Capillarity Vol. 10, No. 1, p. 12-21, 2024

Invited review

A critical review of capillary pressure behavior and characterization in fractional-wet reservoirs

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Keywords:
Fractional-wet reservoirs
capillary pressure
two-phase flow
prediction model

Cited as:
Xiao, Y., You, Z., Wang, L., Du, Z. A critical review of capillary pressure behavior and characterization in fractional-wet reservoirs. Capillarity, 2024, 10(1): 12-21.
https://doi.org/10.46690/capi.2024.01.02

Abstract:
Fractional wettability is common in oil and gas reservoirs, resulting in complex fluid distribution and transport phenomena. A precise understanding of capillary pressure behavior and characterization in fractional-wet reservoirs, including the two-phase flow mechanisms within pores and relationship between capillary pressure and saturation in porous media, is significant to enhanced oil recovery strategies. In this paper, an in-depth review of the two-phase flow mechanisms in fractional-wet pores and capillary entry pressures in various displacement processes was conducted. Furthermore, the effects of oil-wet proportion and contact angle on capillary pressure characterization were summarized, highlighting the emergence of similar capillary pressure curves under conditions of low oil-wet proportions. The prediction models for capillary pressure, containing empirical equations and physics-based models were discussed, with the aim of clarifying the most effective prediction methodologies. Finally, the review was finalized by outlining key findings and future directions for both experimental and theoretical studies in the realm of capillary pressure behavior and characterization.

1. Introduction

Capillary pressure within porous media results from a complex interplay of factors, including the properties of rock and fluids, pore size and geometry, as well as the wetting characteristics (Song et al., 2022; Xiao et al., 2022; Wang et al., 2023). Understanding the two-phase flow mechanisms at the microscopic scale, known as capillary pressure behavior, and establishing the constitutive relationship between capillary pressure and saturation, referred to as capillary pressure characterization, are essential to modeling multiphase flow in porous media(Naik et al., 2015, 2018). This knowledge holds substantial research significance in many fields, such as geological sequestration of carbon dioxide, remediation of non-aqueous phase liquid contaminants in soil, and the extraction of hydrocarbons from petroleum bearing reservoirs.

Heterogeneous wettability is common in natural porous media as a result of: 1) variations in chemical compositions and roughness of pore surface, 2) irregularities in pore geometry, and 3) the presence of adsorbed surfactant groups and weak polar non-hydrocarbon compounds (Ustohal et al., 1998; Song and Kovscek, 2016; Kallel et al., 2017; Karimova et al., 2023). This complex wetting behavior is commonly classified as mixed- and fractional-wet states (Mcdougall et al., 1996; Yang et al., 2022). In mixed-wet systems, wettability is distributed according to pore size, resulting in mixed-wet large and small pores (MWL and MWS), where large pores are hydrophobic, and small pores are hydrophilic. However, in a fractional-wet (FW) system, wettability is uncorrelated to

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Received September 26, 2023; revised October 17, 2023; accepted November 5, 2023; available online November 8, 2023.

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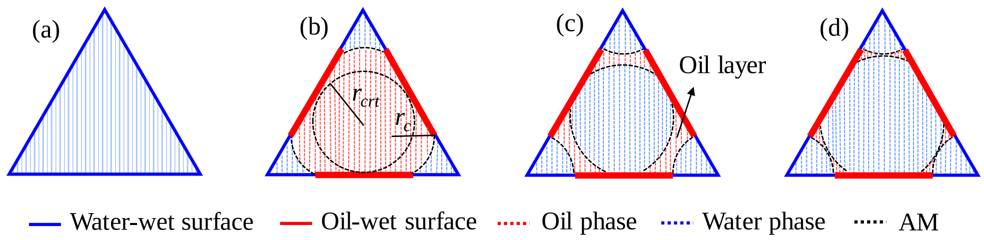

Fig. 1. Fluid distribution in a equilateral triangular pore: (a)-(b) primary oil drainage and aging effect, (c)-(d) formation and collapse of oil layers under primary water imbibition.

pore size, and a single pore has the potential to exhibit different wettabilities. Numerous experimental studies have shown that FW system is the most common one in oil reservoirs (Jerauld and Rathmell, 1997; Hamon, 2000; Dodd et al., 2014; Wang et al., 2022).

Although substantial efforts have been dedicated to clarifying two-phase flow patterns and mechanisms within FW porous media over the past few decades, our understanding of capillary behavior in such pores remains insufficient. Consequently, insights into capillary pressure characterization and its influential factors are restricted. This paper aims to provide a current overview of capillary pressure behavior within FW media. Our review starts with the capillary pressure behavior of FW pores (Section 2), including pore geometry and fluid distribution (Section 2.1), two-phase flow pattern (Section 2.2), and capillary entry pressure (Section 2.3). The two-phase flow pathways and typical capillary pressure curves are presented in Section 3. Then, Section 4 summarizes both the advantages and limitations of prediction models for capillary pressure, and discusses their modeling processes and predictive effectiveness. Finally, Section 5 finalizes the review by outlining key insights and future research directions in the three aforementioned research areas.

2. Capillary pressure behavior

2.1 Pore geometry and fluid distribution

Salathiel (1973) observed a 10% residual oil saturation in a sandstone reservoir in East Texas after 5,000 pore volumes had passed through it, and introduced the concept of mixed-wet state to interpret this phenomenon. It suggested that oil film or oil layer with hydraulic conductivity led to a very low residual oil saturation. To study this phenomenon from a theoretical perspective, researchers began simulating the hydraulic conductivity of these oil layers in polygonal pores, which was substantiated by experimental work of Lenormand et al. (1983). Consequently, the study of polygonal capillaries became fundamental in understanding capillary pressure behaviors in the context of heterogeneous wettability. These polygonal capillaries include various shapes, including squares (Blunt, 1997; Fenwick and Blunt, 1998; Larsen et al., 2000), equilateral triangles (Ma et al., 1996; Helland and Skjaeveland, 2006; Ryazanov et al., 2014; Naik et al., 2021), arbitrary triangles (Mason and Morrow, 1991), tetragonal stars (Kovscek et al., 1993; Man and Jing, 2001), and irregular pores (Lago and Araujo, 2001).

When the oil phase infiltrates a uniformly water-wet pore, the portion of pore surfaces contacted with the oil phase are changed to oil-wet state, thus heterogeneous-wet pores are formed (Figs. 1(a) and 1(b)). In the case of strongly water-wet triangular pores, Fig. 1(b) illustrates the maximum pore size, as defined by the inscribed radius, at which oil can enter at the maximum capillary pressure during the primary drainage stage. This corresponds to the arc meniscus (AM) with a curvature radius r_c at the corners. The wettability of pore surfaces that come into contact with oil in pores changes to oil-wet after aging, a process described by Blunt (1997) using Eq. (1). However, according to Eq. (1), the minimum proportion of oil-wetness required is 44% for equilateral triangular and 47% for square capillary when inscribed radius of pore is equal to critical radius of wettability alteration. Additionally, the contact angle of water-wet surface is limited in order to form corner water (Helland and Skjaeveland, 2006). Consequently, the formation conditions for heterogeneous-wet polygonal pores are fairly demanding, fluid distributions are extremely singular, and the ranges of oil-wetness proportion and contact angle are limited. For heterogeneous-wet pores composed of different minerals, the ranges of contact angle and oil-wetness proportion are wider, and the distribution of different minerals is more diverse, making polygonal capillaries less applicable. Furthermore, oil layers are established after the primary water imbibition under a certain pressure range (Fig. 1(c)), which improve hydraulic conductivity of the residual oil (Salathiel, 1973; Kovscek et al., 1993; Buckley, 1995). The previous studies have investigated oil layer collapse using geometric and thermodynamic principles (Fig. 1(d)), demonstrating that oil layers are prevalent (Blunt, 1997, 1998; Hui and Blunt, 2000; Piri and Blunt, 2004; Van Dijke and Sorbie, 2006). It should be noted that heterogeneous-wet equilateral triangular capillaries is presented, due to their shared fluid configurations across all polygonal capillaries:

$$k_o = \begin{cases} 0, & r < r_{cri} \\ 1 - \dfrac{r_{cri}}{r(1+2\sqrt{\pi G})}, & r \geq r_{cri} \end{cases} \tag{1}$$

where k_o is oil-wet proportion, r is radius of inscribed circle within pore, r_{cri} is critical radius of wettability alteration, and G is shape factor.

2.2 MS-P theory

Entry pressure refers to the required pressure that a fluid is displaced by another in a capillary. However, calculating the entry pressures of irregular pores cannot be accomplished using the Young-Laplace equation alone. The MS-P theory, founded on the minimization of free energy, offers a novel approach to address this scientific inquiry (Mayer and Stowe, 1965; Princen, 1969a, 1969b, 1970).

In the context of irregular capillaries, the entry pressure is a function of the cross-sectional shape of the pore, and it can be determined through the equilibrium state of a three-phase system and surface free energy considerations. This process entails several steps:

Based on the Helmholtz free energy, the relationship between surface free energy and the virtual work done during infinitesimal displacement of the fluid interface is established (Eq. (2)). These complex relationships contain energy balance, capillary shape, and wettability:

$$\begin{cases} 0=(P_o-P_w)A_w\mathrm{d}x+\sigma_{ow}L_{ow}\mathrm{d}x+(\sigma_{ws}-\sigma_{os})L_{os}dx \\ 0=(P_w-P_o)A_o\mathrm{d}x+\sigma_{ow}L_{ow}\mathrm{d}x+(\sigma_{ws}-\sigma_{os})L_{ws}dx \end{cases} \tag{2}$$

where P_o and P_w are oil and water pressure, A_o and A_w are oil and water area from pore cross-section, respectively. σ_{ow}, σ_{ws}, and σ_{os} are oil-water, water-solid, and oil-solid interfacial tension, respectively. L_{ow}, L_{ws}, and L_{os} are perimeters of oil-water, water-solid, and oil-solid interface, respectively. dx is displacement distance.

Then, the curvature radius of fluid interface at the entry pressure is calculated using Eq. (3) by substituting Young's Equation and $P_c=P_o-P_w$ (where P_c is capillary pressure) in Eq. (2). It is important to note that this calculation is focused solely on fluid distribution in the pore cross-section, because the curvatures of the main terminal meniscus (MTM) and AM are considered equivalent (Helland and Skjaeveland, 2006):

$$\begin{cases} r_{co}=\dfrac{A_o}{L_{os}\cos\theta_o+L_c} \\ r_{cw}=\dfrac{A_w}{L_{ws}\cos\theta_w-L_c} \end{cases} \tag{3}$$

where r_{co} and r_{cw} are curvature radiuses of AM in oil- and water-wet region, respectively. θ_o and θ_w are apparent contact angles of oil- and water-wet region, respectively. L_c is arc length of AM.

2.3 Two-phase flow pattern and entry curvature radius

In Fig. 2(a), we provide a detailed representation of three two-phase flow patterns in a heterogeneous-wet angular pore (Blunt, 1997; Øren et al., 1998; Helland and Skjaeveland, 2006). The entry curvature radius can be determined through combining fluid distribution and MS-P theory (Eq. (3)). Moving forward, entry curvature radiuses for different displacement processes containing primary drainage and imbibition are summarized to better understand the flow mechanisms. The entry curvature radius for primary oil drainage can then be calculated using Eq. (4) when $\theta_w<\pi/2-\gamma$ (γ is the half-angle of pore corner):

$$r_c=\frac{1}{2}\frac{\cos\theta_w L_p-\sqrt{\cos^2\theta_w L_p^2-12A_fA_p}}{3A_f} \tag{4}$$

where $A_f=\theta_w+\gamma-\pi/2+[\cos\theta_w\cos(\theta_w+\gamma)]/\sin\gamma$, L_p and A_p are pore perimeter and area from cross-section, respectively.

Starting with configuration A, water displacements can occur through either spontaneous or forced imbibition processes. During spontaneous imbibition A-B-C, which follows when $\theta_o<\pi/2-\gamma$, water initially enters pore corners with decreasing capillary pressure. Three AMs remain pinned at the junction between surfaces with different wettabilities, displacing oil by decreasing curvature until θ_o is reached. The snap-off phenomenon occurs when three AMs touch at the pore center (configurations A-B), resulting in the displacement of residual oil with decreasing capillary pressure (configurations B-C). The capillary pressures involved in the above-mentioned process are positive. The entry curvature radiuses when snap-off occurs (configurations A-B) can be determined by:

$$r_c=\frac{1}{2}\frac{\cos\theta_o L_c-\sqrt{\cos^2\theta_o {L_p}^2-12A_fA_p}}{3} \tag{5}$$

where $A_f=\pi/2-\theta_o+\gamma+[\cos\theta_o\cos(\theta_o-\gamma)]/\sin\gamma$.

The forced imbibition follows paths A-D-E-C or A-D-C when $\theta_o\geq\pi/2-\gamma$, and AMs are pinned to displace oil from configurations A to D. When $\theta_o\leq\pi/2+\gamma$, the curvature signs of AMs changes to displace oil until AMs touch each other at the pore center (configuration E). When $\theta_o>\pi/2+\gamma$, signifying strong hydrophobicity of the oil-wet surface, increasing capillary pressure displaces water from the pore center to the corner. Oil layers are established when AMs touch in the pore corner (configuration F). The entry curvature radiuses of configuration E and F can be calculated using Eqs. (6) and (7), respectively:

$$\begin{aligned} &-A_p+r_cL_p\cos\theta_o+3{r_c}^2\left[\frac{\pi}{2}-\theta_h-\gamma\right. \\ &\left.+(\cos\theta_h-2\cos\theta_o)\frac{\cos\theta_h\cos(\theta_h+\gamma)}{\sin\gamma}\right]=0 \end{aligned} \tag{6}$$

$$r_c=\frac{1}{2}\frac{\cos\theta_o L_p+\sqrt{\cos^2\theta_o {L_p}^2-12A_fA_p}}{3A_f} \tag{7}$$

where $A_f=\pi/2-\theta_o+\gamma+[\cos\theta_o\cos(\theta_o-\gamma)]/\sin\gamma$, θ_h is hinging angle of AM.

Nevertheless, a notable shortcoming in the heterogeneous-wet angular capillary model is that it predicts either positive or primarily negative capillary pressure values due to the pinning of AMs from configuration A to D (Fig. 2(b)), which is inconsistent with the experimental results that show both positive and negative capillary pressures (Killins et al., 1953).

Zheng et al. (2021) introduced theorical models for capillary pressure behavior in heterogeneous-wet circular pores, in order to overcome the shortcomings of polygonal capillaries. In a heterogeneous-wet circular pore, which consists of two surfaces with different wettability, when the oil pressure reaches the entry pressure of heterogeneous-wet capillary, oil

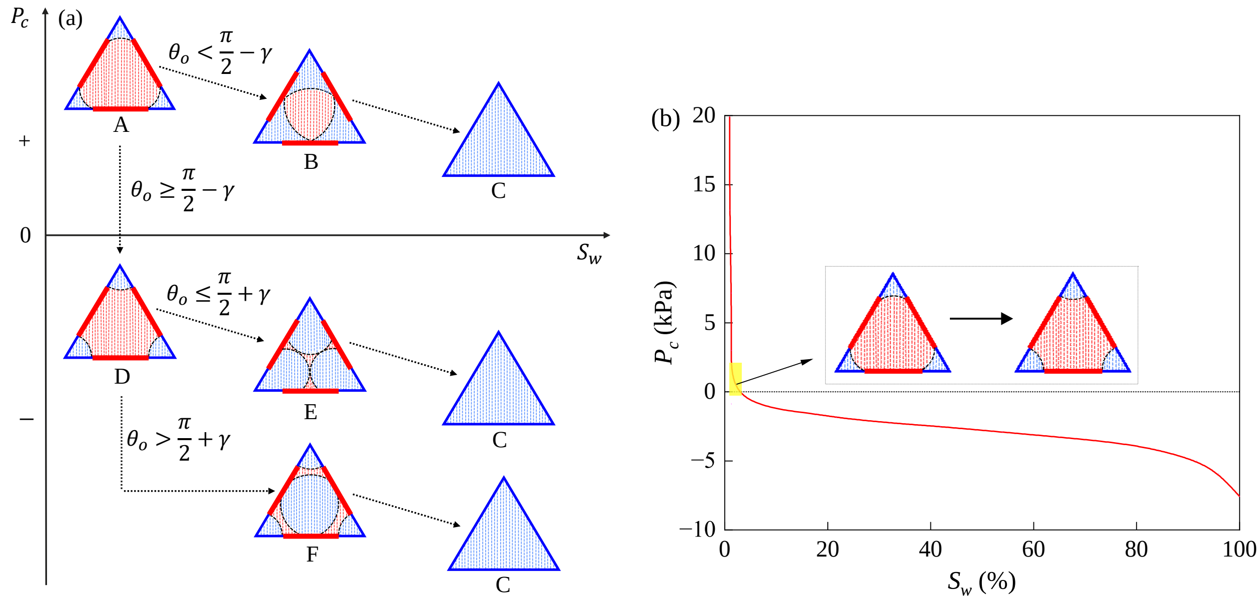

Fig. 2. (a) Two-phase flow patterns of heterogeneous-wet angular pore (the red, blue, and black lines are oil-wet surface, water-wet surface, and AMs, respectively. The red and blue area are oil and water phase, respectively) and (b) capillary pressure curve of primary water imbibition

invades the entire capillary through piston-like displacement.

In this model, a key element is the MTM with double curvatures, where the fluid interfaces near the oil- and water-wet regions exhibit concave and convex curvatures, respectively. This structure displaces water to maintain stable contact angle and pressure system (Fig. 3(a)), which is directly observed from high-resolution X-ray imaging (Lin et al., 2019).

Moreover, two fluids coexist in a heterogeneous-wet circular capillary when the entry pressure of oil-wet region is achieved (Fig. 3(b)). AMs are pinned at the junction between surfaces with different wettabilities to displace water in the vertical direction with increasing capillary pressure (Fig. 3(c)). When the oil pressure reaches the entry pressure of the water-wet region, oil displaces residual water in the water-wet region through the MTM (Fig. 3(d)).

Importantly, this theorical model does not impose limitations on oil-wet proportion and contact angle, allowing it to accurately represent various two-phase flow patterns. In the study of Zheng et al. (2021), entry pressures of oil- and water-wet regions in circular capillary can be calculated using Eq. (8), within which approximation equations for effective contact angles in these regions were introduced (Eqs. (9) and (10)), caused by the absence of analytical solutions within the framework of the MS-P theory (Eq. (3)). Furthermore, these effective contact angles serve a vital role in distinguishing between piston-like (Fig. 3(a)) and stepwise displacement processes (Figs. 3(b)-3(d)):

$$\begin{cases} P_{co,e} = \dfrac{2\sigma_{ow}\cos\theta_{eo}}{r} \\ P_{cw,e} = \dfrac{2\sigma_{ow}\cos\theta_{ew}}{r} \end{cases} \tag{8}$$

$$\begin{aligned} \theta_{eo} = \arccos\Bigg[& \left(\frac{1}{1+e^{8.34-8.34k_o}} - k_o + 1.5 \right) \cos\theta_o \\ & + \frac{(1-k_o)(1.3351k_o^2 - 0.5573k_o - 0.4513)}{k_o} \\ & \cdot \cos\theta_o (1+\cos\theta_o)^{0.55} + 1 - k_o \Bigg] \end{aligned} \tag{9}$$

$$\begin{aligned} \theta_{ew} = \arccos\Bigg[& \left(\frac{1}{1+e^{8.34k_o}} - k_o + 0.5 \right) \cos\theta_w \\ & + \frac{k_o(1.3351k_o^2 - 2.1129k_o - 0.3265)}{1-k_o} \\ & \cdot \cos\theta_w (1-\cos\theta_w)^{0.55} - k_o \Bigg] \end{aligned} \tag{10}$$

where $P_{co,e}$ and $P_{cw,e}$ are entry pressures in oil- and water-wet region, respectively. θ_{eo} and θ_{ew} are effective contact angles in oil- and water-wet region, respectively.

3. Capillary pressure characterization

3.1 Two-phase flow pathways

Capillary pressure curves can reflect two-phase flow patterns, wettability and pore radius distribution (Longeron et al., 1995). To understand and analyze the various pressure-controlled two-phase flows, adjustments in the pressure difference between the inlet and outlet are made, allowing for the establishment of a relationship between capillary pressure and water saturation (Xiao et al., 2022).

Based on the different flow mechanisms and pressure ranges, capillary pressure curves can be categorized into three distinct flow paths (Fig. 4). Initially, in the primary oil drainage ($P_c > 0$), the oil phase enters porous media that is saturated with water, by increasing the oil pressure at the inlet until irreducible water saturation ($S_{wi,1}$) is reached. Subsequently,

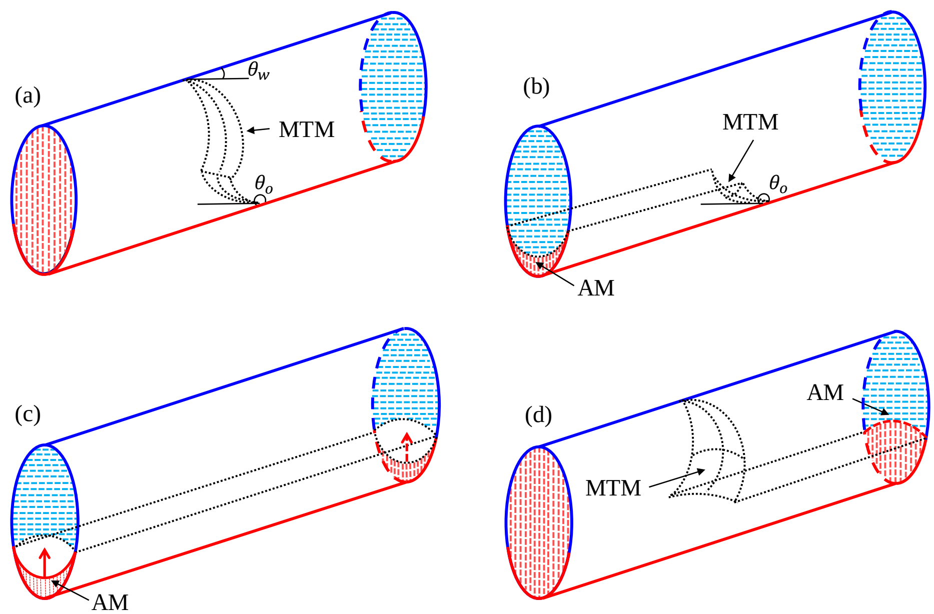

Fig. 3. The fluid configurations of oil drainage stage in heterogeneous-wet circular capillary (Zheng et al., 2021): (a) MTM with double curvatures in piston-like displacement, (b) oil invades oil-wet region, (c) oil displaces water in the vertical direction through AM and (d) oil invades water-wet region by main terminal meniscus

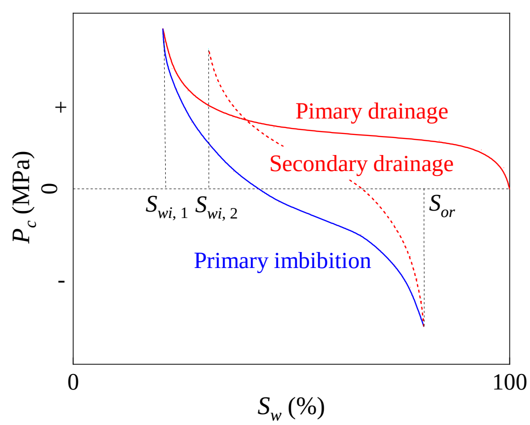

Fig. 4. The capillary pressure curves with different two-phase flow paths.

water begins to spontaneously imbibe ($P_c > 0$) or drain ($P_c < 0$) into the porous media as the oil phase at the inlet is reduced or the water pressure at the outlet is increased, which is referred to as primary water imbibition including both quasi-static and forced imbibition.

Finally, during the secondary oil drainage, a new irreducible water saturation ($S_{wi,2}$) is attained by increasing the oil pressure. It includes quasi-static imbibition ($P_c < 0$) and drainage ($P_c > 0$) processes. The oil drainage processes mimic the primary and secondary migrations of crude oil, while primary water imbibition allows for the investigation of water injection in oil reservoirs. Notably, differences in capillary pressure curves among these three flow paths are quite distinct, primarily due to wettability hysteresis and complex pore structure (Singh et al., 2022).

3.2 Capillary pressure curves

Due to the challenges associated with preparing mixed-wet porous media containing both large and small pores, FW media featuring various oil-wet proportions have become a popular choice to conduct capillary pressure experiments. The experimental results for different flow paths are illustrated in Fig. 5. Although the capillary pressure curves of FW media vary greatly, several basic qualitative trends can still be recognized.

In both primary and secondary oil drainage processes, there is a noticeable reduction in oil drainage pressure as the oil-wet proportion increases, causing the capillary pressure curve to gradually shift downward (Fig. 5(a)). In the case of primary water imbibition, a higher oil-wet proportion results in a less dynamic water imbibition process, similarly causing the capillary pressure curve to gradually shift downward (Fig. 5(b)). These trends have been observed in previous studies (Fatt and Klikoff, 1959; Bradford and Leij, 1995; O'Carroll et al., 2005; Motealleh et al., 2013).

Furthermore, it is worth noting that the heterogeneous distribution of particle sizes can lead to larger capillary pressures and steeper curve slopes (Fig. 6(c)), as evidenced by earlier research (Fatt and Klikoff, 1959).

Interestingly, it is observed that capillary pressure curves are similar when dealing with low oil-wet proportions during primary and secondary oil drainage processes with positive pressure (Fig. 6). This phenomenon was initially observed by Bradford and Leij (1995), who noted that gas-water and oil-water capillary pressure curves for $k_o = 0\%$, 25% and 50% displayed similarities under primary drainage conditions. Subsequently, Ustohal et al. (1998) observed that gas-water capillary pressure curves for $k_o = 0\%$, 50% and 67% exhibited

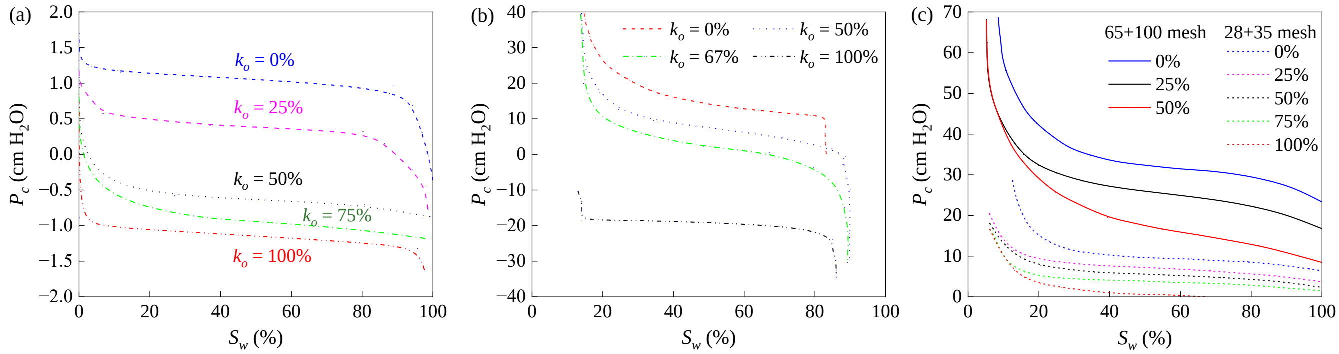

Fig. 5. Capillary pressure curves with different flow paths: (a) primary oil drainage in oil-water system (Motealleh et al., 2013), (b) primary water imbibition in water-gas system (O'Carroll et al., 2005) and (c) the effect of particle size distribution on capillary pressures under primary oil drainage in oil-water system (Fatt and Klikoff, 1959).

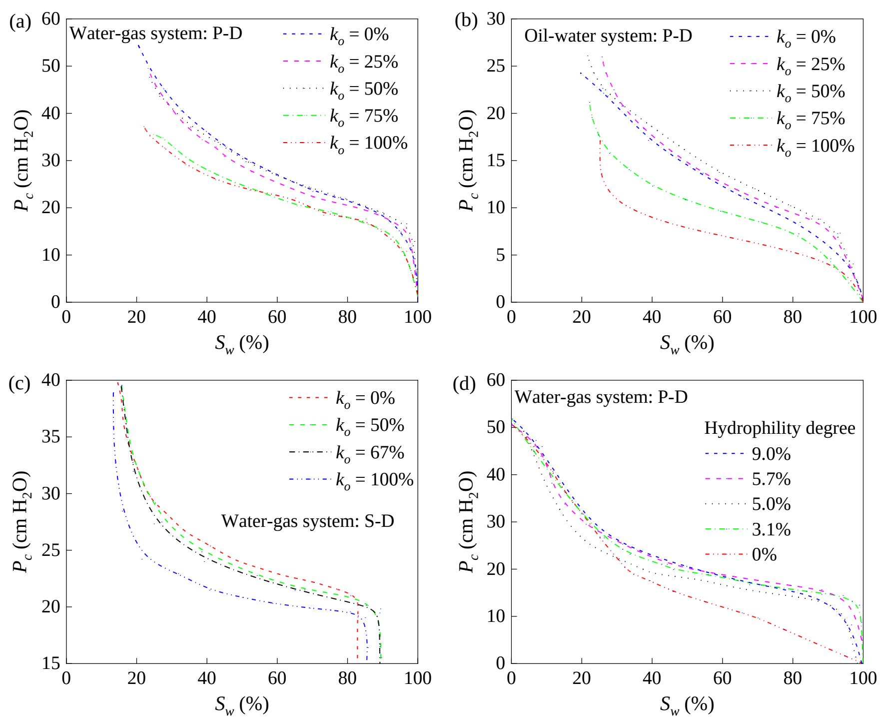

Fig. 6. Similar capillary pressure curves for low oil-wet proportions: (a) primary oil drainage in water-gas system (Bradford and Leij, 1995), (b) primary oil drainage in water-oil system (Bradford and Leij, 1995), (c) secondary oil drainage in water-gas system (Ustohal et al., 1998) and (d) primary oil drainage in water-gas system (Bauters et al., 2000).

resemblances under secondary drainage conditions. Additional studies by Bauters et al. (2000) and Hwang et al. (2006) further verified this phenomenon in water-gas system under primary drainage. They proposed two critical factors to explain this observation: (1) the wetting effect of water phase diminishes the hydrophobicity of oil-wet particles, (2) the water-gas systems tend to exhibit lower contact angles for oil-wet particles, resulting in weaker sensitivity of capillary pressure to changes in oil-wet proportion.

4. Prediction model

4.1 The empirical equations

Many empirical equations have been derived for predicting capillary pressure in FW porous media, often based on the shape of the capillary pressure curve.

Bradford and Leij (1995) introduced an empirical equation to predict both positive and negative capillary pressures by enhancing the Leverett theory (Eq. (11)). Nevertheless, it is worth noting that this equation is not appropriate for uniformly oil-wet porous media:

$$P_{cf}(S_w) = P_{cw}(S_w) - \lambda \tag{11}$$

where P_{cf} and P_{cw} are capillary pressures of FW and homogeneously water-wet porous media, respectively. S_w is water saturation, λ is empirical parameter related oil-wet proportion.

Ustohal et al. (1998) proposed a statistical approach to predict capillary pressures in FW media. While this prediction model applies to a wide range of oil-wet proportions, its predictive accuracy is limited due to the multitude of required parameters.

Skjaeveland et al. (2000) independently predicted both positive and negative capillary pressures for FW porous media using Eq. (12). Although, Their empirical equation can be used to match capillary pressures with different two-phase flow paths, but empirical parameters related to FW states are difficult to determine (Helland and Skjaeveland, 2006):

$$P_{cf}(S_w) = c_w P_{cw}(S_w) + c_o P_{co}(S_w) \tag{12}$$

where P_{co} is capillary pressure of homogeneously oil-wet media, c_w and c_o are empirical parameter about wettability. $c_w = 1$ and $c_o = 0$, as well as $c_w = 0$ and $c_o = 1$ indicate homogeneously water- and oil-wet media, respectively.

O'Carroll et al. (2005) pointed out that the empirical equations proposed by Bradford and Leij (1995) and Skjaeveland et al. (2000) were unable to predict capillary pressures involving different combinations of contact angles, and these equations lacked clear physical interpretations for their empirical parameters. Consequently, Leverett theory and Cassie-Baxter equation were combined to derive the Leverett-Cassie model (Eq. (13)), which shares a similar form with the empirical equation proposed by Skjaeveland et al. (2000) (Eq. (12)). Notably, all parameters in the Leverett-Cassie model possess distinct physical meanings. However, there are several disadvantages associated with the Leverett-Cassie model: (1) capillary pressures for uniformly oil-wet and water-wet porous media cannot be simultaneously predicted; (2) the theoretical basis is weak because of the absence of a rigorous derivation, such as the lack of physical meaning for the weighted contact angle in the Cassie-Baxter equation:

$$P_{cf}(S_w) = (1-k_o)\cos\theta_w P_{cw}(S_w) + k_o \cos\theta_o P_{cw/co}(S_{w/o}) \tag{13}$$

where $P_{cw/co}(S_{w/o}) = P_{co}(S_o)$ when $\theta_o > 90°$, and $P_{cw/co}(S_{w/o}) = P_{cw}(S_w)$ when $\theta_o < 90°$.

Until now, empirical equation of capillary pressure does not escape its intrinsic defects. Foroughi et al. (2022) proposed a closed-form equation (Eq. (14)) to predict capillary pressure in heterogeneous-wet porous media. However, empirical parameters are still difficult to determine, and distinguishing heterogeneous-wet types can not be done reliably by using wettability factor alone. Consequently, empirical equations do not provide an accurate depiction of the intricacies underlying two-phase flow mechanisms, because drainage and imbibition process can coexist in FW porous media, even in pores:

$$P_c = \omega + \xi \tan\left(\frac{\pi}{2} - \pi S_e^{\eta}\right) \tag{14}$$

where ω is wettability factor, $\omega > 0$ and $\omega < 0$ represent water-wet or oil-wet media, respectively, $\omega \to 0$ represents heterogeneous-wet media. ξ is the curvature index, η is the saturation exponent. S_e is the normalized saturation.

4.2 The physics models

Physics-based models of capillary pressure are constructed using pore bundle and network models, incorporating pore geometry, capillary pressure behavior and pore wettability (Blunt, 2017). Thus, two-phase flow mechanisms can be accurately described. Usually, these models employ primary oil drainage, pore surface aging, and primary water imbibition to investigate the formation of heterogeneous-wet media and the behavior of two-phase flow. Subsequently, entry pressures of all pores are calculated using the MS-P theory (Eq. (2)). Finally, capillary pressure curves with different flow paths are generated by considering the pore structure.

However, it is important to note that current physics models of capillary pressure mainly rely on polygonal capillaries for modeling heterogeneous-wet porous media. Thus, the ranges of wettability proportions and contact angles that can be considered in these models are limited (Kumar and Fogden, 2009; Kumar et al., 2012; Kallel et al., 2015, 2017). Furthermore, such prediction models pertain only to MWL porous media, but not to MWS and FW media.

To address the above issues, researchers have attempted to expand the range of wettability parameters by incorporating circular, triangular and square capillaries into pore network models (Ryazanov et al., 2009). This approach involves grouping various regular polygonal capillaries together to increase the shape factor. However, the limited combinations of different capillary shapes fail to cover a wide range of wettability parameters. Additionally, this leads to increased computational difficulty, making it challenging to establish relationships between important parameters, and may result in inefficiency.

In contrast, Zheng et al. (2021) proposed a new capillary pressure prediction model for FW media, based on the capillary pressure behavior of FW circular pores (Fig. 3). Compared to models that rely on polygonal capillaries, the capillary pressures and two-phase flow mechanisms can be revealed in a simpler and more concise way by the prediction model of Zheng et al. (2021). Moreover, all ranges of wettability parameters can be covered. Furthermore, the research conducted a comparison between their new prediction model and the Leverett-Cassie model proposed by O'Carroll et al. (2005). The results of this comparison indicated that while the Leverett-Cassie model can accurately predict capillary pressures under weak wettability heterogeneity conditions (Fig. 7(a)), its notable disadvantage becomes apparent when dealing with strong wettability heterogeneity because its failure to account for the application range of the Cassie-Baxter equation (Fig. 7(b)).

5. Challenges and perspective

In this review, our primary focus has been on examining capillary pressure behavior, capillary pressure characterization, and prediction models tailored to FW porous media. Although

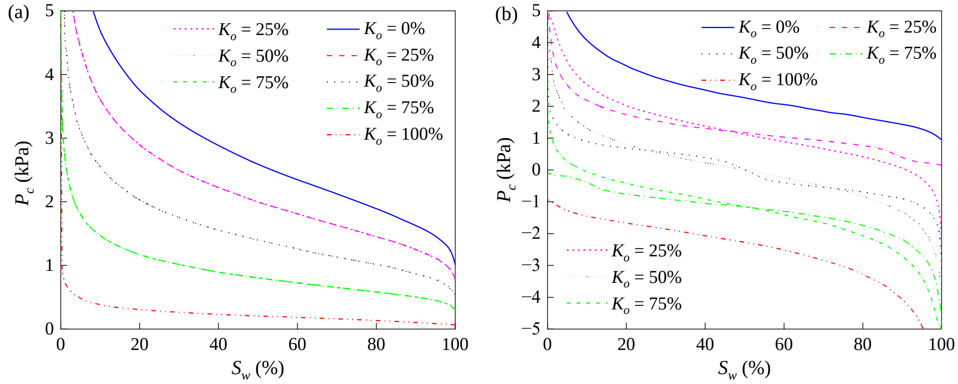

Fig. 7. The comparison of Leverett-Cassie model (dot lines) and the the model proposed by Zheng et al. (2021) (dashed lines) under different ko values: (a) weak wettability heterogeneity with $\theta_w = 0°$ and $\theta_o = 85°$ and (b) strong wettability heterogeneity with $\theta_w = 30°$ and $\theta_o = 150°$.

two-phase flow within FW media has been investigated for more than fifty years, numerous unresolved research challenges persist.

To begin, the concept of polygonal capillaries is inapplicable in the case where FW pores consist of various minerals, resulting in broader ranges of contact angles and oil-wet proportions (k_o), accompanied by more diversified distributions of distinct minerals. While recent advancements, such as FW circular capillaries, show promise in addressing these limitations, they may not accurately represent the complex pore shapes found within oil reservoirs. Thus, future theoretical investigations are essential to address these critical questions.

Uncertainties remain in capillary pressure characterization for FW media, particularly concerning the appearance of similar capillary pressure curves at low k_o values. These interesting phenomena may suggest some percolation transitions (the abrupt change in two-phase flow phenomena) induced by FW states, which can be intensively studied through visualization experiments in upcoming research endeavors.

Additionally, experimental studies focusing on the effects of contact angles on capillary pressure curves are limited because of the difficulties in obtaining particles with a wide range of wettability. As a result, our understanding of two-phase flow remains incomplete. Therefore, the development of modified reagents to alter particle wettability is crucial for advancing this field.

Furthermore, to create a prediction model of capillary pressure that accurately reflects the complex pore structures within oil reservoirs, a simplified calculation method for combining different pore shapes is still needed.

Finally, the effects of capillary pressure behavior and characterization on enhanced oil recovery is most important. For FW reservoirs, the capillary pressure behavior contains both drainage and imbibition process, that is, capillary pressure curve distributes in positive and negative pressure. Thus, alternative injection of low-salinity water and surfactant can improve oil recovery. Spontaneous imbibition of low-salinity water can displace oil in water-wet regions during initial oilfield exploitation. Afterwards, injection of surfactant is beneficial for enhancement of sweep efficiency within oil-wet regions. However, precise wettability distribution and wettability proportion are the premise of the above schemes.

In summary, while significant progress has been made in the study of capillary pressure in FW porous media, these outstanding challenges present exciting opportunities for future research and exploration.

6. Conclusions

In this review, pore-scale flow mechanism, capillary pressure characterization, and prediction model of capillary pressure for fractional-wet porous media are presented. The reviewed literature highlights the distinct nature of two-phase flow in fractional-wet pores compared to uniform-wet pores, where capillary pressure curves exhibit both positive and negative pressures. Moreover, the physics model demonstrates superior accuracy in predicting capillary pressure for fractional-wet porous media compared to empirical equations.

Two-phase mechanism within fractional-wet polygonal capillary contains oil layer flow, water flows from center to corners with positive and negative pressures, and water flow from corners to center with negative pressure. The main terminal meniscus with double curvatures are identified in fractional-wet circular capillary, which enriches our cognitions about two-phase mechanism. Importantly, capillary pressure behaviors of fractional-wet circular capillary overcome drawbacks of polygonal capillary. The above two-phase flows can be quantitatively described using MS-P theory.

The capillary pressures of fractional-wet porous media exhibits both positive and negative pressures, indicating drainage and imbibition are present at the same time. In both displacement processes, there are noticeable reductions in capillary pressures as the oil-wet proportion increases, causing the capillary pressure curves to gradually shift downward. Interestingly, it is observed that capillary pressure curves are similar under low oil-wet proportions during primary and secondary oil drainage processes with positive pressure. For prediction of capillary pressure, the physics model is more accurate than empirical equation, which is benefited from considering capillary pressure behaviors. Moreover, the physics model established on fractional-wet circular capillary is applicable to all ranges of wettability parameters through simple calculations.

Acknowledgements

The authors would like to thank the National Natural Science Foundation of China (No. 52074040), Natural Science Foundation of Sichuan Province (Nos. 2022NSFSC0205 and 2022NSFSC0189) and Open Found of State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation (Chengdu University of Technology) (No. PLC20210313) for financial support.

Conflict of interest

The authors declare no competing interest.

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