareb R M[36] et al. prepared a cationic drag reducer with cetyltrimethyl-ammonium chloride as the main agent, and the drag reduction rate remained above 60% at 70°C with a mass fraction of 0.3%, indicating its good drag reduction effect and temperature resistance. Ellina K[37] et al used the amphoteric surfactant N,N,N-trimethylamine-N-oleamide as a drag reducer for low-permeability reservoirs, and the drag reduction rate could reach 83%. Liu Yi[38] et al prepared the JDZC quaternary ammonium salt gemini surfactant and applied it in the exploitation of low-permeability reservoirs in Nanpu Oilfield. Experiments showed that the pressure reduction rate could reach more than 30% at 120°C, and the single well injection enhancement exceeded 2000m³, with a significant effect of pressure reduction and injection

enhancement. Wang Zengbao[39] et al compounded 0.05% gemini surfactant HA-1, 0.1% ethanolamine (MEA) and 0.1% methanol into a drag reducer for the exploitation of low-permeability reservoirs. Experiments found that the composite system could reverse the oil-wet surface to a water-wet surface, and the water displacement pressure was reduced by 20%. Wei Gaofeng[40] compounded non-ionic surfactants with petroleum sulfonate surfactants and applied them in the exploitation of low-permeability reservoirs in Yanchang Oilfield, realizing the reduction of water injection pressure from 17.0 MPa to 15.0 MPa and the increase of water injection volume by 20%. Shu Qinglin[41] applied the polyether anionic/betaine composite surfactant system in the exploitation of low-permeability reservoirs in Shengli Oilfield and found that the composite system could convert the oil-wet rock surface to a water-wet surface, strip crude oil from the rock surface, and accelerate the invasion of water phase into fractures (as shown in Figure.2). The water injection pressure reduction rate reached 26.18%, with a significant effect of stable and increased production.

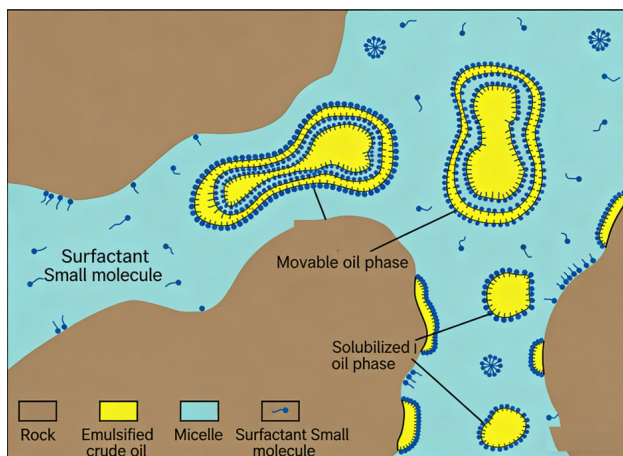


Figure 2. Schematic diagram of surfactant stripping and migrating crude oil

4.2. Current Research Status of Acidic Liquid-Based Drag Reducers for Pressure Reduction and Injection Enhancement

Acidic liquid-based drag reducers can effectively dissolve soluble substances such as carbonates and sulfates in the formation of low-permeability reservoirs, fundamentally remove formation blockage, broaden and increase the pore throat structure, with a significant effect of pressure reduction and injection enhancement. Single acid drag reducers usually have problems such as high cost and easy pollution, and composite acid system drag reducers have attracted extensive attention and research in recent years. Yang Xu[42] et al prepared a salt-tolerant retarded acid drag reducer by inverse emulsion polymerization for the exploitation of carbonate low-permeability reservoirs. Experimental results showed that when the mass concentrations of NaCl and CaCl₂ were 10 g/L, the drag reduction rates of the acid drag reducer could still reach 60% and 45.3%, respectively. Ge Yizhuo[43] prepared a high-temperature resistant polyglycolic acid retarded acid drag reducer to solve the problems of poor stability and fast reaction rate of conventional acid drag reducers. Experimental results showed that the effect of polyglycolic acid retarded acid at 130°C was better than that of mud acid and polybasic acid, and it had weak corrosivity to metal equipment and pipelines. Xu Hang[44] et al prepared

a high-temperature resistant weightable acidic fracturing drag reducer with hydrochloric acid as the pH control agent for the exploitation of high-temperature and deep low-permeability oil and gas reservoirs. Experimental results showed that its drag reduction rate could still reach more than 68.04% at 180°C. Liu Dexin[45] et al prepared a microlactic acid system drag reducer for the development of low-permeability sandstone reservoirs. Experimental results showed that the plugging removal effect of the microlactic acid system drag reducer was 10% higher than that of traditional acid liquids, and it had low corrosivity, which could increase the daily oil production by 53.44% (as shown in Figure.3).

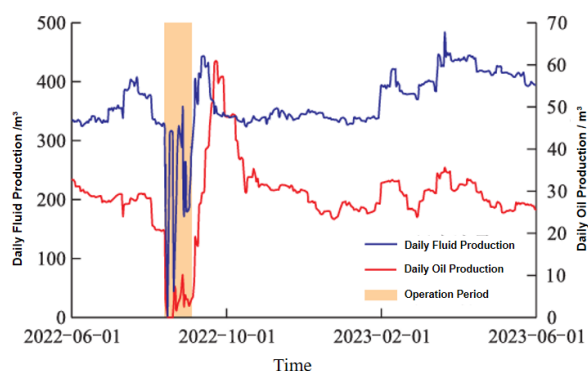


Figure 3. Variation of oil well productivity before and after drag reduction with microlactic acid system

4.3. Current Research Status of Nanomaterial-Based Drag Reducers for Pressure Reduction and Injection Enhancement

Nanoparticles have a large specific surface area and high surface activity. When applied in the displacement and recovery process of low-permeability reservoirs, they can be efficiently adsorbed on the rock surface, significantly alter the wetting characteristics of the rock surface, and achieve the goal of pressure reduction and injection enhancement in the exploitation of low-permeability reservoirs. In recent years, nanomaterial-based drag reducers represented by SiO₂ particles have attracted increasing attention and research. In particular, the surface modification and regulation of nanomaterials, as well as their compounding with polymers to prepare composite drag reducers, have increasingly become a research hotspot[46]. Yang Jinzhou[47] et al prepared SiO₂ nanoparticles by the emulsion template method and applied them in the displacement and recovery process of low-permeability reservoirs with a permeability of 50 mD, and the crude oil recovery rate could be increased by 16.7%. Li Shengsheng [48] et al prepared a new SiO₂-based nano-injection enhancement system to address the problem of "inability to inject water and produce oil" in low-permeability reservoirs. Field application results showed that the water injection pressure decreased by 46.7% and the water injection volume increased by 8 times, with a significant effect of pressure reduction and injection enhancement. Hu Haixia[49] et al prepared functional SiO₂ nanoparticles with a particle size of 20-30 nm, which could be efficiently adsorbed on the surface of formation rocks in low-permeability reservoirs, converting the rock surface from hydrophilic to hydrophobic, and the water injection pressure reduction rate reached 34%. Wei Jie[50] et al studied the effect of SiO₂ nanoparticles with different mass fractions in the pressure reduction and injection enhancement process of low-permeability reservoirs. Experimental results showed that the crude oil recovery rate

of nanofluid with a mass fraction of 0.06% could reach 68.3%, with the best oil displacement effect. Cao zhi[51] prepared SiO₂ nanoparticles by in-situ surface modification for the exploitation of low-permeability reservoirs. Experimental results showed that SiO₂ nanoparticles had good hydrophobicity, and their adsorption on the rock surface could drive away adsorbed water and prevent the hydration expansion of clay in the formation (as shown in Figure.4), which could increase the water phase permeability by 20%, showing good application potential for pressure reduction and injection enhancement.

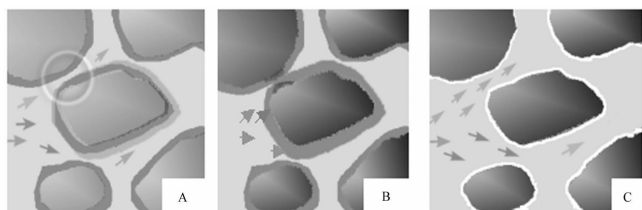


Figure 4. Schematic diagram of injection enhancement mechanism of SiO₂ nanoparticle drag reducer (A: Original formation state, B: Water injection expansion state, C: SiO₂ adsorption anti-expansion state)

5. Conclusion

Low-permeability reservoir exploitation is plagued by problems such as high water injection pressure and low water injection volume. The research and development of high-efficiency formation drag reducers for oil production are of great significance for improving the recovery efficiency of low-permeability reservoirs and safeguarding China's energy security. This paper focuses on sorting out the drag reduction mechanisms, common types and current research status of formation drag reducers for oil production, and the specific conclusions are as follows:

(1) The fundamental reason for the great difficulty in the development and utilization of low-permeability reservoirs is the dense formation core and small pore throat diameter, which lead to high fluid flow resistance. The main mechanism approaches to achieve pressure reduction and injection enhancement during the displacement and recovery process of low-permeability reservoirs include improving the interfacial properties of fluids, expanding the physical channels of fluids, and altering the surface properties of rock formations. Usually, the three mechanism approaches coexist when drag reducers are applied for pressure reduction and injection enhancement in low-permeability reservoirs.

(2) At present, the widely used formation drag reducers for oil production in low-permeability reservoirs mainly include surfactant-based, acidic liquid-based, and nanomaterial-based types. Among them, surfactant-based drag reducers are widely used with relatively mature technology; acidic liquid-based drag reducers have a good effect of pressure reduction and injection enhancement but are prone to cause severe environmental pollution; nanomaterial-based drag reducers have a long validity period but are prone to agglomeration and unstable performance.

(3) Preparing composite drag reducers by systematically combining the advantages of different components is an important development trend of formation drag reducers for oil production in low-permeability reservoirs in the future. Among them, surfactant-based drag reducers mainly need to be compounded to enhance their erosion resistance and long-term stability; acidic liquid-based drag reducers need to

reduce their corrosivity and environmental pollution while ensuring their pressure reduction and injection enhancement performance; nanomaterial-based drag reducers need to further strengthen their anti-agglomeration performance and performance stability.

References

- [1] Liu J, Ni X S, Ning H J, et al. Surfactant Pressure Reduction and Injection Enhancement Technology for Water Injection Wells in Ultra-Low Permeability Reservoirs, *Petrochemical Technology*, 2023, vol.30, no.11, pp.55-57.
- [2] Wang J. Research on Multi-functional Chemical Pressure Reduction and Injection Enhancement System for Low Permeability Reservoirs in Liandaowan of Changqing Oilfield (Dissertation). Qingdao: China University of Petroleum (East China), 2014.
- [3] Ma B Y. Research on Acidizing Pressure Reduction and Injection Enhancement Technology in Low Permeability Oilfields, *China Petroleum and Chemical Standard and Quality*, 2023, vol.43, no.17, pp.160-162.
- [4] Zhang J C, Chen X L, Tian Z H. Experiment of Polysilicic Material for Improving Waterflooding Effect in Low Permeability Oil Reservoir, *Oil & Gas Recovery Technology*, 2003, vol.4, pp.21.
- [5] Cheng Y, Li X, Li Q, et al. "Fabrication and Augmented Injection Performance of Water Based Nanometer Polysilica Latex", *Chemical Research*, 2011, vol.3, pp.6.
- [6] Xiong J, Li Q, Tao J, et al. Nano-injection Technology Application and Understanding in Injection Wells, *Oil Drilling & Production Technology*, 2010, vol.4, pp.29.
- [7] Li T, He M Q, Li S M, et al. Research Status and Prospect of Drag Reducers for Fracturing in Unconventional Oil and Gas Exploitation, *Science Technology and Engineering*, 2024, vol.24, no.17, pp.7014-7023.
- [8] Zhang C Y, Wu J Q, Wang G Z, et al. Study on Drag Reduction Characteristics and Mechanism of Guar Gum, *Applied Chemical Industry*, 2020, vol.49, no.1, pp.63-66.
- [9] Mohammadtabar M, Sanders R S, Ghaemi S. Viscoelastic Properties of Flexible and Rigid Polymers for Turbulent Drag Reduction, *Journal of Non-Newtonian Fluid Mechanics*, 2020, vol.283, pp.104347.
- [10] Hong C H, Choi H J, Zhang K, et al. Effect of Salt on Turbulent Drag Reduction of Xanthan Gum, *Carbohydrate Polymers*, 2015, vol.121, pp.342-347.
- [11] Li Y F, Wang Y L, Cao X C, et al. Research and Application Progress of Drag Reducers for Fracturing in Shale Reservoirs, *Fine Chemicals*, 2018, vol.35, no.1, pp.1-9.
- [12] Abdulbari H A, Amir R. Drag Reduction Performance and Stability of an Organic Polymer, Surfactant, and their Complexes, *Chemical Engineering & Technology*, 2021, vol.44, no.12, pp.2333-2340.
- [13] Liu Q, Guan B S, Liu Y T, et al. Research and Application Progress of Drag Reducers for Slickwater Fracturing Fluid, *Oilfield Chemistry*, 2020, vol.37, no.3, pp.545-551.
- [14] Rodrigues R K, Silva L A S, Vargas G G, et al. Drag Reduction by Wormlike Micelles of a Biodegradable and Non-biodegradable Surfactants, *Journal of Surfactants and Detergents*, 2020, vol.23, no.1, pp.21-40.
- [15] Liu Q S, Mao J C. Salt Tolerance Mechanism and Research Progress of Slickwater Drag Reducers, *Energy Chemical Industry*, 2022, vol.43, no.3, pp.9-14.
- [16] Esfandiari N, Zareinezhad R, Habibi Z. The Investigation and Optimization of Drag Reduction in Turbulent Flow of

- Newtonian Fluid Passing through Horizontal Pipelines Using Functionalized Magnetic Nanophotocatalysts and Lecithin, *Chinese Journal of Chemical Engineering*, 2020, vol.28, no.1, pp.63-75.
- [17] Yu Z D, Liu S X, Tang J, et al. Study on Acid-Surfactant Synergistic Pressure Reduction and Displacement Mechanism in Low Permeability Reservoirs, *Modern Chemical Industry*, 2025, vol.45, Suppl.2, pp.347-353.
- [18] Li G H, Yang W, Wei J, et al. Analysis of Chemical Mechanism of Surfactant Flooding and Experimental Study on Pressure Reduction and Injection Enhancement, *Contemporary Chemical Industry*, 2023, vol.52, no.12, pp.2946-2949.
- [19] Cao Z, Zhang Z J, Zhao Y F, et al. Preparation and Characterization of SiO₂ Nanoparticles for Injection Enhancement in Low Permeability Oilfields, *Chemical Research*, 2005, vol.16, no.1, pp.32-34.
- [20] Lu X B, Zheng Y C, Liu X N, et al. Study on Temperature and Salt Resistant Surfactant Injection Enhancement System in Jiyuan Oilfield (in English), *China Surfactant Detergent & Cosmetics* (Chinese and English), 2022, vol.52, no.10, pp.1040-1048.
- [21] Wang Y, Yang R G, Yu X D, et al. Research on Surfactant Pressure Reduction and Injection Enhancement System for Separate Layer Water Injection Wells in Low Permeability Blocks of Yanchang Oilfield, *Contemporary Chemical Industry*, 2022, vol.51, no.8, pp.1996-1999.
- [22] Cao Y. Heavy Oil Emulsification and Viscosity Reduction Technology Based on Fatty Alcohol Ether Glycoside (Dissertation). Jinan: Shandong University, 2024.
- [23] Liu J P, Wu Y G. Study on the Effect of Alkyl Polyglycoside and Alcohol Ether Glycoside on the Interfacial Tension of Liaohe Heavy Oil, *Applied Chemical Industry*, 2024, vol.53, no.1, pp.126-130.
- [24] Qi C M, Xia Y, Tang S F, et al. Multi-component Composite Acid Plugging Removal Technology for Water Injection Wells in Yanchang Oilfield, *Chemical Engineering of Oil & Gas*, 2025, vol.54, no.6, pp.91-97.
- [25] Zhang J, Tian Y, Zheng H X, et al. Study on Pressure Reduction, Injection Enhancement and Plugging Removal Performance of Composite Acid Based on Gemini Surfactant, *Applied Chemical Industry*, 2024, vol.53, no.12, pp.2826-2831.
- [26] Zhou E J, Yuan H N, Wang X Z, et al. Performance Evaluation of a New Acid Liquid for Pressure Reduction and Injection Enhancement, *Petrochemical Safety and Environmental Protection Technology*, 2024, vol.40, no.6, pp.32-36,6-7.
- [27] Li Y. Research on Pressure Reduction and Injection Enhancement Technology for Low Permeability Reservoirs in Gaoshangpu Oilfield (Dissertation). Chengdu: Southwest Petroleum University, 2023.
- [28] Li J B. Experimental Study on a New Latent Acid Pressure Reduction and Injection Enhancement System, *Shandong Chemical Industry*, 2022, vol.51, no.16, pp.42-44.
- [29] Wang X J, Wu D Z, Li J X, et al. Experimental Study on a New Latent Acid Pressure Reduction and Injection Enhancement System, *Adhesion*, 2022, vol.49, no.3, pp.12-16.
- [30] Ding J, Yang Z Q, Li T. Research Progress of Modified Nano-Silicon Dioxide in Oilfield Development, *Petrochemical Application*, 2025, vol.44, no.9, pp.6-11.
- [31] Liu L J, Zeng S J, Xiong N L, et al. Performance Evaluation of Temperature and Salt Resistant Nano-SiO₂ Microemulsion in Low Porosity and Low Permeability Reservoirs, *Contemporary Chemical Industry*, 2025, vol.54, no.5, pp.1127-1131.
- [32] Chen G G, Yu H J, Lei L, et al. Construction and Performance of Composite Carbon Quantum Dot Pressure Reduction and Injection Enhancement System, *Speciality Petrochemicals*, 2025, vol.42, no.2, pp.11-15.
- [33] Wu K, Wen S C, Shao W, et al. Pressure Reduction and Injection Enhancement Effect of Nano-SiO₂ Microemulsion on Southern Shaanxi Tight Oil Reservoirs, *Oilfield Chemistry*, 2024, vol.41, no.2, pp.245-250.
- [34] Lan S, Zhang D X, Wang Y, et al. Experimental Study on Micro-nanoemulsion Injection Enhancement Technology in Low Permeability Reservoirs, *Petrochemical Technology*, 2024, vol.53, no.4, pp.553-558.
- [35] Wang J H, Li Y, Feng Y B, et al. Preparation of Modified Nano-Silicon Dioxide Fluid and its Pressure Reduction and Injection Enhancement Law, *Petrochemical Technology*, 2023, vol.52, no.3, pp.352-357.
- [36] Mohareb R M, Badawi A M, El-Din M R N, et al. Synthesis and Characterization of Cationic Surfactants Based on Cetyl Trimethyl Ammonium Chloride as Drag Reduction Agent, *Journal of Surfactants and Detergents*, 2015, vol.18, no.3, pp.1-7.
- [37] Ellina K, Gabriel O, David J H, et al. Study on the Characteristics of Novel Zwitterionic Surfactants as Drag Reducing Agents", *Journal of Polymer Research*, 2015, vol.21, pp.212-217.
- [38] Liu Y, Wu J, Song Y Z, et al. "Application Research of Gemini Surfactant Injection Enhancement Technology in Low Permeability Reservoirs of Nanpu Oilfield, *China Mining Magazine*, 2022, vol.31, Suppl.1, pp.460-464.
- [39] Wang Z B, Wang J, Tong M, et al. Study on Surfactant/Organic Base Pressure Reduction and Injection Enhancement System for Low Permeability Reservoirs, *Oilfield Chemistry*, 2014, vol.31, no.4, pp.573-577.
- [40] Wei G F. Research on Surfactant Pressure Reduction and Injection Enhancement System for Low Permeability Reservoirs in Yanchang Oilfield, *Petrochemical Technology*, 2024, vol.31, no.12, pp.21-23.
- [41] Shu Q L, Mu M, Zhang X Y, et al. Mechanism and Application of Drag Reduction-Imbibition-Displacement Synergistic Development Technology, *Petroleum Geology and Recovery Efficiency*, 2023, vol.30, no.6, pp.72-79.
- [42] Yang X, Lai X J, Duan G D, et al. Development of Salt-Tolerant Retarded Acid Drag Reducer GnR-1, *Modern Chemical Industry*, 2020, vol.40, no.12, pp.164-167,172.
- [43] Ge Y Z, Zhao W N, Zhang C, et al. Preparation and Performance Evaluation of High Temperature Resistant Polyglycolic Acid Retarded Acid, *Oilfield Chemistry*, 2023, vol.40, no.3, pp.394-400.
- [44] Xu H, Zhou F J, Yang S S, et al. Development and Performance Evaluation of High Temperature Resistant Weightable Acidic Cross-linked Fracturing Fluid, *Petroleum Science Bulletin*, 2024, vol.9, no.3, pp.503-512.
- [45] Liu D X, Zhao H, Dong Y L, et al. Homologous Heteromorphic Microlactic Acid Plugging Removal System and its Mechanism for Low Permeability Sandstone Reservoirs, *Petroleum Geology and Recovery Efficiency*, 2025, vol.32, no.3, pp.88-99.
- [46] Li J H, Fan H M, Wei Z Y, et al. Research Progress and Prospect of Nanomaterials in Low Permeability Reservoirs, *Chemical Industry and Engineering Progress*, 2025, vol.44, no.3, pp.1485-1495.
- [47] Yang J Z, Xu G R, Li X, et al. Test and Profile Control Performance of Pickering Emulsion System Based on Janus Nanoparticles, *Speciality Petrochemicals*, 2024, vol.41, no.6, pp.30-34.

- [48] Li S S, Feng Q, Gong R X, et al. Performance Evaluation and Application of Multi-functional Nano-Injection Enhancement System in Offshore Medium and Low Permeability Reservoirs, *Chemical Engineering of Oil & Gas*, 2023, vol.52, no.5, pp.80-85.
- [49] Hu H X, Zhang J, Lu D L. Preparation of Functional Nanofluid Dispersion and Pressure Reduction for Oil Drainage, *Science Technology and Engineering*, 2020, vol.20, no.16, pp.6429-6432.
- [50] Wei J, Zheng S, Deng S X, et al. Research on the Influence of Nanofluid Chemical Flooding on Improving Oil Recovery in Oilfields, *Contemporary Chemical Industry*, 2023, vol.52, no.5, pp.1216-1219.
- [51] Cao Z, Zhang Z J, Zhao Y F, et al. Preparation and Characterization of SiO₂ Nanoparticles for Injection Enhancement in Low Permeability Oilfields, *Chemical Research*, 2005, vol.16, no.1, pp.32-34.