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Experimental Study of Foamy Oil Solution Gas Drive Process in an Etched Glass Micromodel

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Abstract. Foamy oil phenomenon is of great significance for the exploitation of some heavy oil reservoirs. Many researchers have conducted a lot of research on foamy oil, but there is still no systematic research on why foamy oil phenomenon only appears in some special heavy oil reservoirs. Therefore, it is of great significance to study the formation of foamy oil in depth. This paper simulates the process of three kinds of heavy oil solution gas drive processes with different types of heavy oil under the formation conditions in an etched glass micromodel, and the flow characteristics of gas bubbles in the micromodel were observed. The results show that the location of gas bubbles nucleation was mainly distributed in the main channel and the rock surface of the micromodel. Compared with gas bubbles in the foamy oil, the dispersed gas bubbles in the conventional heavy oil had a shorter existence time and no obvious foamy oil phenomenon, the size of gas bubbles in the conventional heavy oil was larger, and the migration, growth and coalescence rate were faster.

1. Introduction
Heavy oil is abundant in the world. How to effectively and economically develop heavy oil resources has become the key to solve the current energy contradiction. Foamy oil flow occurs in some Canadian and Venezuelan heavy oil reservoirs [1-3]. The foamy flow occurs when the solution gas is released and dispersed in oil phase during the primary production [4-11]. Currently, there is still no systematic research on why foamy oil phenomenon occurs only in those special heavy oil reservoirs. Therefore, it is very important to study the formation of foamy oil in depth. The micromodel experiment is a good method to study flow mechanisms of fluids in porous media [12-17]. In the experiments, the heavy oils with and without foamy oil phenomenon were used to simulate solution gas drive processes under the reservoir conditions. The nucleation, growth, coalescence, and breakup of gas bubbles in the foamy oil were observed in the experiments. Meanwhile, the mechanism of foamy oil phenomenon was analyzed at the microscopic view by comparing the gas bubbles flow characteristics in foamy oil and conventional heavy oils.

2. Experimental materials and setup
The crude oil samples used in the experiments were Venezuela Orinoco heavy crude oil (foamy oil), Bohai Bay heavy crude oil (conventional heavy oil), and Xinjiang heavy crude oil (conventional heavy

oil). The gas was a mixture of methane and carbon dioxide, and the molar fractions of the two are 88.9% and 11.1% respectively. The etched glass micromodel has a porosity of 33.56%, a permeability of 16.3 D. The setup is shown schematically in Figure 1.
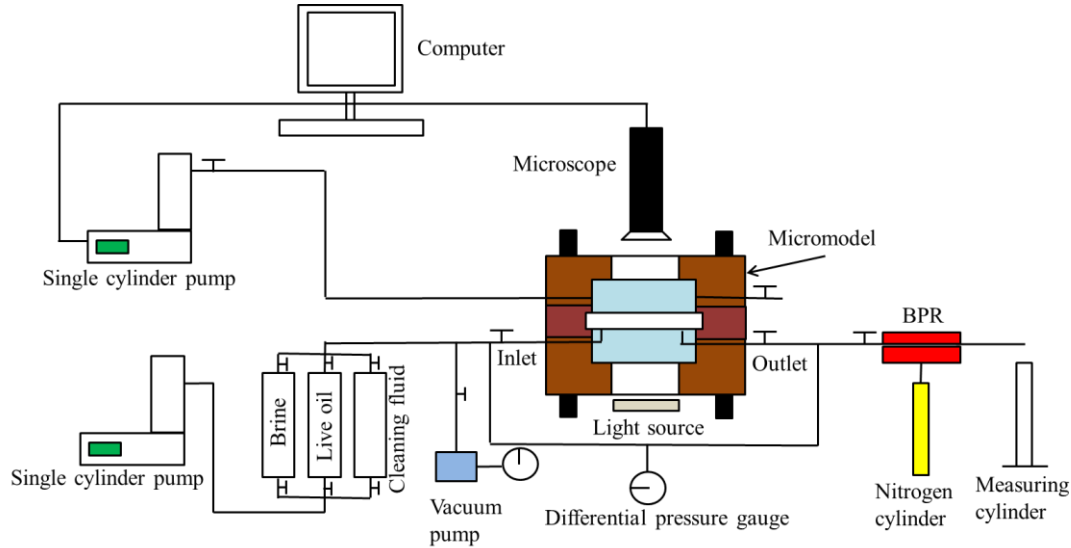
Figure 1. Schematic of experimental set-up

3. Experimental procedure

All experiments were carried out at 54.2 ℃. The experiments included the following steps: 1. The micromodel was cleaned with toluene, methylene chloride, acetone, and de-ionized water; 2. Then the brine was injected to saturate the micromodel at a pressure higher than the bubble point pressure of the oil; 3. Live oil was flushed through the micromodel for a sufficiently long time until the water inside the model became immobile; 4. The pressure was gradually reduced by decreasing the BPR pressure. The pressure depletion rate was 0.6 MPa/h. The experimental parameters are shown in Table 1.

Table 1. Experimental parameters

| Test No.	Oil sample	Temperature	Pressure	Pressure depletion rate	Solution gas-oil ratio
		°C	MPa	MPa/h	m^3/m^3
1	Orinoco heavy oil	54.2	6	0.6	15
2	Bohai Bay heavy oil	54.2	6	0.6	15
3	Xinjiang heavy oil	54.2	6	0.6	15

4. Results and analysis

4.1. Flow characteristics of gas bubbles in foamy oil

4.1.1. Nucleation and growth of gas bubbles. When the pressure reduced below the bubble point pressure of the foamy oil, the solution gas in the foamy oil was released from the oil. The reduced pressure led to the nucleation of gas bubbles within the pores in the micromodel. A further decline in pressure caused the gas bubbles to grow and migrate towards the outlet end of the micromodel. There are two kinds of gas bubbles nucleation: primary nucleation and secondary nucleation. Primary nucleation refers to the nucleation process in which no bubble nucleus exists in the crude oil and the gas molecules spontaneously form bubble nucleus. Secondary nucleation refers to the formation of new bubble nuclei induced by the original bubble nucleus.

Generally, there are cracks or depressions on the surface of the rock, which are the main sites for

secondary nucleation of gas bubbles. Primary nucleation is a common form of bubble nucleation in oilfield development. Primary nucleation includes both primary homogeneous nucleation and primary heterogeneous nucleation. Researchers have shown that primary heterogeneous nucleation is the main form of gas bubble nucleation in porous media [18]. Therefore, if crude oil contains a large amount of asphaltenes or colloidal particles, the gas bubble nucleation rate will be relatively high, which may be an intrinsic reason for the formation of foamy oil phenomenon.

As shown in Figure 2 and Figure 3, there are two types of gas bubble nucleation and growth processes. Figure 2 shows that gas bubble nucleated on a crystal particles surface with a scale of 20 microns. Figure 3 shows that gas bubble nucleated on a surface of rock. From Figure 2 and Figure 3, we can observe that with the migration of gas bubbles, the size of gas bubbles increased continuously. The change of micromodel pressure is the reason of gas bubbles growth. The decrease of micromodel pressure promotes the growth of gas bubbles. It found that the nucleation and growth of gas bubbles were not uniform distribution, and the growth rate of gas bubbles in the main channel was faster. In the edge position of the micromodel, gas bubbles may be produced rapidly and grow slowly (Figure 2 shows the edge position of the micromodel, and Figure 3 shows the main channel of the micromodel). Therefore, the gas bubble nucleation and growth are related to the crude oil composition distribution, the depletion rate, and other factors.
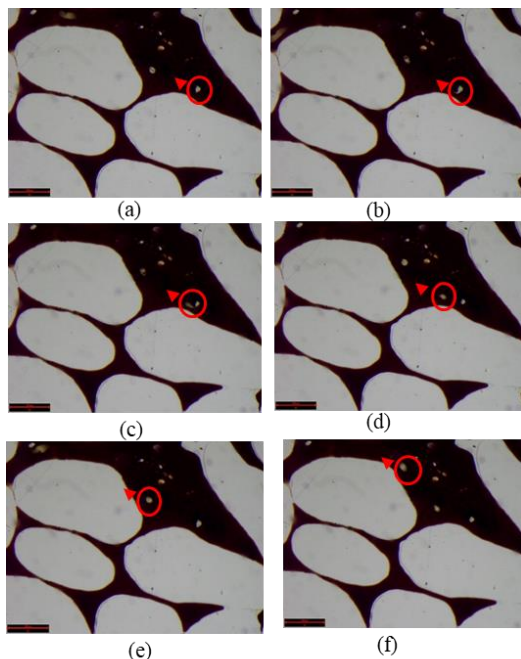
Figure 2. Gas bubbles' nucleation process on the surface of crystal particles (3.83 MPa, time delay is 8 s)
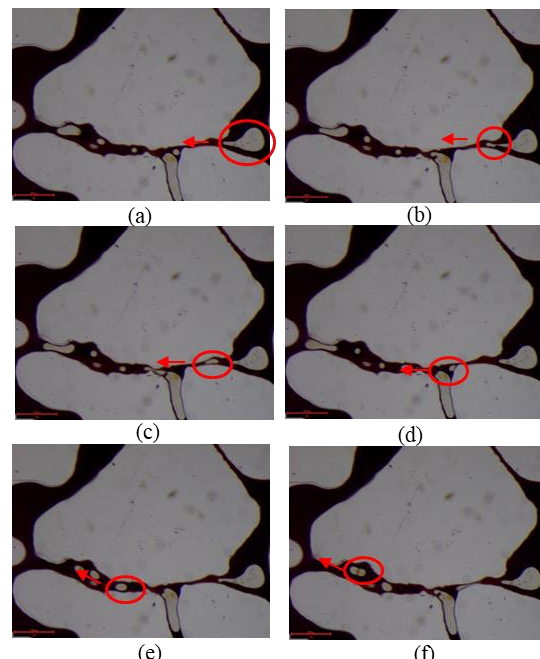

Figure 3. Gas bubbles' nucleation process on the surface of rocks (3.83 MPa, time delay is 8 s)

It can be seen from Figure 2 and Figure 3 that the gas bubbles formed in foamy oil are dispersed in oil, unlike the gas bubbles formed by other conventional heavy oils or light oils where gas bubbles quickly coalesced and formed the continuous gas phase. The oil couldn't flow with the solution gas after the gas bubbles formed continuous gas phase in conventional heavy oils. But in foamy oil, the heavy oil flowed with the dispersed gas bubbles.

4.1.2. Gas bubble breakup. Gas bubble breakup is an important mechanism of foamy oil flow in porous media. Because of gas bubble breakup, the gas bubbles can be dispersed in the heavy oil. Gas bubble breakup is affected by rock particles, pore distribution and smaller size gas bubbles.

As shown in Figure 4, when a gas bubble passed through a narrow pore, the gas bubble was elongated

and deformed. The gas bubble moved slowly, and the gas bubble was elongated and broken into several small gas bubbles. As shown in Figure 5, a large gas bubble flowed to the convex edge of the pore, and the large gas bubble broken up into two parts, and the two parts flowed in the different pores respectively. It's found that the breakup was due to the blockage of the rock during the flow of the gas bubbles. This form of breakup is the most common form of gas bubble breakup in foamy oil. As shown in Figure 6, due to the stable oil/gas interface of the gas bubble in the foamy oil, the large gas bubble couldn't coalesce with small gas bubble when it was close to small gas bubble. The large gas bubble was divided into two small gas bubbles. This is because the smaller the gas bubbles diameter is, the stronger the liquid film is.
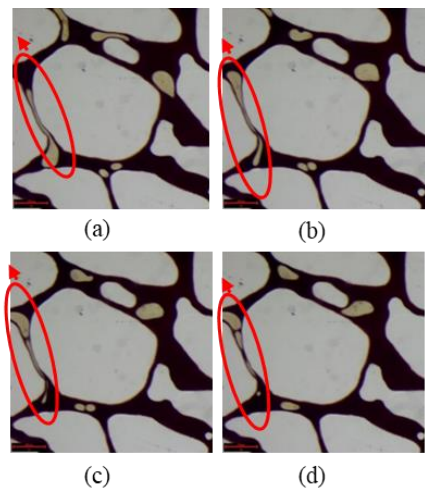
Figure 4. Gas bubbles' breakup process affected by narrow pores (2.61 MPa, time delay is 5 s)
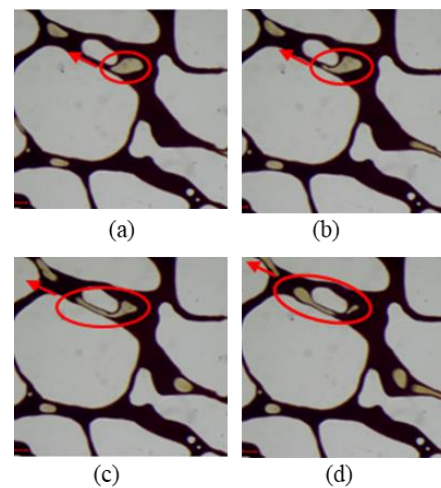
Figure 5. Gas bubbles' breakup process affected by rock' blocking (2.61 MPa, time delay is 5 s)
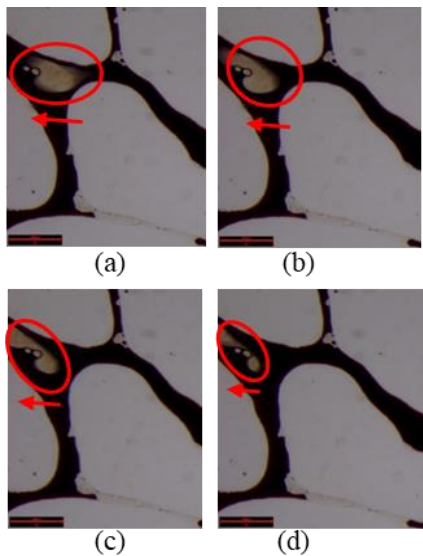
**Figure 6.** Gas bubbles' breakup process affected by small gas bubble (2.69 MPa, time delay is 5 s)
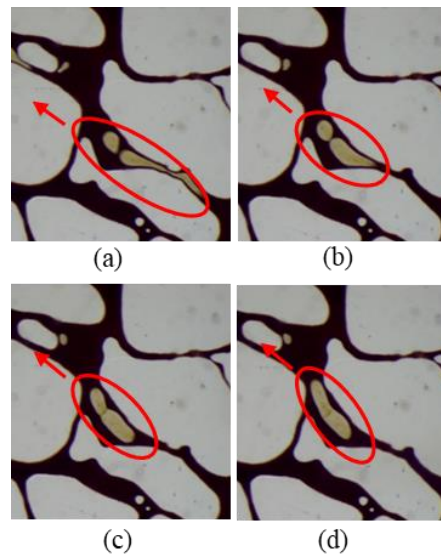
Figure 7. Gas bubbles' coalescence process (2.61 MPa)

4.1.3. Gas bubble coalescence. Gas bubble coalescence is another important mechanism that affects the size and distribution of gas bubbles in porous media. The larger the gas bubbles diameter is, the easier it

is to coalesce. Because the larger the gas bubbles diameter, the smaller the resistance between the gas bubbles and the easier the gas bubbles coalesces. The gas bubble coalescence process is generally slow. This is caused by two reasons. On the one hand, the viscosity of foamy oil is generally high, so the pressure difference between gas bubbles is relatively small. Coalescence process of gas bubbles caused by pressure difference is generally relatively slow. On the other hand, because of the higher content of active components, such as asphaltenes, the adhesion between the two gas bubbles is stronger in foamy oil. The coalescence process is shown in Figure 7. As the two gas bubbles approached each other, the liquid film between the two gas bubbles became thinner until the two gas bubbles coalesced into one gas bubble.

4.1.4. Gas bubble deformation. As shown in Figure 8, a gas bubble elongated when it passed through the throat. After passing through the throat, the gas bubble returned to a nearly circular shape due to interfacial tension. Due to the Jamin effect, this process increases the gas phase flow resistance, thereby reducing the gas mobility, reducing the production gas/oil ratio, and effectively improving the foamy oil recovery.
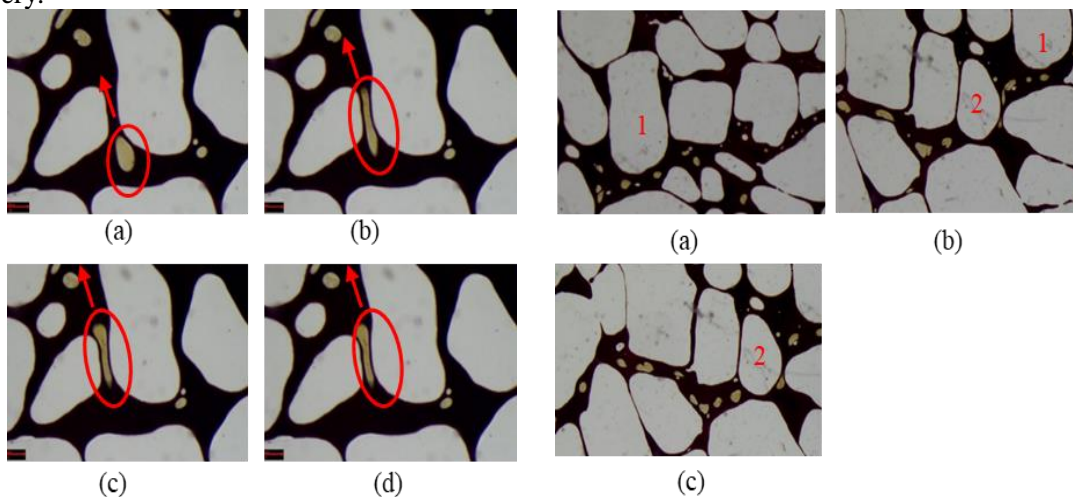
Figure 8. Gas bubbles' deformation process (2.69 MPa, time delay is 5 s)

Figure 9. Gas bubbles' migration process (2.65 MPa)

4.1.5. Gas bubble migration. As shown in Figure 9, gas bubbles migrated mainly in the main channel. With the flow to the micromodel outlet, the size of gas bubbles increased. As shown in Figure 10, gas bubbles were formed near the outlet end, but the gas bubbles near the inlet end were still in the nucleation process.

The experimental results show that when the gas bubbles in the foamy oil approached the pores, their moving speed increased significantly. Meanwhile, the gas bubbles of different sizes had different migration characteristics. For a larger diameter gas bubble, the front end of the gas bubble was first adsorbed by the asphaltenes when it passed through the pores. As a result, the front end of the gas bubble moved slowly, while back end of the gas bubble still kept moving at the original speed, which led to the inversion of the front end and the back end of the gas bubble.

Small size gas bubbles passed through the pores without being affected by rock or asphaltenes. This indicates that the active components in the crude oil have a significant effect on the flow characteristics of the gas bubbles during the gas bubble migration.

4.1.6. Foamy oil flow characteristic. The flow of foamy oil during the solution gas drive is shown in Figure 11. As shown in Figure 11a, the micromodel pressure was higher than the bubble point pressure and the oil in the micromodel was in continuous oil phase. The gas bubble nucleation as shown in Figure

11b shows that the gas bubbles were mainly adsorbed on the rock surface and the gas bubbles couldn't flow. As shown in Figure 11c, the number of gas bubbles increased as the micromodel pressure dropped. At the beginning the velocity of gas bubbles was slow, and the gas bubbles were mainly distributed in the main channel and the edge of the micromodel. The number of mobile gas bubbles increased as the micromodel pressure continued to decrease. As shown in Figure 11d, when the micromodel pressure was lower than the pseudo-bubble point pressure, the gas bubbles in the micromodel coalesced into continuous gas phase. The flow velocity of gas bubbles became significantly slower due to Jamin effect and lower pressure in the micromodel. When the micromodel pressure was between 3.89 MPa and 1.88 MPa, the gas bubbles were dispersed in the micromodel, and the foamy oil phenomenon was obvious.
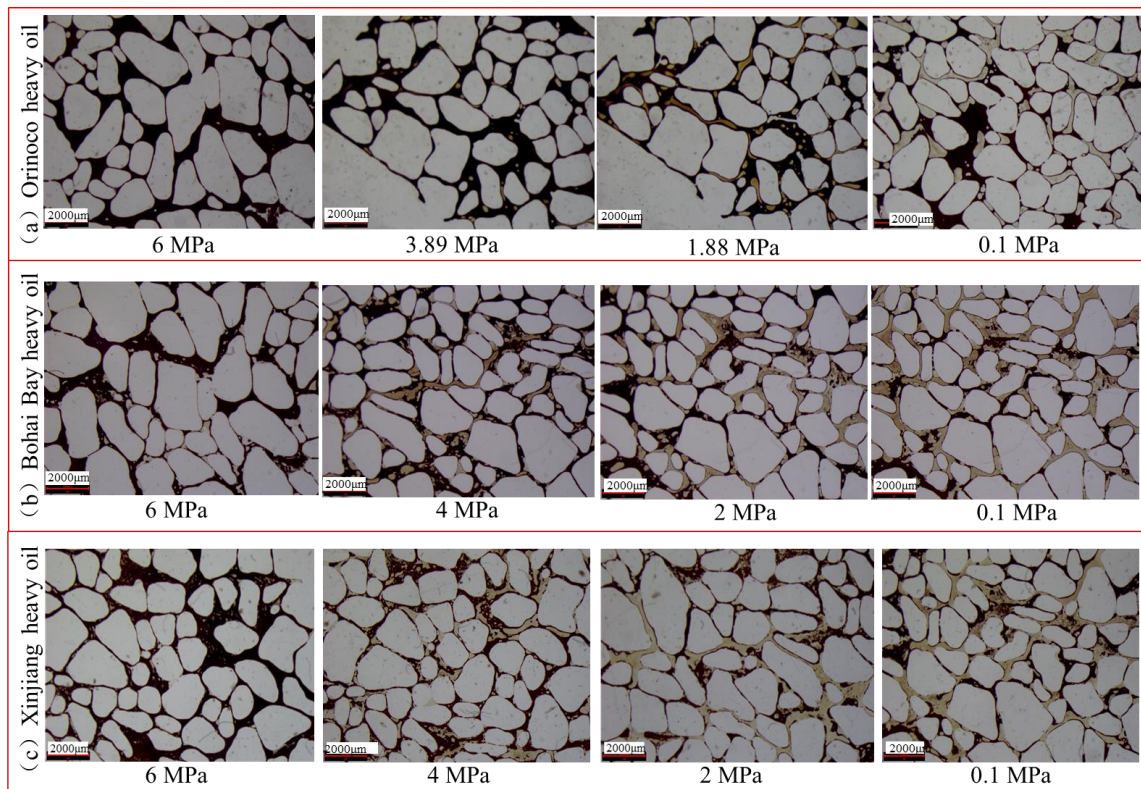

Gas bubble flow stage   Gas bubble nucleation stage
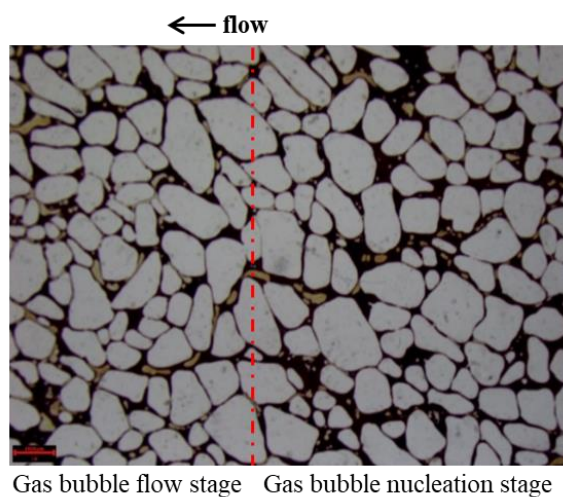
Figure 10. Different flow stages at different positions (2.65 MPa)

(a) 6MPa   (b) 3.89MPa

(c) 3.69MPa   (d) 1.88MPa
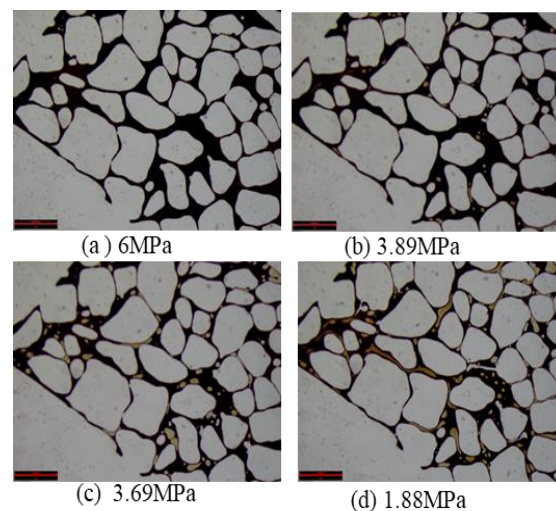
Figure 11. Different flow stages

4.2. Flow characteristics comparison between foamy oil and conventional heavy oils

Figure 12 shows the flow characteristics of three heavy oils during solution gas drive process. The dispersed gas bubbles appeared in the process of solution gas drive in Bohai Bay heavy oil and Xinjiang heavy oil, but the existence time of the gas bubbles was very short. The existence time of gas bubbles in Bohai Bay heavy oil lasted only from 5.17 MPa to 4.97 MPa. The existence time of gas bubbles in Xinjiang heavy oil lasted from 5.3 MPa to 4.89 MPa. Therefore, there was no obvious foamy oil phenomenon in Bohai Bay heavy oil and Xinjiang heavy oil. It was found that the size of gas bubbles in the conventional heavy oils was larger, and the migration velocity, growth and coalescence rate were bigger. The breakup of gas bubbles in conventional heavy oils is due to the blockage of rocks. The gas bubbles quickly passed through the middle area of the pores, and there was no special gas bubble migration characteristic, such as gas bubble inversion in foamy oil. The reason for the above differences is that the content of the active component of the asphaltenes in the conventional heavy oil is smaller, and the viscosity of the conventional oil is significantly lower than that of the foamy oil, resulting in weak adhesion of the gas bubbles liquid film.

Figure 12. Flowing state of three heavy oils during the solution gas drive

5. Conclusions

(1) Primary heterogeneous nucleation is a common form of gas bubble nucleation in foamy oil. The location of gas bubble nucleation and growth is mainly distributed in the main channel of the micromodel and the surface of the rock. The gas bubble nucleation is not only affected by pressure drop, but also related to the heavy oil components distribution.

(2) The gas bubbles in foamy oil showed special migration characteristics. When the gas bubbles in the foamy oil were close to the rock pores, its velocity became faster. Different size gas bubbles had different flow characteristics.

(3) For foamy oil, gas bubbles flowed with oil phase. For other conventional heavy oils or light oils, the gas bubbles quickly gathered and formed continuous gas, and gas bubbles moved faster than oil.

(4) The dispersed gas bubbles in the conventional heavy oils existed a shorter time and had no obvious foamy oil phenomenon. It indicates that the foamy oil has a more stable oil/gas interface in porous media.

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