

# Review Snap-Off during Imbibition in Porous Media: Mechanisms, Influencing Factors, and Impacts

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Abstract: The phenomenon of snap-off during imbibition in porous media, a fundamental two-phase fluid flow phenomenon, plays a crucial role in both crude oil production and carbon dioxide (CO<sub>2</sub>) utilization and storage. In porous media where two phases coexist, the instability of the phase interface may give rise to various displacement phenomena, including pore-body filling, piston-like displacement, and snap-off. Snap-off, characterized by the generation of discrete liquid droplets or gas bubbles, assumes paramount significance. This study provides a comprehensive overview of snap-off mechanisms, influencing factors, and impacts. Snap-off initiation arises from variations in the curvature radius at the interface between two phases within narrow regions, primarily influenced by capillary pressure. It can be influenced by factors such as the characteristics of multiphase fluids, the wettability of porous media, as well as the pore-throat geometry and topology within porous media. In turn, snap-off exerts a discernible influence on the fluid dynamics within the porous medium, resulting in impacts that encompass unrecoverable oil droplet formation, the oil bridging effect, drainage-imbibition hysteresis, strong foam generation and transient/dynamic effects. Although the snap-off phenomenon exerts detrimental effects during the conventional waterflooding in oil production, its potential is harnessed for beneficial outcomes in CO<sub>2</sub>-EOR and CO<sub>2</sub> storage. This study significantly advances our understanding of snap-off and its multifaceted roles in multiphase fluid dynamics, offering vital insights for the precise prediction of fluid flow behavior and strategic control. These valuable insights can serve as a theoretical foundation to guide our deliberate modulation of snap-off phenomena, aiming at optimizing oil-recovery processes and enhancing the safety and stability of CO<sub>2</sub> storage.

Keywords: snap-off; multiphase fluid flow; imbibition; porous media; CO<sub>2</sub> utilization and storage

## 1. Introduction

Imbibition during oil reservoir exploration is a universally present and crucial process, where a nonwetting phase is displaced by a wetting phase within porous media [1–3]. Specially, when there are two immiscible liquids present within porous media, capillary forces drive the wetting phase to infiltrate, displacing the initial nonwetting phase. Imbibition, as a primary mechanism for displacing crude oil, plays a pivotal role, particularly in heterogeneous oil reservoirs [4–6] and heavy oil-recovery processes [3,7–9]. By influencing the flow and distribution of fluids, imbibition significantly impacts crude oil-recovery rates. The competition between viscous forces and capillary forces has been verified as the cause of imbibition [10–12]. In particular, capillary forces induced by surface tension promote the spontaneous movement of the wetting phase within narrow channels, while viscous forces determined by liquid viscosity and flow velocity hinder the flow of the nonwetting phase within pores. Under different types of porous media and fluid conditions, the relative magnitudes of capillary forces and viscous forces vary, thus affecting the efficiency and outcomes of the imbibition process [10,13,14]. This ultimately results in different characteristics of imbibition under various reservoir and rock conditions.



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Imbibition, with its distinct characteristics, can be further categorized into three categories: quasistatic imbibition, spontaneous imbibition, and dynamic forced imbibition. In quasistatic imbibition [15,16], the process involves promoting imbibition by gradually diminishing the impact of capillary forces. Specially, capillary forces are altered by adjusting external conditions or medium properties, thereby influencing the progression of imbibition. Spontaneous imbibition [1,4,13] is an outcome that occurs independently of external conditions. In this scenario, imbibition is propelled solely by the interaction of various forces within the medium, without any external interference. Dynamic forced imbibition [1,12] occurs when an external force is deliberately applied to inject a wetting phase into subsurface porous media, displacing the nonwetting phase. In this case, the imbibition process is significantly influenced by an external force. Due to differences in the flow direction, imbibition processes can be further classified into two categories: cocurrent imbibition and countercurrent imbibition. When cocurrent imbibition occurs, the nonwetting phase is displaced by the wetting phase, which flows in the same direction as it does [17,18]. Conversely, countercurrent imbibition occurs when the flow of the nonwetting phase within the porous media is the opposite the flow of the wetting phase [19-21]. These distinct types and flow directions of imbibition processes yield diverse effects on the ultimate oil recovery during practical oil reservoir exploitation.

In porous media where two phases coexist, the instability of the phase interface may give rise to various displacement phenomena during the imbibition process. Typical phenomena include piston-like displacement, pore–body filling, and snap-off. The imbibition process allows the wetting phase to efficiently ingress and continuously displace the nonwetting phase in porous media with wide-ranging continuous-flow pathways. This displacement results in the formation of a piston-like front that progressively advances along the flow pathways in porous media, and this phenomenon is known as piston-like displacement [22]. When small pores are present within porous media, the wetting phase can fully occupy these pores during imbibition, entirely displacing the nonwetting phase. This phenomenon is known as pore–body filling [23]. When porous media contain flow pathways characterized by intricate geometric configurations or narrow constrictions, localized fluid pinching may occur at these constrictions as the wetting phase penetrates to displace the nonwetting phase. Then, snap-off is the term for the phenomena when discrete small droplets are formed as a result of this pinching [24]. These three phenomena result from the interaction between the wetting phase and the nonwetting phase during the imbibition process, influenced by factors such as the geometric structure of the porous media, fluid properties, and flow conditions. Piston-like displacement and pore-body filling are generally regarded as beneficial for the crude oil-recovery process, since they effectively displace the nonwetting phase within porous media. On the contrary, snapoff, characterized by the generation of discrete small droplets that trap the nonwetting phase within narrow constrictions, poses challenges to achieve complete displacement. Consequently, it is generally regarded as unfavorable for conventional oil production.

In the context of imbibition processes within porous media, compared to piston-like displacement and pore–body filling, snap-off has a more pronounced impact [25] due to its association with distinctive challenges, including fluid retention, discontinuous flow, and reduced sweep efficiency. As a result, the study of snap-off is experiencing a growing trend, as researchers realize its substantial influence on both crude oil recovery and long-term reservoir capacity. Currently, there are several review articles that summarize research related to the snap-off phenomenon, with their main contents presented in Table 1. However, these review articles usually concentrated on a singular facet of the snap-off phenomenon, with few articles offering a systematic and comprehensive overview of various aspects associated with snap-off. To address the current lack of comprehensive literature on snap-off, this study undertakes a more thorough analysis and summary across four key perspectives: the mechanisms governing snap-off formation, the factors influencing snap-off, the impacts caused by snap-off, and the potential applications of snap-off under varying external conditions.

Authors	Content	Year	References
Liu et al.	This paper presents a review of the pore-scale dynamics associated with snap-off, highlighting that capillary-dominated immiscible displacement serves as the predominant mechanism governing the snap-off phenomenon.	2019	[26]
Zhou et al.	This paper provides a comprehensive review of snap-off-induced emulsions and their application in enhanced oil recovery, elucidating that snap-off represents the fundamental mechanism responsible for emulsion formation within porous media.	2019	[27]
Li et al.	This paper presents an in-depth review of residual water formation during the CO <sub>2</sub> storage process in deep saline aquifers, underscoring the pivotal and determining role that snap-off plays in shaping the CO <sub>2</sub> storage capacity.	2017	[28]
Hamza et al.	This paper offers an overview of the stability and performance of EOR foam, demonstrating snap-off as a critical mechanism for EOR foam generation.	2017	[29]
Diamantopoulos and Durner	This paper offers an overview of effective modeling approaches for assessing the impact of snap-off on dynamic imbibition at a macroscopic scale.	2012	[30]
Rossen	This paper provides a critical review on the applicability of the snap-off mechanism in generating foam at steady-state in homogeneous porous media.	2003	[31]

Table 1. Summary of literature reviews on snap-off.

This review was conducted through a series of steps, including literature collection, categorization, analysis, and summarization. The selection of target articles was carried out using 'snap-off' as a keyword in the Web of Science core database and the China Integrated Knowledge Resources System. This encompassed review and research articles published from 1960 to 2022. Subsequently, a thorough reading was performed to identify the various emphases of these articles on snap-off phenomena, classifying them based on mechanisms, influencing factors, impacts, and applications. Further, detailed analysis, subdivision, and summarization were carried out for the literature within each category. Based on this wealth of information, a comprehensive overview of relevant theories, experiments, and simulations of snap-off during imbibition is presented. Building on this framework, we further highlight the challenges currently faced in snap-off research and propose potential future research directions. This review study provides an expansive perspective for a deeper understanding of the snap-off phenomenon and reveals its critical role in multiphase fluid dynamics. These valuable insights can not only be utilized for the accurate predication of fluid behavior within porous media, but also serve as a theoretical foundation to guide our deliberate modulation of snap-off phenomena, with the aim of achieving specific objectives, such as enhancing crude oil recovery and improving the  $CO_2$  utilization and storage [32].

# 2. Mechanisms of Snap-Off

The occurrence of snap-off was initially noted during investigations of fluid transport within porous media in the early 1960s [24,33]. This phenomenon encompasses the snap-off of gas bubbles in the presence of water, as well as the snap-off of oil droplets in the context of oil–water coexistence.

Snap-off of gas bubbles was initially documented in 1961 within porous media where gas and water coexist [34]. Fried observed gas bubbles resulting from the snap-off phenomenon and proposed two processes for it: (1) Snap-off occurs when gas flows through a liquid-filled constriction, causing a new bubble to form. (2) When a long gas bubble transits through a liquid-filled constriction, snap-off ensues, resulting in the division of the long gas bubble into smaller gas bubbles. These two snap-off processes are illustrated in Figure 1. Subsequently, in 1962, Goldsmith and Mason observed and recorded bub-

bles generated through snap-off at the narrow gap of a cylindrical capillary [35]. They created an artificial narrow-gap structure by connecting capillaries with cross-sectional radii of 0.1 cm and 0.4 cm. Later, Mast [36] and Ransohoff et al. [37] conducted more comprehensive investigations into the snap-off phenomenon when both gas and water were present. Mast conducted experiments by using etched-glass micromodels, which featured a constricted section with a smaller cross-sectional area than the rest of the model. These models were saturated with a detergent solution, and gas was subsequently introduced to observe changes in the gas-liquid interface when both phases were present. The results of the experiments revealed notable changes in the gas-liquid interface at the constricted region, which caused gas bubbles to form. It is important to note that these bubbles could potentially become trapped at the constriction. Consequently, flow patterns were modified due to variations in the resistance to the flow in different directions through the porous network, subsequently affecting capillary resistance and resulting in the regeneration of smaller gas bubbles within the blocked constriction. Ransohoff et al. [37] focused on the gas-liquid interface changes within the cornered cross-sectional area of two-dimensional gas-saturated noncircular pores. Their finding indicates that the films of the wetting phase lining the straight sections were thin enough to be neglected in comparison to the flow in the corners. Furthermore, compared to the pores with circular cross-sections, the variation in the two-phase interface curvature within noncircular cross-sections had a larger extent, explaining the faster occurrence of gas bubble formation in noncircular cross-sectional pores. These studies illustrate that the presence of flow restrictions and capillary effects within porous media can lead to the division of gas phases and the occurrence of snap-off of gas bubbles through changes in the interface curvature and flow patterns.



**Figure 1.** Two typical snap-off processes. (**a**) Formation of a new gas bubble through snap-off. (**b**) Division of a long gas bubble into two smaller ones through snap-off.

Roof observed oil droplets formed through snap-off during waterflooding experiments in 1970 [24]. In this experiment, glass tubing with circular cross-sectional pore-throat structures was utilized to replicate the waterflooding process within water-wet media, and the snap-off phenomenon was observed, wherein oil was displaced from the channel walls by water, ultimately leading to the formation of discrete oil droplets. The glass tubing used in the experiment had undergone treatment with a hydrofluoric acid solution to render it water-wet. During this snap-off process, water formed a film that spread along the tube walls, displacing the oil phase to the center of the tube and forming a symmetrical collarshaped oil–water interface within the narrow constriction. The collar-shaped interface destabilized as water continued displacing oil, gradually reducing its diameter to zero and leading to the snap-off-induced small oil droplets. This visual experiment provided a comprehensive documentation of snap-off oil droplet formation. It emphasized that, as two-phase fluids flowed from wider tube sections into narrow constrictions, the curvature radius of the two-phase fluid interface underwent significant changes. At this juncture, the interfacial curvature exceeded that observed in other sections of the tubing system. Subsequently, Falls et al. [33] also observed a similar phenomenon in their experiments and proposed that the greater curvature of the two-phase interface at the narrow constriction would lead to higher capillary pressure at that location compared to other positions. Additionally, they noted that the thickness of the wetting-phase layer exceeded the intermolecular interaction distance, leading to the ingress of the wetting-phase fluid into the constriction. Within this region, the fluid accumulates and forms a collar-shaped interface. This collar-shaped interface continues to accumulate, becoming progressively unstable, and eventually detaches at the constriction, thereby giving rise to the snap-off phenomenon.

Based on these early experimental studies, the mechanisms underlying snap-off encompass variations in the curvature radius of the two-phase fluid interface within confined regions and the impact of capillary pressure. These mechanisms give rise to the instability of the collar-shaped interface of the two-phase fluids, ultimately resulting in the occurrence of the snap-off phenomenon within the narrow constriction.

In recent years, owing to advancements in manufacturing and visualization techniques, as well as the heightened computational capabilities, both experimental and numerical studies have further validated the snap-off formation mechanisms proposed earlier. Tables 2 and 3 provide summaries of representative experimental and numerical studies on snap-off, indicating their respective techniques, advantages, and disadvantages. Figures 2 and 3 present key findings from these research endeavors. Although the areas of emphasis in these studies may diverge, their consensus substantiates that the primary mechanism governing snap-off formation is capillary-pressure-driven, achieved through alterations in the two-phase interfacial curvature.

Authors	Category	Content	Advantages	Disadvantages	Year	References
Lebedeva and Fogden	Imaging technique	- This study employed the micro-CT imaging technique to investigate multiphase flow phenomena, such as snap-off and pore-body filling, in the context of saline waterflooding.	Precise 3D reconstructions of porous-medium structures without altering or causing damage to the specimen Suitable for quantitative analysis of a wide range of parameters	<ul> <li>Limited</li> <li>penetration depth</li> <li>Resource-intensive</li> <li>in terms of data</li> <li>processing and</li> <li>analysis</li> </ul>	2011	[38]
Singh et al.	Imaging technique	This paper provides a 3D dynamic visualization study of snap-off occurring during two-phase fluid flow, employing fast synchrotron X-ray microtomography.	Detailed 3D representations within porous media, facilitating the visualization and analysis of fluid flow phenomena inside the porous medium	<ul> <li>Time-consuming and costly</li> <li>Complex sample preparation</li> <li>Generates massive data volume, demanding significant computational resources</li> </ul>	2017	[39]

Table 2. Summary of representative experimental studies on snap-off.

Table 2.	Cont.
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Authors	Category	Content	Advantages	Disadvantages	Year	References
Tian et al.	Fabrication technique	- This study employed a standard lithography process and hydrofluoric (HF) acid etching to fabricate a glass microfluidic device to investigate the dynamic gas snap-off mechanisms under the capillary dominant flow regime in 2D micro channels.	Characterized by transparency, making it conducive for - real-time observation under a microscope Characterized by a relatively high strength and hardness, along with heat resistance, making it suitable for high-temperature and high-pressure experiments	<ul> <li>Geometric constraints caused by 2D microfluidic models</li> <li>Finite manufacturing precision limits precise resolution for simulating finer microscale pore structures</li> </ul>	2020	[40]
Li et al.	Fabrication technique	This paper employed soft lithography manufacturing techniques to fabricate a polydimethylsiloxane (PDMS) microfluidic platform for studying the dynamic snap-off process of droplets in short constrictions.	Characterized by transparency, making it conducive for real-time observation under a microscope Low time and economic costs for design and manufacturing	<ul> <li>Finite         <ul> <li>manufacturing             precision limits             precise resolution             for simulating finer             microscale pore             structures</li> <li>PDMS microfluidic             models have             limited pressure             resistance, making             them unsuitable for             conducting             high-pressure             experiments</li> </ul> </li> </ul>	2021	[41]
Liu et al.	Fabrication technique	This study employed the femtosecond pulsed-laser direct-writing technique to fabricate 3D microfluidic models with triangular cross-sections for the investigation of snap-off-induced emulsions in low-salinity waterflooding.	3D micromodels enable more realistic complex porous-medium structures.	<ul> <li>High equipment costs for femtosecond pulsed-laser direct-writing equipment</li> <li>Complex operation for laser microfabrication</li> </ul>	2021	[42]

Author	Category	Content	Advantages	Disadvantages	Year	References
Bandara et al.	Direct numerical simulations (DNS)	This paper utilizes a smoothed particle hydrodynamics (SPH) model for simulating pore-scale displacement and elucidating the capillary-trapping mechanisms of supercritical CO <sub>2</sub> . It illustrates that snap-off is the predominant displacement behavior under capillary-dominant conditions.	<ul> <li>Removes the need for distributing integration points in intricate pore spaces, reducing computational expenses and enhancing efficiency</li> <li>Comprehensive parameter space sampling enhances predictability and replicability</li> </ul>	<ul> <li>Limited time-stepping stability criteria</li> <li>Difficulties in imposing accurate boundary conditions</li> <li>Additional stability criteria for specific issues</li> </ul>	2011	[43]
Starnoni and Pokrajac	Direct numerical simulations (DNS)	This study employed the volume-of-fluid (VOF) method and developed a computational fluid dynamics (CFD) code to numerically simulate snap-off phenomena within pore-throat constrictions characterized by varying cross-sectional geometries.	<ul> <li>Precision in characterizing the pore structures</li> <li>No mass conservation problems</li> </ul>	<ul> <li>Interfacial property calculation involves approximations, leading to a reduction in accuracy</li> <li>Requires substantial computational resources</li> </ul>	2018	[44]
Zhou et al.	Direct numerical simulations (DNS)	This study elucidates the formation process of snap-off-induced emulsion using a ternary Lattice–Boltzmann method (LBM), which models the streaming of fluids in space.	<ul> <li>An uncomplicated algorithm grounded in a statistical equation that characterizes the movement and interaction of fluid molecules</li> <li>No discretization technique is required; avoids truncation errors</li> <li>Precision in representing intricate pore structures and complex topologies</li> </ul>	<ul> <li>Requires substantial computational resources</li> <li>Fluid viscosity greatly influences the behavior of the LBM method</li> </ul>	2019	[27]

 Table 3. Summary of representative numerical studies on snap-off.

		Table 3. Cont.				
Author	Category	Content	Advantages	Disadvantages	Year	References
Kohanpur et al.	Pore space geometrical idealization	This study employs pore–network modeling (PNM) to predict the trapping of CO <sub>2</sub> bubbles induced by snap-off.	<ul> <li>The multiphase algorithms are simplified</li> <li>High computational efficiency for modeling large domains</li> </ul>	<ul> <li>Geometrical simplifications lead to a loss of detailed geometrical and topological information</li> <li>Inaccurate in the unconventional reservoirs with both fracture networks and micropores</li> </ul>	2021	[45]



**Figure 2.** Typical instances of experimental studies on snap-off. (a) Observation of snap-off phenomena in core samples using the micro-CT imaging technique, reprinted from Ref. [38]; (b) Threedimensional visualization of snap-off occurring during two-phase fluid flow by employing the fast synchrotron X-ray microtomography technique. (i) to (viii) show the oil-water interface veration within the porous media over time reprinted from Ref. [39]; (c) Gas snap-off in a 2D glass microchannel. (i–iv) demonstrate the changes in the gas-water interface during the gas bubble snap-off formation, reprinted from Ref. [40]; (d) Generation of two daughter droplets through the snap-off mechanism in a PDMS microfluidic device. (i) and (ii) show the real-time experimental observation of daughter droplet formation through snap-off, while (iii) and (iv) are the schematic diagrams for parameter analysis, reprinted from Ref. [41]; (e) Snap-off-induced emulsions in a 3D pore-throat micromodel with triangular cross-sections, reprinted from Ref. [42].

Moreover, when comparing early investigations dating back to the 1960s with recent research endeavors, it is evident that experimental snap-off research has undergone a substantial shift as due to improvements in manufacturing and visualization techniques. This evolution has transitioned the paradigm from employing centimeter-scale experimental models to adopting micron-scale platforms. Consequently, these advancements have contributed to experimental investigations that better emulate real-world scenarios. In the realm of numerical investigations on snap-off, the ever-increasing computational capabilities and ongoing refinements in relevant algorithms have collectively led to increasingly accurate and detailed microscale simulations. These simulations are tailored to represent multiphase flow within porous media, all within more confined temporal and spatial dimensions. This precision in microscale simulations enhances the realism and applicability of the findings.



**Figure 3.** Typical instances of numerical studies on snap-off. (a) SPH modeling for snap-off formation, reprinted from Ref. [43]; (b) Simulation of snap-off formation within pore-throat constrictions using VOF combined with CFD, reprinted from Ref. [44]; (c) Simulation of snap-off-induced emulsion using a ternary LBM, reprinted from Ref. [27]; (d) Illustration of two pore-network models: the sphere pack model with (a1) a sphere pack, (a2) pore body and throat network, and (a3) connectivity of the throat-corner network, and a cubic model with (b1) a longitudinal section of pore elements and (b2) a cross-section of the throat, reprinted from Ref. [46]; (e) Pore-network modeling for  $CO_2$  trapping, with isolated  $CO_2$  bubbles generated by snap-off, reprinted from Ref. [45].

## 3. Influencing Factors of Snap-Off

The aforementioned studies on the snap-off mechanism indicate that the occurrence of snap-off involves the influence of specific factors, which is ultimately manifested visually through changes in the curvature radius of the two-phase fluid interface within narrow regions and the influence of capillary pressure. The interface curvature radius stands as a fundamental property parameter governing the interfaces between distinct phases, symbolizing the degree of curvature induced by interphase interactions. Capillary pressure signifies the difference in pressure between the wetting and nonwetting phases. Notably, the interface curvature radius and capillary pressure, both pivotal parameters within the snap-off mechanism, can be directly correlated through the Young–Laplace equation [47,48], presented as Equation (1), where  $r_1$  and  $r_2$  represent the principal radii of curvature (one along horizontal axis and vertical axis),  $P_i$  and  $P_j$  denote the pressures of the phases on either side of the interface, and  $\sigma_{ij}$  signifies the interfacial tension.

$$P_c = P_i - P_j = \sigma_{ij} \left( \frac{1}{r_1} + \frac{1}{r_2} \right) \tag{1}$$

In this context, interfacial tension is primarily governed by the properties of the two-phase fluids. Furthermore, the variation in the curvature radius of the interface is elucidated through the consideration of the two principal radii of curvature. While the curvature radius serves as a scalar value characterizing the mean curvature of the interface, the principal radii of curvature provide a more nuanced depiction of the local curvature in two mutually perpendicular directions. It is noteworthy that the radii of curvature of the interface are influenced not only by the intrinsic properties of the two-phase fluids but also by the intricate interplay with the attributes of porous media through which the fluid traverses, encompassing factors like wettability and geometric properties. Therefore, in this section, this study provides an overview of typical factors that can exert an influence on the snap-off phenomenon. These factors include the characteristics of multiphase fluids, the wettability of porous media, as well as pore-throat geometry and topology within porous media.

#### 3.1. Characteristics of Multiphase Fluids

#### 3.1.1. Capillary Number

The capillary number (Ca) is a dimensionless number used to describe the flow behavior of fluids within capillaries or small channels [49,50]. It is defined as Equation (2), where  $\mu$  represents the viscosity of the continuous phase or the wetting phase in the two-phase fluid, *V* signifies the characteristic shear rate (a product of shear rate and droplet radius), and  $\sigma_{ij}$  stands for the interfacial tension between the continuous (wetting) and dispersed (nonwetting) phases.

$$Ca = \mu V / \sigma_{ij} \tag{2}$$

The capillary number represents the relative effect of viscous force to interfacial tension force in fluids and holds particular significance in multiphase flows [51]. Its magnitude influences fluid behavior under various flow conditions and is commonly employed to describe liquid flow and interface phenomena, including snap-off, within porous media. Regarding the snap-off event, viscous forces are typically observed to be the driving force, whereas interfacial tension forces are the resisting force [52]. This implies that a higher capillary number amplifies the influence of viscous forces in the continuous phase (wetting phase), facilitating the stretching and deformation of the dispersed phase. Consequently, this promotes the rapid formation of smaller-sized droplets during snap-off. Conversely, a lower capillary number accentuates the role of interfacial tension forces between the two phases, making it more challenging for the dispersed phase (nonwetting phase) to stretch and deform. Consequently, this hinders the occurrence of snap-off, impedes droplet detachment, and leads to the formation of larger-sized droplets [52].

The snap-off phenomenon occurs within a specific range of capillary numbers [41,53]. Tsai and Miksis investigated how snap-off was affected by the capillary number [54]. Using simulation methods, they determined two critical values of the capillary number that indicate when snap-off occurs. When the capillary number falls below the first critical value, a thin layer of wetting-phase film forms on the wall of the porous media, and the liquid flows slowly toward the narrow constriction. In such a scenario, the snap-off phenomenon

can still occur, but requires a longer time to manifest. If the actual capillary number falls within the range defined by the first and second critical values, snap-off can occur more rapidly. When the capillary number is higher than the second critical threshold, the liquid spends very little time in the constriction, which is insufficient for the snap-off phenomenon to take place. Additionally, further investigation into the connection between the capillary number and snap-off formation time was carried out by Ransohoff et al. [55] and Mohanty et al. [56]. They established a specific functional correlation between these two parameters. In their experimental studies, they introduced a transition capillary number, which they compared to the actual capillary number. When the actual capillary number exceeded this transitional value, the formation time of snap-off remained unaffected by variations in the capillary number. However, when the actual capillary number was below this transitional threshold, the formation time of snap-off demonstrated a direct proportionality to the capillary number. Deng et al. [57] utilized the BD model [58] to investigate the impact of dynamic factors on snap-off in constricted capillary tubes and calculated the required time for snap-off. This model is based on the volume conservation of fluid flow and the lubrication approximation for describing the velocity profile. Their research findings reveal an explicit relationship between the time needed for snap-off occurring and the capillary number in constricted tubes, as illustrated in Figure 4.



**Figure 4.** Relationship between the capillary number and snap-off time using the BD model. (a) Schematic representation of the single-pore geometry in the simulation; (b) Corresponding required snap-off formation time at different capillary numbers. (i–iii) demonstrate the inhibition of snap-off occurrence with capillary numbers of 0.0006, 0.001 and 0.0019, respectively, reprinted from Ref. [57].

#### 3.1.2. Viscosity Ratio

Viscosity is a fundamental property of fluids, quantifying internal resistance within fluids, and it plays a pivotal role in fluid dynamics. Particularly, in scenarios involving the coexistence of multiphase fluids, viscosity not only directly influences fluid flow behaviors, such as velocity distribution and velocity profiles, but also has an effect on factors at the interfaces of these phases. These factors encompass interfacial tension, curvature, inertial forces, and cohesion. The magnitude of the disparity in viscosity between the wetting and nonwetting phases within a medium intensifies the impacts on the interfaces between these phases.

When both wetting and nonwetting phases coexist within a porous medium, their viscosity ratio, denoted as the wetting–nonwetting viscosity ratio  $\gamma = \mu_w / \mu_{nw}$ , can be em-

ployed to analyze the fluid dynamics of these two-phase systems. It has been proved that the volume of droplets formed through snap-off increases when the wetting-nonwetting viscosity ratio decreases [59]. This is because a decrease in the wetting-nonwetting viscosity ratio signifies a relative rise in the sheared nonwetting phase's viscosity. Consequently, the wetting phase requires a greater generation of shear forces to counteract the resistance exerted by the nonwetting phase, characterized by higher viscosity. This implies that a lower viscosity ratio hinders the separation of nonwetting-phase droplets from the continuous wetting phase, making the interfacial alterations for snap-off more challenging and leading to larger droplet volumes. Notably, Pena et al. conducted experimental investigations to elucidate that, when the wetting–nonwetting viscosity ratio becomes sufficiently low ( $\gamma < 0.0175$ ), with the nonwetting phase having a noticeably higher viscosity than the wetting phase, the nonwetting phase becomes impervious to shearing by the wetting phase [53]. This makes it nearly impossible to achieve the interfacial force balance conditions required for snap-off droplet formation, thereby preventing the snap-off phenomenon over any capillary number range, as shown in Figure 5. In essence, variations in the viscosity ratio exert a direct influence on the interactions between the wetting and nonwetting phases, profoundly affecting the occurrence of snap-off and the ensuing behaviors at their interfaces.



**Figure 5.** Snap-off emulsion in a constricted capillary. (a) Collar structure variations during snap-off formation; (b) Map of viscosity ratio and capillary number conditions for snap-off formation, reprinted from Ref. [53].

## 3.1.3. Flow Rate Ratio

The flow rate ratio, which represents the ratio of flow rates between the wetting and nonwetting phases, significantly influence the size, quantity, distribution, and stability of droplets formed during the snap-off process [59]. Generally, a rise in the flow rate ratio results in snap-off droplets with smaller dimensions, a higher quantity of droplets, uneven spatial distribution, and reduced stability. In contrast, a decrease in the flow rate ratio leads to snap-off droplets with larger dimensions, a lower quantity of droplets, uniform distribution, and enhanced stability. The reason for these observed outcomes is the direct effect of the flow rate ratio on the capillary and inertial forces acting at the interface of the two phases. An increased flow rate ratio enhances capillary forces, facilitating the formation of smaller-volume droplets, while simultaneously reducing inertial forces, which, in turn, challenge droplet stability.

However, it is worth noting that, when different fluids are utilized, although the trends in the influence of the flow rate ratio on snap-off remain consistent, the underlying mechanisms may exhibit slight variations. Herring et al. comprehensively investigated the influence of flow rate on snap-off within specific ranges of capillary numbers and viscosity ratios [60]. They utilized the same wetting phase (brine) but employed two different nonwetting phases (n-decane liquid and air). In the case of n-decane liquid serving as the nonwetting phase, a decrease in the flow rate ratio, with a constant brine flow rate but a high-n-decane flow rate, primarily resulted in an enlargement of the n-decane droplets. This outcome can primarily be attributed to the ability of high-flow-rate n-decane to infiltrate smaller pore throats, facilitating the creation of larger and more interconnected droplets.

On the other hand, when air is employed as the nonwetting phase, a reduction in the flow rate ratio, with a constant brine flow rate but a high air flow rate, allows air to infiltrate relatively smaller pore throats to form larger bubbles. This outcome resembles the result observed with n-decane as the nonwetting phase. However, several factors contribute to the heightened levels of snap-off in this scenario. These factors include the high compressibility and low viscosity of the air, along with the stronger water-wet conditions between the air and brine within the porous medium [60]. Therefore, when evaluating the specific impact of the flow rate ratio on snap-off, it becomes imperative to comprehensively consider multiple factors, including the capillary number, fluid viscosity, compressibility, and the wetting properties of both the medium and the fluid.

## 3.2. Wettability of Porous Media

Wettability, as an intrinsic property of porous media, assumes a crucial role in fluid flow processes. It serves as a parameter to assess the relative affinity of two-phase fluids for the surfaces of porous media, exerting a decisive influence on fluid distribution, arrangement, and migration within such media [59,61,62]. In the context of oil and gas reservoir exploration, it is customary to conduct wettability measurements on the porous rocks of reservoirs [63,64]. These measurements aid in predicting the oil and water distribution, optimizing recovery techniques, and maximizing production yields.

Numerous studies have substantiated the profound influence of porous-media wettability on the snap-off phenomenon [65–67]. In the context of typical water-wet oil reservoirs, characterized by a porous medium with a contact angle less than 70°, distinct behaviors emerge during the imbibition process as water displaces oil [66]. In this scenario, water, acting as the wetting phase, readily infiltrates the pores, swiftly occupying their interiors and forming a continuous wetting-phase film along the pore walls. In contrast, oil, the nonwetting phase, experiences repulsion from the pore walls, leading to its accumulation in the pore centers, distanced from the walls. The fluid distribution within the medium is driven by the pursuit of minimizing the interfacial energy, ultimately seeking a stable equilibrium within the system [68,69]. Consequently, hydrophilic porous media promote the aggregation of water around oil, manifesting as snap-off droplets. This reduces the contact between oil and the medium, ultimately achieving a state of minimal interfacial energy within the fluid-medium system [24]. Furthermore, in water-wet media, heightened hydrophilicity characterized by a smaller contact angle approaching zero augments the likelihood of snap-off phenomenon occurrence, thereby facilitating the formation of oil droplets.

On the contrary, regarding oil–wet porous media, the oil phase assumes the role of the wetting phase, while water becomes the nonwetting phase. Consequently, snap-off phenomena can still occur, but they result in water droplets. In porous media with intermediate wettability, where the contact angles are approximately 90°, a state of relatively balanced affinity between the two-phase fluids and the surface of the medium is observed. This equilibrium implies that neither phase (e.g., water and oil) exhibits a strong inclination to preferentially adhere to nor wet the solid surfaces within the porous medium. In such conditions of intermediate wettability, the occurrence of snap-off phenomena is significantly reduced [70]. However, it is essential to recognize that intermediate wettability of the media, while reducing the occurrence of pronounced snap-off phenomena, results in a more even distribution of oil and water within such media. This, in turn, can lead to less-efficient displacement of crude oil.

#### 3.3. Pore–Throat Geometry and Topology

Real-world porous media typically exhibit intricate pore structures and diverse shapes, encompassing a broad spectrum of pore sizes and forms. Frequently, the actual geometry proves more complex than any idealized representations, especially in heterogeneous porous media. The dimensions and configurations of individual pores, as well as their interconnection and arrangement, wield substantial influence over fluid flow, transport phenomena, and various other properties within these porous media.

## 3.3.1. Cross-Sectional Shape

In contemporary research focused on multiphase fluid flow within porous media, it is a prevailing practice to reasonably simplify the geometry and topology of these pore structures [12,71–73]. Drawing from typical rock core samples obtained from oil reservoirs, the topology of the porous medium is frequently simplified into regular patterns, as illustrated in Figure 6. Consequently, the cross-sectional shapes of the reservoir pores are simplified into circles, rectangles (including squares), and triangles [12].



**Figure 6.** Schematic representation of cross-sectional pore and throat structures simplified based on porous media topology.

Early investigations of snap-off phenomena usually employed glass tubes with circular cross-sections as representative flow media [74–78]. Circular shapes, due to their relatively simple geometry, were convenient for construction. Additionally, the predictability and ease of modeling fluid flow through pores with circular cross-sections made them a popular choice in related studies. However, it is essential to acknowledge that such geometries may not fully capture the intricacies of irregularly shaped pores. With advancements in manufacturing techniques, structures with angular profiles, featuring rectangular and triangular cross-sections derived from the arrangement of irregular grains or particles commonly encountered in real porous media, have gained prominence in snap-off research.

Noncircular cross-sections can have various effects on fluid flow and interface behavior compared to simple circular cross-sections, primarily due to factors like the corner effect and shape-dependent surface tension. Experimental observations have demonstrated that the snap-off process occurs more rapidly in channels with noncircular cross-sections when compared to circular cross-sections [79]. This outcome is attributed to reduced flow resistance within the noncircular channels, primarily due to the presence of corners. This corner effect, by reducing resistance, facilitates higher flow rates of the continuous wetting phase [79], thereby promoting the snap-off process.

Besides the corner effect, noncircular cross-sections can induce shape-dependent surface tension, which, in turn, affects the capillary pressure within porous media accommodating two-phase fluids due to the presence of more complex interfaces in such noncircular geometries. These interfaces comprise two distinct types: the main terminal meniscus (MTM) and arc menisci (AMs). The MTM, which divides wetting and nonwetting phases in the center of the pore and throat, represents the invading meniscus located at the pores and throats. It constitutes the primary curvature between the two phases and is present in both circular and noncircular cross-sectional geometries. In contrast, the AMs are interfaces that only exists in noncircular cross-sections, typically occurring at the corners of such geometries, and they are considered secondary curvatures [80]. The presence and characteristics of the AMs heavily depend on the specific angular geometry of the noncircular cross-section. Figure 7 provides a schematic representation of both the MTM and AMs for various cross-sectional shapes. Consequently, the formula for calculating capillary pressure, as depicted in Equation (1), can be tailored for different cross-sectional shapes, taking into account the contributions of the MTM and AMs.



**Figure 7.** Schematic of the MTM and AMs for different cross-sectional shapes. (**a**) In the pore with a circular cross-section, only the MTM is present in the side view, and the AM is absent in the cross-section. (**b**) In the pore featuring a rectangular cross-section, the MTM is present in the side view, and four AMs are present in the cross-section. (**c**) In the pore featuring a triangular cross-section, the MTM is present in the side view, and three AMs are present in the cross-section.

In the case of circular cross-sections, the principal radii of curvature ( $r_1$  and  $r_2$ ) represent the distances from the center of the circle to any point on the boundary along two perpendicular directions. In circular interfaces, all points on the boundary are equidistant from the center, making  $r_1 = r_2 = r$ , where r is the radius of the circular interface. Additionally, r can be further expressed as  $r = R/cos\theta$ , where R represents the radius of the circular tube,  $\sigma_{ij}$  signifies the interfacial tension, and  $\theta$  denotes the contact angle. Therefore, Equation (1) can be simplified as shown in Equation (3),

$$P_c = \sigma_{ij} \left(\frac{1}{r_1} + \frac{1}{r_2}\right) = \frac{2\sigma_{ij}}{r_1} = \frac{2\sigma_{ij}}{r_2} = \frac{2\sigma_{ij}}{r} = \frac{2\sigma_{ij}}{R} \cos\theta$$
(3)

In the case of noncircular cross-sections, the interface between the two-phase fluids becomes more complex. The curvature of the interface is assumed to be negligible in the plane perpendicular to that of the paper, which implies that the principal radii of curvature would be  $r_1 = r$  and  $r_2 = \infty$  [80]. Under these circumstances, the capillary pressure across the interface can be simplified using Equation (4), where the specific value of r is closely related to the characteristics of the MTM and AMs in different noncircular cross-sections. In

other words, the MTM and AMs exhibit distinct characteristics in various noncircular crosssections, and the specific values of the capillary pressure for two-phase fluids in different noncircular cross-sections can be further calculated in detail using the MS-P theory [80–82] and the formulas introduced by Ma et al. for the curvature and radius variation calculations of the MTM and AMs [83].

$$P_c = \sigma_{ij} \left( \frac{1}{r_1} + \frac{1}{r_2} \right) = \sigma_{ij} \left( \frac{1}{r} + \frac{1}{\infty} \right) = \frac{\sigma_{ij}}{r}$$
(4)

The MS-P method is based on equating the pressure difference across the AMs at the capillary tube's corners to that of the MTM [80]. In conjunction with a multiphase system at a constant temperature, the Helmholtz free energy (F) can be expressed as:

$$F = F_i + F_j + F_{interface} \tag{5}$$

Here, for the bulk phase *i* and *j*, there are  $dF_i = -P_i dV_i$ ,  $dF_j = -P_j dV_j$ , and  $dF_{interface} = -\sigma_{ij} dA_{ij}$ . Equation (5) can be further represented as Equation (6):

$$dF = -\sum_{i=1}^{j=n} P_i dV_i + \sum_{ij=12,13\dots,23,24\dots}^{n!/2(n-2)!} \sigma_{ij} dA_{ij}$$
(6)

In a system with constant temperature and constant total volume, equilibrium is achieved when the Helmholtz free energy *F* reaches its minimum value, which is represented as

d

$$F = 0 \tag{7}$$

Combining Equations (6) and (7), for a noncircular cross-section containing two phases, water and oil, there is

$$-\sum_{i=1}^{2} P_{i} dV_{i} + \sum_{ij}^{ws, os, wo} \sigma_{ij} dA_{ij} = 0$$
(8)

By incorporating the geometric relationships [80] among water, oil, and the soil surface (Equation (9)) into Equation (8), the final expression for the capillary pressure in a noncircular cross-section [80] is derived as Equation (10),

$$\sigma_{os} - \sigma_{ws} = \sigma_{ow} \cos\theta \tag{9}$$

$$P_c = \frac{\sigma_{ow}[L_{ow}^n + L_{os}^n \cos\theta_{ow}]}{A_o^n} \tag{10}$$

where  $\sigma_{ow}$  represents the interfacial tension between water and oil,  $L_{ow}^n$  is contact line between water and oil after displacement,  $L_{os}^n$  is contact line between the oil and solid surface after displacement,  $\theta_{ow}$  denotes contact angle of water on the reservoir porous medium, and  $A_o^n$  is the contact area of the oil on the solid surface.

Upon comparing Equations (3) and (10), it becomes evident that the determination of the capillary pressure involved in the two-phase fluids within porous media featuring circular cross-sections is relatively straightforward, requiring the interfacial tension, contact angle, and pore cross-section radius. However, in porous media characterized with angular cross-sectional structures, determining the capillary pressure becomes notably intricate. It involves considerations of the interfacial tension, contact angle, and contact status of water–oil–solid surface (encompassing the water–oil contact line, oil–solid surface contact area). Notably, irrespective of whether the pore geometry features a circular or noncircular cross-section, the capillary pressure exhibits a dependence on the contact angle, which is dictated by wettability. This observation signifies that changes in the wettability can induce alterations in the capillary pressure as the primary mechanism governing snap-off formation, it is possible to exercise control over the variations in the capillary pressure to determine the distribution of fluids. This can be accomplished by

manipulating the cross-sectional shapes of pore structures or adjusting wettability within any pore geometry, thereby exerting influence over the occurrence of snap-off.

## 3.3.2. Pore–Throat Connection

Porous media fundamentally consist of network systems composed of relatively largervolume pores interconnected by smaller-volume throats or constrictions. This structural connectivity not only delineates porous media but also significantly influences fluid flow phenomena within them, particularly in multiphase flow scenarios.

In the context of pore-throat systems, the occurrence of snap-off phenomena is influenced by the geometric configuration of the pore-throat, specifically the ratio of the throat length to the pore diameter, abbreviated as the length-to-diameter ratio. Yao et al. conducted experiments using microfluidic pore-throat systems in which they systematically varied the length-to-diameter ratio during oil-water imbibition experiments to analyze the impact of pore-throat connections on snap-off phenomena [12,52,71,84]. The experimental results demonstrated that, under different length-to-diameter ratios, distinct displacement behaviors occurred, as depicted in Figure 8. Specifically, when the length-to-diameter ratio was less than  $\pi$ , piston-like displacement dominated as the primary mode during imbibition. Despite the nonwetting phase still being located at the pore-throat center due to wettability effects, it collectively moved forward as it was displaced by the wetting phase. Conversely, when the length-to-diameter ratio equaled or exceeded  $\pi$ , the snap-off phenomenon became nearly inevitable. This implies that the geometric dimensions of the pore-throat can reliably serve as a determinant for evaluating the likelihood of snap-off occurrence. These research findings align with the Rayleigh–Plateau instability theory [85,86], which posits that a liquid column, subject to the influence of interfacial tension, undergoes fragmentation due to interface instability when its length approaches approximately 3.13 to 3.18 times its diameter, approximating the value of  $\pi$ . This experimental validation, to a considerable extent, supports the applicability of the Rayleigh–Plateau instability theory in understanding the formation of snap-off phenomena within the pore-throat system. It also underscores the direct influence of pore-throat geometric characteristics on snap-off occurrences. Moreover, it is noteworthy that for porous media with noncircular cross-sections, the hydraulic diameter [37,87] can serve as a suitable proxy for the diameter when applying the Rayleigh–Plateau instability theory to assess the potential for snap-off.

After confirming the possibility of snap-off occurrence through the Rayleigh–Plateau instability theory, the volume and position of the resulting snap-off bubble or droplet can be determined based on the aspect ratio, which is defined as the ratio of the throat length to the throat width [52]. Regarding the volume of the snap-off droplet, when the throat width remains constant, the volume decreases as the aspect ratio increases. In terms of the location where the snap-off droplet forms, when the aspect ratio exceeds 1, the resulting droplet forms within the throat. Conversely, when the aspect ratio is less than 0.75, the snap-off droplet forms in the wider pore region after passing through the throat. When the aspect ratio falls within the range of 0.75 to 1, both of these scenarios may occur [52]. Compared to larger droplets formed in narrow structures, smaller droplets or those formed in wider pore locations exhibit improved flow characteristics.

The studies underscore the significant impact of pore-throat connections within porous media on snap-off phenomena. The geometric ratios of these pore-throat connections can dictate the probability of snap-off events, and the geometrical proportions within the throat regions directly affect the size and position of snap-off droplets. Therefore, adjusting the geometry of pore-throat connections provides a method for controlling snap-off phenomena.



**Figure 8.** Two-phase flow behaviors within pore–throat connections with different length-to-diameter ratios. (a) Piston-like displacement at the length-to-diameter ratio of 2.22. (b) Snap-off at the length-to-diameter ratio of 3.44.

It is important to note that there are significant differences between laboratory studies and real-field scenarios, particularly when it comes to parameters that influence the occurrence of snap-off events. Laboratory studies are typically conducted in controlled environments, employing idealized conditions to investigate snap-off and other multiphase flow phenomena, thereby simplifying complexity. However, real-reservoir conditions are typically more intricate and variable. For example, in laboratory studies, capillary tubes and glass or PDMS microfluidic devices with uniform and consistent surface properties are usually used as platforms for studying multiphase flow processes, allowing for the controlled wettability of porous media. Nevertheless, in real reservoirs, factors such as the surface roughness of rocks, variations in the cementation between rocks, and other complexities can lead to nonuniform or inconsistent wetting properties within the porous media. Such complexity cannot be entirely replicated in laboratory experiments. Furthermore, in real reservoirs, interactions occur not only between oil and water but also between oil and rocks, as well as between water/brine and rocks. These interactions can significantly impact various properties, including fluid composition, pH, rock composition, wettability, fluidinterface charges, as well as the overall porosity and permeability of the reservoir. This further complicates the multiphase fluid processes in real-field scenarios. Therefore, while laboratory research plays a crucial role in providing theoretical and foundational support, its application to real reservoirs requires comprehensive consideration of various factors and complex conditions to better understand and predict snap-off phenomena accurately.

## 4. Impacts of Snap-Off

The snap-off phenomenon, arising from the flow of two-phase fluids within porous media, subsequently exerts a discernible influence on fluid dynamics within the porous medium [88]. These impacts primarily encompass the unrecoverable oil droplet formation, oil bridging effect, drainage–imbibition hysteresis, and strong foam generation.

#### 4.1. Unrecoverable Oil Droplet Formation

Unrecoverable oil droplets represent a direct outcome of the snap-off phenomenon, and they play a pivotal role in shaping the microscopic distribution of the remaining oil within porous media in reservoirs [76,89]. In the context of reservoir exploitation, water-flooding stands as a prevalent method. During waterflooding operations, the nonwetting phase, typically crude oil, undergoes displacement by the wetting phase, which is water. Within this process, snap-off events may transpire. To elaborate, when crude oil is displaced to the central region of pore throats and gradually dislodged from the pore walls by the advancing wetting phase, snap-off occurrences lead to the formation of oil droplets. These oil droplets become entrapped within the pores, rendering them immobile and resistant to further displacement, hence the designation unrecoverable oil droplets. The impact of these unrecoverable oil droplets on crude oil production is substantial [90]. Due to their inability to be effectively recovered, they persist as residual oil within the reservoir, ultimately reducing the actual volume of crude oil that can be produced and diminishing the recovery rate, thereby impinging on the efficiency of reservoir exploitation.

## 4.2. Oil Bridging Effect

The oil bridging effect [76,91] represents a significant potential outcome of snapoff phenomena, particularly noteworthy in heterogeneous reservoirs characterized by a diverse range of pore sizes and geometries. This effect arises from the intricate interplay between snap-off events and the inherent properties of such heterogeneous porous media. It results in the entrapment of nonwetting-phase droplets within pore throats, giving rise to bridging-like structures or obstructions [92,93], rather than spherical shapes.

In these heterogeneous oil reservoirs, significant disparities exist in the dimensions of pores and throats, manifesting substantial differences in their interactions with fluids. Larger pores, characterized by their expansive cross-sectional areas and lower hydraulic resistance, tend to facilitate fluid flow, resulting in heightened fluid-pore interactions and consequential alterations in surface properties, particularly wettability. Conversely, smaller throats, characterized by their reduced cross-sectional areas and higher hydraulic resistance, impede fluid flow, maintaining their inherent wettability with limited fluid interactions. In instances where larger pores with significantly modified wettability are interconnected with smaller throats exhibiting unaltered wettability, forming integrated pore-throat systems, the formation of snap-off-induced droplets leads to distinct interfacial tension at interfaces near pore surfaces and those adjacent to throat surfaces. This variance in interfacial tensions results in droplet deformation, ultimately culminating in the formation of bridge-like structures. Additionally, the substantial dissimilarities in shape between the larger pores and throats cause considerable variations in local pressure and saturation within the porous medium. These disparities can lead to variations in the stability of nonwetting-phase droplets at different locations, thereby facilitating the formation of bridge-like structures.

These bridge-like obstructions impede the subsequent progression of the wetting phase through the porous media, leading to a significant reduction in fluid flow efficiency by disrupting continuous flow. Furthermore, the decreased reservoir connectivity, caused by these bridge-like structures, diminishes the effective permeability of the porous media, ultimately adversely impacting the final oil-recovery rates.

#### 4.3. Drainage–Imbibition Hysteresis

Snap-off serves as the fundamental cause of drainage–imbibition hysteresis [78,94,95], a phenomenon characterized by distinct variations in flow dynamics during drainage (the expulsion of liquid from pores) and imbibition (the infiltration of liquid into pores) processes within porous media.

This hysteresis can significantly influence fluid behaviors and flow mechanisms in such media, most notably evident in the nonalignment of relative permeability curves for the wetting phase during drainage and imbibition processes [49,96]. During drainage, the relative permeability of the wetting phase is higher, indicating relatively easier pore occu-

pancy. However, in the imbibition process, particularly in porous media with nonuniform pore structure or microscale heterogeneity [97], the relative permeability of the wetting phase decreases, indicating the challenges for the wetting phase in completely occupying the pore space.

The presence and distribution of the trapped nonwetting-phase droplets, a direct outcome of snap-off, introduce the complexity into fluid flow behavior within porous media. As a result, flow pathways and velocities of the phases are altered, exacerbating the effects of drainage–imbibition hysteresis [98]. Following the occurrence of hysteresis, the reduced relative permeability of the wetting phase during imbibition poses a substantial challenge for it to displace the nonwetting phase. This challenge is particularly significant in oil reservoirs, where the wetting phase is typically water, intensifying the difficulty of water displacing oil. As a consequence, this phenomenon considerably decreases oil recovery.

#### 4.4. Strong Foam Generation

Foam generation is essentially synonymous with gas bubble generation [99]. Consequently, the production of foam within porous media is closely intertwined with snap-off phenomena. Foam generation denotes the occurrence wherein gas bubbles form within the porous medium during the multiphase flow, with the wetting phase and nonwetting phase within the porous medium assuming the roles of liquid and gas phases, respectively. Previous studies on the mechanism of gas bubble formation have identified snap-off as one primary principal mechanism responsible for the generation of strong foam [100–102].

During multiphase fluid flow, foam generation can be classified into different categories, including strong foam and weak foam. Strong foam is the term used to describe relatively large and stable gas bubbles that are produced when the wetting phase rapidly pinches off the nonwetting phase. In contrast, weak foam consists of smaller and less stable bubbles. In porous media where gas and liquid coexist, gas, acting as the nonwetting phase, undergoes separation from the wetting liquid phase through snap-off phenomena, leading to the formation of larger gas bubbles. These bubbles, characterized by their size, stability, and persistence for an extended duration during multiphase fluid flow, are categorized as strong foam. Therefore, snap-off is recognized as a pivotal mechanism driving strong foam generation within porous media [100,101]. The generation of strong foam can have both advantageous and detrimental effects depending on specific conditions. In some instances, it may enhance recovery efficiency, while in others, it can introduce operational complexities and increase energy consumption. Therefore, practical applications necessitate a thorough evaluation of the influence of strong foam under distinct scenarios, followed by the implementation of corresponding measures for regulation and control.

## 4.5. Transient/Dynamic Effects

Apart from the aforementioned microscale consequences, snap-off can also exert an influence on specific macroscopic or continuum-scale parameters within the realm of porous media and multiphase flow. These effects are categorized as transient/dynamic effects, which are typically more pronounced in porous media characterized by coarser textures [103,104].

Droplets and bubbles, generated through snap-off, have been proven to influence fluid redistribution and introduce macroscale inhomogeneities at transient state [103,105]. When snap-off events occur, the entrapment of oil droplets or gas bubbles occupies a portion of the pore volume within the porous medium. Consequently, this augments the relative proportion of the nonwater phase in the reservoir, leading to a reduction in water saturation. It is essential to note that water saturation maintains a well-established constitutive relationship with relative permeability [103]. During multiphase flow, the decline in water saturation typically coincides with a decrease in the water relative permeability. This decrease implies greater challenges in displacing oil or gas by water, ultimately resulting in a reduced oil-recovery rate.

Additionally, some studies have revealed that the entrapment of the nonwetting phase can lead to modifications in the typically parabolic relationship between water saturation and the specific interfacial area [106,107]. Then, water saturation and the specific interfacial area can collaborate to alter capillary pressures, which, in turn, influence the rearrangement of immiscible two-phase interfaces [30]. However, the specific interfacial area, being a novel parameter of interest, presents challenges in direct measurement using existing experimental methodologies. Therefore, further experimentation is essential to validate the effect.

Furthermore, it is imperative to recognize that trapped droplets or bubbles, which act as impediments, exert influence on macroscale heterogeneity [103]. Consequently, this elevates the resistance in flow pathways characterized by these constrictions, favoring the flow of water in regions characterized by lower resistance, such as fissures, fractures, and faults. This leads to the formation of finger flow patterns for oil or gas [108], signifying a decrease in sweep efficiency during the displacement process. As a result, the overall recovery of oil or gas is reduced.

## 4.6. Interconnections between Effects

The various effects induced by snap-off, as previously elucidated, are not isolated but rather interconnected. The most conspicuous and common effect of snap-off is the formation of unrecoverable oil droplets. When these unrecoverable oil droplets occur within heterogeneous oil reservoirs characterized by a wide range of pore sizes and geometries, factors such as disparities in the interfacial tension, local pressure, and saturation, resulting from significant variations in pore and throat dimensions, lead to the deformation of trapped oil droplets, transforming them from spheres into bridge-like shapes and giving rise to the oil bridging effect.

Whether in the form of spherical trapped oil droplets or deformed oil bridges, these entities, serving as obstacles within the porous medium, can alter fluid distribution at the microscopic level. Consequently, this alteration initiates drainage–imbibition hysteresis and transient/dynamic effects, leading to a reduction in key macroscopic parameters, such as water saturation within the porous medium and water relative permeability in the context of two-phase flow. This reduction has a significant adverse impact on oil- or gas-recovery processes. In summary, these interconnected effects clarify the correlation between dynamic changes at the microscopic scale and their macroscopic consequences, providing a theoretical foundation for the future development of microscale strategies aimed at achieving specific macroscopic objectives.

#### 5. Prevention and Utilization of Snap-Off

## 5.1. Prevention of Snap-Off in Waterflooding for Oil Production

During the crude oil production through waterflooding, the occurrence of snap-off typically exerts a detrimental influence on crude oil-recovery rates. This adverse impact arises from the interaction of oil and water phases during the waterflooding process, where the oil phase frequently undergoes snap-off events [1,71,92]. Consequently, this leads to the formation of unrecoverable oil droplets, some of which may become entrapped in the narrow constrictions of the reservoir's porous media. These trapped oil droplets pose significant challenges to effective displacement, rendering them irrecoverable residual oil droplets. Furthermore, the subsequent oil bridging effect, induced by the presence of these residual oil droplets resulting from snap-off, further obstructs the unimpeded flow of the displacing phase within the porous media. This additional hindrance substantially diminishes crude oil-recovery rates. Moreover, the drainage–imbibition hysteresis triggered by snap-off introduces complexities and inefficiencies into the process. It exerts an influence on the distribution and flow of fluids during various stages of waterflooding, rendering the overall crude oil-recovery process intricate and less efficient.

Essentially, during the waterflooding process, the formation of unrecoverable oil droplets, the oil bridging effect, and drainage–imbibition hysteresis caused by the snap-off

phenomenon collectively contribute to an increased volume of trapped oil within subterranean reservoirs. This trapped oil becomes inaccessible, ultimately leading to lower oil recovery. Therefore, extensive research and technological advancements within the petroleum industry are directed towards mitigating or preventing the snap-off phenomenon to enhance recovery rates [109,110]. Several strategies, such as lowering the interfacial tension, adjusting the fluid viscosity, modifying the fluid-injection rate, and altering the pore-throat geometry through the fracturing process, have been identified to effectively reduce the occurrence of snap-off events. In a pioneering endeavor, Sukee et al. introduced an innovative approach of surfactant usage [111]. Differing from the conventional method of instantaneously reducing the interfacial tension to the target value through a typical single-reduction scheme, they chose to gradually modulate the surfactant concentration using a sequential-reduction method, ultimately attaining the same target interfacial tension. Their research demonstrated that the novel sequential reduction technique led to a significant 2.5% increase in oil recovery compared to the traditional single-reduction scheme. Furthermore, they provided evidence that this increase results from a more effective conversion of snap-off events into pore-filling occurrences, thus reducing the presence of unrecoverable oil droplets. Shams et al. employed a two-phase flow DNS model to simulate snap-off in a capillary-dominated flow regime within a water-wet limestone rock sample and validated it with experimental results [109]. Their study revealed that, in the simulation, injecting the wetting phase at a rate about two to four orders of magnitude faster than in the experiment led to higher local capillary numbers, making snap-off events more likely to occur. Conversely, reducing the injection rate of the wetting phase proved effective in preventing snap-off. Gong et al. employed dynamic pore-scale modeling to investigate the influence of pore geometry on two-phase relative permeability in rough-walled fractures [112]. Their study indicated that the phase relative permeabilities during imbibition are highly influenced by fracture geometry, with larger smooth fractures favoring piston-like displacement and minimizing snap-off events.

It is essential to highlight that the application of these strategies requires a thorough evaluation of geological conditions, reservoir characteristics, and production methodologies to identify the most suitable approach tailored for specific reservoir conditions. Furthermore, fine-tuning these factors through a combination of simulations and experiments can effectively reduce snap-off occurrences, thereby leading to enhanced crude oil-recovery rates in practical field productions.

#### 5.2. Utilization of Snap-Off in CO<sub>2</sub>-EOR

CO<sub>2</sub>-EOR, also referred to as CO<sub>2</sub> flooding, is a reservoir engineering technique employed to enhance oil recovery using CO<sub>2</sub> [32,113,114]. Typically, it finds application in reservoirs where conventional waterflooding has been conducted, yet a substantial quantity of crude oil remains within the porous media of reservoirs. The fundamental principle underlying  $CO_2$ -EOR involves the injection of  $CO_2$  into the reservoir, primarily to reduce the viscosity of crude oil by blending with it within the interstitial spaces of the porous medium. This process plays a pivotal role in enhancing the flowability of crude oil, consequently elevating the sweep efficiency, and thereby increasing both the oil-production efficiency and oil-recovery rate. Furthermore, during the implementation of  $CO_2$ -EOR, the introduction of appropriate foaming agents alongside CO2 can lead to interactions with reservoir fluids that induce the occurrence of snap-off phenomena [115]. This phenomenon results in the formation of gas bubbles within the oil phase, which are effectively stabilized by the foaming agents. Notably, the entrapped gas bubbles within the oil phase give rise to a gas-in-oil foam structure. Characterized by stability and the capacity to enhance the mobility of the oil phase, this unique structure significantly contributes to improved sweep efficiency during the EOR process.

In essence, by capitalizing on the snap-off phenomenon to induce the generation of strong foam, injected  $CO_2$  can undergo a transition from its conventional gaseous state to a foam state within the porous media of the reservoir, facilitated by the presence of foaming

agents. Consequently, through the utilization of this resulting CO<sub>2</sub> foam, characterized by its dynamic and evolving structure, improvements in oil mobility and sweep efficiency are realized, ultimately fulfilling the purpose of enhancing oil recovery during CO<sub>2</sub> flooding.

## 5.3. Utilization of Snap-Off in CO<sub>2</sub> Storage

During the process of  $CO_2$  geological storage, the occurrence of the snap-off phenomenon significantly enhances storage efficiency [32]. The characteristics of  $CO_2$  storage in saline aquifers share similarities with oil production through waterflooding in oil reservoirs, both involving immiscible two-phase fluids within porous media. Typically, brine or water serves as the wetting phase, while  $CO_2$  gas or oil function as the nonwetting phase. Therefore, findings related to snap-off in oil reservoirs can contribute to a deeper understanding of the theoretical aspects and mechanisms behind  $CO_2$  storage in saline aquifers.

Research conducted by Krevor et al. [116] elucidates that  $CO_2$  storage in saline aquifers relies on the capillary trapping mechanism, with storage potential primarily controlled by the interplay between snap-off and piston-like advance. In this competition, piston-like advance reduces trapping, while snap-off enhances it [28]. Notably, during  $CO_2$  injection into saline aquifers, strong foam generation occurs due to snap-off, resulting in robust  $CO_2$ bubbles. In the subsequent multiphase flow, the influence of residual water saturation within the porous medium of saline aquifers becomes particularly significant. Just as in oil reservoirs, where water saturation also impacts the relative permeability, studies indicate that in the porous medium of saline aquifers, higher residual water saturation leads to higher water relative permeability [28]. This is detrimental to  $CO_2$  capillary trapping associated with snap-off, thus preventing stable storage. In essence, the  $CO_2$  storage potential decreases as residual water saturation increases in saline aquifers [28]. Suekane et al. [117] conducted experiments using Berea sandstone to validate this conclusion and used it as the basis for evaluating the  $CO_2$  storage potential in saline aquifers in Japan. Similarly, Bachu [118] conducted experiments using rocks from various deep carbonate and sandstone aquifers in central Alberta, western Canada, confirming the conclusion. In light of this fact, the transient/dynamic effects induced by snap-off can effectively lower water saturation and reduce water relative permeability within saline aquifers, thereby ensuring the stable storage of  $CO_2$  bubbles.

In summary,  $CO_2$  geological storage in saline aquifers leverages the strong foam generation effect of snap-off to promote the formation of large, stable  $CO_2$  bubbles. Subsequently, transient/dynamic effects induced by snap-off lead to a reduction in water saturation. As a consequence, water relative permeability decreases, impeding water flow within the porous medium, thereby facilitating the primary goal of stably storing  $CO_2$  bubbles within saline aquifer porous media. To optimize the efficient application of snap-off for  $CO_2$  geological storage, several technical measures should be considered. It is necessary to evaluate the storage capacity and sealing properties of the selected saline aquifers. The  $CO_2$  injection flow rate and pressure should be controlled within manageable ranges. Additionally, the implementation of numerical simulations before  $CO_2$  injection, real-time monitoring during injection, and long-term poststorage monitoring are essential components of this process.

## 6. Limitations and Future Improvements

For experimental studies of the snap-off phenomenon and other microscale interfacial phenomena, two categories of techniques are conventionally employed. One approach involves the replication of porous media structures through specialized manufacturing processes, thereby facilitating the creation of microfluidic models. These models enable researchers to engage in direct observations and data recording, frequently utilizing instruments such as microscopes and high-speed cameras. Representative manufacturing techniques encompass soft photolithography, ultrafast pulsed-laser cutting, and 3D printing. The other approach entails using cutting-edge visualization and imaging techniques to scrutinize real-world reservoir porous media. Prominent techniques include magnetic resonance imaging (MRI), CT scanning, and synchrotron X-ray microtomography. Never-

theless, it is imperative to recognize that both of these methodological categories confront specific limitations at present.

Regarding the first approach, although contemporary 3D manufacturing techniques can achieve a precision of 20 micrometers [73,119,120] in fabricating microfluidic models, the endeavor to create even smaller pore structures, particularly at or below 10 micrometers, remains a formidable challenge. Consequently, one of the prospective research directions involves pushing the boundaries of manufacturing techniques to attain higher precision in crafting experimental models with sophisticated pore configurations. This advancement is indispensable to meet the research demands associated with the intricate multiphase fluid dynamics within reservoirs characterized by the minuscule pore structures prevalent in tight oil and shale gas reservoirs.

Regarding the second category of methods, these advanced state-of-the-art visualization and imaging techniques typically entail elevated utilization expenses, with the principal technical challenge centered around the scanning resolution. Therefore, the economically efficient accomplishment of high-resolution scanning emerges as a prospective direction for future investigations within this methodological domain. Specifically, it may necessitate refinements in detector technology and scanning algorithms to elevate the spatial and temporal resolution. Furthermore, the integration of automation and artificial intelligence methodologies to curtail manual intervention can bolster both data acquisition and analytical efficiency, thereby leading to cost reduction.

With the advent of enhanced modern computing capabilities and decreased CPU time costs, contemporary numerical simulation models are generally capable of faithfully simulating snap-off phenomena and other complex multiphase flow dynamics within porous media. However, it is worth noting that certain models may resort to simplifications regarding porous media attributes during simulations. These simplifications encompass assumptions of rigidity, incompressibility, and isotropy, aimed at accelerating computational processes but often at the expense of precision. Recent investigations have demonstrated the potential of dynamic pore-network models in offering more accurate insights into the transient behavior of multiphase flow systems. Nevertheless, these dynamic pore–network models necessitate the utilization of intricate programming, robust solution methodologies, and streamlined algorithms, given the challenges posed by numerical convergence and instability concerns. Meanwhile, the computational demands for simulating dynamic capillary effects tend to be substantial in terms of both processing power and memory utilization, primarily due to the complicated nonlinear interactions between viscous and capillary forces in multiphase fluid flow. Therefore, the core challenge in numerical simulation studies of multiphase flow phenomena, such as snap-off, revolves around the delicate balance between computational efficiency and simulation precision.

To address this challenge, it is advisable to direct research efforts towards the advancement of more efficient algorithms aimed at supporting the numerical stability and computational efficiency of dynamic pore–network models. Furthermore, the incorporation of parallel and distributed computing methodologies can be utilized to expedite the simulation processes of dynamic pore–network models, thereby diminishing computational time and memory requisites. Additionally, refining the physical representation of these models is of paramount importance to encapsulate fluid dynamics and a spectrum of mechanical intricacies more precisely within the porous network, making dynamic pore–network models a more viable choice for practical applications.

#### 7. Conclusions

Snap-off, observed during imbibition in porous media, is a common and crucial microscale phenomenon at multiphase interfaces. In response to the existing gap in the extensive literature on snap-off, this review conducts a comprehensive examination and synthesis from four essential viewpoints: the mechanisms governing snap-off formation, factors influencing snap-off, impacts caused by snap-off, and potential applications of snap-off. The following conclusions have been deduced.

- (1) The formation of snap-off is governed by changes in the interface curvature within confined regions and the impact of the capillary pressure, resulting in the destabilization of the meniscus interface between the two-phase fluids. Ultimately, this instability leads to the occurrence of snap-off phenomena at the constrictions.
- (2) The snap-off phenomenon is primarily influenced by factors, including the characteristics of multiphase fluids, the wettability of porous media, and the pore-throat geometry and topology within porous media.
- (3) Numerous effects are brought about by snap-off, such as the unrecoverable oil droplet formation, the oil bridging effect, drainage–imbibition hysteresis, strong foam generation, and transient/dynamic effects.
- (4) During the conventional waterflooding for oil production, the snap-off phenomenon detrimentally impacts oil recovery. It results in unrecoverable oil droplets, the oil bridging effect, and drainage–imbibition hysteresis, significantly reducing crude oilrecovery rates. Therefore, pertinent measures should be implemented to avoid the occurrence of the snap-off phenomenon during waterflooding.
- (5) In the CO<sub>2</sub>-EOR context, snap-off mechanisms facilitate the generation of robust foam structures, which, in turn, serve to improve oil mobility and enhance the sweep efficiency, ultimately leading to an enhancement in crude oil-recovery rates.
- (6) In the context of CO<sub>2</sub> storage within saline aquifers, large, stable CO<sub>2</sub> bubbles are generated through the strong foam generation effect of snap-off within the reservoir porous media. Subsequently, snap-off-induced transient/dynamic effects reduce water saturation and lower the water relative permeability, facilitating stable CO<sub>2</sub> storage in saline aquifers.
- (7) Experimental studies of snap-off face limitations, such as difficulties in manufacturing microfluidic models with sub-10-micrometer pore structures, and issues related to the high expenses and low resolution of advanced visualization techniques. To address these challenges, future improvements should focus on refining manufacturing techniques for precise models, as well as enhancing the time–space scanning resolution of imaging techniques.
- (8) The core challenge in numerical simulation studies of snap-off revolves around the delicate balance between computational efficiency and simulation precision. To address the challenge, future enhancements should focus on the development of more efficient algorithms to support numerical stability, the utilization of parallel and distributed computing to expedite simulations and curtail computational resources, and the refinement of model physical representations for practical applications.

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