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Invited review

The effects of clay minerals on imbibition in shale reservoirs: A review

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Abstract:
The imbibition process plays a crucial role in the development of shale reservoirs, particularly during the volume fracturing and water injection development phases. This process significantly influences the production capacity of shale and also serves as a essential parameter for assessing reservoir performance. Clay minerals contribute to the formation of numerous micro-pores and micro-fractures, exhibit strong plasticity and are prone to swelling. The unique structures and properties of clay minerals have a profound impact on shale imbibition. This review analyzes the effects of clay minerals on imbibition from different perspectives, finding that the effect is closely related to the total amount of clay minerals, as well as to specific mineral types and content. Clay minerals exhibit a dual impact on imbibition, which can either facilitate imbibition by promoting micro-fractures formation or hinder it by reducing pore throats and migrating to block flow paths due to swelling. While capillary action is usually considered the main mechanism for fluid displacement during the imbibition, the osmotic pressure formed by clay minerals can also serve as a driving force for imbibition, positively contributing to shale oil and gas recovery. This review aims to provide a comprehensive understanding of the role of clay minerals on the imbibition, providing a theoretical foundation and practical guidance for future research and efficient development of shale reservoirs.

1. Introduction

Compared to conventional oil and gas reservoirs, shale reservoirs exhibit more complex micro-nano scale pore and throat structures, with typically lower porosity, lower permeability, and reduced natural energy within the reservoir (Lin et al., 2017; Mustafa et al., 2019; Xia et al., 2021; Cai et al., 2024). Such characteristics pose greater challenges in developing shale reservoirs and make it more difficult to attain and maintain stable industrial production levels. To effectively unlock the potential of reservoirs, large-scale volumetric fracturing technology is widely regarded as an essential strategy (Zou et al., 2013; Clarkson et al., 2016; Zhou et al., 2023). In the process of volumetric fracturing, the role of imbibition in enhancing the recovery rate of shale reservoirs has emerged as a significant research focus both domestically and internationally (Cai et al., 2014; Diao et al., 2021; Guo et al., 2024). In the fields of earth science and engineering, imbibition is a key process for fluid flow in porous media (Cai, 2021). Shale reservoirs exist a multitude of micro-nano scale pores and fractures, which cause the fracturing fluid to undergo imbibition and oil expulsion effects under the influence of capillary forces. The process is crucial for enhancing well production capacity and boosting the recovery rates of oil from reservoirs (Li et al., 2019; Wang et al., 2020).

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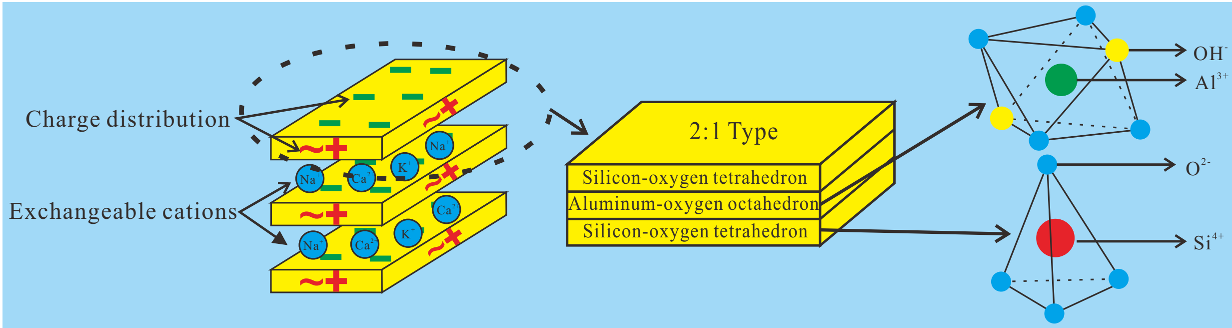

Fig. 1. Montmorillonite unit cell structure schematic diagram.

Imbibition describes the spontaneous flow process of fluids in porous media (Rose, 2001; Mason and Morrow, 2013), which includes two types: Spontaneous imbibition and forced imbibition (Morrow and Mason, 2001; Deng and King, 2019). The former refers to the process where, without external pressure, the wetting phase (such as water) spontaneously enters the rock pores and displaces the non-wetting phase (such as oil) due to capillary action (Hu et al., 2020). The latter refers to the process where, under the drive of an external pressure difference, fluids are forced into the rock pores, which can be a water flooding oil or gas displacing liquid process. Imbibition patterns and mechanisms involve complex physical and chemical processes, including cation exchange of clay minerals, capillary pressure effects, fluid dynamic migration, and the impact of temperature and wettability (Zhang et al., 2022; Huang et al., 2024). The study of imbibition is of great significance for the development of oil and gas fields, helping to optimize water injection strategies, increase oil and gas recovery rates, and design more effective enhanced oil recovery technologies.

Imbibition is not only related to fluid dynamics but is also closely related to the physicochemical properties of different substances. In shale reservoirs, clay minerals such as montmorillonite, illite, kaolinite, and mixed-layer clays are very common. The minerals play an important role in the imbibition due to their unique structures and properties. The distribution of clay minerals in the reservoir pores and their changes after contact with water significantly affect the pore structure and connectivity, thereby affecting the efficiency of imbibition. The content and types of clay minerals will have varying degrees of impact on the imbibition characteristics (Graham et al., 2001; Zhang et al., 2020). Generally, the interaction of clay minerals with water can cause them to swell, disperse, and potentially dissolve, leading to secondary precipitation. These reactions can readily block the flow channels within the reservoir, resulting in a reduction of its average permeability (Chakraborty and Karpyn, 2015; Yan et al., 2015). The lower the permeability of the reservoir, the greater the impact of clay minerals on the seepage characteristics. However, the clay minerals can swell upon contact with water, potentially leading to the formation of micro-fractures (Sun et al., 2015b; Liu et al., 2018; Xu et al., 2019). The micro-fractures can enhance the physical properties of the reservoir by creating additional flow channels (Gupta et al., 2017; Zhang et al., 2017; Wang et al., 2019), which has a positive impact on the imbibition. Clay minerals, acting as a "semi-permeable membrane" in the reservoir, forming an osmotic pressure effect that creates a dynamic imbibition mechanism in the reservoir (Van Olphen, 1964; White, 1965; Fritz, 1986), which positively promotes the development of shale oil and gas.

To achieve a thorough understanding of how clay minerals affect imbibition characteristics, the review first discusses the structure, properties and hydration swelling of clay minerals. It then delves into the influence of clay minerals content and types, their swelling and migration behaviors, as well as the osmotic pressure, on the imbibition within shale formations. The aim is to provide a theoretical basis and practical guidance for the effective development and long-term management of oil and gas reservoirs in shale, promoting the efficient exploitation and utilization of shale oil and gas resources.

2. The structure, properties and hydration swelling of clay minerals

2.1 The structure and properties

Among the many clay minerals, montmorillonite, illite, kaolinite, and illite-montmorillonite mixed-layer (I/S) have a particularly significant impact on the imbibition, and some of their structure and properties are shown in Table 1. As shown in Fig. 1, montmorillonite unit cell consist of two layers of silicon-oxygen tetrahedra sandwiching a layer of aluminum-oxygen octahedra. The interlayer space between two unit cells of montmorillonite is held together by weak binding forces and predominantly contains ions like Ca^{2+} and Na^{+}, with occasional K^{+} ions. It is well known for its unique ability to swell upon water absorption (Uddin, 2008), playing an important role in improving and damaging reservoir permeability. Montmorillonite's high specific surface area and the presence of exchangeable cations between its layers enable it to absorb substantial amounts of water molecules. This absorption increases the interlayer spacing, resulting in swelling (Bakandritsos et al., 2004; Laird, 2006).

Illite unit cell, similar to montmorillonite, possess a three-layer structure, with interlayer ions primarily composed of K^{+}. The layer bonding strength in illite is stronger than montmorillonite but weaker than kaolinite, positioning its properties between the two. Illite's potential damage to the reservoir is mainly manifested as particle migration and throat blocking,

Table 1. Structure and properties of clay minerals (Zhang et al., 2010; Cheng and Heidari, 2017; Chai et al., 2020).

Minerals	Unit cell structure	Cation exchange (meq/100g)	Sensitivity
Montmorillonite	2:1 Type	70-150	Water
Illite	2:1 Type	10-40	Water and speed
Kaolinite	1:1 Type	3-15	Speed and alkali
I/S	Mixed-layer	Related to content	Water and speed

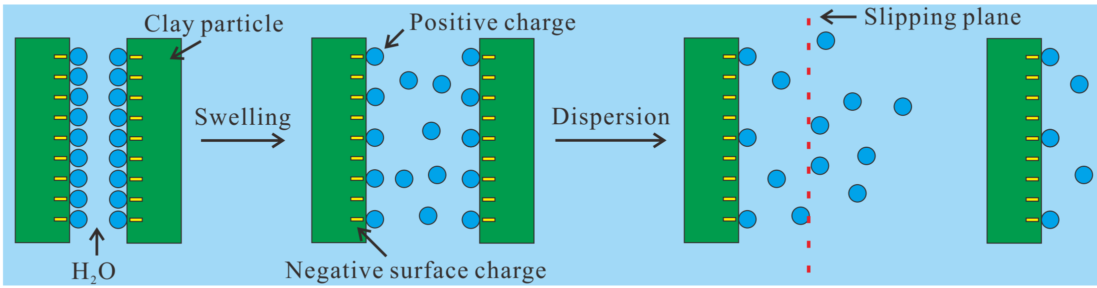

Fig. 2. Formation of the diffuse double layer.

thereby reducing the reservoir's permeability. However, the needle-like and fibrous structures of illite can also absorb water and swell, causing severe damage to the pores (Cheng et al., 2024). Kaolinite unit cell consist of one layer of silicon-oxygen tetrahedron and one layer of aluminum-oxygen octahedron stacked together. The interlayer forces are strong, with no ions present between the layers, making it difficult for water molecules to penetrate the interlayers. Kaolinite is a non-expanding type of clay mineral, but in an alkaline fluid environment, it can undergo dissolution, dispersion, and migration. The substances produced by the dissolution can precipitate in the form of colloids or particles in the pore throats, affecting reservoir permeability. Kaolinite is not tightly attached to the rock surface and has larger particles that are easily detached by fluid erosion and transported to the pore throat to cause blockage. Due to their complex structure, I/S exhibit more intricate properties. They have a larger specific surface area, can absorb a large amount of water molecules (Ge et al., 2015; Cheng et al., 2024), and the presence of swelling layers may also induce the disintegration and migration of minerals.

2.2 Hydration swelling

The hydration swelling of clay minerals include surface hydration, osmotic hydration and capillary condensation (Wang et al., 2021). Surface hydration involves the direct adsorption of water molecules through hydrogen bonds by H^+ and OH^- on the clay surface, as well as the indirect adsorption of water molecules through adsorbed exchangeable cations. This is a short-range interaction between clay and water, which proceeds to a thickness of four water molecule layers between the clay layers, approximately 1 nm (Rao et al., 2013). Once the distance between the clay layers surpasses 1 nm, the ongoing swelling of the clay is predominantly driven by osmotic pressure and the electrostatic double-layer repulsion. As shown in Fig. 2, as water molecules enter between the clay layers, the cations adsorbed on the clay surfaces become hydrated and diffuse into the water, forming what is known as the diffuse double layer. This process generates a negative charge, causing repulsion between layers and increasing the interlayer spacing (Nye, 1966). Consequently, the repulsion of the double layer gradually takes the leading role, causing further swelling of the clay layer spacing. Due to concentration gradients, clay layers act as osmotic membranes, driving water molecules into their interlayer spaces under osmotic pressure, which leads to further swelling of the clay (Karpiński and Szkodo, 2015). The swelling caused by osmotic hydration can increase the spacing between the clay layers to 12 nm, and increasing the salt concentration in the solution can reduce the layer spacing of the clay swelling (Zhou et al., 2024). When clay particles reach an equilibrium hydration and swelling state, with an interlayer spacing of approximately 12 nm, the application of shear force causes the crystal cells to separate, leading to the dispersion of clay in water. Capillary condensation refers to the process in which water molecules coalesce in pores due to capillary action, forming water bridges that connect particles. It can lead to changes in the bonding forces between clay mineral particles, thereby affecting the swelling behavior and permeability of clay minerals.

3. The effects of clay mineral content and types on imbibition

The structural diversity of clay minerals impacts the reservoir's imbibition characteristics, influenced not only on the total content but is more significantly by the specific types and content (Yang et al., 2019b). The imbibition swelling of clay minerals may increase the pore space, leading to excessive water absorption. The imbibition capacity is positively correlated with the total content of clay minerals. Clay-rich shale reservoirs absorb a volume of water much

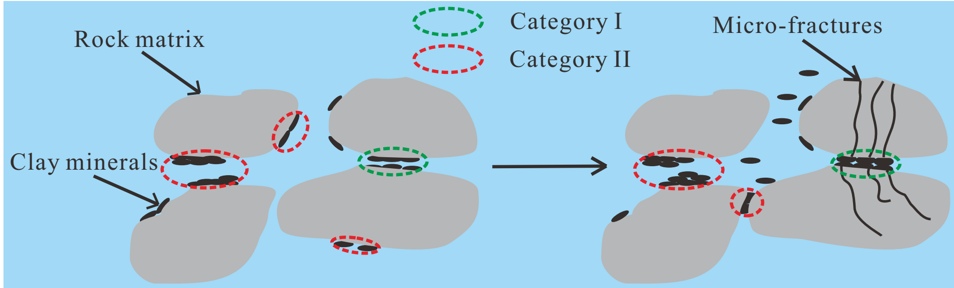

Fig. 3. Distribution of clay minerals in shale reservoirs.

larger than their measured porosity, which positively affects the recovery rate during spontaneous imbibition (Makhanov et al., 2012; Yan et al., 2015). However, the impact of different types of clay minerals on reservoir properties varies. Yang et al. (2017) conducted indoor spontaneous imbibition experiments and concluded that the imbibition capacity and ion diffusion capacity of shale are well positively correlated with the content of kaolinite and I/S. In contrast, the illite content has no substantial impact on the imbibition/diffusion rates in shale. Zeng et al. (2022) have found that the imbibition capacity of shale is positively correlated with the content of clay minerals. The higher the content of clay minerals, particularly chlorite and I/S, the greater the imbibition capacity of shale. This means that even with the same total content, different types and content of clay minerals will also exert different regulatory effects on the total amount and rate of imbibition.

The content and types of clay minerals can significantly affect the reservoir's adsorption capacity for water molecules and the swelling response, thereby influencing the distribution and flow of fluids within the reservoir (Wilson et al., 2014; Cai et al., 2024). The influence of clay minerals on the imbibition is not a simple direct proportionality and may involve a critical threshold (Yang et al., 2019a; Cheng et al., 2024). When the clay content falls below a certain threshold, the presence of clay minerals can enhance the reservoir's water absorption and induce lattice swelling upon contact with water. This swelling can squeeze the oil within the pores and lead to the generation of micro-fractures, which facilitates the expulsion of oil from the pores. However, as the content of clay minerals continues to increase, it can cause extensive blockage of pores within the matrix, diminishing pore connectivity and inhibiting the occurrence of imbibition. This suggests that maintaining an optimal clay content is crucial for enhancing the efficiency of imbibition (Ghanbari and Dehghanpour, 2015; Zhang et al., 2020; Xue et al., 2022; Cheng et al., 2024). Therefore, a detailed analysis of the types of clay minerals in the reservoir and the precise determination of their content are crucial for understanding and predicting the imbibition of the reservoir (Sharifigaliuk et al., 2021; Xie et al., 2024). At the same time, they also suggest that in reservoir modification and fracturing design, the impact of clay mineral content and types on imbibition should be considered to achieve the best development results.

4. The effects of clay mineral swelling and migration on imbibition

To gain a deeper understanding of the role of clay minerals in the development of shale reservoirs, as shown in Fig. 3, clay minerals are categorized into two types based on effects. The first category of clay minerals, after absorbing water and swelling, can facilitate the creation of micro-fractures within the reservoir. The micro-fractures provide additional flow channels for fluids, increasing the reservoir's permeability and enhancing the imbibition efficiency. The second category of clay minerals, upon absorbing water and swelling, reduces or narrows the effective permeable pathways of fractures and pores. Some clay minerals with weak bonding to the rock framework may also detach from the pore walls, disperse, and migrate, leading to the blockage of throats. The behaviors reduce the permeability of the reservoir, hinders the flow of fluids, and has a negative impact on the infiltration effect. Different types of clay minerals have significant differences in their impact on reservoir modification, and these differences will ultimately lead to different imbibition effects.

As shown in Fig. 3, the first category of clay minerals play a crucial role in the imbibition process of shale reservoirs, particularly their characteristic of absorbing water and swelling, which is considered one of the main causes of micro-fractures formation in reservoirs (Lal, 1999; Guo et al., 2012; Al-Arfaj et al., 2014; Sun et al., 2015a). The micro-fractures significantly impact the physical properties and fluid flow characteristics of the reservoir. When the sum of the fluid pressure inside the pores and fractures and the stress of clay mineral hydration and swelling exceeds the tensile strength of the reservoir, micro-fractures may form within the reservoir. The micro-fractures can significantly modify the reservoir's properties by increasing its permeability. They increase permeability by creating additional flow channels, expanding the imbibition contact area, and improving the efficiency of oil-water displacement, thus enhancing the overall effectiveness of fluid extraction from the reservoir (Lu et al., 2021). Dehghanpour et al. (2013) found through spontaneous imbibition experiments that clay minerals produce micro-fractures due to swelling during the imbibition process, thereby increasing the total amount of imbibed water. Ge et al. (2015) conducted comparative experiments using deionized water and KCl solutions and found that KCl inhibits clay swelling, reducing the opportunity for fracture formation, thus significantly lowering the imbibition capacity compared to deionized water. Similarly, Morsy and Sheng (2014) found through comparative experiments that layering fractures caused by clay swelling resulted in a higher recovery rate of distilled water (24%) than that of 2% KCl (12.8%). When clay minerals come into contact with water, micro-fractures may be generated within the reservoir. The micro-fractures increase the imbibition channels and the contact area between the fractures and the matrix, leading to a higher imbibition rate for reservoirs with induced fractures. Additionally, the micro-fractures also increase the pore volume of liquid imbibition, resulting in an increase in imbibition volume (Meng et al., 2020).

However, as shown in Fig. 3, during the imbibition process, the second category of clay minerals swell upon contact with water, migrate and disperse, or dissolve to form secondary precipitates. The actions can potentially block the flow channels within the reservoir, leading to a decrease in the average permeability of the reservoir. Particularly when the permeability of the reservoir is low, the impact of clay minerals on the seepage characteristics is particularly significant. Shen et al. (2016) believed that the swelling of clay minerals upon water absorption and the resulting blockage of seepage channels are the reasons for the low water absorption capacity of continental shale and the loss of permeability after water absorption. Wang et al. (2023) conducted indoor high-temperature and high-pressure imbibition simulations and found that contact between fracturing fluid and clay minerals can cause clay swelling and migration, blocking the small throats of shale and thereby affecting the imbibition rate and oil displacement efficiency of fracturing fluid within smaller throats. Liao et al. (2023) conducted spontaneous imbibition experiments and found that due to the hydration swelling of clay minerals, which block the throats, the seepage channels in the reservoir become more complex, the pore space decreases, resulting in reduced imbibition rate and total imbibition volume.

The swelling and migration of clay minerals in shale reservoirs have a complex dual impact on the imbibition of the reservoir. On the one hand, the water absorption and swelling of clay minerals can promote the formation of microfractures, which change the physical structure of the reservoir and provide additional flow channels. This may improve the permeability of the reservoir and have a positive effect on oil and gas extraction. However, whether this experimental conclusion is applicable to reservoirs requires further discussion, as strong in-situ stress conditions may inhibit the formation of microfractures. On the other hand, the swelling, dispersion migration, or secondary precipitation after dissolution of clay minerals may cause the flow channels in the reservoir to be blocked. This can reduce the permeability of the reservoir and thus having an adverse effect on imbibition.

5. The effects of osmotic pressure on imbibition

In the imbibition process, capillary action is usually considered the only mechanism for fluid displacement (Hadley and Handy, 1956; Handy, 1960). However, as shown in Fig. 4, the diffuse double layer of clay minerals will form a "semi-permeable membrane" with selective permeability under the influence of surface adsorption (Stern layer) and diffusion movement (Diffuse layer) (Van Olphen, 1964). The "semi-permeable membrane" allows water molecules to pass through but restricts the passage of salt ions (White, 1965; Fritz, 1986), and the osmotic pressure caused is also one of the driving forces for imbibition (Lu et al., 2021; Xu et al., 2023). The osmotic pressure caused by clay minerals plays an important role in the imbibition and fracturing process of shale oil and gas reservoirs. It not only affects the distribution of fluids in the reservoir but may also affect the efficiency and long-term performance of fracturing fluids, thus having a potential positive impact on improving the recovery rate of oil and gas.

The presence of clay minerals provides the necessary conditions for the generation of osmotic pressure. When there is a concentration difference between the low-mineralized fracturing fluid injected into the formation and the high-mineralized water in the formation, the "semi-permeable membrane" effect will generate osmotic pressure within the formation (Fakcharoenphol et al., 2014). The water molecules in the low-mineralized fluid will be driven by osmotic pressure to enter the interior of the reservoir through the semi-permeable membrane composed of clay minerals. This process not only promotes the imbibition of water molecules but also helps to displace the oil phase, causing it to precipitate from larger pores and throats, thereby enhancing the displacement effect of imbibition (Xu et al., 2022). Yang et al. (2023a) conducted experiments with rock samples having a contact angle of 118°, using heavy water as the imbibition fluid, and observed that capillary forces provided resistance to fluid flow. In this scenario, the main driving force for imbibition shifts to the osmotic pressure generated by the absorption of water by clay minerals in the shale. Yang et al. (2023a) believed that during the process of fluid invasion into the matrix pores, in addition to being affected by the positive pressure gradient, the fluid is also influenced by capillary forces within the pores, permeation pressure, and viscous resistance, where the osmotic pressure is given by:

$$\triangle P = \triangle P_d + P_c + P_\pi - P_v \tag{1}$$

$$P_\pi = E\frac{RT}{V}\ln\frac{C_f}{C_m} \tag{2}$$

where $\triangle P$ is the driving pressure difference that the fracturing fluid experiences, $\triangle P_d$ is the hydraulic positive pressure difference, P_c is the capillary pressure, P_π is the osmotic pressure of clay minerals, P_v is the viscous resistance, E is the rock semi-permeable membrane coefficient, R is the universal gas constant, T is the system temperature, V is the molar volume of pure water, C_f is the activity of the external fluid, C_m is the activity of the formation of water. Osmotic pressure is highly sensitive to C_f and C_m, adding salt ions to deionized water will reduce the activity of water (Ding et al., 2022; Zhu et al., 2022), thereby reducing osmotic pressure and the driving force for osmosis. Consequently, the careful design of fracturing fluid during the development process is crucial for enhancing production.

A more intuitive approach has been adopted to reveal

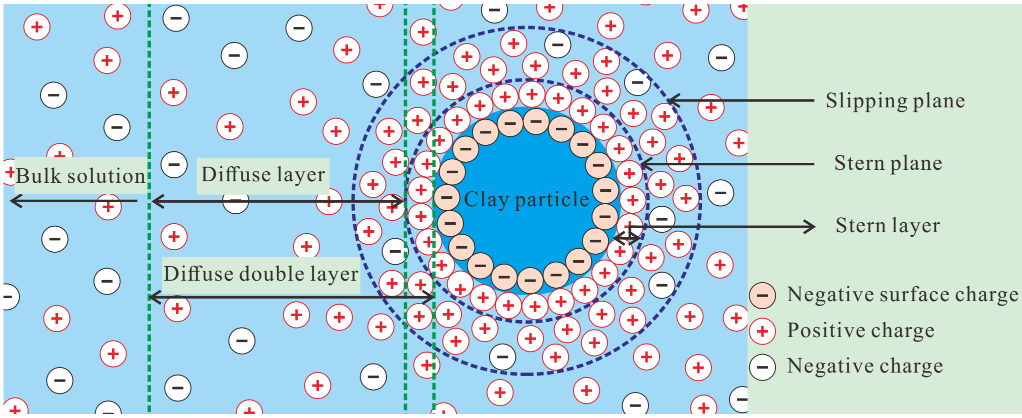

Fig. 4. Diffuse double layer on clay particle surface.

the impact of osmotic pressure formed by clay minerals on imbibition. Yang et al. (2023b) established an expression for the imbibition rate incorporating osmotic pressure as shown:

$$A=\sqrt{\frac{2\phi K_w(S_f-S_i)(P_c+P_\pi)}{\dfrac{\mu_g}{K_g}+\dfrac{\mu_w}{K_w}}} \tag{3}$$

where A is the imbibition rate, ϕ is the porosity, K_w is the water relative permeability, S_f is the water saturation, S_i is the initial water saturation, μ_g is the gas viscosity, K_g is the gas relative permeability, μ_w is the fluid viscosity. Similarly, Zhao et al. (2023) believed that the driving force for imbibition comes from the combined action of capillary force and osmotic pressure, and established a model for the imbibition depth of a single elliptical clay capillary tube as shown:

$$L=\sqrt{\frac{\sigma\omega\cos\theta}{3\mu}+\frac{\varepsilon E_\pi RT(X_m-X_f)\omega^2}{6\mu}}\sqrt{t} \tag{4}$$

where L is the imbibition depth, σ is the interfacial tension, ω is the width of the clay pore fracture, θ is the wetting contact angle of the water phase, μ is the viscosity of the imbibition fluid, ε is the number of ions after solute ionization, E_π is the efficiency of semi-permeable film, X_m is the molar concentrations of the formation water phase, X_f is the molar concentrations of the fracturing fluid water phase, t is the imbibition time. Eqs. (3)-(4) reveal from the aspects of imbibition rate and imbibition amount that in addition to capillary force, osmotic pressure as a driving force for imbibition should also be given corresponding attention in the actual oil field development process.

Layered clays exhibit the characteristics of an ideal semi-permeable membrane, allowing water molecules to pass through the clay layer and restricting the passage of salt ions (Cey et al., 2001; Rousseau-Gueutin et al., 2010). To quantitatively describe this phenomenon, Xu (2021) introduced the parameter of membrane permeability rate to quantify the selective permeability ability of the semi-permeable membrane. The membrane permeability rate is given by:

$$\frac{\varphi_f-\varphi_m}{V_w}=P_f-P_m+\lambda\frac{RT}{V_w}\ln\frac{X_f}{X_m} \tag{5}$$

where φ_f is the chemical potential of the fracturing fluid, φ_m is the chemical potential of original formation water in the matrix, V_w is the partial molar volume of the water phase, P_f is the pore pressure in the fracture, P_m is the pore pressure in the matrix, λ is the membrane permeability. Xu (2021) found that a higher content of clay minerals in the core can significantly increase the specific surface area of shale particles. On the one hand, this leads to an increase in capillary pressure, and on the other hand, it results in a larger membrane efficiency λ, collectively leading to an increase in the driving force term, thereby enhancing the imbibition front distance and water absorption. Considering the effect of chemical osmotic pressure, the cumulative gas production is less than the calculated value when ignoring the chemical osmotic pressure, with the maximum difference reaching 10.7%. In actual mine applications, the capillary pressure curve that takes into account the effect of chemical osmotic pressure should be used to obtain higher simulation accuracy.

When there is a concentration difference between the low-mineralized fracturing fluid injected into the formation and the high-mineralized water in the formation, the osmotic pressure generated due to the presence of clay minerals will act as a driving force for imbibition, promoting imbibition. Furthermore, the extent of the chemical potential difference has a direct impact on the intensity of imbibition. In other words, a larger chemical potential difference leads to stronger imbibition, which in turn corresponds to a faster imbibition rate (Zhou et al., 2016; Xu, 2021; Yang et al., 2023b). These findings are of great significance for understanding and optimizing the design of fracturing fluid in shale reservoirs. By adjusting the mineralization degree of the fracturing fluid, the chemical osmotic pressure can be effectively utilized to promote the imbibition of fracturing fluid in the reservoir, thereby improving the efficiency of oil and gas extraction. At the same time, this also provides new theoretical basis and technical support for the development of shale oil and gas, which helps to develop more efficient development strategies.

6. Conclusions and outlook

Clay minerals play a complex and critical role in the imbibition of shale reservoirs. Their content and types significantly influence the reservoir's physical properties, thereby affecting the distribution and flow characteristics of fluids within the reservoir. Swelling and migration of clay minerals can have dual impacts on imbibition: Promoting permeability through micro-fractures formation or reducing permeability via secondary precipitation. Furthermore, the concentration gradient between the low-mineralization fracturing fluid injected into the formation and the high-mineralization water within the formation generates osmotic pressure, which promotes imbibition. A greater chemical potential difference, enhances the imbibition effect and rate.

Based on this, several key questions regarding the impact of clay minerals on imbibition arise, and the discussing these issues is crucial for a deep understanding of the role of clay minerals in the development of shale oil and gas. To further this understanding, several key areas for future research emerge:

1) Chemical composition of fracturing fluids: The review primarily discusses the effects of clay minerals on shale imbibition from the clay perspective. However, the impact of the chemical composition of fracturing fluids on clay minerals is also very important in actual formations. Future research could focus on the chemical composition of fracturing fluids to analyze the effects of clay minerals on imbibition and further optimize research methods.
2) Critical threshold for clay content: The content of clay minerals has a significant impact on the imbibition process, and there is a critical threshold for this impact. Although there is no unified standard to precisely define this threshold at present, in-depth analysis of the types of clay minerals in the reservoir and accurate determination of the content are crucial for predicting and optimizing the imbibition behavior of the reservoir. Therefore, future research can focus on determining the threshold value of clay content.
3) Micro-fractures and reservoir conditions: Based on findings from laboratory experiments, micro-fractures induced by the hydration swelling of clay minerals can improve imbibition. However, whether this experimental conclusion can be directly applied to actual reservoir conditions requires further discussion, as strong in-situ stress conditions may inhibit the formation of micro-fractures. Therefore, future research should focus more on actual reservoir conditions to enhance fluid flow efficiency and increase the development potential of shale reservoirs.
4) Role of osmotic pressure: In addition to traditional capillary force in shale reservoirs, the osmotic pressure generated by clay minerals is also a key factor affecting fluid imbibition behavior. This consideration of osmotic pressure provides a new perspective for understanding and predicting the imbibition behavior in shale reservoirs. It provides a new method to evaluate and utilize the fluid dynamics characteristics in shale reservoirs. Therefore, future research directions can concentrate on how to enhance the efficiency of oil and gas extraction through osmotic pressure.

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Conflict of interest

The authors declare no competing interest.

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