Influence of temperature and pressure change on \( \text{CO}_2 \) foaming characteristics in crude oil

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Abstract: \( \text{CO}_2 \) flooding is an effective technology to improve oil recovery. However, because the foam layer produced in the actual production may affect the gas-liquid separation effect, a set of equipment for analyzing the foaming behavior of dissolved gas crude oil by using the depressurization method is designed, to record the generation and decaying process of foam. The effects of depressurization method, depressurization rate, initial pressure and temperature on the foaming process of crude oil are studied. Studies showed that the use of stepwise depressurization and low depressurization rate is beneficial to increase the effect of gas-liquid separation. There is an optimal temperature to maximize the separation effect.

1. Introduction

In recent years, due to the widespread application of gas flooding oil recovery technology, a large amount of gas is often dissolved in the produced crude oil. When the produced fluid enters the separator, the gas releases and forms a foam layer due to the decrease in pressure, which has a great influence on the separation effect of the separator. If the foam enters the downstream pump station from the liquid phase outlet of the separator, cavitation and other serious accidents may occur [1]. Therefore, understanding the foaming characteristics of gas-containing crude oil is of great guiding significance for preventing the hazards caused by foam. Chen et al. believe that different crude oil components will also cause different crude oil foaming trends. They used pneumatic and depressurization tests to study the influence of acidic components and gas saturation on crude oil foam, and the studies have found that the surface tension and viscosity of the liquid may be beneficial to the stability of the foam. Some acidic components such as naphthenic acids and long-chain fatty acids will significantly increase the foaming volume [2]. Hussain et al. found that by changing the apparent viscosity of the three phases of oil, gas and water, the amount of foam produced will be affected, and as the apparent viscosity increases, the amount of foam decreases [3]. Callaghan used the pneumatic method to study the foam stability in crude oil with a viscosity less than 20 mPa\(\cdot\)s, and found that the foam life and viscosity are approximately linear [4].

At present, the experimental research methods for the crude oil foam problem mainly include the pneumatic method and the depressurization method. The principle of the pneumatic method is to fill a certain amount of solution into a graduated container, pass gas into the container at a constant speed, stop the gas supply after a period of time, and record the maximum volume and half-life of the foam. In the actual production process, the main reason for the foaming of crude oil is the formation of foam, caused by the release of gas due to the depressurization. Therefore, the gas is dissolved in the crude oil...
under a certain pressure, and then the pressure is reduced to make the gas escape, which is more similar with the actual situation. This paper designs a set of equipment for studying the foaming characteristics of CO₂-crude oil system. High-speed camera is used to record the process from foam generation to death under different conditions. Testing and analyzing with different temperatures, initial pressures, and defoaming time, how the foaming behavior of the CO₂-crude oil system changes, and these studies are expected to provide guiding suggestions for separation process optimization.

2. Method and experimental devices

2.1. Experimental devices

Experimental system includes high-pressure reactor, gas supply system, temperature control system, data acquisition system and high-speed camera system, shown in Figure 1.

Figure 1. The high-pressure reactor is a 10 cm-edge cube with designed volume 900 ml and maximum pressure 10 MPa, and the internal could be observed by transparent glass. The CO₂ gas used in the experiment is extracted from a gas cylinder with a conventional pressure of 5 MPa and a purity of 99.99%. A constant temperature water bath is used to control the temperature inside the reactor to stabilize the temperature at the setting temperature. The pressure sensor and temperature sensor are installed in the high-pressure reactor, and their measurement errors are ±0.25% and ±5% respectively. The experiment uses a data acquisition system to monitor and record the temperature and pressure data in the reactor in real time. A high-speed video camera is used to record the foam behavior during the experiment.

2.2. Experimental materials and parameters

The tested crude oil is from Black-46 wellhead in Jilin Oilfield, and the volume is 400 ml. The saturates is 69.54% (mass fraction), the aromatics is 22.48%, the resins is 7.40%, and the asphaltenes is 0.58%. All the parameter is tested under the standard of NB/SH/T 0509-2010 Test Method for separation of asphalt into four fractions. The shear rate is selected as 10 s⁻¹, the viscosity of the crude
oil selected in the experiment is 1.4 Pa·s at 35 °C, 0.44 Pa·s at 40 °C, and 0.146 Pa·s at 45 °C.

2.3. Experimental scheme
Pour the preheated crude oil into the reactor; use a water bath to keep the container constant; inject CO2 into the reactor to slightly higher than the specified pressure; after a period of stabilization, when the gas is partially dissolved and the pressure drops to a constant value, continue to inject carbon dioxide; repeat this process, until the pressure in the reactor stabilizes to the target pressure; open the needle valve to reduce the pressure of the reactor until the pressure reaches the target condition and close the needle valve. The depressurization rate is controlled by adjusting the opening of the needle valve. Obverse the process of foaming and compare the bubble size under different conditions, the variables include temperature, initial pressure, depressurization method, depressurization rate.

3. Results and discussion

3.1. Influence of depressurization method
Since the initial pressure of the fluid produced by CO2 flooding is relatively high, if the fluid is directly depressurized before entering the separator in first station, it may cause serious abrasion the pressure reducing valve and also affect the separation efficiency. Therefore, a stepwise depressurization method is often used to avoid this problem. The experiment compared the foaming behavior under direct depressurization and stepwise depressurization.

3.1.1. Direct depressurization

Figure 2 Foaming under direct depressurization with 40 °C and initial 2.5 MPa

Figure 2 shows that the entire depressurization process can be divided into five stages: bubbles generation, bubbles arrangement, bubbles polymerization, violent foaming and gas-liquid balance [5]. There is no foaming in the reactor at the initial stage. When the pressure drops to 1.3 MPa, bubbles start to form, but there are only 1-2 small bubbles with a diameter of about 0.1 cm below the gas-liquid interface. As the pressure is further reduced, the number of bubbles gradually increases and is arranged neatly. The bubble diameter is 0.1-0.2 cm, the bubble spacing is larger than the bubble diameter, and the height difference with the liquid level is maintained at about 0.25 cm. Continue to reduce the pressure, the diameter of the bubble is larger and the position rises significantly, and the two bubbles with a smaller distance are polymerized. Since then, bubbles continue to merge and decay, and large-diameter bubbles are produced. When the pressure drops to 0.5 MPa, violent foaming occurs until the CO2 that can release from the crude oil completely enters the gas phase.

3.1.2. Stepwise depressurization
If after each decrease of 0.5 MPa, there is 5 minutes to stable. When the pressure drops to 1.1 MPa, small bubbles appear, there is no violent foaming in the whole process, and the foaming volume is significantly less than that of direct depressurization. When the pressure is reduced step by step, each 0.5 MPa reduction provides enough time for the bubble to decay. Before the next depressurization, more escaped gas enters the gas phase. During the whole process, there is no large amount of gas dissolved in the crude oil escaping in a short time, so no obvious violent foaming occurs. Therefore, the stepwise depressurization method can make the gas-liquid separation better.
3.2. Influence of depressurization rate
The experiment compared the effect of different depressurization rates on the pressure inside the reactor when the bubbles are first generated under the same initial pressure and temperature conditions. Figure 3 shows that as the depressurization rate increases, the first bubble generation time is earlier. But the obtained pressure values are around 1 MPa. This is because when the pressure drops to 1 MPa, the CO2 dissolved in the crude oil has reached a supersaturated state, and CO2 begins to escape, but the depressurization rate has almost no effect on the solubility of CO2 in crude oil, so the first bubble generation pressure is not affected by the rate of depressurization.

![Depressurization curves under different depressurization rate](image)

In addition, experiments have found that increasing the depressurization rate can accelerate the rate of bubble generation and bursting in the reactor. And under the high depressurization rate, the foam layer produced has the highest height in a short time. This situation will affect the separation effect of the separator, so it is recommended to use a low depressurization rate in the actual separation process.

3.3. Influence of initial pressure
As shown in Figure 4, the experiment compares the effect of different initial pressures on foaming behavior at the same temperature and depressurization rate. When the initial pressure is 1.5 MPa, the generation of bubbles is not violent, both the polymerization rate and the rupture rate are slow. Although small bubbles are polymerized, the diameter of the bubbles does not exceed 0.6 cm, indicating they are relatively stable small-diameter bubbles. When the initial pressure is 2 MPa, the number of small bubbles is large, and the bubble generation rate, polymerization rate, and burst rate are faster. Small bubbles will produce larger diameter bubbles after polymerization. When the initial pressure is 2.5 MPa, the bubbles number increases, forming a staggered double-layer arrangement, the maximum bubble diameter can reach 0.9 cm, and the polymerization of small bubbles to larger bubbles continues, with the larger bubbles possessing better stability.
3.4. Influence of Temperature

Figure 5 indicates that under the same initial pressure and depressurization conditions, the maximum bubble diameter at 35 °C is about 0.9 cm, the maximum bubble diameter at 40 °C is about 0.6 cm, and the maximum bubble diameter at 45 °C is about 0.4 cm. As the temperature increases, the diameter of the largest bubble decreases. This is because the increase in temperature will reduce the fluid viscosity and the strength of the liquid film, causing the bubbles to burst before they polymerize, and the propagation rate between phase components under high temperature conditions is higher, making the bubbles generate and burst faster, and the half-life of the bubble bursting is shorter. However, the gas solubility is high under low temperature conditions, and more CO2 is dissolved before the pressure is reduced, which causes more CO2 to escape after the pressure is reduced. However, due to the high strength of the liquid film, the bubbles are not easy to burst, so there are larger bubbles.

The initial pressure is 1.5 MPa and 2.0 MPa, the pressure drop rate is 0.27 MPa/min, and the pressure in the reactor when the bubbles first appeared at different temperatures are compared, as shown in Figure 6. Since previous experiments have proved that the depressurization rate has no effect on the pressure when the first bubble is generated, compare the pressure for the first foaming at different temperatures. The pressure in the reactor is the highest when bubbles appear for the first time at 35 °C, and the pressure in the reactor is the lowest when bubbles appear for the first time at 40 °C. This is due to the fact that there is more dissolved gas under low temperature conditions and the same depressurization. More gas will escape, so the bubble will be generated earlier.

The increase in temperature will reduce the viscosity of the fluid and the strength of the liquid film, which can also increase the rate of bubble generation and bursting. Therefore, under same depressurization at 45 °C, compared with at 40 °C, and the pressure in the reactor is higher when bubbles are generated. Therefore, there is an optimal temperature, which can not only ensure that the pressure in the reactor is lower when the bubbles are generated at first time, but also make the formation and bursting rate of bubbles in the reactor faster.

4. Conclusion

Compared with direct depressurization, the stepwise depressurization method produces less foam, making influence of foam layer on separation effect less, so it should be used in gas-liquid separation.

Increasing the depressurization rate can change the rate of bubble generation and bursting in the reactor. And under the high depressurization rate, the foam layer produced in the reactor has the highest height in a short time. This situation will affect the performance of the separator, so it is recommended to use a low depressurization rate in the actual separation process.

There should be an optimal temperature in actual production, which can ensure the pressure lower in the reactor at the time of first bubble generation and make the forming and bursting rate of bubbles in the reactor faster. It is recommended this temperature as the requirement of design maintained temperature during the separation process.

CRediT authorship contribution statement
Shuhao Zhang: Conceptualization, Formal analysis, Visualization, Writing-original draft.
Writing-review & editing. Hongtao Ma: Conceptualization, Methodology, Experiment, Formal analysis, Writing-original draft. Yuxing Li: Conceptualization, Supervision, Writing-review & editing.

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