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Pore-Scale Interaction of Oil-in-Water Emulsions with Porous-Medium Grains: Effects of Viscosity Ratio and Capillary Number

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ABSTRACT: In this experimental study, the pore-scale interaction between a flowing oil-in-water emulsion and a porous-medium grain are considered to elucidate how the viscosity ratio between the oil and continuous phases governs the resulting flow behavior. Relevant microfluidic experiments were conducted using sodium dodecyl sulfate as the emulsifier and three types of dimethyl silicone oil with different viscosities as the dispersed oil phase. The results show that, upon interacting with a porous-medium grain, a single oil-in-water emulsion can undergo three distinct flow regimes: deformation and passage through the grain, incomplete breakup, and complete breakup. The transitions between these regimes are governed by the capillary number of the continuous phase and the viscosity ratio of the oil to the continuous phase. For all emulsions investigated, a critical continuous-phase capillary number exists below which the emulsion undergoes deformation and passage without breakup, whereas complete breakup occurs above a second, higher critical capillary number. Increasing the viscosity ratio from 26.0 to 113.3 systematically shifts both transition thresholds toward lower capillary numbers. Specifically, the critical capillary number for complete breakup decreases from 15.96×10^{-4} to 4.70×10^{-4} , while that for deformation and passage decreases from 6.29×10^{-4} to 2.13×10^{-4} . Overall, these results demonstrate that increasing the oil-to-continuous-phase viscosity ratio promotes emulsion breakup during pore-scale flow and significantly alters the conditions governing droplet deformation and fragmentation.

KEYWORDS: Porous media; oil-in-water emulsion; microfluidic; microscopic mechanism

1 Introduction

In petroleum development, a large volume of residual oil generally remains trapped in reservoirs after waterflooding [1]. Chemical agents, including surfactants, polymers, and nanoparticles, are widely used in enhanced oil recovery (EOR) [2,3]. For surfactants, they can mobilize the residual oil through three main mechanisms: the reduction of interfacial tension, the shift of surface wettability toward a water-wet state, and the promotion of emulsification [4–6]. The injection of water-soluble surfactants with strong emulsifying capability can emulsify a portion of the residual oil into oil-in-water emulsions. The oil-in-water emulsions are then easily transported by the continuous phase [7,8].

Many researchers have investigated the flow behavior of oil-in-water emulsions in porous media through one-dimensional flooding experiments.

For instance, Chen et al. [9] revealed that oil-in-water emulsions can exhibit plugging performance through sand-pack displacement experiments. They further found that the plugging performance of oil-in-water emulsions is correlated with the oil phase viscosity. Ding et al. [10] focused on the plugging

performance of oil-in-water emulsions as well. Based on a series of sand-pack flow experiments, they found that the plugging performance can be optimized by selecting an appropriate emulsion system. Zhou et al. [11] investigated the evolution of oil-in-water emulsions at different positions of a long sand-pack model (60 cm). The results showed that the particle size of emulsions is smaller and the distribution density is higher near the outlet at a fixed injection volume. This is attributed to the shear effect of the porous media. Błaszczuk et al. [12] established a model to predict the pressure change during the oil-in-water emulsion flow based on core flooding experiments. Their model incorporates emulsion concentration, injection rate, and core length as key parameters.

The flow of oil-in-water emulsion in porous media is inherently a complex process. The interaction between emulsions and porous media microstructures can lead to multiple flow phenomena at the pore scale. However, conventional sand-pack or core flooding experiments cannot provide direct pore-scale visualization, and thus are unable to elucidate the fundamental mechanisms.

As an experimental technique, microfluidics enables researchers to conduct more quantitative fluid manipulation at the pore scale [13,14]. In microfluidic experiments, fluids are constrained to flow in micro-channels etched on transparent chips. By systematically adjusting the experimental conditions, researchers can observe and characterize various microscopic flow phenomena [15–17]. In the field of oil and gas development, numerous microfluidic studies have been conducted to investigate the dynamic emulsification process and flow behaviors.

For instance, Mohammadzadeh et al. [18] conducted displacement experiments in a 2D glass-etched microfluidic chip. They developed a novel surfactant and demonstrated that prolonged contact between the surfactant solution and the oil phase in porous media can promote the generation of oil-in-water emulsions. Xu et al. [19] designed a 2.5D glass-etched microfluidic chip and observed that larger oil-in-water emulsions experienced significant size reduction shortly after entering the porous media structure. Azizov et al. [20] used a microfluidic chip with homogeneous porous media to study the retention of oil-in-water emulsions. The results showed that emulsions larger than pore throats tended to be completely retained, whereas those smaller than pore throats showed little or no retention. Wang et al. [21] found that adding polymer (hydrolyzed polyacrylamide) to the continuous phase can effectively prevent the retention of oil-in-water emulsions in porous media.

Additionally, other investigations have examined the interactions between specific microstructures and oil-in-water emulsions.

Reservoir porous media contain abundant pore-throat structures. Accordingly, several studies have employed microfluidic experiments to investigate the flow behavior of oil-in-water emulsions passing through such pore-throat structures. For instance, Cobos et al. [22] investigated the pressure response of a single oil-in-water emulsion flowing through a pore-throat structure. The results showed that emulsions larger than the pore throats generated high pressure at the pore-throat entrance under low capillary number. Wang et al. [23] found that the continuous phase with higher viscosity can facilitate the break-up as oil-in-water emulsions pass through the pore-throat structure. When the continuous phase and oil phase flow simultaneously in porous media, the continuous phase can continuously impact the oil phase. This interaction disperses the oil phase into the continuous phase to form oil-in-water emulsions. Regarding this microscale flow mechanism, Costa et al. [24] investigated the effect of the two-phase flow rate ratio on the emulsion formation and determined the flow rate ratio ranges corresponding to different flow phenomena. Seo et al. [25] developed a novel biodegradable nonionic surfactant and compared its performance with that of conventional sodium dodecyl sulfate (SDS). The results demonstrated that the novel surfactant exhibited superior emulsification performance compared to SDS.

It can be seen from the above-mentioned studies that many researchers have focused on the influence of a single pore throat structure on oil-in-water emulsion flow at the pore scale. In addition, there have been many microfluidic investigations of the formation of oil-in-water emulsions within interconnected channels due to the two-phase flow of the continuous phase (surfactant solution) and the oil phase. However, in addition to the single pore throat structure and the interconnected channels, the porous media grain which is a widely distributed microstructural feature can also affect the flow of oil-in-water emulsions.

As for the dynamic flow behavior of a single oil-in-water emulsion flowing to a single porous media grain, it is still unclear how the capillary number of continuous phase, emulsion length, and the viscosity ratio of oil phase to continuous phase influence the flow phenomena occurring between an oil-in-water emulsion and a porous media grain. For experiments based on porous media micromodels with pore-throat structures, the experimental analysis of the flow of oil-in-water emulsions is often challenging due to the simultaneous occurrence of multiple flow phenomena caused by various microstructural features. Therefore, in this study, we designed a microfluidic chip containing a single porous media grain structure, allowing us to directly focus on the effect of the grain on flowing oil-in-water emulsions without interference from other microstructural features.

Based on microfluidic experimental results, we analyzed the dynamic process of three microscopic flow phenomena, including deformation and pass-through, incomplete break-up, and complete break-up. In contrast to the complete break-up, the incomplete break-up generates a daughter oil-in-water emulsion with a diameter smaller than the microchannel width. Moreover, we investigated the effect of the viscosity ratio of the oil phase to the continuous phase on the flow phenomena through the established flow phenomena distribution map. According to the distribution maps, there exists a critical pass-through capillary number of the continuous phase and a critical complete break-up capillary number of the continuous phase, with the former being smaller than the latter. In addition, both the critical capillary numbers decrease as the viscosity ratio of oil phase to continuous phase increases.

2 Materials and Experimental Methods

In our experiments, three types of silicone oil (Shanghai Macklin Biochemical Co., Ltd., China) with different viscosities were used as the oil phase. At 25°C, the viscosities of the three types of silicone oil were 24.4, 52.7, and 106.5 mPa·s, respectively. The densities of the silicone oils with viscosities of 24.4, 52.7, and 106.5 mPa·s were 0.944, 0.952, and 0.963 g/cm³, respectively. The continuous phase was the 1 wt% sodium dodecyl sulfate (Shanghai Macklin Biochemical Co., Ltd., China) solution prepared with distilled water. At 25°C, the viscosity of the continuous phase was 0.94 mPa·s. The interfacial tension (IFT) between the oil phase and the continuous phase was measured at 25°C, and the results are listed in Table 1.

Table 1: IFT between silicone oil and 1 wt% sodium dodecyl sulfate.

Oil Phase	Oil Phase Viscosity (mPa·s)	Oil Phase Density (g/cm ³)	IFT (mN/m)
Silicone oil 1	24.4	0.944	3.24
Silicone oil 2	52.7	0.952	3.55
Silicone oil 3	106.5	0.963	3.67

The microfluidic chip used in our microfluidic experiments is made of polymethyl methacrylate (PMMA). The layout of the microfluidic chip is shown in Fig. 1. Each chip consists of two continuous phase channels, one oil phase channel, one emulsion flow channel, one continuous phase inlet, one oil phase inlet, and one outlet. Both the continuous phase channels and the oil phase channel are designed with a width

and depth of 100 μm . The emulsion flow channel has a depth of 100 μm and a width of 500 μm . As can be seen from Fig. 1, the emulsion flow channel contains a circular solid structure, serving as a simplified porous media grain, which is located at the center of the emulsion flow channel and near the outlet. The diameter of the circular solid structure in the microfluidic chip is 150 μm .

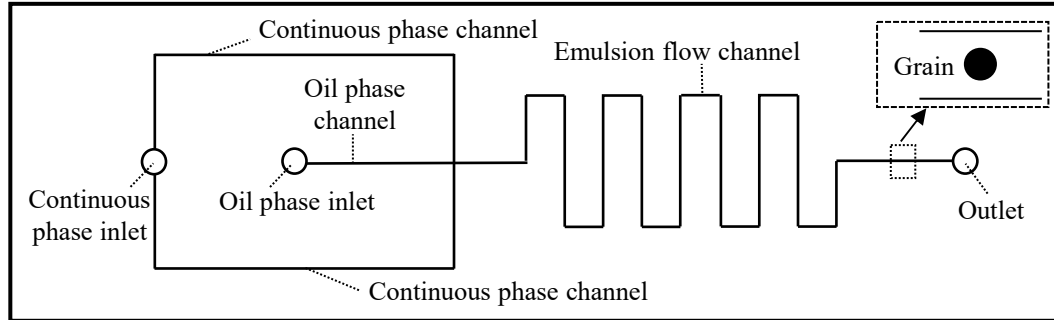


Figure 1: Layout of the microfluidic chip.

Fig. 2 shows the schematic diagram of the experimental setup. It includes two syringes (Hamilton, 10 mL, USA), two syringe pumps (Harvard Apparatus, PHD 2000, USA), and the microscope (Leica, Z16, Germany). Two syringes were respectively placed on the two syringe pumps. The microfluidic chip was placed on the platform of the microscope.

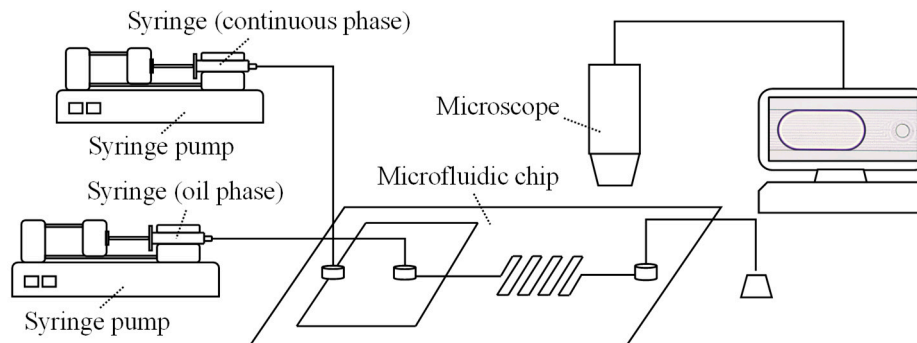


Figure 2: Schematic diagram of the experimental setup.

All flow experiments were conducted at 25°C. Each flow experiment was repeated three times. Before each flow experiment, the channels were immersed in the 1 wt% SDS solution for 3 h to maintain the microchannels in a water-wet state. The contact angle of silicone oil with the PMMA in the 1 wt% SDS aqueous solution was measured to be 52° at 25°C.

The main experimental procedures are as follows:

Step 1: The continuous phase was injected into the microfluidic chip from the continuous phase inlet at a constant flow rate until all microchannels were completely filled with the continuous phase, and then the flow rate was kept constant.

Step 2: The oil phase was injected from its inlet at a constant flow rate.

Step 3: The flow rates of the continuous phase and the oil phase were adjusted and then kept constant, resulting in the generation of an emulsion with a certain length at the junction of the continuous phase channel and the oil phase channel.

Step 4: The injection of the oil phase was stopped, and the flow rate of the continuous phase was adjusted. The microscope was used to observe and capture the flow phenomena of oil-in-water emulsions with the same length as they flowed to the circular solid structure under different flow rates.

Step 5: The flow rates of the continuous phase and the oil phase were adjusted to generate oil-in-water emulsions with different lengths, and then step 4 was repeated. The captured images were analyzed using Fiji Image J software.

The detailed flow conditions for the length of oil-in-water emulsions are provided in the Supplementary Materials. The detailed flow conditions corresponding to each initial emulsion length are summarized in Tables S1–S3.

3 Results and Discussions

3.1 Deformation and Pass-Through

Fig. 3 demonstrates the deformation and pass-through of an oil-in-water emulsion as it flows to a circular solid structure. This flow phenomenon occurs when the capillary number of the continuous phase is relatively low. As shown in Fig. 3a, the oil-in-water emulsion flows forward under the displacement of the continuous phase. When it impacts the circular solid structure, its front interface deforms and attempts to pass from both sides of the circular solid structure, as depicted in Fig. 3b. Then, the interfaces above and below the circular solid structure become non-uniform. This is because the lower capillary number of the continuous phase results in a weaker driving force on the oil-in-water emulsion. Acting as a resistive force, the capillary force on the interface below the circular solid structure is higher than that on the upper side. Subsequently, the interface on the lower side ceases its forward movement and instead moves backward, as shown in Fig. 3c. As a result, the oil-in-water emulsion eventually passes through the circular solid structure with its own deformation, as shown in Fig. 3d,e.

3.2 Incomplete Break-Up

Fig. 4 demonstrates the incomplete break-up of an oil-in-water emulsion as it flows to a circular solid structure. As shown in Fig. 4a,b, similar to the phenomenon of deformation and pass-through, the front interface of the oil-in-water emulsion deforms and attempts to pass from both sides after the oil-in-water emulsion contacts the circular solid structure. The interfaces above and below the circular solid structure are non-uniform as well. However, unlike the deformation and pass-through phenomenon, the front interface of the oil-in-water emulsion on the lower side does not move backward, as shown in Fig. 4c. Then, driven by the continuous phase, the oil-in-water emulsion continues to flow forward and eventually breaks up into two daughter emulsions, as shown in Fig. 4d. One daughter emulsion has a width smaller than the width of the emulsion flow channel, as shown in Fig. 4e.

3.3 Complete Break-Up

Fig. 5 demonstrates the complete break-up of an oil-in-water emulsion as it flows to a circular solid structure. This flow phenomenon occurs when the capillary number of the continuous phase is relatively high. As shown in Fig. 5a,b, unlike the incomplete break-up and the deformation and pass-through, the interfaces on both sides of the structure are relatively uniform after the oil-in-water emulsion impacts on the circular solid structure. Then, driven by the continuous phase, the oil-in-water emulsion eventually breaks up into two daughter oil-in-water emulsions, as shown in Fig. 5c,d. As can be seen in Fig. 5e, the width of each daughter oil-in-water emulsion is equal to the width of emulsion flow channel.

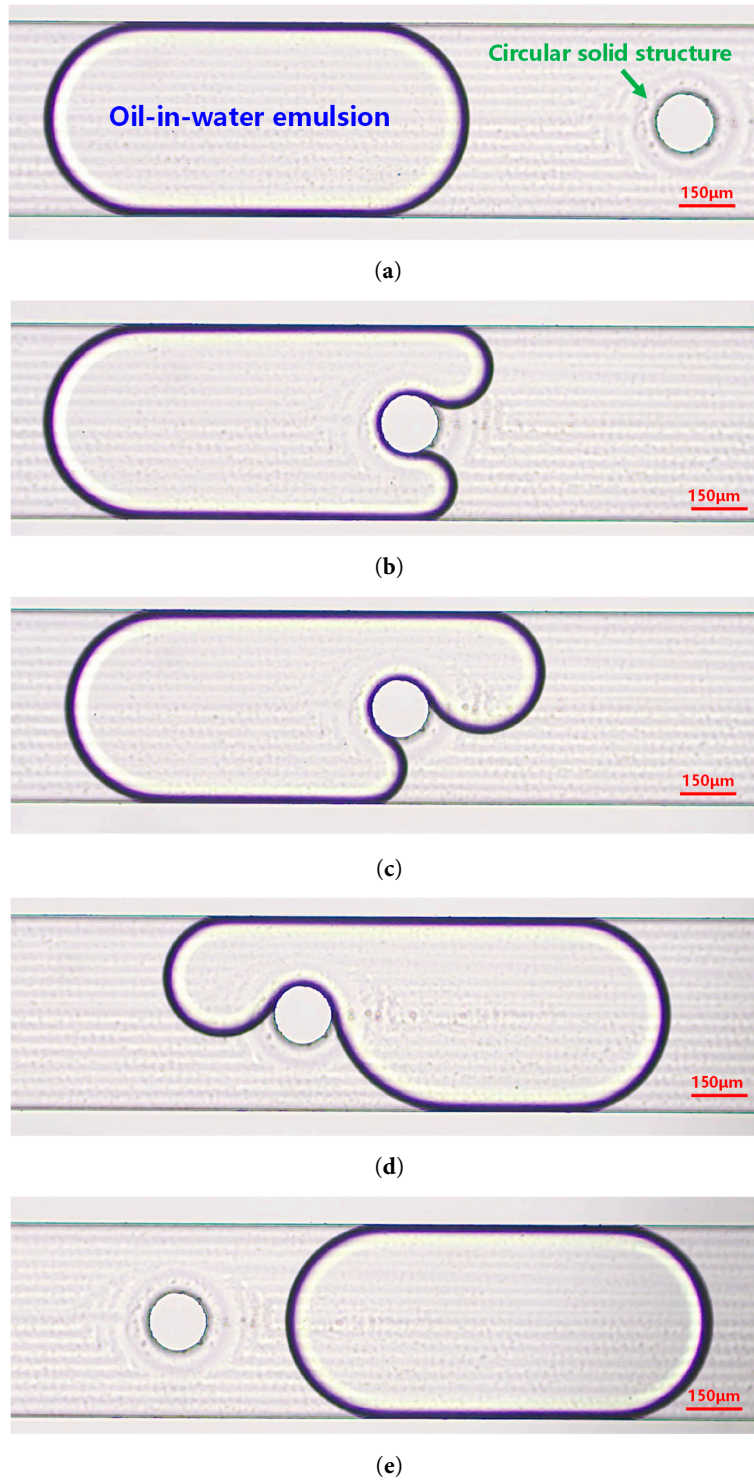


Figure 3: Deformation and pass-through. (a) Initial state of a flowing oil-in-water emulsion; (b) Oil-in-water emulsion in contact with circular solid structure; (c) Retreat of interface on one side of circular solid structure; (d) Interface completely on one side of circular solid structure; (e) Pass through of oil-in-water emulsion.

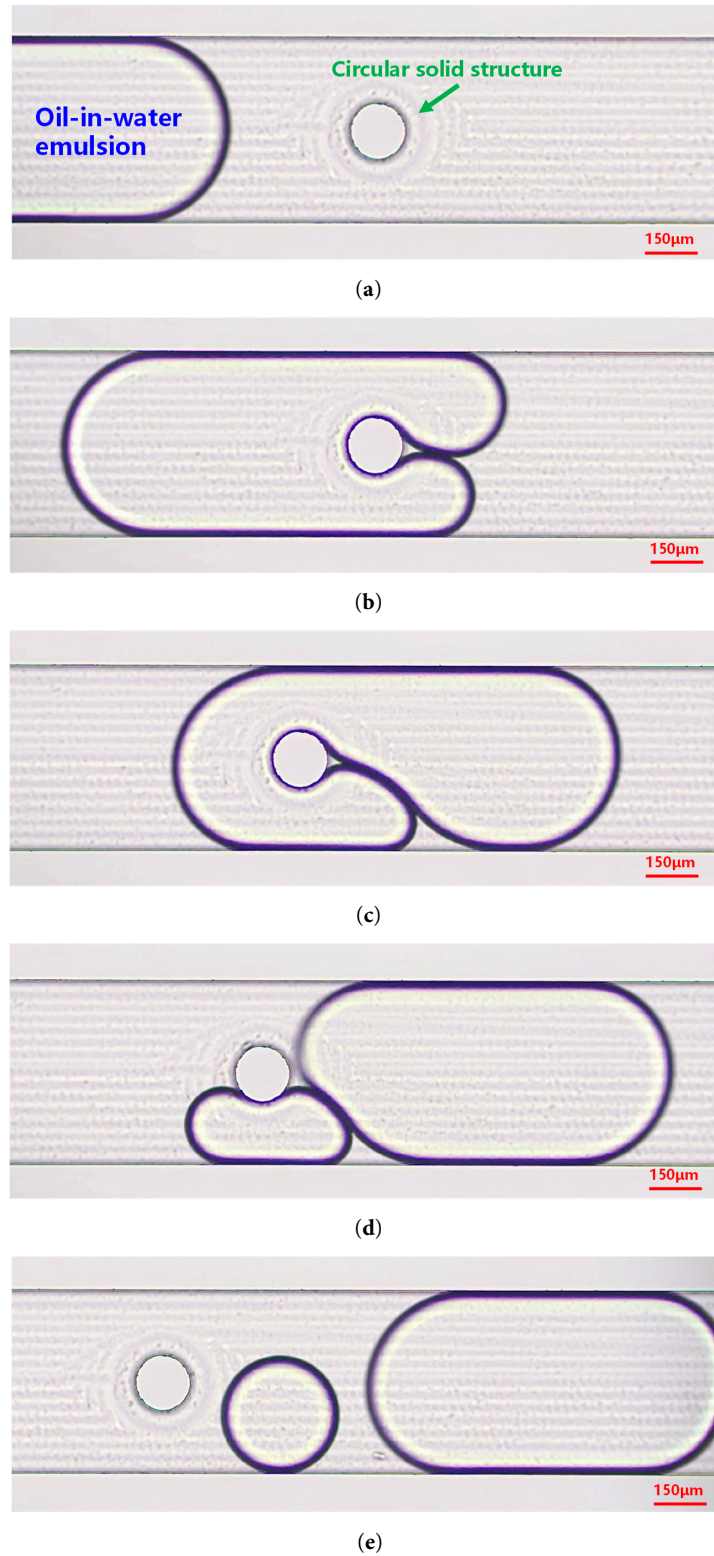


Figure 4: Incomplete break-up. (a) Initial state of a flowing oil-in-water emulsion; (b) Oil-in-water emulsion in contact with a circular solid structure; (c) Forward motion of interfaces on both sides of the circular solid structure; (d) Generation of two daughter emulsions; (e) Forward flow of a daughter emulsion with a width smaller than that of the emulsion flow channel and a daughter emulsion with a width equal to that of the emulsion flow channel.

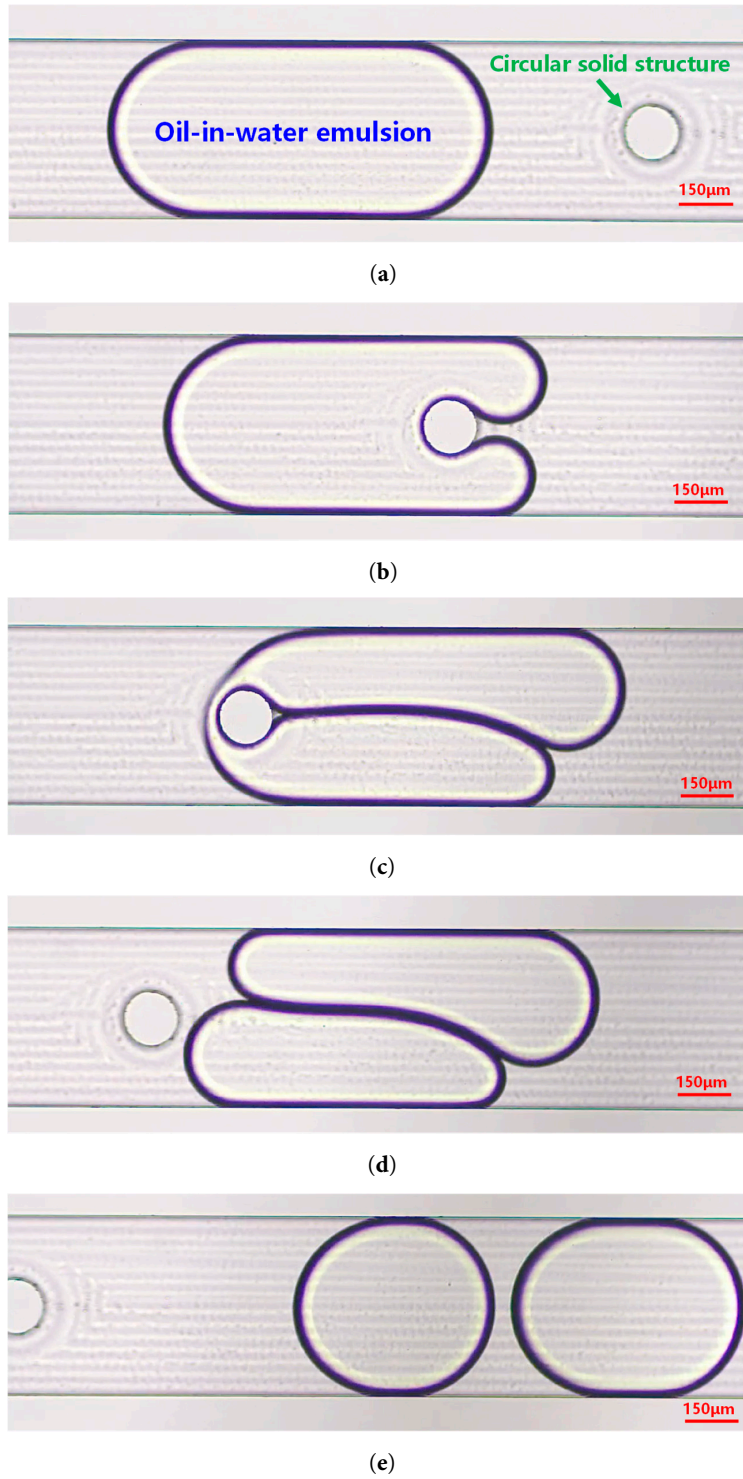


Figure 5: Complete break-up. (a) Initial state of a flowing oil-in-water emulsion; (b) Oil-in-water emulsion in contact with a circular solid structure; (c) Forward motion of interfaces on both sides of the circular solid structure; (d) Generation of two daughter emulsions with a width equal to that of the emulsion flow channel; (e) Forward flow of two daughter emulsions.

It can be seen from our experimental results that the circular solid structure causes only two types of break-up for a single oil-in-water emulsion. For both break-up phenomena, the initial oil-in-water emulsion splits into only two daughter emulsions. This behavior shares both similarities and differences with another widely distributed microstructure in reservoir porous media, i.e., the pore-throat structure. As shown in Ref. [23], the break-up also occurs when an oil-in-water emulsion flows to a single pore-throat structure. However, the pore-throat structure can break an oil-in-water emulsion not only into two daughter emulsions, but also into three or more. Furthermore, another difference from our results is that the break-up caused by the pore-throat structure predominantly occurs at a relatively low capillary number of the continuous phase. This demonstrates the complementarity of our single-grain model and the pore-throat structure model in the literature.

In addition, compared with the simplified single grain structure used in this study, the real porous media contains much more complex structures, including interconnected pore-throat networks, tortuous flow paths, and multiple grains. According to the research in of Ref. [25], when the continuous phase and oil phase flow simultaneously in interconnected pore-throat networks, they can interact to form oil-in-water emulsions. Then, these emulsions can be transported by the continuous phase through tortuous paths. However, due to the presence of numerous grains in the real porous media, the probability of interactions between emulsions and grains increases as these emulsions continuously flow forward. If the capillary number of the continuous phase is relatively high, the oil-in-water emulsions are more prone to break up into daughter emulsions. Subsequently, these daughter emulsions may undergo further break-ups during their migration, eventually evolving into even smaller oil-in-water emulsions.

3.4 Effect of Viscosity Ratio

Fig. 6 shows the flow phenomenon distribution map when the viscosity ratio of oil phase to continuous phase is 26. The vertical axis represents the capillary number of the continuous phase. The horizontal axis represents the dimensionless length of the oil-in-water emulsion. Since the oil-in-water emulsion spans the full channel width, the width of the emulsion flow channel is used as the characteristic length for normalizing the oil-in-water emulsion length. The dimensionless length can be expressed as

$$l^* = \frac{l_e}{w} \quad (1)$$

where l_e is the actual length of oil-in-water emulsion, and w is the width of emulsion flow channel.

It can be observed that when the capillary number of the continuous phase is as low as $(6.29 \pm 0.05) \times 10^{-4}$ (95% CI: $6.17\text{--}6.41 \times 10^{-4}$), oil-in-water emulsions with different lengths all exhibit the phenomenon of deformation and pass-through as they flow to the circular solid structure.

The possible reason is that the driving force acting on the oil-in-water emulsion is relatively weak due to the low capillary number of the continuous phase. Then, the entire oil-in-water emulsion can pass along the side of the circular solid structure with lower capillary force. In this study, this capillary number is defined as the critical pass-through capillary number.

As the capillary number of the continuous phase increases to 8.22×10^{-4} , oil-in-water emulsions with dimensionless length ranging from 1.78 to 3 exhibit the phenomenon of incomplete breakup. However, for oil-in-water emulsions with a dimensionless length equal to or higher than 3.2, they still exhibit the phenomenon of deformation and pass-through. This is mainly because, for the oil-in-water emulsion with a relatively long dimensionless length, the larger portion of oil-in-water emulsion on one side of the circular solid structure can compress the portion of oil-in-water emulsion on the opposite side. Therefore,

the oil-in-water emulsion interface on the opposite side moves backward and then bypasses the circular solid structure.

As the capillary number of the continuous phase increases to 10.15×10^{-4} , oil-in-water emulsions with a dimensionless length of 4 began to exhibit incomplete breakup. When the capillary number reached 12.09×10^{-4} , the deformation and pass-through phenomenon disappeared, and the oil-in-water emulsion with a dimensionless length of 1.78 exhibited the complete break-up phenomenon. As the capillary number increased further to 14.02×10^{-4} , the dimensionless length of oil-in-water emulsions with the complete break-up phenomenon further increased. When the capillary number comes to $(15.96 \pm 0.09) \times 10^{-4}$ (95% CI: $15.74\text{--}16.18 \times 10^{-4}$), the incomplete break-up phenomenon disappears, all oil-in-water emulsions flowing to the circular solid structure exhibit the complete break-up phenomenon. In this study, this capillary number was defined as the critical complete break-up capillary number.

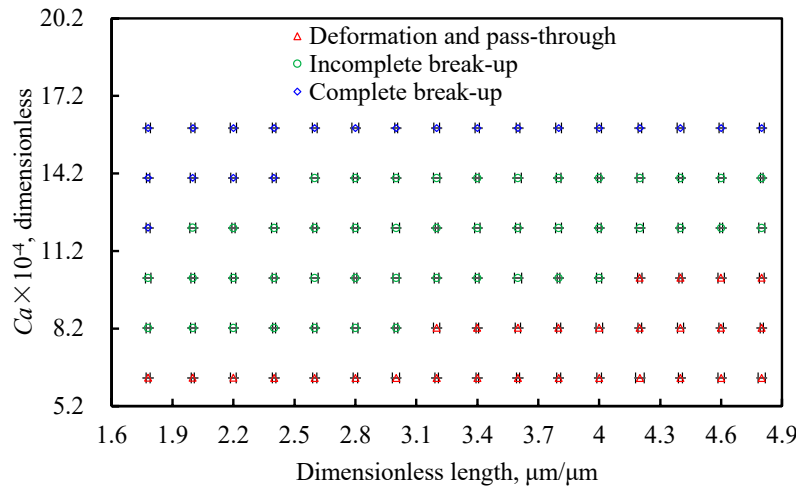


Figure 6: Distribution map at a viscosity ratio of 26.

Fig. 7 shows the flow phenomenon distribution map when the viscosity ratio of oil phase to continuous phase is 56.1. Fig. 8 shows the flow phenomenon distribution map when the viscosity ratio of the oil phase to the continuous phase is 113.3. When the viscosity ratio of the oil phase to the continuous phase was 56.1, the critical complete break-up capillary number and the critical pass-through capillary number were $(6.18 \pm 0.05) \times 10^{-4}$ (95% CI: $6.06\text{--}6.31 \times 10^{-4}$) and $(3.53 \pm 0.05) \times 10^{-4}$ (95% CI: $3.41\text{--}3.66 \times 10^{-4}$), respectively. Moreover, when the viscosity ratio of oil phase to continuous phase was 113.3, the critical complete break-up capillary number and the critical pass-through capillary number were $(4.70 \pm 0.05) \times 10^{-4}$ (95% CI: $4.58\text{--}4.83 \times 10^{-4}$) and $(2.13 \pm 0.05) \times 10^{-4}$ (95% CI: $2.01\text{--}2.26 \times 10^{-4}$), respectively. Therefore, it can be concluded that as the viscosity ratio of the oil phase to the continuous phase increases, both the critical complete break-up capillary number and the critical pass-through capillary number decrease.

This may be mainly because, when an oil-in-water emulsion formed with the high-viscosity oil phase contacts the circular solid structure, the relatively high viscous force inside the oil-in-water emulsion hinders the two portions of the oil-in-water emulsion on both sides from moving backward to bypass the structure. As a result, the two-phase interfaces on both sides of the circular solid structure are more likely to move forward. Consequently, the oil-in-water emulsion formed with the high viscosity oil phase tend to exhibit break-up phenomenon more readily than the oil-in-water emulsion formed with the low viscosity oil phase. However, we acknowledge that this interpretation is based on indirect experimental evidence and requires further validation.

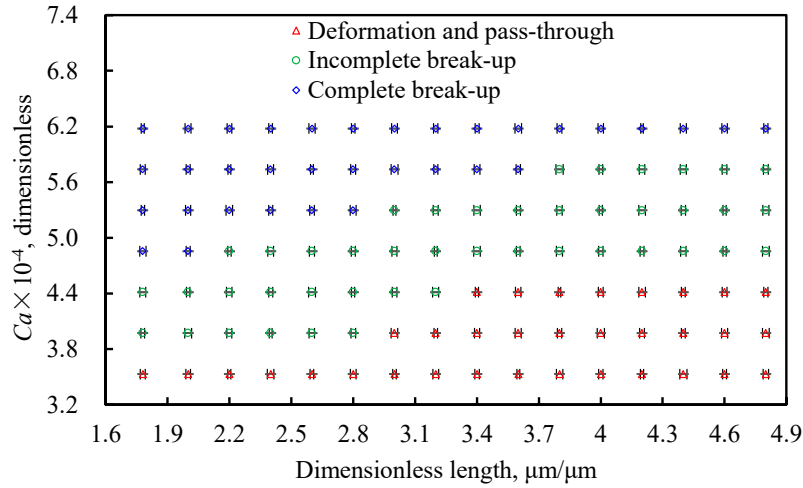


Figure 7: Distribution map at a viscosity ratio of 56.1.

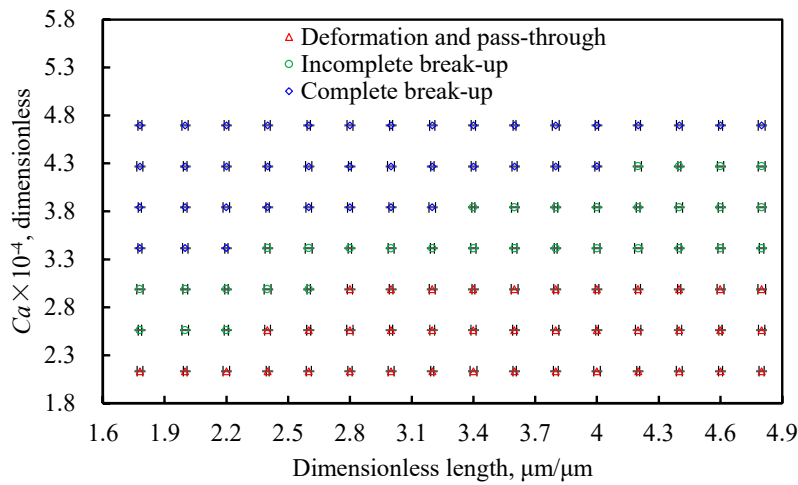


Figure 8: Distribution map at a viscosity ratio of 113.3.

3.5 Scaling to Reservoir Conditions

Although the absolute size of our model is larger than typical reservoir pores, the capillary number serves as the key dimensionless parameter governing the flow phenomena. For typical sandstone reservoirs under surfactant flooding, the capillary number of the continuous phase is estimated to be on the order of 10^{-5} to 10^{-3} . In this study, the capillary number of the continuous phase ranged from 2.13×10^{-4} to 15.96×10^{-4} . Thus, our experimental capillary number range overlaps with the capillary number range of reservoir conditions. This overlap suggests that the oil-in-water emulsion flow mechanisms observed in our simplified microfluidic model are relevant to the oil-in-water emulsion flow under reservoir conditions.

4 Conclusions

In this study, we experimentally investigated the effect of the viscosity ratio of the oil phase to the continuous phase on three flow phenomena of an oil-in-water emulsion flowing to a simplified porous media grain. Within the scope of the present experimental conditions (viscosity ratio ranging from 26.0 to 113.3; fixed channel depth, channel width, grain diameter, surfactant concentration, and continuous phase viscosity), the following conclusions can be drawn:

- (1) With the displacement of the continuous phase, oil-in-water emulsions flowing to the circular solid structure can exhibit three phenomena, including the deformation and pass-through, the incomplete break-up, and the complete break-up.
- (2) There exists a critical pass-through capillary number at which oil-in-water emulsions can exhibit deformation and pass-through, and a critical complete break-up capillary number at which oil-in-water emulsions can exhibit complete break-up. The critical complete break-up capillary number is higher than the critical pass-through capillary number.
- (3) Both the critical complete break-up capillary number and the critical pass-through capillary number decrease as the viscosity ratio of oil phase to continuous phase increases.

It should be emphasized that the quantitative values of the critical capillary number demonstrated in this work are specific to the present experimental conditions. The effects of other governing parameters, such as interfacial tension, surfactant concentration, channel depth, channel width, grain diameter, and continuous phase viscosity, were not systematically investigated in this work. Therefore, more studies are needed to explore the influence of these parameters. Such investigations would provide further insight into the microscopic interactions between the oil-in-water emulsion and the porous media grain. Moreover, although this study provides a quantitative experimental characterization, a predictive model for the transition between different phenomena is not established. The development of such a model is therefore a clear direction for future work.

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Availability of Data and Materials: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Supplementary Materials: The supplementary material is available online at <https://www.techscience.com/doi/10.32604/fdmp.2026.089107/s1>.

References

1. Yu H, Wang Y, Zhang L, Zhang Q, Guo Z, Wang B, et al. Remaining oil distribution characteristics in an oil reservoir with ultra-high water-cut. *Energy Geosci.* 2024;5(1):100116. [CrossRef].
2. Hasan MM, Al-Zuhairi FK, Sadeq AH, Azeez RA. Assessment of nanoparticle-enriched solvents for oil recovery enhancement. *Fluid Dyn Mater Process.* 2023;19(11):2827–35. [CrossRef].
3. Wu D, Yu C, Lu X, Tao D, Li X, Song H. Mechanisms and controlling factors of displacement-front evolution during chemical flooding in high water-cut reservoirs. *Fluid Dyn Mater Proc.* 2026;22(6):11. [CrossRef].

4. Alaamri J, Iglaue S, Hoteit H. Interplay of interfacial tension and capillarity: optimizing surfactant displacement efficiency in reservoirs. *J Mol Liq.* 2024;395:123915. [[CrossRef](#)].
5. Das S, Katiyar A, Rohilla N, Nguyen QP, Bonnecaze RT. Wettability alteration and adsorption of mixed nonionic and anionic surfactants on carbonates. *Langmuir.* 2020;36(50):15410–22. [[CrossRef](#)].
6. Li X, Yue XA, Zou J, Yan R. Effect of *in-situ* emulsification of surfactant on the enhanced oil recovery in low-permeability reservoirs. *Colloids Surf A Physicochem Eng Aspects.* 2022;634:127991. [[CrossRef](#)].
7. Malkin AY, Zuev KV, Arinina MP, Kulichikhin VG. Modifying the viscosity of heavy crude oil using surfactants and polymer additives. *Energy Fuels.* 2018;32(11):11991–9. [[CrossRef](#)].
8. Wang Y, Wang Q, Han Y, Zheng C, Jiang C, Wang C, et al. The structure effect on the physicochemical properties of Gemini surfactants used as viscosity reducer for heavy oil. *J Mol Liq.* 2023;390:123055. [[CrossRef](#)].
9. Chen Z, Dong M, Husein M, Bryant S. Effects of oil viscosity on the plugging performance of oil-in-water emulsion in porous media. *Ind Eng Chem Res.* 2018;57(21):7301–9. [[CrossRef](#)].
10. Ding B, Dong M. Optimization of plugging high mobility zones in oil sands by injection of oil-in-water emulsion: experimental and modeling study. *Fuel.* 2019;257:116024. [[CrossRef](#)].
11. Zhou K, Zhai M, Su K, Wei Z, Du Q, Liu Y, et al. Experimental study on *in-situ* emulsification of heavy oil in porous media. *J Mol Liq.* 2024;411:125798. [[CrossRef](#)].
12. Błaszczak MM, Sęk JP, Przybysz Ł. Modeling of flow resistance and concentration changes during the pressure transport of emulsion through porous media. *Chem Eng Res Des.* 2017;127:10–21. [[CrossRef](#)].
13. Esfandiarian A. A comprehensive visual study on *in-situ* oil-in-water and water-in-oil emulsification through oil thin film in oil-wet and mixed-wet porous media: a microfluidic approach. *J Mol Liq.* 2023;385:122331. [[CrossRef](#)].
14. Zhu X, Wang K, Yan H, Liu C, Zhu X, Chen B. Microfluidics as an emerging platform for exploring soil environmental processes: a critical review. *Environ Sci Technol.* 2022;56(2):711–31. [[CrossRef](#)].
15. Cheng Z, Li Y, Xie C, Du F, Zhao H, Yin X, et al. Effect of fracture-matrix interaction on CO₂-oil displacement via dual-permeability microfluidics. *Energy Fuels.* 2025;39(36):17386–96. [[CrossRef](#)].
16. Shaik IK, Aichele CP, Bikkina PK. Microfluidics-based low salinity wettability alteration study of naphthenic-acid-adsorbed calcite surfaces. *Energy Fuels.* 2022;36(4):1842–53. [[CrossRef](#)].
17. Wang W, Chang S, Gizzatov A. Toward reservoir-on-a-chip: fabricating reservoir micromodels by *in situ* growing calcium carbonate nanocrystals in microfluidic channels. *ACS Appl Mater Interfaces.* 2017;9(34):29380–6. [[CrossRef](#)].
18. Mohammadzadeh O, Sedaghat MH, Kord S, Zendejboudi S, Giesy JP. Pore-level visual analysis of heavy oil recovery using chemical-assisted waterflooding process—Use of a new chemical agent. *Fuel.* 2019;239:202–18. [[CrossRef](#)].
19. Xu K, Liang T, Zhu P, Qi P, Lu J, Huh C, et al. A 2.5-D glass micromodel for investigation of multi-phase flow in porous media. *Lab Chip.* 2017;17(4):640–6. [[CrossRef](#)].
20. Azizov I, Dudek M, Øye G. Studying droplet retention in porous media by novel microfluidic methods. *Chem Eng Sci.* 2022;248:117152. [[CrossRef](#)].
21. Wang H, Wei B, Hou J, Sun Z, Du Q, Zhou K. Investigation of microflow mechanisms and emulsion size distribution in porous media. *Phys Fluids.* 2023;35(10):102003. [[CrossRef](#)].
22. Cobos S, Carvalho MS, Alvarado V. Flow of oil–water emulsions through a constricted capillary. *Int J Multiph Flow.* 2009;35(6):507–15. [[CrossRef](#)].
23. Wang X, Liu Y, Liu D, Ge X, Li L, Qiu T. Droplet breakup in the square microchannel with a short square constriction to generate slug flow. *AIChE J.* 2022;68(8):e17739. [[CrossRef](#)].
24. Costa ALR, Gomes A, Cunha RL. Studies of droplets formation regime and actual flow rate of liquid-liquid flows in flow-focusing microfluidic devices. *Exp Therm Fluid Sci.* 2017;85:167–75. [[CrossRef](#)].
25. Seo S, Mastiani M, Mosavati B, Peters DM, Mandin P, Kim M. Performance evaluation of environmentally benign nonionic biosurfactant for enhanced oil recovery. *Fuel.* 2018;234:48–55. [[CrossRef](#)].