Dynamic Behaviors and Mechanisms of Air-Foam Flooding at High Pressure and Reservoir Temperature via Microfluidic Experiments

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ABSTRACT: Air injection has been proven to be an effective improved oil recovery technique for deep and light oil reservoirs with low permeability and poor water injectivity. But the efficiency of air injection in highly heterogeneous reservoirs is low due to poor gas sweeping that may lead to early oxygen breakthrough caused by gas channeling and viscous fingering. Foam can be used to assist air injection to overcome the obstacles of early gas breakthrough and to increase the displacement and sweeping efficiency. In this paper, laser-etched visual microscopic pore models were used as microfluidic devices to study the air-foam flooding process in porous media at reservoir temperature and high pressure. The dynamic behaviors and relevant mechanisms of air-foam flooding were investigated. Typical mechanisms of foam generation in porous media are achieved in different parts of the micromodel, which can be listed as follows: lamella leave-behind, lamella division, and snap off. Analysis on flow states of air foam showed that foams migrate in porous media by bursting and regenerating during the flooding process. It can be observed that the flow mode of foam in porous media is the separate flow of gas and liquid through microscopic displacement experiments, suggesting that foam should not be treated as a homogeneous phase in heterogeneous porous media. The pressing, occupying, and selective blocking effects of foam in porous media exhibited different oil displacement performances with the presence of various pore geometries and networks. Tiny foams also showed stripping and carrying effects on larger oil droplets benefiting from the lipophilicity of foam. Through comprehensive analysis on overall and local oil displacement mechanisms, air-foam injection could enhance the microscopic sweep volume and improve the oil displacement efficiency.

1. INTRODUCTION

In recent years, proven oil reserves in low-permeability reservoirs make up a growing percentage of the totally proven oil reserves worldwide.1−3 The main challenges associated with oil production in low-permeability reservoirs are as follows: (1) the oil production declines rapidly induced by the fast decrease in near-wellbore reservoir pressure during the primary recovery process using natural power; (2) the injection pressure increases with improved starting pressure gradient; (3) the efficiency of oil recovery with the water flooding process is poor due to low absorbing capacity.4 These phenomena are mostly caused by the existence of a starting pressure gradient in low-permeability reservoirs and the zones with high resistance and thick fluidity between oil and water wells.5 Previous studies have shown that enhancing oil recovery by gas injection (including natural gas injection, CO₂ injection, N₂ injection, air injection, flue gas injection, etc.) is an effective method to improve oil recovery in reservoirs with the problems of low permeability, high water cut, and water sensitivity.6−9 Although the injection feasibilities of natural gas, CO₂, and N₂ have been demonstrated in both laboratory and field pilot experiments, large-scale field applications may be restricted by the gas source or economic cost.10 Hence, injected gas sources that are cheap and widely available are needed to meet the demand of field application. Air injection in low-permeability reservoirs has been regarded as an economic and effective secondary and tertiary recovery technology coupled with advantages of wide source, low cost, and broad prospects.11

Air injection in low-permeability reservoirs can not only complement production energy but also speed up oil production. In particular, improved oil displacement efficiency can be achieved from additional thermal effects generated by low-temperature oxidation reactions between oil and O₂ in air. The LTO reaction of crude oil is a very complicated process. However, it can be simplified into two steps: oxidation and decarbonylation. Crude oil is first oxidized to produce hydrocarbon oxides and water, and then the decarbonylation reaction occurs, producing CO₂ and other products. After air injection into low-permeability and light oil reservoirs, O₂ can be consumed through low-temperature oxidation reactions,

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which will generate hydrocarbon oxygenates and CO\textsubscript{2}. In the oxidation processes, the generated heat can increase the reservoir temperature and promote the volatilization of light components in oil. Therefore, the displacement performance is directly achieved by the flue gas, which is composed of CO\textsubscript{2} and N\textsubscript{2} generated in reservoirs and light components extracted from oil.\textsuperscript{12,13} Generally speaking, air injection into low-permeability and light oil reservoirs is an effective method that can improve oil recovery more economically and efficiently with important practical significance and broad market prospects.

Nevertheless, it is not easy to obtain ideal oil displacement performance in strong heterogeneous reservoirs by merely applying air injection. Low sweep efficiency and recovery during the air injection process arise from gravity override, viscous fingering, and channeling through reservoir heterogeneities.\textsuperscript{14} Further, there are great concerns on the application of air injection, which are mainly due to the safety and explosion of flammable natural gas and O\textsubscript{2} caused by air channeling and viscous fingering.\textsuperscript{15,16} Foam is one of the proper candidates to assist air injection to overcome the obstacle of O\textsubscript{2} early breakthrough and the associated safety problems with advantages of reduced gas–liquid relative permeability, enhanced oil displacement efficiency, and increased swept volume.\textsuperscript{15,17} With the addition of polymer and alkali into foam agent solution, the generated foam quality and stability will be improved greatly and enhanced viscoelasticity with low interfacial tension can be achieved at the same time. Under this condition, the generated foam has a larger foam volume, finer morphology, and more stable characteristics than ordinary foam. The enhanced air foam can also enter a tiny pore throat to displace more oil with the stronger ability of antideformation.\textsuperscript{18,19} Air Foam flooding combines the superiorities of air injection, ASP flooding, and foam flooding, which can enlarge swept volume, improve oil displacement efficiency, block gas channeling, and reduce water cut. There are many kinds of reservoirs in which air foam profile control and displacement technology can be applicable including the secondary and tertiary oil recovery in low-permeability reservoirs with serious heterogeneity, blocking gas or water channeling and enhancing oil recovery in low-permeability reservoirs with the existence of microfractures or big channels. However, few studies on dynamic behaviors and performances of air foam flooding have been conducted in realistic reservoir pore medium and at high pressure using visual microfluidic devices. Therefore, it is necessary to carry out research works on the dynamic behaviors and relevant mechanisms of air foam flooding from a microview, which can exhibit the intrinsic mechanism of air foam profile control and displacement.

Porous medium micromodels in different devices with various materials have been used to better understand multiphase fluid transport at the pore-level scale. Micromodel systems allow real-time, in situ observation of relevant fluid transport in complex systems involving multiple phases, pore geometries, and fractures. With the maturing of laser etching model manufacturing technology, many researchers use this kind of micromvisual model more frequently to study the mechanisms of gas-water relative permeability, water alternating gas injection, polymer flooding, etc.\textsuperscript{17,20} Using microvisual models to study the mechanisms of foam flooding also received extensive attention. Conn et al. studied the oil displacement with foam in a microfluidic device with permeability contrast. The results showed an increase in apparent viscosity for foam with an accompanying decrease in oil saturation. Foam was shown to more effectively mobilize trapped oil by increasing the flow resistance in the fracture and high-permeability zones and by diverting the surfactant solution into adjacent low-permeability zones.\textsuperscript{17} Marmottant and Raven described the spontaneous generation and flow of foams within microchannels. Their work indicated that the bubbles come into contact and flow as a crystalline foam when their concentration is high enough in a channel. The experimental results also showed that the flow of the foams depends strongly on the arrangement of bubbles within the channel, which entails original dynamic behaviors such as the superstability of the flow or, on the contrary, spontaneous oscillations.\textsuperscript{21} Zhou et al. carried out a series of micromodel and core-flooding experiments to investigate the feasibility of polymer-enhanced foam flooding for the thin heavy oil reservoirs. Their results showed that foam quality has significant effects on the resistance factor and heavy oil recovery of the PEF flooding using micromodels. Further core-flooding experiments revealed that there is an optimal slug size under the experimental conditions.\textsuperscript{19} Quennouz et al. studied foam flow in different channel geometries using microfluidic devices in the framework of EOR. Two processes of foam formation were investigated, including co-injection of water and gas illustrated by a phase diagram or fragmentation of large bubbles by porous media and the flow of foam in a comb-like channel with a “two permeabilities” geometry. Their observations may be a basic illustration of some principles of EOR with foams.\textsuperscript{22} Das et al. investigated foam–microemulsion interaction during low-tension gas flooding using microfluidics in a pore scale. The results showed that the presence of foam facilitates faster and better oil displacement. The microemulsion equilibration time was improved in the presence of foam due to the increased mixing of the liquid phases. The presence of trapped gas helped divert the flowing surfactant/microemulsion to regions with trapped remaining oil and thus improved oil recovery.\textsuperscript{23} Nguyen et al. studied the effectiveness of supercritical-CO\textsubscript{2} and N\textsubscript{2} huff-and-puff methods of enhanced oil recovery in shale fracture networks using micro-experiments. Their results exhibited that supercritical CO\textsubscript{2} huff-and-puff injection can significantly increase recovery in shale and gas injection is more effective in connected fracture networks. The visualization results also revealed the mechanisms of bubble nucleation, growth, and coalescence in fracture networks. Significantly, their works indicated that the efficiency of the huff-and-puff process is dependent on the solubility and miscibility of the injection fluid with oil.\textsuperscript{24}

In this paper, the laser-etched visual microscopic pore model is adopted to investigate the air-foam flooding process in multiporous media at high pressure and reservoir temperature. Dynamic behaviors and mechanisms of air-foam displacement are researched using this microfluidic device. Microfluidic studies are also conducted to examine the microscale sweep mechanisms of air foam especially for the heterogeneous reservoir model. These results can provide references for the application of air-foam flooding field work.

2. EXPERIMENTAL SECTION

Microfluidic chips were used in this study for direct visualization of fluid injection, multiphase flow, and oil recovery processes. The microfluidic chip to simulate the porous media is a laser-etched glass visual microscopic pore...
model with the dimension of 40 mm × 40 mm and the diameter of aperture ranging from 50 to 800 μm. The wettability of chips used for experiments is water-wet. The pore distribution of the heterogeneous visual microscopic pore model is exhibited in Figure 1.

Figure 1. Heterogeneous 2D micromodel.

The simulated oil was achieved after mixing simethicone and kerosene with a proportion of 1:1 and dyeing the mixture red with eosin. The salinity of simulated formation water is 20,000 mg/L, and it was dyed blue with methyl blue. The alkaline/surfactant/polymer (ASP) flooding system includes sodium hydroxide (content ≥ 96.0%, Tianjishi Baishi Chemical Co., Ltd.), sodium dodecylbenzenesulfonate (content ≥ 90.0%, Sinopharm Chemical Reagent Co., Ltd.), polyacrylamide (solid content of 85.0% above, Sinopharm Chemical Reagent Co., Ltd.), and distilled water. The concentration of sodium dodecylbenzenesulfonate is 1% with a moderate amount of sodium hydroxide and polyacrylamide. The gas source applied in these microfluidic experiments is air with a purity of 99.99%, which was purchased from Qingdao Tianyuan Gas Manufacturing Co., Ltd.

The microscope camera system was adopted to record a real-time video during the experimental process, and the displacement power was provided by a constant-flux pump. The resolution of the microscope camera is 1280 × 1024. The experimental temperature is set at 70 °C with a backpressure of 0.6 MPa and a displacing velocity of 0.01 mL/min. In this work, the pictures of the microscopic oil displacement process in the microscopic pore model were converted into digital computer signals. The microfluidic experimental apparatus is depicted schematically in Figure 2.

The experimental device consists of the following: (1) an injection system with a positive displacement pump for injecting different fluids into the microscopic pore model through floating-piston transfer cylinders; (2) a model holder inside of which a high-temperature and pressure visual microscopic pore model is placed; (3) a sample collection system that collects the produced oil and brine; (4) microscope camera system and computer to collect the real-time pictures and videos and convert them into digital signals. A typical picture achieved during the experimental process is exhibited in Figure 3. The maximum working pressure and temperature of this microfluidic device are 3 MPa and 100 °C, respectively. In Figure 3, the blue, light red, and transparent parts represent saline, oil, and foam, respectively. The microscope camera was first adjusted to capture the experimental processes. Then, the microfluidic model was vacuumed using a vacuum pump. Prior to the microscopic oil displacement, brine and then oil saturation was conducted until connate water saturation was reached. An initial water

Figure 2. Schematic figure of the flow diagram of micromodel tests.

Figure 3. Distribution of saline, simulated oil, rock particles, and foam during the air-foam flooding process.
flooding (or air injection) was then started until oil production became negligible. After the initial air injection, the model was subjected to air-foam flooding and then water flooding. The ratio of air to ASP solution is set at 1:1 during the co-injection process. The displacing velocity of 0.01 mL/min was adopted during the flooding process. The microscopic displacement process was monitored by the microscope camera throughout the whole experiment process. After changing the experimental scheme, the above procedures were repeated.

3. RESULTS AND DISCUSSION

3.1. Mechanisms of Air-Foam Generation. Air-foam generation mechanisms are captured and analyzed in these microfluidic experiments, including lamella leave-behind, lamella division, and snap-off in porous media. The relevant behaviors and their descriptions are exhibited as follows.

3.1.1. Lamella Leave-Behind. As shown in Figure 4, the phenomenon of lamella leave-behind refers to the formation of a “concave lens”-like liquid film when air passes through the porous channels that are occupied by liquid. The generated liquid film is parallel to the flow direction that cannot lead to a significant increase in fluid resistance. Therefore, continuous foam can generate from this effect and be regarded as weak foam.

3.1.2. Lamella Division. Lamella division takes place after the liquid film comes into being and the pressure gradient is needed to encourage the locomotion of lamella. When the lamella encounters two or more forks in flow channels, it will be divided into two or more bubbles and each bubble flows along the corresponding channel. The liquid films created from this effect are perpendicular to the flow direction, which can increase the number of flowing liquid films. As shown in Figure 5, foams generated from this effect are discontinuous, which lead to improved flow resistance and exhibit the performance of strong foam.

3.1.3. Snap-Off. The so-called snap-off is a kind of mechanical process that occurs when multiphase fluids flow through pores. Foams generated from the effect of snap-off are also strong and discontinuous. This effect comes into play when the gaseous phase passes through the pore throat and the pressure of the pore throat end is greater than that before the lamella interface. As depicted in Figure 6, the single bubble will be cut off into two bubbles when it passes through the pore throat. The capillary pressure (CP) plays an important role in the process of snap-off. First, the CP must be equal to or greater than the capillary inlet pressure before air can enter the pore throat. Second, the snap-off effect cannot be achieved unless the CP is reduced to a critical value. Meanwhile, the snap-off phenomenon also depends on pore geometry, fluid saturation, and heterogeneity.

3.2. Flow State of Foam in Porous Media. It can be observed that the flow mode of foam in porous media is the separate flow of gas and liquid through microscopic displacement experiments. Gas–liquid contact can produce abundant liquid films. As shown in Figure 7, the liquid phase flows in the liquid film net and fine pore. However, air migrates through the porous media by the deformation and rupture of liquid films in the pore throat and regeneration of liquid films after getting through the pore throat. The liquid portion of the injected air foam requires lower pressure gradients than the gas portion to invade small pores, so low-permeability regions become liquid-enriched. High-permeability regions become
gas-rich as bubbles are immobilized and lamella-drained. At the same time, the liquid film tends to move along the pore wall with the presence of hydrophilic wettability. All these factors induce this special flow state of air foams in porous media based on the microfluidic device. This phase separation of the injected foam suggests that foam should not be treated as a homogeneous phase in heterogeneous porous media.

3.3. Air-Foam Flooding Characteristics in Porous Media. 3.3.1. Squeezing and Occupying Effects of Air Foam. As exhibited in Figure 8, foams can squeeze and shear the oil droplets, which push oil droplets out within regular connected channels in porous media. Then, the channels will be occupied by the foams. As shown in Figure 9, for dead-end pores, small bubbles are first squeezed into the entrances of blind ends by fast moving larger bubbles and then pushed into the deep blind ends by the subsequent bubbles. The space of oil droplets can be occupied by the intrusive small bubbles, and the oil phase in the blind ends will be discharged along the edges of foam liquid films.

3.3.2. Selective Blocking Effect on a Large Pore Path. As shown in Figure 10, foams tend to flow in larger pores and gather along the wall of pore paths, which will induce larger flow resistance and block large pore path selectively. The accumulations of the Jamin effect and the enhanced apparent viscosity of the foam system in larger pores contribute to the selective blocking performance. With displacement going on, remaining oil around the big bubbles will be continuously driven and the big bubbles remain at the original position in the pore paths.

3.3.3. Cutting-Off and Carrying Effects of Foam. During the migration processes of fine foams generated from air-foam flooding, foams first attach to the oil droplets because of the oleophilic property of foam. Then, the cutting-off effect of foam works to divide the oil droplets into smaller ones and urge them to move forward under the action of pressure differences. As shown in Figure 11, this process repeats and bigger oil droplets are divided into smaller ones until oil droplets are completely cleaned out with the development of displacement.

3.4. Oil Displacement Mechanisms of Air-Foam Flooding. 3.4.1. Improved Microscopic Swept Volume. In the processes of water flooding and air flooding after oil saturation (as exhibited in Figure 12-1), water and air mainly transport in relatively larger pore paths, which induced that many other smaller pore paths cannot be swept (as shown in Figure 12-2,3). Inversely, the major portion of pore paths can be swept with application of air-foam flooding as exhibited in Figure 12-4. By comparing Figure 12-2 (water flooding after oil saturation) with Figure 12-5 (air-foam flooding after water flooding), the effect of air-foam flooding on improving swept volume can be observed obviously. The Jamin effect is an important mechanism for foam flooding to control mobility. Mobility refers to the ratio of the relative permeability to the viscosity of the displacing phase or the displaced phase. The strength and frequency of the Jamin effect determine the effectiveness of foam mobility control. Because of the larger pores and throats presented in a high-permeability reservoir, the injected air foams will preferentially flow into the high-permeability zone with low flow resistance. Further, the subsequently injected fluids tend to flow into smaller pores and throats with the positive roles of the Jamin effect. Meanwhile, sweep performance is related to the viscosity of injecting fluid: a higher viscosity can provide a lower mobility ratio and better overall sweep performance.
Although air foam is a dispersion of separate phases, it is sometimes treated as a single phase with an apparent viscosity. Hence, the improved blocking and mobility control ability and sweep efficiency are achieved.

3.4.2. Enhanced Oil Displacement Efficiency. Air has relatively higher mobility than oil and water, so the residual oil in blind ends of pore paths and tiny pore throats is difficult to be displaced (shown in Figure 13-1). With the good oil displacement performance of foam, the residual oil can be almost cleaned out after air-foam flooding as exhibited in Figure 13-2. During the enhanced oil recovery process, residual oil saturation ($S_{or}$) is mainly determined by the capillary number ($N_{cap}$), which is defined as the ratio of viscous force to capillary force, as shown in the following equation:

$$N_{cap} = \frac{\text{viscous force}}{\text{capillary force}} = \frac{\nu \mu}{\sigma \cos \theta}$$  \hspace{1cm} (1)

where $\nu$ and $\mu$ are the velocities of displacing fluid (injected water or air), $\sigma$ is the interfacial tension (IFT) between displaced fluid (oil) and displacing fluid, and $\theta$ is the contact angle. The oil recovery increases with the increase in $N_{cap}$. The corresponding $N_{cap}$ value for gas flooding is three orders of magnitude smaller than that for foam flooding. With the presence of air foam, the viscosity of displacing fluid will be enhanced. Foam agents in the liquid film can serve as surfactants, which will lower the IFT. Hence, the EOR mechanism using air-foam flooding mostly involves the increasing number of capillaries from these two aspects.

4. CONCLUSIONS

1. Air-foam generation mechanisms, including lamella leave-behind, lamella division, and snap-off, in porous media at high pressure and reservoir temperature are exhibited by a series of microfluidic experiments.

2. The flow mode of air foam in porous media is identified as the separate flow of gas and liquid through microscopic displacement experiments. Air foams migrate in porous media by bursting and regenerating during the flooding process.

3. Microscopic oil displacement characteristics of air-foam flooding in porous media mainly consist of pressing and
occupying effects, selective blocking effect on a large pore path, and cutting-off and carrying effects.

4. The oil recovery is greatly improved with the effects of improved microscopic swept volume and enhanced oil displacement efficiency during the air-foam flooding process in porous media, given the accumulation of the Jamin effect and increased capillary number.

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**Notes**

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**REFERENCES**

(1) Tian, F.; Zhao, Y.; Yan, Y.; Gou, X.; Shi, L.; Qin, F.; Shi, J.; Lv, J.; Cao, B.; Li, Y.; Lu, X. Analysis of the static and dynamic imbibition effect of surfactants and the relative mechanism in low-permeability reservoirs. ACS Omega 2020, 5, 17442–17449.

(2) Liu, Q.; Wu, K.; Li, X.; Tu, B.; Zhao, W.; He, M.; Zhang, Q.; Xie, Y. Effect of displacement pressure on oil-water relative permeability for extra-low-permeability reservoirs. ACS Omega 2021, 6, 2749–2758.

(3) Zhang, L.; Zhang, J.; Wang, Y.; Yang, R.; Zhang, Y.; Gu, J.; Zhang, M.; Ren, S. Experimental investigation of low-salinity water flooding in a low-permeability oil reservoir. Energy Fuels 2018, 32, 3108–3118.

(4) Wang, D.; Luo, Y.; Lai, R.; Cui, K.; Li, H.; Zhang, Z.; Zhang, Y.; Shi, R. New technique for enhancing oil recovery from low-permeability reservoirs: the synergy of silica nanoparticles and biosurfactant. Energy Fuels 2021, 35, 318–328.

(5) Yun, M.; Yu, B.; Cai, J. A fractal model for the starting pressure gradient for Bingham fluids in porous media. Int. J. Heat Mass Transfer 2008, 51, 1402–1408.

(6) Zhao, Y.; Song, Y.; Liu, Y.; Liang, H.; Dou, B. Visualization and measurement of CO₂ flooding in porous media using MRI. Ind. Eng. Chem. Res. 2011, 50, 4707–4715.

(7) Xu, Z.; Li, B.; Zhao, H.; He, L.; Liu, Z.; Chen, D.; Yang, H.; Li, Z. Investigation of the effect of nanoparticle-stabilized foam on EOR: nitrogen foam and methane foam. ACS Omega 2020, 5, 19092–19103.

(8) Chen, Z.; Wang, L.; Duan, Q.; Zhang, L.; Ren, S. High-pressure air injection for improved oil recovery: low-temperature oxidation models and thermal effect. Energy Fuels 2013, 27, 780–786.

(9) Chen, H.; Li, H.; Li, Z.; Li, S.; Wang, Y.; Wang, J.; Li, B. Effects of matrix permeability and fracture on production characteristics and residual oil distribution during flue gas flooding in low permeability/tight reservoirs. J. Pet. Sci. Eng. 2020, 195, No. 107813.

(10) Li, D.; Ren, S.; Zhang, P.; Zhang, L.; Feng, Y.; Jing, Y. CO₂-sensitive and self-enhanced foams for mobility control during CO₂ injection for improved oil recovery and geo-storage. Chem. Eng. Res. Des. 2017, 120, 113–120.

(11) Fan, C.; Zan, C.; Zhang, Q.; Shi, L.; Hao, Q.; Jiang, H.; Wei, F. Air injection for enhanced oil recovery: in situ monitoring the low-temperature oxidation of oil through thermogravimetry/differential scanning calorimetry and pressure differential scanning calorimetry. Ind. Eng. Chem. Res. 2015, 54, 6634–6640.

(12) Huang, S.; Zhang, Y.; Sheng, J. J. Experimental investigation of enhanced oil recovery mechanisms of air injection under a low-temperature oxidation process: thermal effect and residual oil recovery efficiency. Energy Fuels 2018, 32, 6774–6781.

(13) Zhang, L.; Deng, J.; Wang, L.; Chen, Z.; Ren, S.; Hu, C.; Zhang, S. Low-temperature oxidation characteristics and its effect on the critical coking temperature of heavy oils. Energy Fuels 2015, 29, 538–545.

(14) Wu, F.; Liu, J.; Wei, X.; Pu, C. A study on oxygen consumption mechanism of air-flooding in low-temperature oil reservoir. J. Pet. Sci. Eng. 2018, 161, 368–380.

(15) Huang, L.; Wang, Y.; Yang, Z.; Wang, Q.; Pei, S.; Zhang, L.; Ren, S. Flammability and explosion characteristics of methane in oxygen-reduced air and its application in air injection IOR Process. Energy Fuels 2019, 33, 11850–11860.

(16) Huang, L.; Wang, Y.; Li, Z.; Zhang, L.; Yin, Y.; Chen, C.; Ren, S. Experimental study on piloted ignition temperature and autoignition temperature of heavy oils at high pressure. Energy 2021, 229, No. 120644.

(17) Conn, C. A.; Ma, K.; Hirasaki, G. J.; Biswal, S. L. Visualizing oil displacement with foam in a microfluidic device with permeability contrast. Lab Chip 2014, 14, 3968–3977.

(18) Wu, W.; Fan, J.; Guo, M. Mechanisms of oil displacement by ASP-foam and its influencing factors. Pet. Sci. 2010, 7, 100–105.

(19) Zhou, W.; Xin, C.; Chen, S.; Yu, Q.; Wang, K. Polymer-enhanced foam flooding for improving heavy oil recovery in thin reservoirs. Energy Fuels 2020, 34, 4116–4128.

(20) Lifon, V. A. Microfluidics: an enabling screening technology for enhanced oil recovery (EOR). Lab Chip 2016, 16, 1777–1796.

(21) Marmottant, P.; Raven, J.-P. Microfluidics with foams. Soft Matter 2009, 5, 3385.

(22) Quennouz, N.; Ryba, M.; Argillier, J. F.; Herzhaft, B.; Peysson, Y.; Panaccioni, N. Microfluidic study of foams flow for enhanced oil recovery (EOR). Oil Gas Sc. Technol. 2014, 69, 457–466.

(23) Das, A.; Mohanty, K.; Nguyen, Q. A pore-scale study of foam-microemulsion interaction during low tension gas flooding using microfluidics - Tertiary recovery. J. Pet. Sci. Eng. 2021, 203, No. 108596.

(24) Nguyen, P.; Carey, J. W.; Viswanathan, H. S.; Porter, M. Effectiveness of supercritical-CO₂ and N₂ huff-and-puff methods of enhanced oil recovery in shale fracture networks using microfluidic experiments. Appl. Energy 2018, 230, 160–174.

(25) Wen, Y.; Lai, N.; Du, Z.; Xu, F.; Zhang, X.; Han, L.; Yuan, L. Application of orthogonal experiment method in foam flooding system composition and injection parameter optimization. J. Pet. Sci. Eng. 2021, 204, No. 108663.

(26) Niu, J.; Liu, Q.; Lv, J.; Peng, B. Review on microbial enhanced oil recovery: Mechanisms, modeling and field trials. J. Pet. Sci. Eng. 2020, 192, No. 107350.

(27) Simjoo, M.; Dong, Y.; Andrianov, A.; Talanana, M.; Zitha, P. L. J. CT scan study of immiscible foam flow in porous media for enhanced oil recovery. Ind. Eng. Chem. Res. 2013, 52, 6221–6233.