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Invited review

Recent research progress on imbibition system of nanoparticle-surfactant dispersions

Wenhao Shao[1,2], Jinzhou Yang[3], Haoyi Wang[3], Jiawei Chang[1,2], Hairong Wu[1,2]*, Jirui Hou[1,2]*

[1]State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum-Beijing, Beijing 102249, P. R. China
[2]Unconventional Petroleum Research Institute, China University of Petroleum-Beijing, Beijing 102249, P. R. China
[3]COSL Production Optimization, China Oilfield Services Limited, Tianjin 300452, P. R. China

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Abstract:
Nanotechnology has been increasingly applied in the petroleum industry in recent years. In particular, dispersions consisting of nanoparticles and surfactants have been widely investigated. The imbibition system compounded by nanoparticle and surfactant was found to display a high efficiency in enhancing oil recovery. This paper briefly reviews the factors influencing imbibition efficiency. At the same time, the application and mechanism of the imbibition system of nanoparticle-surfactant dispersion in the field of enhanced oil recovery are introduced. Additionally, the limitations and challenges that the imbibition system of nanoparticle-surfactant dispersions may face in enhanced oil recovery applications are put forward. The current work reveals that the imbibition system with nanoparticle-surfactant dispersion is an ideal candidate for enhanced oil recovery in tight and low-permeability reservoirs.

1. Introduction

The development of unconventional oil reservoirs has been pivotal to increasing the production of oil. In unconventional reservoir production, hydraulic fracturing and water flooding are commonly used. In this way, high oil production can be obtained in the early stage of fracturing; however, oil production decreases rapidly with the extension of waterflood development time (Wang et al., 2017). This is mainly because after a large amount of water in formation fractures has been absorbed, subsequent water injection will produce channeling along large pores and fractures, while water that has entered the tiny pores is untoward. Correspondingly, the sweeping efficiency is reduced, causing a decline in oil production and an increase in water content (Li et al., 2016; Ji, 2020; Wang et al., 2021).

Imbibition is a vital mechanism in the development of tight and low-permeability reservoirs (Liu et al., 2021). In particular, in the unswept region of the fracturing fluid in this type of reservoir, the permeability is low and the starting pressure is high; therefore, it is essential to build a displacement system with high efficiency. Oil production primarily depends on the imbibition process, which leads to the exchange of oil and water between the matrix of reservoir and natural fractures. Intense imbibition may help the core to absorb liquid remained in the main flow channel, unchoke the channels in the course of the shut-in stage, restore the permeability of blocked channels, and enhance reservoir pressure. Hence, the investigation of imbibition oil recovery technology is of great significance for improving oil recovery in tight and low-permeability reservoirs.

Owing to its economical efficiency and good applicability to the above reservoir types, water imbibition has become a common strategy for production. The process of the wetting

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*Corresponding author.
E-mail address: swhx0904@163.com (W. Shao); yangjzh14@cnooc.com (J. Yang); wanghy117@cosl.com.cn (H. Wang); cjw19980714@163.com (J. Chang); wuhairong-123@163.com (H. Wu); houjirui@126.com (J. Hou).

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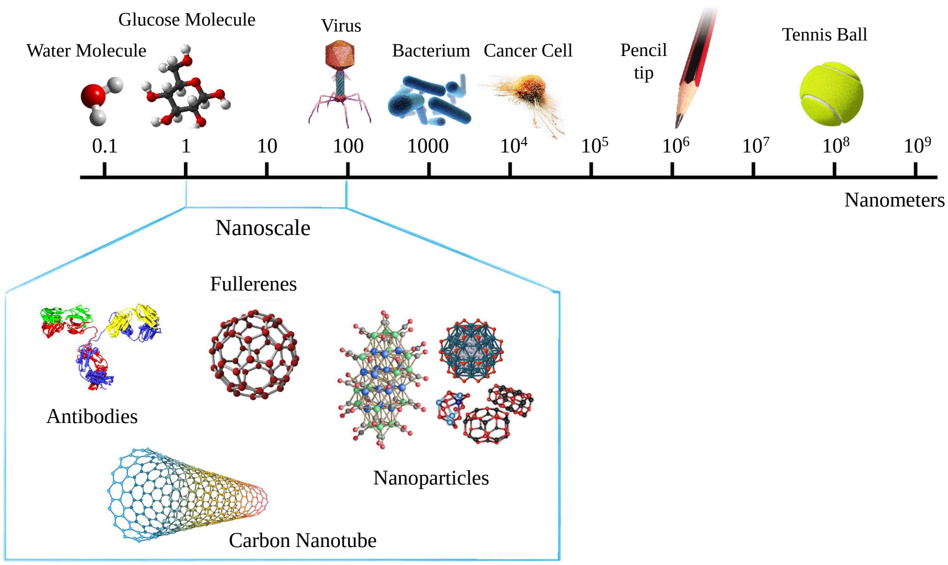

Fig. 1. Scale comparison (Lau et al., 2017).

phase entering the pore throat and displacing the non-wetting phase is termed as imbibition, with its main driving force being the capillarity force (Cai et al., 2014; Yang et al., 2017). One study showed that water imbibition is always accompanied by water displacement in low-permeability reservoirs (Zhang et al., 1996). However, due to capillarity force and other factors, the oil recovery rate of the water imbibition process is low (Iffly et al., 1972; Schechter et al., 1991; Li and Horne, 2001), which necessitates finding more effective imbibition agents to improve the oil recovery rate.

To achieve the above aim, researchers have commonly investigate surfactants to enhance imbibition recovery. Surfactant molecules are able to enter the fine pore throats, mainly by improving rock surface wettability and decreasing oil-water interfacial tension, and can accelerate the imbibition flow rate and improve the oil recovery via imbibition (Bai et al., 2020). However, surfactants are greatly influenced by the reservoir conditions, suffer from excessive adsorption, and are unstable under harsh reservoir conditions (Isaac et al., 2022). Over the years, nanoscale materials have been studied and employed increasingly in the oil and gas field due to their large specific surface area, small particle size, and unique thermodynamic properties (Khalil et al., 2017). The diameter of nanoparticles applied in enhanced oil recovery (EOR) is relatively small as compared to that of the pore throat sizes (El-Diasty et al., 2015). The EOR mechanism of nanoparticles includes reducing interfacial tension, changing the rock wettability by nanoparticle adsorption, and structural separation pressure (Hendraningrat et al., 2013). The interfacial properties can also be improved by adsorbing on the surface of the rock and the interface between oil and water (Khalilnezhad et al., 2019). In particular, nanoparticles create structural separation pressure, and oil droplets are then stripped off from the surface of the rock (Zhao et al., 2018). To prepare nanofluids with good performance, many research groups focused on the interaction between nanoparticles and surfactants and the corresponding synergistic effects between them on the interfacial properties. It was found that the imbibition recovery of nanoparticle-surfactant nanofluids was much larger than those of surfactant and silica nanoparticles alone (Kuang et al., 2018; Hou et al., 2020; Zhao et al., 2022). Thus, the compounding of surfactants with SiO_2 nanoparticles is an important approach to improving imbibition recovery for low-permeability reservoirs.

In this paper, the relevant research on enhancing imbibition recovery by nanoparticle-surfactant dispersions is systematically reviewed. The influencing factors on imbibition efficiency are also discussed. The imbibition system of nanoparticle-surfactant dispersions shows their synergistic effect and helps to improve the imbibition recovery. This review explicitly indicates that the imbibition system of nanoparticle-surfactant dispersions can not only enhance the dispersion stability of nanoparticles in the solution but also help to enhance the imbibition efficiency.

2. Research on nanoparticles

2.1 Background

Nanoparticles are small particles with a diameter in the range of 1-100 nm (Lechner and Mächtle, 1999). The scales of various constituting materials are illustrated in Fig. 1. Nanoparticles are featured by small size, great specific surface area and high surface energy (Sun and Ge, 2022). They can be chemically modified to obtain materials with ideal properties for enhanced recovery. Moreover, they are mechanically and thermally stable to withstand harsh reservoir environments.

The application of nanotechnology in the field of oil and gas has been studied extensively in recent years. In terms of enhanced recovery applications, nanoparticles can be mainly divided into four categories (Almahfood and Bai, 2018): metal oxide particles, magnetic particles, organic particles, and inorganic particles.

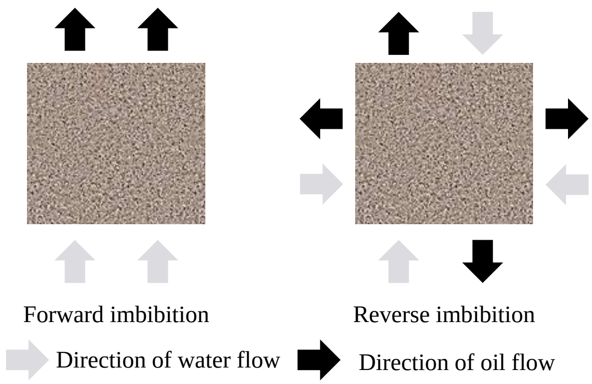

Fig. 2. Schematic diagrams of forward and reverse imbibition.

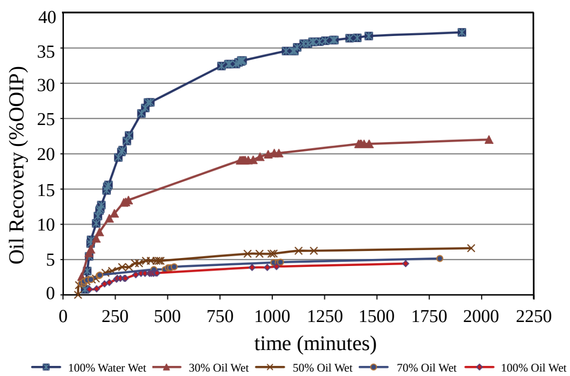

Fig. 3. Imbibition recovery curves under various wettability conditions (Rezaveisi et al., 2012).

2.2 Application in EOR

With the emergence of nanotechnology and its unique properties, enhanced oil recovery employing nanoparticles has attracted much attention. The key features of nanofluids largely depend on the diameter and properties of nanoparticles (Chen et al., 2017). Experimental studies have shown that nanomaterials such as SiO_2 (Rahmani, 2018), ZrO_2 (Karimi et al., 2012), TiO_2 (Ehtesabi et al., 2015), Fe_3O_4 (Zhou et al., 2012), Al_2O_3 (Seid et al., 2014), and $CaCO_3$ (Ahmadi et al., 2021) can improve the oil flooding efficiency. Among the nanoparticles used to improve recovery, silica nanoparticles have been studied the most frequently. This mainly arises from the environmental friendliness, abundant resources and low cost of SiO_2 nanoparticles, as well as the fact that their surface can be easily grafted by carbon chains with functional chemical groups.

Ju et al. (2002) indicated the influence of lipophobic and hydrophilic polysilicon (LHP) on the wettability of porous core. The results showed that LHP nanoparticles could adsorb on the surface of the porous core and alter the pore surface of rocks from lipophilic to hydrophilic. Khosravi et al. (2021) found that nanoparticles altered the wettability of reservoir rocks and thereby improved the recovery rate. The transformation process of rock wettability from the oil-wet state to the water-wet state was modeled using a dynamic wettability change method. The spontaneous imbibition experiment with nanoparticles was explained by numerical models. The simulation results agreed well with the experimental results, which was conducive to understanding the spontaneous imbibition recovery performance of nanoparticles. Active silica nanoparticles were prepared by the reaction of adipic acid with the -OH group of silica (Li et al., 2018). According to the spontaneous imbibition experiment, the unmodified SiO_2 nanoparticles and the modified silica nanoparticles could both improve the imbibition efficiency. The imbibition recovery of the modified active nanoparticles increased to 38.8%, which was 11.5% and 25% higher than those of the unmodified NPs and saline flooding, respectively.

3. Spontaneous imbibition and its influencing factors

3.1 Imbibition concept

Imbibition is the process during which the non-wetting phase is replaced by the wetting phase due to capillary force and gravity (Yang et al., 2017). Conventionally, imbibition is categorized based on two principles. Depending on the experimental environment, imbibition is classed into dynamic imbibition and static imbibition. Dynamic imbibition represents the spontaneous imbibition process accompanied with the flow of the external liquid, whilst static imbibition stands for spontaneous imbibition that occurs when the external liquid is in the static state. Based on the difference in the flow directions of oil and water, imbibition can be divided into forward imbibition and reverse imbibition (Zhou et al., 2002). The sketches of these two imbibition types are illustrated in Fig. 2. The leading force of forward imbibition is gravity. In this situation, the flow directions of both water and oil are the same. Moreover, the leading force of reverse imbibition is the capillarity force. In this case, the flow directions of water and oil are opposite.

3.2 Influencing factors of imbibition

Imbibition is a significant means for production in tight and low-permeability reservoirs (Cai et al., 2020). Many studies have been conducted on the influencing factors of core imbibition. Imbibition efficiency is influenced by many factors, such as core permeability, wettability, oil-water interfacial tension, reservoir temperature, pressure, and core boundary conditions, which are elaborated below.

3.2.1 Wettability

Wettability is a crucial parameter that affects the process of imbibition in the reservoir (Goharzadeh et al., 2023). As wettability becomes more hydrophilic, spontaneous imbibition can improve the oil-wet rock recovery. Roosta et al. (2015) demonstrated that, at higher temperatures, rock wetting reversal ability was stronger, the rock became more hydrophilic, and oil imbibition recovery efficiency was significantly improved. In their study, the transition from oil wettability to water wettability was one of the causes for enhanced oil recovery in the process of imbibition. Rezaveisi et al. (2012) performed five experiments with different wettabilities, with the results

Table 1. Core permeability and imbibition recovery.

Sample	Permeability (μm^2)	Recovery ratio (%)
1	0.086×10^{-3}	25.11
2	0.756×10^{-3}	34.82
3	1.54×10^{-3}	37.64

shown in Fig. 3. The more hydrophilic the glass bead medium, the higher the imbibition recovery rate that could be achieved.

3.2.2 Permeability

As permeability increases, the pore radius enlarges and the capillarity force decreases. Meanwhile, there are diverse points of views on the effect of permeability on imbibition recovery. Xu et al. (2022) investigated the relationship between permeability and imbibition efficiency, and found that imbibition efficiency showed a positive correlation with permeability (Table 1). However, Liang et al. (2022) discovered that the difference between the bedding and structural fracture imbibition efficiency of the Lucaogou Formation in Jimsal Sag and the ultimate imbibition rate was inversely proportional to both porosity and permeability (Fig. 4). Permeability has a remarkable influence on imbibition efficiency, although no scientific consensus has been reached on this point.

3.2.3 Boundary conditions

The boundary conditions can be used to characterize the degree of suture network development. Liu et al. (2022a) investigated spontaneous imbibition under four different boundary conditions. It was found that the spontaneous imbibition rates and final recoveries were discrepant under various boundary conditions. Under all full open (AFO) and two face open (free) (TFO-free) boundary conditions, the imbibition rate was the fastest and the ultimate recovery was the highest in Fig. 5. This study provided a pore-scale perspective on the complex fluid dynamic imbibition mechanism between fractures and matrix in fractured oil and gas reservoirs.

3.2.4 Viscosity of crude oil

The viscosity of crude oil determines the ease of flow; the higher the viscosity, the greater the flow resistance, that is, the harder it is for the fluid to flow. In contrast, the flow will be easier if the viscosity is low. Rezaveisi et al. (2012) asserted that crude oil viscosity also had a prominent influence on oil recovery. The fact that imbibition oil recovery was significantly reduced with the elevation of oil phase viscosity was confirmed experimentally. In Fig. 6, the viscosity of kerosene (2.09 cP) is twice that of n-octane (1.06 cP), which was the cause for the diverse oil recovery.

3.2.5 Temperature and pressure

The effect of temperature and pressure on imbibition cannot be ignored. Zhu et al. (2022) found that imbibition recovery will increase with the rise in temperature and pressure. The authors analyzed the influences of temperature and pressure on imbibition recovery by fixing the salinity, and the results indicated that imbibition recovery increased with rising temperature (Fig. 7(a)). The production rates in the early stage (within 12 h) under the high pressure condition were significantly higher than those under the low pressure condition (Fig. 7(b)).

3.2.6 Interfacial tension

Variation in the interfacial tension will lead to corresponding variation in the capillarity force; therefore, interfacial tension has a great influence on imbibition. An investigation by Gao et al. (2021) suggested that the reduction in interfacial tension helps to reduce flow resistance, which significantly enhances the degree of oil exploitation in the coarse pores of the core (Fig. 8). As the capillarity force decreases, it becomes insufficient to overcome the viscous resistance in small pores. Accordingly, the oil in the small pores cannot be completely displaced.

4. Synergistic system of nanoparticle and surfactant

4.1 Synergistic effect

The application of nano-silica in oil and gas industry development has increased recently, especially in the aspect of EOR. Surfactants, as traditional imbibition agents, have good wetting reversal capability and they reduce the interfacial tension between oil and water. Nevertheless, EOR can be achieved through the use of surfactants and nanoparticles, owing to the synergistic effect of the two (Xu et al., 2023).

Nanofluids mixed with silica and surfactant prepared by Zhao et al. (2022) obviously improved salt tolerance, temperature tolerance, and dispersion stabilization. Importantly, the imbibition recovery of surfactant and silica nanoparticles alone was less than that of nanofluids. Based on the possible mechanisms of enhanced oil recovery from silica nanofluids, these included the decrease in interfacial tension, wettability alternation ability, and structural separation pressure. Zhou et al. (2019) prepared a novel nanofluid by combining SiNP-NH_2 with anionic surfactants. It could remain stable for more than 30 days under high-salinity and high-temperature conditions without aggregation. It was found that the imbibition recovery of this nanofluid was higher than those of nanoparticles or surfactants alone. This is primarily attributed to the reduction in the capillarity resistance of oil-wet reservoir, wettability change, reduction in interfacial tension, and enlarged sweep volume. Kuang et al. (2018) studied the synergies between nanoparticles and surfactant molecules. The researchers found that SiOx + non-ionic surfactant nanofluids were effective in improving the imbibition recovery efficiency of sandstone crude oil. Hou et al. (2020) showed that a nanoactive fluid composed of nanoparticles and gemini surfactants was more beneficial for the surface wettability of oil-wet sandstone. After treatment with gemini surfactant and nanoactive solution, the contact angles of the oil droplets were 45° and 36°, respectively. In addition, the final imbibition recovery rate of the nanoactive fluid was larger than that of the gemini surfactant. Zhong et al. (2019, 2022) proposed a highly stable and active nanofluid. In their imbibition experiment, nanopar-

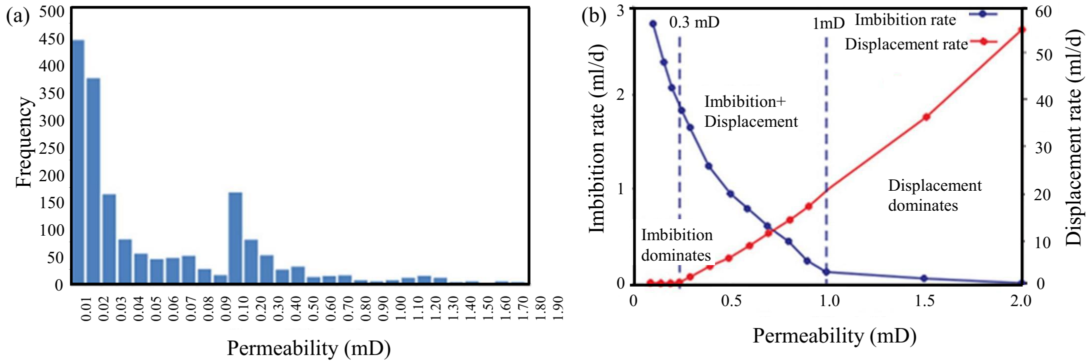

Fig. 4. (a) Permeability frequency distribution chart and (b) the influenced curve of permeability for imbibition and displacement (Liang et al., 2022).

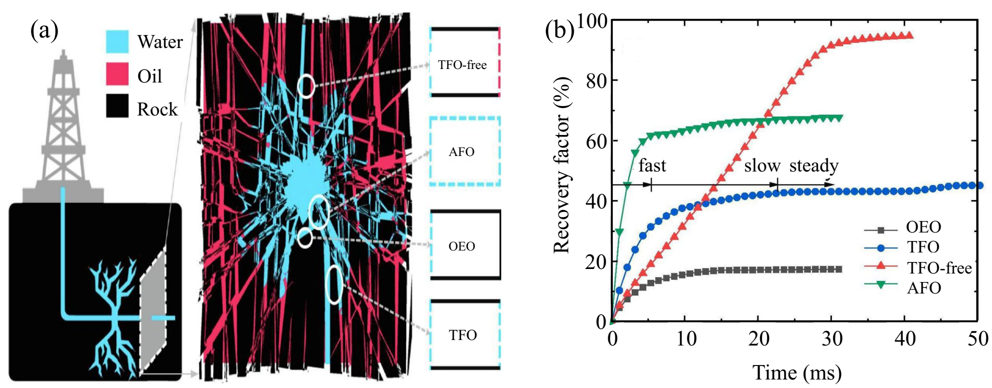

Fig. 5. (a) Boundary condition type, (b) oil recovery curve vs time under various boundary conditions (Liu et al., 2022a).

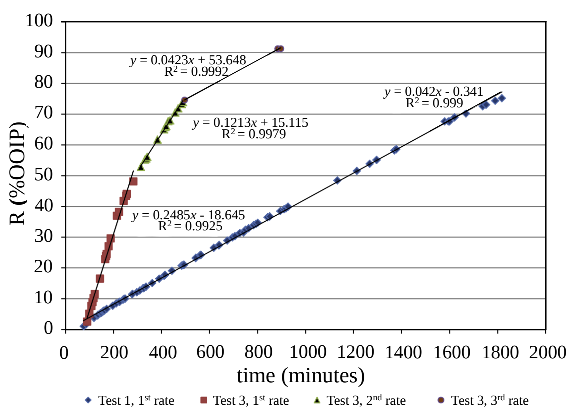

Fig. 6. Comparison of oil recovery efficiency of kerosene (Test 1) and n-octane (Test 3) (Rezaveisi et al., 2012).

ticles effectively improved the function of surfactant. The positive synergistic effect between nanoparticles and surfactants favored the improvement of imbibition recovery.

The interaction between nanoparticles and surfactants as well as the synergistic effect on the interface properties lead to the improved performance of nanofluids. Therefore, combining surfactants and nanoparticles is a significant approach to improve the imbibition recovery efficiency in tight and low-permeability reservoirs.

4.2 Mechanism of nanofluid EOR

4.2.1 Structural separation pressure

Compared with conventional oil displacing agents, nanofluids work via a unique oil displacing mechanism, i.e., the structural separation pressure mechanism. Nanoparticles can automatically absorb at the oil/solid/water interface to form a wedge film and generate structural separation pressure. Eventually, the oil droplets will be mobilized from the rock surface due to the pressure gradient.

Choi et al. (2017) elucidated the performance of associative silica nanoparticles (ASNPs) at the oil-rock surface and conducted a simulation experiment. In their experimental model, they dropped n-decane into a glass capillary channel filled with ASNP nanofluids, and observed through a microscope how the nanofluids performed in a wedge-shaped state when n-decane was dropped on the media surface. They found the formation of a colloidal film in this state, which was often was termed as wedge-shaped film (Fig. 9). Under the action of the wedge film, the wettability of oil droplets on the glass surface was easily changed. These findings showed that the injection of ASNP nanofluids could effectively extract the oil phase adhered to the rock surface, thus enhancing oil recovery by 5%. Similarly, the changes of oil droplets could be seen more directly in the study of Liang et al. (2019). Fig. 10 shows

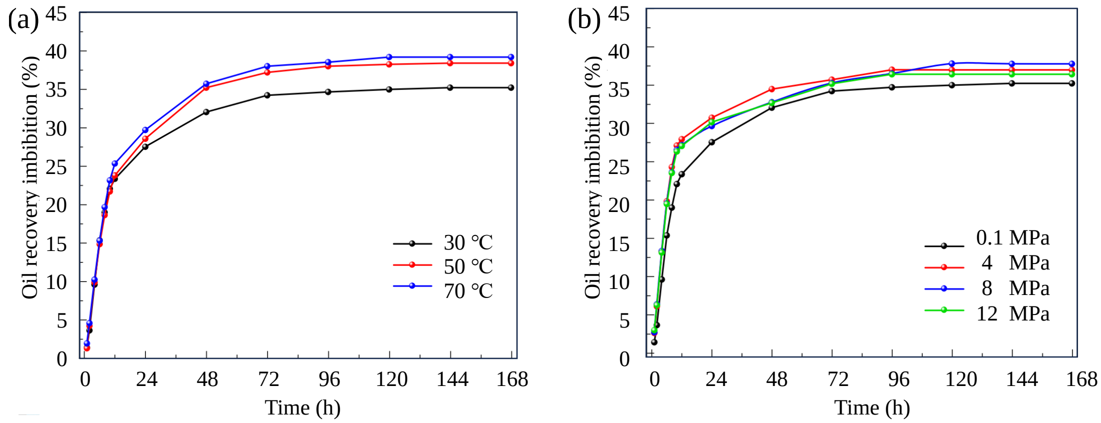

Fig. 7. Imbibition results under different (a) temperatures and (b) pressures (Zhu et al., 2022).

the characteristics of an oil drop immersed in a dispersion of static nanogel particles versus time. The oil drops were placed after filling the nanogel dispersion. It is worth noting that at both ends of the three-phase contact zone, the oil droplets gradually moved away from the solid. This result was attributed to the diffusion of nanogel particles along the solid surface, creating a structural separation pressure. The alteration of the disjoining pressure helped to mobilize oil at the microscopic level (Alnarabiji and Husein, 2020).

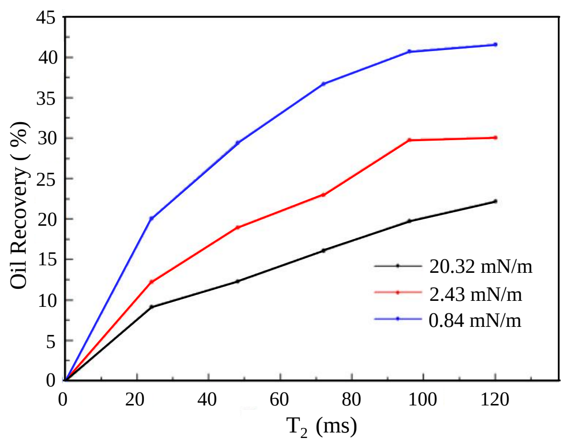

Fig. 8. Curves of oil recovery under different interfacial tensions (Gao et al., 2021).

The nonionic surfactant TX-100 was applied as the dispersant and enhancer of nanoparticles (Zhao et al., 2018). SiO_2 nanofluid could form a flimsy film in the three-phase contact region, generating structural separation pressure and resulting in thin film diffusion. Subsequently, the oil droplets could peel off. Due to the synergistic effect of surfactants and nanoparticles, the EOR performance of silica nanofluid enhanced by surfactant was better than applying surfactant alone. Furthermore, the wettability of the core surface was also considered to be an essential factor affecting the recovery rate. As a result of the synergistic action, the surfactant-enhanced silica nanofluid was able to spontaneously alter the surface of the pore from oil-wet to water-wet. Free surfactants could diffuse and penetrate into smaller pores, enhancing oil recovery. The self-imbibition mechanism of SiO_2 nanofluid, composed of TX-100 and silica nanoparticles, could be attributed to the synergistic action of silica nanoparticles and surfactants. In another study, Zhao et al. (2022) also explained the mechanism of structural separation pressure (Fig. 11). A large diffusion force would be generated when the number of nanoparticles was high enough due to Brownian motion and electrostatic repulsion among nanoparticles. When the electrostatic repulsion force on the rock surface exhibited a lopsided pattern, a smaller water phase contact angle and a larger oil phase contact angle appeared, thus a wedge structure via self-assembly formed in the three-phase contact region. This wedge induced positive thrust, which was the structural separation pressure. The wedge-shaped nanofluid film pushed the oil droplets moving forward, while the contacting area between the oil droplets and the rock surface further decreased while the oil droplets changed its shape gradually. Then, the surfactant molecules of the nanofluid system could enter smaller-sized pore throats. Consequently, the oil droplets could be removed from the surface of the rock due to structural separation pressure, reduced interfacial tension, and the wetting reversal of the system, greatly enhancing the oil washing ability of the nanofluid.

4.2.2 Reduction in interfacial tension

Interfacial tension plays a crucial role in the characterization of fluid migration and distribution in the porous media, and reducing interfacial tension is a further important mechanism for improving oil recovery.

The interfacial tension between 15 wt% NaCl saline and crude oil was found to be 13.78 mN/m (Zhou et al., 2019). In addition, the interfacial tension of the dispersion composed of SiO_2-NH_2 nanoparticles and surfactant was significantly reduced. When 0.05 wt% nanoparticles and 0.2 wt% surfactant were applied, the interfacial tension declined to 0.02 mN/m. Therefore, nanofluid is considered to significantly reduce the oil-water interfacial tension. As can be seen from Fig. 12, the lower the interfacial tension, the easier the oil can be displaced from the rock surface, resulting in improved oil recovery (Zhou

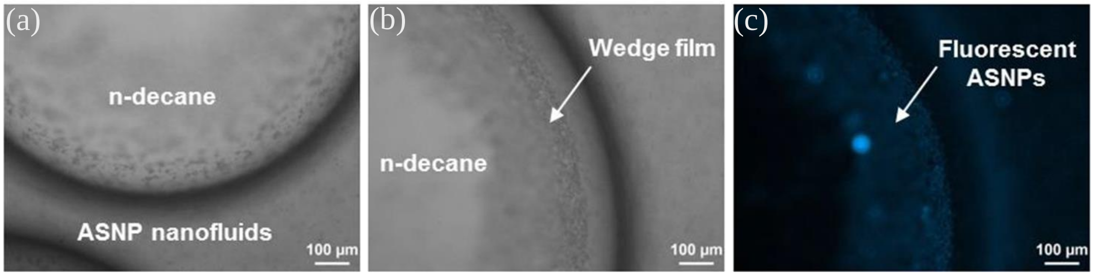

Fig. 9. Observations of wedge film formed between n-decane and the nanofluid interface. (a) Image at the time of preparation, (b) image after 60 s and (c) fluorescent image of the wedge film (Choi et al., 2017).

et al., 2019).

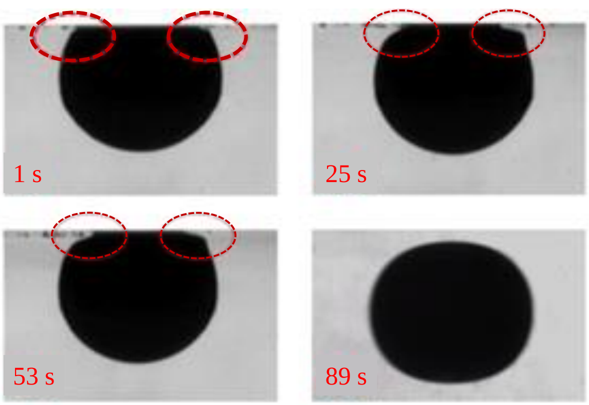

Fig. 10. Characteristics of oil drop immersing in dispersion of nanogel particles versus time (Liang et al., 2019).

Xu et al. (2019) studied the effect of nanoparticle concentration on the interfacial tension of the dispersions formulated by surfactant KD and SiO_2 nanoparticles. A concentration of 0.05 wt% KD was used to compound with 0.01 wt%, 0.03 wt% and 0.05 wt% nano-SiO_2, with the corresponding results shown in Fig. 13. The data suggested that the compounded system could reduce the oil-water interfacial tension to less than 10^{-1} mN/m. With the progress of time, KD-nanoparticle systems with various concentrations presented different characteristics. For the interfacial tension reduction capability, the optimal concentration of nanoparticles was determined as 0.01 wt% (see Fig. 13(a)). However, the imbibition recovery rate for the system with 0.05 wt% KD and 0.01 wt% SiO_2 nanoparticle was not ideal. As shown in Fig. 13(b), the highest imbibition recovery was achieved when 0.03 wt% nanoparticle was added. Although the reduction in interfacial tension is one of the important mechanisms to enhance imbibition recovery, it is not the only criterion for screening imbibition systems.

4.2.3 Wettability changes

The process when one fluid displaces another fluid on a solid surface is generally known as wetting. Contact angles are commonly used to evaluate wettability (Liu et al., 2022b), which is one of the most important factors controlling subsurface pore-scale fluid displacement and has a significant impact on subsurface multiphase fluids.

Zhao et al. (2022) studied the corelation between the contact angle of the compounded system of nanoparticles and surfactant over time (Fig. 14). When 0.1 wt% nano SiO_2 was introduced to the Anionic Surfactant (AOS) surfactant solution, the contact angle of an oil droplet on the oil-wet glass increased from 44.2° to 131.8° (see Fig. 14(b)), transforming the oil-wet glass sheet from the oil-wet to water-wet. When 0.2 wt% nanoparticle was added, the oil contact angle increased from 44.6° to 134.6°, as shown in Fig. 14(c). This increase was larger than that of the 0.1 wt% nanoparticle system. In addition, the change in contact angle was dramatic within 10 hours. Subsequently, the contact angle remained nearly constant. The results demonstrated that the surfactant AOS alone could change wettability (Fig. 14(a)), whereas the introduction of nanoparticles could enhance the wettability alternation ability. Fig. 15 shows the wettability trend of the nanoparticle and surfactant compounded system. According to the observations, the wetting state was largely changed by the compounded system (Nwidee et al., 2017). While surfactants could alter wettability and diffusion, the addition of nanoparticles could enhance these effects on solid surfaces.

5. Challenges and prospects

Although many laboratory experiments have shown that nanoparticle-surfactant dispersions have great potential to enhance oil recovery, their application to actual reservoirs has some limitations. The following aspects should be considered in further research:

1) For tight and low-permeability reservoirs, the pore throats are small, and whether the nanofluid imbibition system can enter the pore throat through the tiny pore is essential for the desired imbibition effect. Nanoparticles tend to aggregate under the harsh reservoir conditions, such as reservoirs with high temperatures and high salinities. Depending on the requirements of the actual reservoir, it is beneficial to prepare an imbibition system composed of nanoparticles and surfactants with good performance to avoid micropore clogging under harsh reservoir conditions.
2) At present, there is a lack of systematic studies on nanoparticle-surfactant dispersions, thereby it is important to systematically investigate the imbibition effect of the nanoparticle-surfactant dispersions and reveal the

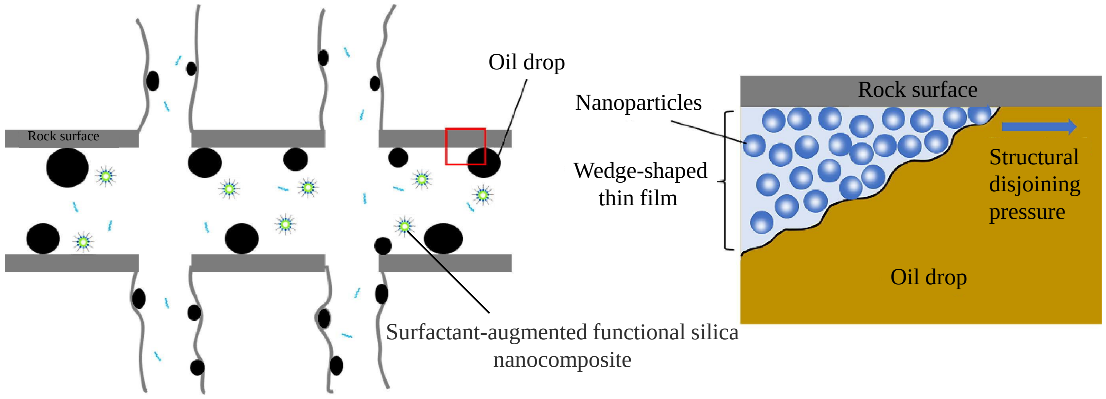

Fig. 11. Chart of the structural separation pressure mechanism (Zhao et al., 2022).

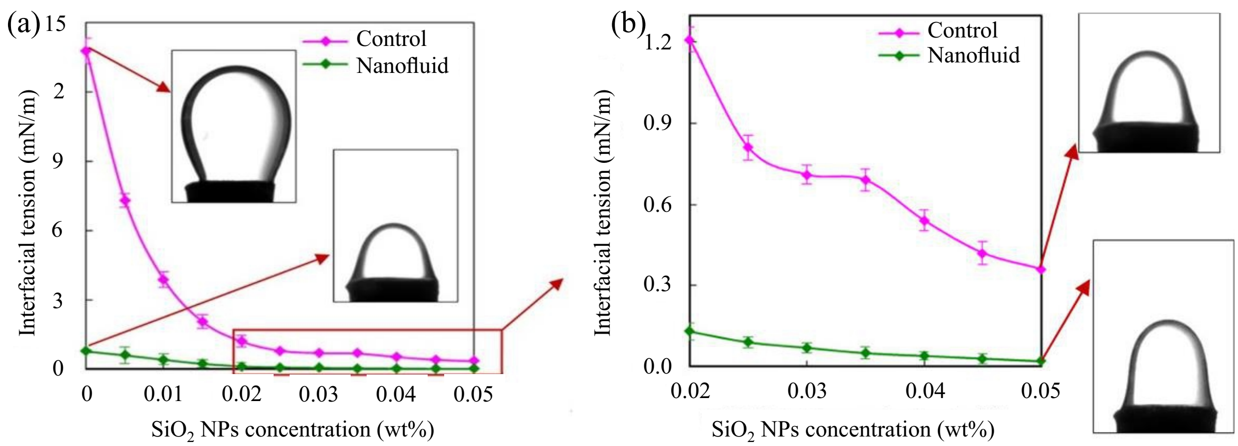

Fig. 12. Curves of oil-water interfacial tension of SiO_2-NH_2 nanoparticle solution under different concentrations in 15 wt% NaCl solution or surfactant at 65 °C: (a) overall data, (b) enlarged image of the red region in (a) (Zhou et al., 2019).

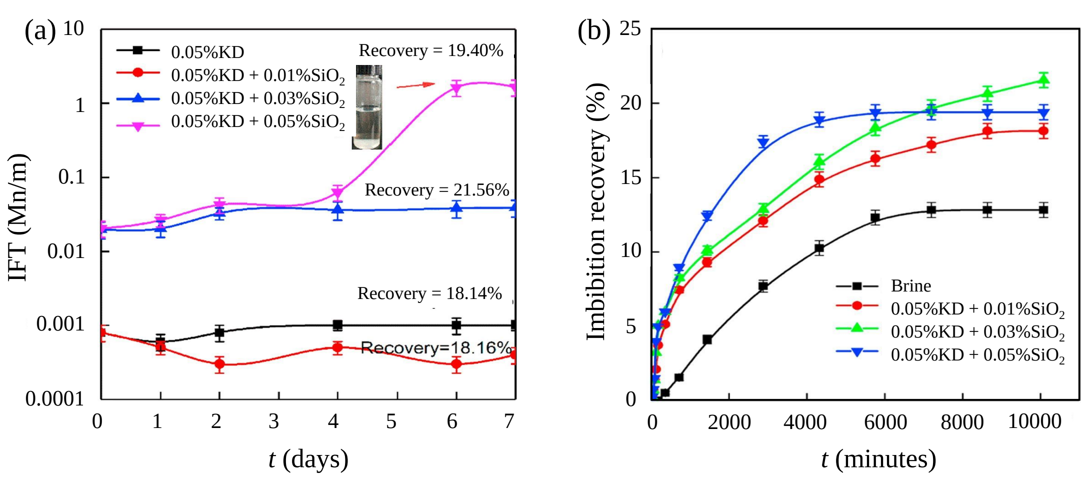

Fig. 13. Curves of (a) interfacial tension (IFT) reduction and (b) imbibition recovery (Xu et al., 2019).

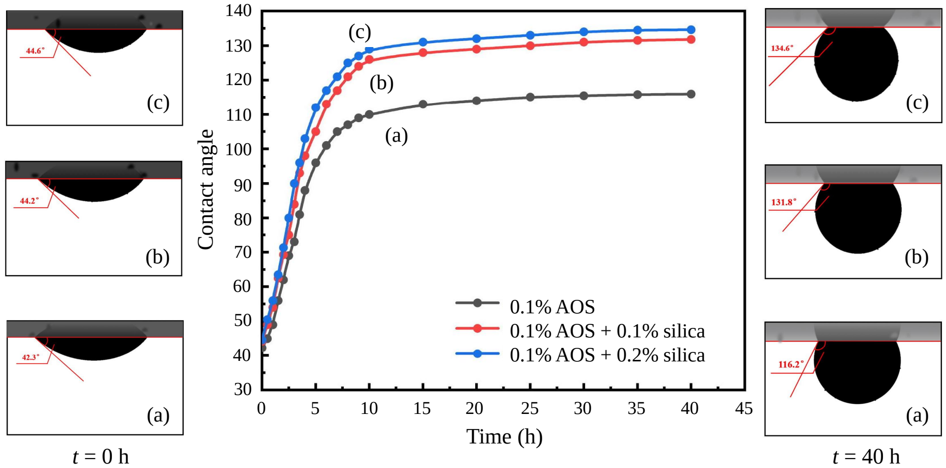

Fig. 14. Dynamic contact angle as a function of time. (a) 0.1 wt% surfactant AOS. (b) 0.1 wt% AOS + 0.1 wt% nanosilica. (c) 0.1 wt% AOS + 0.2 wt% nanosilica (Zhao et al., 2022).

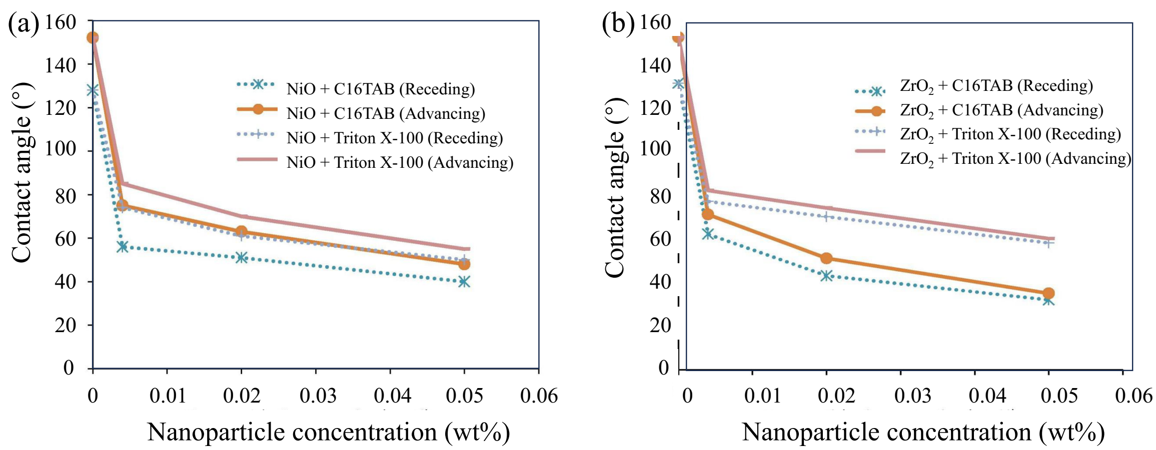

Fig. 15. Curves of wettability alteration: (a) NiO-0.5 wt% CTAB and TX-100 in toluene (1-h exposure time); (b) ZrO_2-0.5 wt% CTAB and TX-100 blends in toluene (1-h exposure time) (Nwidee et al., 2017).

corresponding mechanism.

6. Conclusion

This paper reviewed the progress on the imbibition system of nanoparticle-surfactant dispersions. The basis of nanoparticles and their applications in EOR were first introduced. Then, the effects of wettability, permeability, boundary conditions, viscosity of crude oil, interfacial tension, temperature and pressure on the imbibition efficiency were discussed. The general rules of those factors for imbibition recovery were then obtained. It could be noted that nanoparticle-surfactant dispersions can achieve synergistic effects and thus help improve the imbibition recovery efficiency. The EOR mechanism of nanoparticle-surfactant dispersions includes structural separation pressure, reduction in the interfacial tension, and rock wettability modification towards water-wet. Through this review, we could clearly indicate that the nanoparticle-surfactant dispersions have great salt tolerance, temperature tolerance and dispersion stabilization effect. With the continuous advancement of studies on spontaneous imbibition, nanoparticle-surfactant dispersions can be applied in more field trials rather than remaining at the laboratory research stage.

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Conflict of interest

The authors declare no competing interest.

References

Ahmadi, R., Osfouri, S., Azin, R., et al. Adsorption of natural $CaCO_3$ nanoparticles on the reservoir rock surfaces in the enhanced oil recovery process: Equilibrium, thermodynamics, and kinetics study. Journal of Dispersion Science and Technology, 2021, 42(13): 1963-1976.

Almahfood, M., Bai, B. The synergistic effects of nanoparticle-surfactant nanofluids in EOR applications. Journal of Petroleum Science and Engineering, 2018, 171: 196-210.

Alnarabiji, M. S., Husein, M. M. Application of bare nanoparticle-based nanofluids in enhanced oil recovery. Fuel, 2020, 267: 117262.

Bai, Y., Cao, G., Wei, G., et al. Mechanism of permeability and oil recovery during fracturing in tight oil reservoirs. Processes, 2020, 8(8): 972.

Cai, J., Li, C., Song, K., et al. The influence of salinity and mineral components on spontaneous imbibition in tight sandstone. Fuel, 2020, 269: 117087.

Cai, J., Perfect, E., Cheng, C. L., et al. Generalized modeling of spontaneous imbibition based on Hagen–Poiseuille flow in tortuous capillaries with variably shaped apertures. Langmuir, 2014, 30(18): 5142-5151.

Chen, H., Wu, Y., Lu, Y., et al. A review on molten salt-based nanofluids: Recent developments. Energy Storage Science and Technology, 2017, 7(1): 48-55. (in Chinese)

Choi, S. K., Son, H. A., Kim, H. T., et al. Nanofluid enhanced oil recovery using hydrophobically associative zwitterionic polymer-coated silica nanoparticles. Energy & Fuels, 2017, 31(8): 7777-7782.

Ehtesabi, H., Ahadian, M. M., Taghikhani, V. Enhanced heavy oil recovery using TiO_2 nanoparticles: Investigation of deposition during transport in core plug. Energy & Fuels, 2015, 29(1): 1-8.

El-Diasty, A. I., Aly, A. M. Understanding the mechanism of nanoparticles applications in enhanced oil recovery. Paper SPE 175806 Presented at SPE North Africa technical conference and exhibition, Cairo, Egypt, 14-16 September, 2015.

Gao, H., Wang, Y., Xie, Y., et al. Imbibition and oil recovery mechanism of fracturing fluids in tight sandstone reservoirs. ACS Omega, 2021, 6(3): 1991-2000.

Goharzadeh, A., Fatt, Y. Y., Sangwai, J. S. Effect of TiO_2-SiO_2 hybrid nanofluids on enhanced oil recovery process under different wettability conditions. Capillarity, 2023, 8(1): 1-10.

Hendraningrat, L., Li, S., Torsæter, O. A coreflood investigation of nanofluid enhanced oil recovery. Journal of Petroleum Science and Engineering, 2013, 111: 128-138.

Hou, B., Jia, R., Fu, M., et al. Mechanism of synergistically changing wettability of an oil-wet sandstone surface by a novel nanoactive fluid. Energy & Fuels, 2020, 34(6): 6871-6878.

Iffly, R., Rousselet, D. C., Vermeulen, J. L. Fundamental study of imbibition in fissured oil fields. Paper SPE 4102 Presented at SFall Meeting of the Society of Petroleum Engineers of AIME, San Antonio, Texas, 8-11 October, 1972.

Isaac, O. T., Pu, H., Oni, B. A., et al. Surfactants employed in conventional and unconventional reservoirs for enhanced oil recovery-A review. Energy Reports, 2022, 8: 2806-2830.

Ji, M. Economic benefit evaluation of waterflooding development of tight oil horizontal wells under different displacement modes-by taking M area in J oilfield as an example. Petroleum Geology and Engineering, 2020, 34(4): 69-73. (in Chinese)

Ju, B., Dai, S., Luan, Z., et al. A study of wettability and permeability change caused by adsorption of nanometer structured polysilicon on the surface of porous media. Paper SPE 77938 Presented at SPE Asia Pacific oil and gas conference and exhibition, Melbourne, Australia, 8-10 October, 2002.

Karimi, A., Fakhroueian, Z., Bahramian, A., et al. Wettability alteration in carbonates using zirconium oxide nanofluids: EOR implications. Energy & Fuels, 2012, 26(2): 1028-1036.

Khalil, M., Jan, B. M., Tong, C. W., et al. Advanced nanomaterials in oil and gas industry: Design, application and challenges. Applied Energy, 2017, 191: 287-310.

Khalilnezhad, A., Rezvani, H., Ganji, P., et al. A complete experimental study of oil/water interfacial properties in the presence of TiO_2 nanoparticles and different ions. Oil and Gas Science and Technology-Revue d'IFP Energies Nouvelles, 2019, 74: 39.

Khosravi, R., Chahardowli, M., Keykhosravi, A., et al. A model for interpretation of nanoparticle-assisted oil recovery: Numerical study of nanoparticle-enhanced spontaneous imbibition experiments. Fuel, 2021, 292: 120174.

Kuang, W., Saraji, S., Piri, M. A systematic experimental investigation on the synergistic effects of aqueous nanofluids on interfacial properties and their implications for enhanced oil recovery. Fuel, 2018, 220: 849-870.

Lau, H. C., Yu, M., Nguyen, Q. P. Nanotechnology for oilfield applications: Challenges and impact. Journal of Petroleum Science and Engineering, 2017, 157: 1160-1169.

Lechner, M. D., Mächtle, W. Characterization of nanoparticles. Macromolecular Symposia, 1999, 145(1): 1-7.

Li, Y., Dai, C., Zhou, H., et al. Investigation of spontaneous imbibition by using a surfactant-free active silica water-based nanofluid for enhanced oil recovery. Energy & Fuels, 2018, 32(1): 287-293.

Li, X., Fan, F., Yang, H. Volumetric fracturing technology of low-pressure tight oil reservoirs horizontal wells under different development conditions in Ordos Basin. Drilling & Production Technology, 2016, 39(3): 34-36. (in Chinese)

Li, K., Horne, R. N. Characterization of spontaneous water imbibition into gas-saturated rocks. SPE Journal, 2001, 6(4): 375-384.

Li, C., Singh, H., Cai, J. Spontaneous imbibition in shale: A review of recent advances. Capillarity, 2019, 2(2): 17-32.

Liang, T., Hou, J., Qu, M., et al. The EOR mechanism and flow behaviors of high-viscosity modified starch nanogel particles in porous media. Paper SPE 196414 Presented at SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition, Bali, Indonesia, 29-31 October, 2019.

Liang, C., Liu, A., Luo, Q., et al. Differences in imbibition efficiency between bedding and tectonic fractures in the Lucaogou formation in the Jimusar Sag: Evidence from simulation experiments. Frontiers in Earth Science, 2022, 10: 918244.

Liu, Y., Chen, M., Sun, S., et al. Effects of grain shape and packing pattern on spontaneous imbibition under different boundary conditions: Pore-scale simulation. Journal of Hydrology, 2022a, 607: 127484.

Liu, K., Gao, Z., Wang, C. Research progress of imbibition oil production in low-permeability reservoir. Oilfield Chemistry, 2021, 38(4): 747-753. (in Chinese)

Liu, D., Zhang, X., Tian, F., et al. Review on nanoparticle-surfactant nanofluids: Formula fabrication and applications in enhanced oil recovery. Journal of Dispersion Science and Technology, 2022b, 43(5): 745-759.

Nwidee, L. N., Lebedev, M., Barifcani, A., et al. Wettability alteration of oil-wet limestone using surfactant-nanoparticle formulation. Journal of Colloid and Interface Science, 2017, 504: 334-345.

Rahmani, O. Mobility control in carbon dioxide-enhanced oil recovery process using nanoparticle-stabilized foam for carbonate reservoirs. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2018, 550: 245-255.

Rezaveisi, M., Ayatollahi, S., Rostami, B. Experimental investigation of matrix wettability effects on water imbibition in fractured artificial porous media. Journal of Petroleum Science and Engineering, 2012, 86: 165-171.

Roosta, A., Roostaee, A. R., Rahbar, M. Temperature effect on wettability and oil recovery efficiency during spontaneous imbibition. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2015, 37(18): 1988-1995.

Schechter, D. S., Denqen, Z., Orr, F. M. Capillary imbibition and gravity segregation in low IFT systems. Paper SPE 22594 Presented at SPE Annual Technical Conference and Exhibition, Dallas, Texas, 6-9 October, 1991.

Seid, M. M., Moghadasi, J., Naseri, S. An experimental investigation of wettability alteration in carbonate reservoir using γ-Al_2O_3 nanoparticles. Iranian Journal of Oil and Gas Science and Technology, 2014, 3(2): 18-26.

Sun, X., Ge, J. Synergism between lipophilic surfactant and lipophilic SiO_2 nanoparticles enhances self-emulsification performance. Journal of Petroleum Science and Engineering, 2022, 216: 110760.

Wang, L., Tian, Y., Yu, X., et al. Advances in improved/enhanced oil recovery technologies for tight and shale reservoirs. Fuel, 2017, 210: 425-445.

Wang, D., Zhan, Z., Ma, B. Dynamic imbibition characteristics and influencing factors of water injection huff-puff in tight oil reservoir. Journal of Xi'an Shiyou University (Natural Sciences Edition), 2021, 36: 50-56. (in Chinese)

Xu, D., Bai, B., Wu, H., et al. Mechanisms of imbibition enhanced oil recovery in low permeability reservoirs: Effect of IFT reduction and wettability alteration. Fuel, 2019, 244: 110-119.

Xu, G., Chang, J., Wu, H., et al. Enhanced oil recovery performance of surfactant-enhanced Janus SiO_2 nanofluid for high temperature and salinity reservoir. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2023, 657: 130545.

Xu, R., Yang, S., Xiao, Z., et al. Quantitatively study on imbibition of fracturing fluid in tight sandstone reservoir under high temperature and high pressure based on NMR technology. Journal of Petroleum Science and Engineering, 2022, 208: 109623.

Yang, L., Ge, H., Shi, X., et al. Experimental and numerical study on the relationship between water imbibition and salt ion diffusion in fractured shale reservoirs. Journal of Natural Gas Science and Engineering, 2017, 38: 283-297.

Yang, L., Wang, S., Cai, J., et al. Main controlling factors of fracturing fluid imbibition in shale fracture network. Capillarity, 2018, 1(1): 1-10.

Zhang, X., Morrow, N. R., Ma, S. Experimental verification of a modified scaling group for spontaneous imbibition. SPE Reservoir Engineering, 1996, 11(4): 280-285.

Zhao, M., Cheng, Y., Wu, Y., et al. Enhanced oil recovery mechanism by surfactant-silica nanoparticles imbibition in ultra-low permeability reservoirs. Journal of Molecular Liquids, 2022, 348: 118010.

Zhao, M., Lv, W., Li, Y., et al. Study on the synergy between silica nanoparticles and surfactants for enhanced oil recovery during spontaneous imbibition. Journal of Molecular Liquids, 2018, 261: 373-378.

Zhong, X., Chen, J., Xu, F., et al. Experimental investigation of zwitterionic surfactant-based silica nanofluid spontaneous imbibition at high salinity and elevated temperature conditions. Journal of Molecular Liquids, 2022, 364: 119995.

Zhong, X., Li, C., Pu, H., et al. Increased nonionic surfactant efficiency in oil recovery by integrating with hydrophilic silica nanoparticle. Energy & Fuels, 2019, 33(9): 8522-8529.

Zhou, D., Jia, L., Kamath, J., et al. Scaling of counter-current imbibition processes in low-permeability porous media. Journal of Petroleum Science and Engineering, 2002, 33(1-3): 61-74.

Zhou, J., Wang, L., Qiao, X., et al. Pickering emulsions stabilized by surface-modified Fe_3O_4 nanoparticles. Journal of Colloid and Interface Science, 2012, 367(1): 213-224.

Zhou, Y., Wu, X., Zhong, X., et al. Surfactant-augmented functional silica nanoparticle based nanofluid for enhanced oil recovery at high temperature and salinity. ACS Applied Materials & Interfaces, 2019, 11(49): 45763-45775.

Zhu, D., Li, B., Li, H., et al. Effects of low-salinity water on the interface characteristics and imbibition process. Journal of Petroleum Science and Engineering, 2022, 208: 109564.