Study on the Influence Law of CO_2 Treatment on Emulsion Stability

Peiyu Lu, Shuxuan Jiang

School of Xi'an, Xi'an Shiyou University, Xi'an Shaanxi, 710000, China

Abstract

The formation of water-in-oil (W/O) emulsions during crude oil extraction leads to increased pipeline load, higher energy consumption, and elevated demulsification costs. CO_2 flooding technology can significantly improve emulsion stability by altering oil/water interfacial properties. This study investigates the influence law of CO_2 on the stability of W/O emulsions through experimental and theoretical analyses. Using a pressurized emulsification device and a high-speed microscopic observation system, combined with the water separation rate method and micromorphological analysis, the demulsification mechanism of CO_2 was revealed. Experimental results show that as the CO_2 pressure increases from atmospheric pressure to 2 MPa, the demulsification rate increases and the interfacial tension decreases. High-speed microscopic observations indicate that the droplet coalescence process can be divided into four stages: contact, deformation, film rupture, and coalescence. A mathematical stability model incorporating a deformation coefficient, contact angle correction, and pressure coefficient was established. CO_2 destabilizes emulsions through a dual mechanism: reducing the oil-phase viscosity and weakening the interfacial film strength. This study provides an important theoretical basis for optimizing CO_2 flooding technology.

Keywords

Water-in-oil (W/O) Emulsion; CO_2; Demulsification Mechanism; Mathematical Model.

1. Introduction

Due to the presence of surface-active substances such as resins and asphaltenes in crude oil, studies by Arnold[1], You[2], Been[3], and others have shown that during crude oil extraction and transportation, crude oil undergoes emulsification with the aqueous phase under the shearing action of wellbores, chokes, valves, pumps, and other equipment, forming water-in-oil (W/O) or oil-in-water (O/W) emulsions. This further leads to difficulties in displacement and flow, environmental pollution, increased pipeline load during storage and transportation, and higher energy consumption during oil refining. Since emulsions are extremely harmful, they must be broken to achieve oil-water separation. The demulsification process generally consists of three stages: aggregation of emulsified droplets, discharge of the oil film between oil droplets, and coalescence of oil droplets. Oil droplet coalescence is a crucial step in crude oil demulsification. During the coalescence of emulsified oil droplets, small oil droplets gradually move towards larger ones. Subsequently, coalescence is completed, and the Ostwald ripening phenomenon occurs. In industrial treatment, studies by Arnold[4], Sjöblom[5], and others have shown that various methods such as demulsifiers, heating, distillation, filtration, centrifugation, sedimentation, and electrostatic coalescence are usually employed for large-scale emulsion treatment to achieve oil-water separation. However, all the aforementioned processes consume substantial energy and chemical agents. Therefore, CO_2 flooding is widely used as it can improve crude oil recovery and reduce costs.

Scholars at home and abroad have conducted extensive research on this technology. Studies by Li[6], Park[7], Fathinasab[8], and others have focused on the influence of CO_2 on emulsion systems, given that crude oil serves as the external phase in W/O emulsions. Tao[9] and others studied the effects of CO_2 and emulsifiers on the physical properties of extra-heavy oil, and the results showed that the formation of W/O emulsions in extra-heavy oil systems often leads to an increase in crude oil viscosity and a decrease in temperature sensitivity. However, when high-pressure CO_2 is added, stable W/O emulsions can be easily separated into oil and aqueous phases within a short time. Post S.L.[10] proposed that when CO_2 comes into contact with emulsions, part of the CO_2 dissolves into the external phase under high-pressure conditions. During the depressurization process, CO_2 bubbles accumulate at the oil/water interface, thereby weakening the stability of emulsion droplets (Post and Abraham, 2002). Zaki N.[12] and others hypothesized that when the external-phase oil is under high pressure, CO_2 dissolved in the external-phase oil causes asphaltene deposition at the asphaltene/water interface, thereby disrupting the stability of emulsion droplets. In 2005, Yang[11] and others confirmed that when CO_2 is added to a saline-containing oil phase under high pressure, the interfacial tension between oil and water is lower than that in systems without CO_2. Studies by Mohammed[13], Rosman[14], Hemmati-Sarapardeh[15] (2014), Zhang[16], Lashkarbolooki [17] (2018), Simon[18], and others have shown that the reduction in viscosity caused by CO_2 dissolution in the oil phase also increases the likelihood of emulsion coalescence and accelerates the sedimentation process of the emulsion system.

Currently, there is limited research on the emulsification stability of gas-saturated crude oil. Therefore, it is necessary to study the process of droplet coalescence, establish a mathematical model for droplet coalescence, and analyze the microscopic characteristics and influencing factors of the droplet coalescence process. Additionally, the intrinsic relationship between the macroscopic phenomena of the emulsification stability of gas-saturated crude oil and the microscopic characteristics of the droplet coalescence process should be explored. This work further improves the coalescence theory of oil droplets and is of great significance for enhancing the oil-water separation efficiency of gas-saturated crude oil and reducing the burden of storage and transportation.

2. Experiment Equipment of Methods

2.1. Experiment Equipment

A pressurized gas-dissolving emulsification device [20] was used for pressurized gas-dissolving emulsification of mixed crude oil and formation water. Schematic diagrams of the device are shown in Figures 1-2.

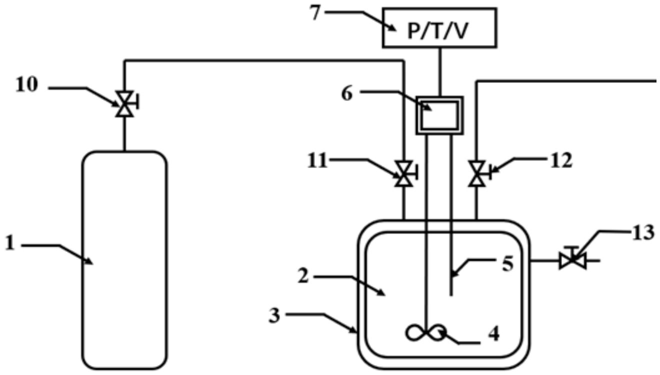

Fig 1. Schematic Diagram of the Pressurized Emulsification Device

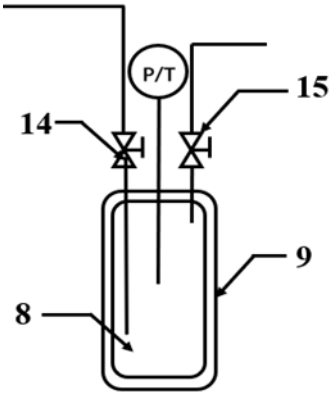

Fig 2. Schematic Diagram of the Gas Dissolution Characteristic Device

Steps for using the pressurized gas-dissolving emulsification device:

(1) Crude oil injection: Add a certain volume ratio of mixed crude oil and formation water into the PVT reactor 2, and heat the PVT reactor 2 using the water bath 3 to the emulsification temperature specified in the experimental conditions;

(2) Gaseous CO_2 pipeline purging: Open valves 10, 11, and 12, purge the PVT reactor 2 with CO_2 from the gas cylinder 1, and then close valves 10, 11, and 12;

(3) CO_2 injection: Open valves 10 and 11, close valves 12 and 13, open the CO_2 gas cylinder 1 to introduce CO_2 into the PVT reactor 2, close valves 14 and 16, and adjust and monitor the required pressure in the PVT reactor 2 through the console;

(4) Reactor treatment of crude oil: Treat the crude oil using the built-in four-blade 45° inclined stirring paddle 4 of the PVT reactor 2;

(5) Oil sample transfer: Open valve 15 to introduce a small amount of CO_2 into the pressure-resistant test tube 8, then close valve 15; Open valves 12 and 14 to transfer the oil sample from the PVT reactor 2 to the pressure-resistant test tube 8, and heat the pressure-resistant test tube 8 using the water bath 9 to the demulsification temperature specified in the experimental conditions;

(6) Open valve 13 to empty the remaining gas in the PVT reactor 2, then close valve 13; Clean the residual crude oil in the PVT reactor 2; Turn off all water baths.

2.2. Experiment Methods

2.2.1. Preparation of Gas-Saturated Crude Oil Emulsion

A high-speed emulsifier was used to mix crude oil and formation water to prepare simulated emulsions. The temperature inside the emulsification reactor was heated to the preset experimental temperature using a constant-temperature water bath, and the pressurized emulsification device was purged with the gas to be dissolved (CO_2). A certain volume ratio of oil sample and water sample was added to the high-pressure emulsification reactor, and CO_2 gas was injected. The gas to be dissolved increased the pressure inside the emulsification reactor to the preset experimental pressure until the temperature and pressure stabilized at the preset values. The oil and water were emulsified at a certain stirring intensity to obtain a gas-saturated (CO_2) emulsion. The gas was released to reduce the pressure to atmospheric pressure, and the gas-saturated emulsion was taken out.

2.2.2. Determination of Crude Oil Emulsion Stability by Water Separation Rate Method

The temperature inside the gas dissolution characteristic device was heated to the preset experimental temperature, and the gas dissolution characteristic device was connected to the pressurized emulsification device. The test tube of the tester was purged with the gas to be dissolved (CO_2). The prepared W/O emulsion was transferred to the pressure-resistant test tube at a slight pressure difference, placed in a constant-temperature water bath for standing, and timing was started immediately. The volume of water separated from the emulsion at different times was recorded, and the change in the water separation rate f_v of the emulsion at different times was calculated according to the formula:

$$f_v = {}^{V_1}/_{V_2} \times 100\% \tag{1}$$

3. Macroscopic Study on the Stability of Gas-Saturated Crude Oil Emulsions

3.1. Influence of Pressure on Crude Oil Emulsion Stability

Figure 3 shows the water separation rate of crude oil emulsions under different pressure conditions. The emulsification temperature was 50℃, the test temperature was 70℃, and the preparation conditions of the crude oil emulsion were: emulsification time 15min, stirring speed 1000rpm, and oil-water ratio 7:3.

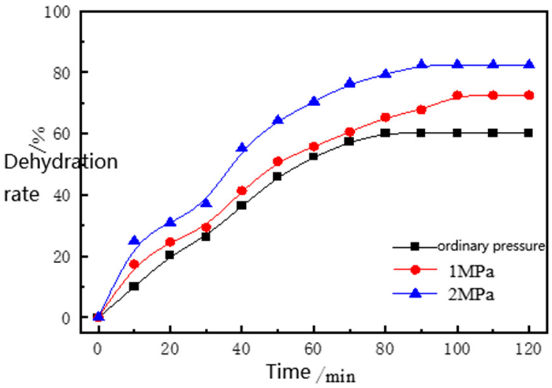

Fig 3. Change in Dehydration Rate of Oil Samples with Time Under Different Pressure Conditions

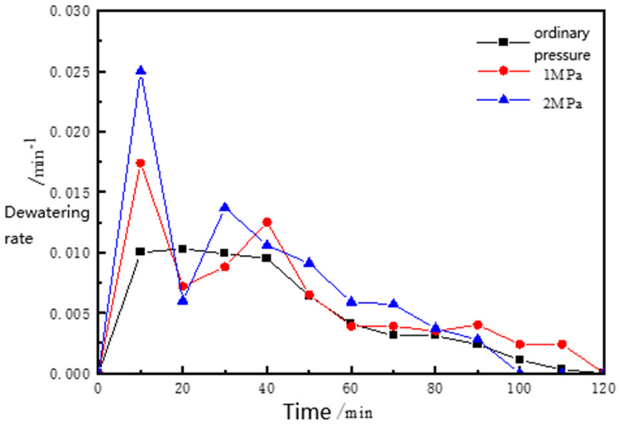

Fig 4. Change in Demulsification Rate of Oil Samples Under Different Pressure Conditions

As shown in Figure 4, the aqueous phase of the prepared gas-saturated emulsion began to separate at a relatively high rate at approximately 5min, and the separation rate significantly decreased and tended to stabilize at around 60min. The gas-saturated crude oil emulsion formed under atmospheric pressure was the most stable, followed by that formed under a pressure of 1MPa, and the gas-saturated crude oil emulsion formed under a pressure of 2MPa was the least stable. With the increase in gas dissolution pressure (CO_2), the dehydration rate of the crude oil emulsion gradually increased, and the demulsification process accelerated.

As shown in Figure 4, as the CO_2 pressure increased from atmospheric pressure to 2MPa, the demulsification rates of both oil samples significantly increased. Pressure changes can affect emulsion stability in two aspects: On one hand, an increase in gas dissolution pressure leads to more CO_2 dissolving in the oil phase, reducing the oil-phase viscosity. The decrease in oil-phase viscosity weakens the resistance to the movement of dispersed water droplets, making it easier for dispersed water droplets to collide, migrate, and coalesce and settle, which is manifested as an increase in dehydration rate and accelerated demulsification. On the other hand, CO_2 dissolved in the system and natural surface-active substances in crude oil are synergistically adsorbed on the oil-water interface film, hindering the cross-linking effect between asphaltene aggregates, resulting in a decrease in the strength of the rigid film at the oil-water interface. This effect significantly reduces the film resistance that water droplets need to overcome during coalescence, further promoting oil-water separation.

3.2. Gas-Saturated Oil/Water Interfacial Tension

A high-speed microscopic experimental system was used to record the microscopic behaviors of the entire process of contact, deformation, film rupture, and coalescence of gas-saturated emulsion droplets (pressure 1MPa, oil-water ratio 7:3, emulsification temperature 45℃), as shown in the figures.

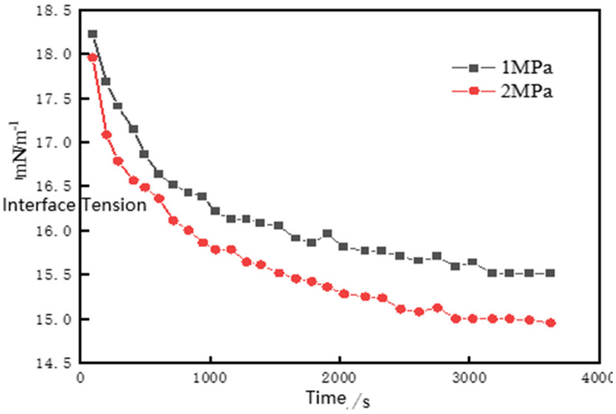

Fig 5. Change in Interfacial Tension of CO_2-Saturated Crude Oil Emulsions (Oil Sample 2)

As shown in Figure 5, with the extension of the oil-water interface formation time, the interfacial active substances in the oil phase gradually migrate and adsorb at the oil-water interface, forming a relatively stable interfacial film with a certain spatial thickness at the interface, resulting in a gradual decrease in the oil-water interfacial tension over time; with the increase in gas dissolution pressure, more CO_2 dissolves in the crude oil, further reducing the oil-phase viscosity, which is conducive to the diffusion, migration, and adsorption of asphaltenes in the oil phase at the oil-water interface, thereby further reducing the interfacial tension.

4. Summary

Through macroscopic experiments and microscopic analysis, this study systematically reveals the influence law of CO_2 treatment on the stability of water-in-oil (W/O) emulsions:

The macroscopic influence of CO_2 treatment on the stability of gas-saturated crude oil emulsions under different gas dissolution pressures (atmospheric pressure, 1MPa, 2MPa) was systematically studied using the water separation rate method. With the increase in pressure, the dehydration rate of the emulsion significantly increases, and the demulsification rate accelerates. The increase in pressure promotes more CO_2 to dissolve in the oil phase, reducing the oil-phase viscosity and weakening the movement resistance of the dispersed water droplets, thereby accelerating the collision, migration, coalescence, and sedimentation of the water droplets. The dissolved CO_2 and natural surface-active substances in crude oil are synergistically adsorbed at the oil-water interface, hindering the cross-linking effect of asphaltene aggregates, leading to a decrease in the strength of the interfacial rigid film. This effect significantly reduces the film resistance that water droplets need to overcome during coalescence, further promoting oil-water separation.

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