Effect of mechanical stirring on CO2 foaming in petroleum

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Abstract: CO2 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 and cause damage to downstream devices. Therefore, it is necessary to study the defoaming technology in the separator. This paper mainly studies the influence of different stirring speeds on the death of the foam layer during the depressurization process and after the depressurization is stopped. The stirring blade can accelerate the formation and disappearance of foam, and the final result is to reduce the time required for defoaming. During the whole process, the survival time of large bubbles is short, but stirring has less influence on small bubbles. Stirring will increase the height of the foam layer, which will affect the gas-liquid separation efficiency in severe cases. Therefore, if the fluid entering the separator has good foam-ability, it is not recommended to directly use mechanical stirring to eliminate foam in the gas-liquid separation process.

1. Introduction

In order to control global warming, a large amount of CO2 needs to be stored underground [1]. Most of the CO2 emissions come from the combustion of hydrocarbons and industrial activities. Despite the need to reduce CO2 emissions, the assumption that the combustion of hydrocarbons will be significantly reduced in the next few decades is hard to achieve [2]. By using CO2 flooding technology, it can effectively increase the oil recovery and reduce CO2 emissions.

The foam produced during oil displacement can improve the oil displacement efficiency when CO2 is injected into the formation by reducing the fluidity of CO2. However, when the displacement fluid enters the separator, due to the pressure reduction, the gas released by the displacement fluid forms a foam layer in the separator, which influences the separation effect of the separator. If foam enters the downstream pumping station from the liquid phase outlet of the separator, cavitation and other serious accidents may even occur [3].

At present, there have been some studies on the use of chemical or physical methods to analyze foam stability. Phukan et al.[4] found that the stability of foam produced by fluids containing CO2 decreases with increasing temperature, and the addition of surfactants can increase the stability of bubbles. Karakashev et al.[5] proposed a new parameter of foaming characteristics of surfactant solutions, unifying the measurement about rate of foam generation and extinction, using shaking to generate foam, and they found the foaming characteristics of surfactant solutions are related to the way the bubbles are generated, and stronger surfactants do not always produce more stable foam than weaker surfactants. Winterburn et al.[6] showed that ultrasound can increase the speed of liquid film drainage, accelerate the thinning of the liquid film, and increase the speed of foam elimination.
This paper analyzes the feasibility of using a defoaming blade in the separator to defoam by studying the influence of external force on foam generation and extinction behavior.

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. 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. There is a stirrer in device with 30-150 r/min rotation rate. 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 10.44 Pa·s at 40 °C.

2.3. Experimental scheme
Preheated crude oil is poured into the reactor; Water bath is used to keep the container constant; CO₂ is injected 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, carbon dioxide is continue to be injected; This process is repeated until the pressure in the reactor stabilizes to the target pressure (2.5 MPa); Needle valve is opened to reduce the pressure of the reactor until the pressure reaches the target condition (0.5 MPa) and the needle valve is closed. The depressurization rate is controlled by adjusting the opening of the needle valve. Process of foaming is observed and the bubble size under different conditions is compared. The variables include temperature, initial pressure, depressurization method, depressurization rate. During the depressurization process, it could that choose whether to turn on the stirring, and the
Rotation rate of the stirring paddle can be adjusted between 30 r/min-140 r/min. The experiment has studied the volume change of the foam layer during the process of depressurization in the reactor, when the stirring is not started, and the stirring rate is 75 r/min, 110 r/min, and 140 r/min respectively. Meanwhile, the volume change of the foam layer is observed when the depressurization process reduced to 0.5 MPa and stopped. The mechanism of stirrer that accelerate the disappearance of foam is also studied.

3. Results and discussion

3.1. Stirring in depressurization process

The foaming is shown in Figure 2, with stirring rate 75 r/min, initial pressure 2.5 MPa and liquid phase 40°C constantly. As the pressure decreases, the pressure when bubbles are first generated is higher than that without external force. This is because the external force generated by the stirring destroys the viscous force of the crude oil itself and accelerates the escape of gas from the dissolved crude oil, so that the system can generate bubbles earlier.

![Figure 2 Slow stirring rate in depressurization process](image)

In the subsequent depressurization process, the height of foam layer is higher than that of the foam layer without external force is applied. The large bubbles generated rapidly burst, and the escaped gas mainly exists in the form of small bubbles before entering the gas phase. This is due to the movement of crude oil due to stirring, and its partial pressure is lower than when it is standing, so foam can exist in a larger space, which is different from the reason why the bubble volume can be increased by bubble drainage in the direct depressurization process.

The stirring during the depressurization process cannot provide sufficient bubble drainage time for the bubbles. Large bubbles mainly rely on the combination of small bubbles, and the liquid film is subjected to shearing force due to stirring, so large bubbles are more likely to be squeezed and collapsed quickly.

Different from the phenomenon that large bubbles are at the highest position in the direct depressurization process, shown in Figure 2, there are more stable small bubbles near the gas-liquid two-phase interface, and the nearby bubbles are similar in size, which is not easy to generate small bubbles to large bubbles due to pressure difference. As a result, it increases the difficulty of the disappearance of small bubbles in the stirring process.

As shown in Figure 3, at the same temperature, initial pressure, and depressurization rate, compared to direct depressurization, the first bubble generation time is earlier if stirring is applied. After stirring, the foaming is more intensive, and the rate of bubble formation and extinction is increased, and the height of the foam (foam layer height and liquid phase height) during the foaming process is higher than the height when the pressure is directly reduced. However, compared with direct pressure reduction, the volume of the foam layer when stirring is applied begins to decrease earlier, and after the depressurization is stopped, the extinction rate of the foam is faster.

3.2. Influence of stirring speed

In order to study the influence of stirring on the generation and extinction of gas-bearing crude oil foam well, it is necessary to further study the foam behavior in the reactor when the pressure is
reduced at different stirring rates.

The experiment compares the change of the foam layer volume in the reactor with the time when the stirring rate is 75, 110, 140 r/min respectively in depressurization process. As shown in the Figure 3, during the depressurization process, the volume of the foam layer produced by the three stirring rates is greater than the volume of the foam layer produced under no external force, and as the stirring rate increases, the volume of the foam layer produced is larger.

![Figure 3 Foam layer volume under different conditions](image)

However, when the depressurization stops, the time required for the demise of the foam layer is shorter. Because at high stirring rates, the foam gathers more toward the edges of blades, which increases the collision and coalescence between the bubbles, intensifying the foaming phenomenon. The gas where the foam gathers is hard to enter the gas phase directly, so more gas escapes can only exist in the form of bubbles, which influences the efficiency of gas-liquid separation. When the depressurization is stopped, mechanical stirring becomes the main factor affecting the demise of the foam layer. High stirring rate has more obvious effects on increasing the permeability coefficient of the liquid film and the convective mass transfer rate [7], so the time required for the demise of the foam layer is more obviously short. For whole process, the higher the stirring rate, the much smaller the difference between change of foam layer volume.

4. Conclusion
Stirring can make the foam layer hardly contain large bubbles, and effectively shorten the demise time of the foam layer. However, the application of mechanical stirring during the depressurization process has little direct influence on the rupture of small bubbles, so the foam cannot be eliminated directly by stirring during the production process.

When a gravity separator is used, since stirring will increase the height of the foam layer and affect the efficiency of gas-liquid separation in severe cases, it is not recommended to use mechanical stirring to eliminate foam during the gas-liquid separation process merely.

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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