The Phase Behavior Study of Air-foam Flooding in Changqing Ultra-Low Permeability Reservoirs

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Abstract

For phase change characteristics of air foam flooding in Changqing ultra-low permeability reservoirs, experiments were performed with the air and the gas-phase oxidation of P-X diagram under reservoir conditions using the PVT high pressure physical device and gas chromatograph. The phase behavior of crude oil and air bubbles after multiple contacts was determined by PVT simulation and the phase equilibrium model. The critical temperature and critical pressure of crude oil were determined to be 424.4℃ and 9.85MPa. Results show gas dissolved in crude oil after oxidation was strong in the air under the same pressure. Because the foam system and crude oil emulsification during contact have produced multiple contact oxidation, the effect was less than that in air and oil, resulting in a relatively small oxidation of C_2-C_6, while the oxidation of C_7-C_{16} was relatively more. Furthermore, the trend of gas phase composition approaching C_2-C_6 was relatively slow, while oil phase composition was closer to C_{7+}, due to the increase in the C_7-C_{16} component. The study provides important insight for miscible flooding and non-miscible flooding applications, as well as for gas injection project design.

Introduction

Air-foam flooding has been proven to be a very promising technology to enhance oil recovery (EOR). In the air-foam flooding process, the study of phase behavior is very important for the gas injection process. When there are multiphase flow, interphase mass transfer and heat transfer will co-exist in the oil-gas system. When the gas is injected, the physical and chemical properties of the fluid, such as viscosity, density, volume coefficient, interfacial tension, bubble point pressure, and gas-liquid components and composition, will change (Wang et al. 2008; Yan et al. 2008; Guo et al. 2003). Therefore, a quantitative description of the phase change in the air / air foam flooding process is essential to understand the latest changes in reservoir fluid parameters, which is also an important basis for studying the mechanism of miscible and immiscible flooding, and for gas injection engineering design (Zhang et al. 2009; Li and Zhang 2001). Guo et al. (2000) had measured the PVT of crude oil after different amounts of CO_2 were injected into the oil system at reservoir temperature, using the high-pressure phase equilibrium experiment device. The results showed that different composition of oil sample had a great influence on the phase behavior of CO_2 injection. In the process of air-foam flooding, the phase behavior of air, foam, and crude oil has not been studied and reported yet. Therefore, this study aimed to quantify the phase behavior of air and foam on crude oil under different conditions through experiments.

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The study area is in the Wuliwan District of Jing'an oilfield. The producing formation was the Chang 6 oil formation of Triassic. The initial driving mechanism was a dissolved gas drive. The main properties of the reservoir are shown in **Table 1**. The pressure difference between reservoir and saturation pressure is small. The average permeability of the formation is $1.5\times10^{-3}\mu m^2$. The original gas oil ratio is high. It was a typical low porosity, low permeability, and low viscosity reservoir.

Table 1—Main reservoir properties of the target reservoir.

Parameter	**Value**	**Parameter**	**Value**
Reservoir pressure, MPa	12.26	Viscosity of surface crude oil, mPa·s	7.69
Bubble point pressure, MPa	7.5	Viscosity of formation crude oil, mPa·s	2.0
Reservoir temperature,℃	56	Specific gravity, g/cm^3	0.8559
Permeability, $10^{-3}\mu m^2$	1.5	Porosity, %	8

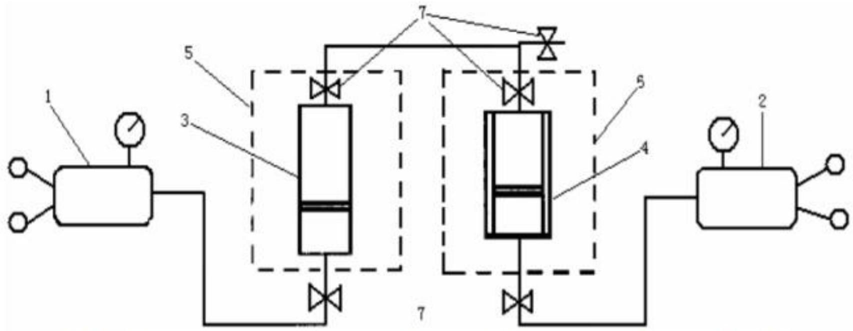
Experiment Preparation

Experimental Instruments. To conduct the experiment, the following devices and instruments were chosen:

- JEGRI-PVT analysis system of the DBR company of Canada. The main features of the device include the volume of the PVT chamber is 150 ml; PVT chamber is set to overall visibility; test temperature ranges from 30 to 200℃; temperature test accuracy is 0.1℃; test pressure ranges between 0.1 and 70 MPa; pressure test accuracy is 0.007MPa;
- American HP-6890 gas chromatograph. Temperature control ranges from 0 to 399.0℃; minimum energy detection is 3×10^{-2}g/s; maximum sensitivity is 1×10^{-12}A/mv;
- Ruska automatic pump. The working pressure ranges between 0 and 70 MPa; working temperature ranges from 0 to 40.0℃; resolution is 0.001ml;
- Sample preparation device;
- Intermediate container;
- Injected air was provided by Xianyang Yanshan Chemical Co., Ltd.

Experiment Steps. *Preparation of crude oil*. In most previous study, single methane was selected as dissolved gas(Liu and Zhang 1996; Wang et al. 2001; Ke et al.1994). To better simulate the properties of crude oil under formation conditions, we prepared associated gas and formation degassed crude oil under the conditions of formation temperature and formation pressure, fully considering the bubble point pressure and original gas-oil ratio. The composition of the oil sample was the same as in reservoir conditions, making the research results more reliable and convincing.

1. The experiment process is shown in **Figure 1.** 500 ml of degassed crude oil was injected into the sample preparation container. The associated gas volume required was calculated according to the original producing gas-oil ratio and the bubble point pressure (7.5MPa). The associated gas at the separator temperature was transferred into the piston type high-pressure vessel by the gas booster pump, and was pressurized to the sample preparation pressure. After the oil and gas samples were injected into the sample preparation device, they were heated to the formation temperature and stirred to form the crude oil samples that were not degassed.
2. The gas-bearing crude oil in the sample preparation device was fully stirred for six hours under the formation conditions, and then was flashed to the atmosphere for single degassing experiment. As a result, the composition of the oil and gas phase after degassing, the flash gas-oil ratio, and the density of the degassed crude oil were determined.



1,2-High pressure metering pump; 3-Separator oil (gas) storage bottle; 4-Sample preparation device; 5,6-Thermostatic bath; 7-Valve

Figure 1—PVT experimental flow chart.

PVT Properties Of Crude Oil. A certain volume of formation crude oil (40ml) was transferred into DBR-PVT cylinder under reservoir condition. The following steps were conducted:

1. Adjusting PVT cylinder to experiment required temperature, depressurizing from a relatively high pressure (20MPa) step by step, waiting for the crude oil to stabilize for half an hour after each depressurization, and then recording the expansion volume of the crude oil;
2. When the pressure dropped below the bubble point pressure, recording the total volume of oil and gas expansion;
3. Changing the experimental temperature, and repeat Steps 1 and 2.

Phase Diagram And Phase State Characteristics Under Reservoir Conditions. A certain volume of formation crude oil (40ml) was transferred into DBR-PVT cylinder under reservoir condition. The following test was performed:

1. Calculating the volume of gas that was added to the oil system at each time according to the percentage of air (oxidized gas) and crude oil (6%, 12%, 18%, 24%, 30%, 36%, 42%, etc.)
2. According to the calculated volume of gas, air (oxidized gas) to the PVT cylinder in turn, and then the air was pressurized and stirred until it dissolved. When the gas completely dissolved to saturation, measuring the bubble point pressure and crude oil expansion volume.
3. According to the calculated volume (the volume ratio of oil- gas-foam system is 2:2:1), 40ml crude oil and 40ml air (Note: the volume of gas was the volume under the reservoir condition) and 20ml foam system were injected into the PVT cylinder respectively; measuring the gas phase composition and oil phase composition after 6-8 hours of reaction, and then the ternary phase diagram were determined.

Experimental Results and Analysis

P-V Diagram of Crude Oil. Through the composition test of oil samples, the results show that its composition and physical properties were consistent with the formation oil in the study area and were consistent with the experimental oil.

The relationship between relative volume and pressure was studied at 46℃, 56℃ and 66℃. The results are shown in **Figure 2**. The relative volume of crude oil refers to the ratio of oil-gas volume under the same temperature but different pressures to crude oil volume at bubble point pressure.

With a gradually decreasing of pressure, the volume of crude oil increased, indicating an expansion performance. At the same time, it can be seen that there were obvious inflexion points in the three curves in the figure. When the pressure dropped to a certain level, the dissolved gas in the crude oil gradually separated, resulting in an obvious increase of oil-gas volume, and the corresponding pressure at this inflexion point was the bubble point pressure at current temperature. The bubble point pressure of crude oil at 46℃ and 66℃ was 7.2 MPa and 8.0 MPa, while that at reservoir temperature was 7.5 MPa (**Table 2**). As the temperature increased, the bubble point pressure increased. At the same time, it can be seen from the figure that the higher the temperature, the greater the volume of crude oil increased when the same pressure value was reduced, indicating that the higher the temperature, the higher the expansion performance of the crude oil under the reservoir conditions.

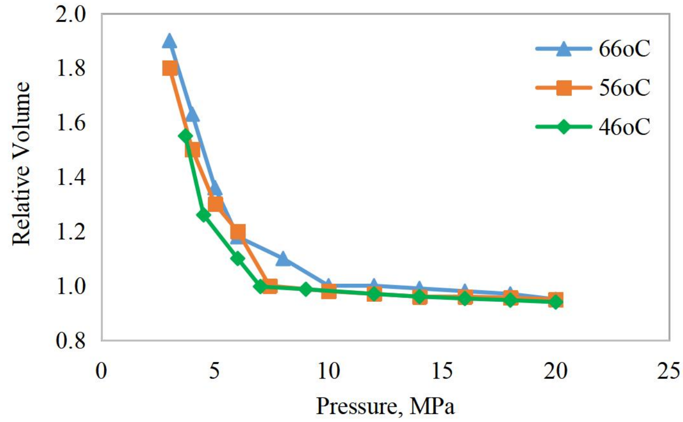


Figure 2—P-V diagram of crude oil at different temperatures.

Table 2—Bubble point pressure of crude oil at different temperatures.

Temperature (℃)	46.0	56.0	66.0
Bubble point pressure (MPa)	7.2	7.5	8.0

P-T Diagram Of Crude Oil. The bubble point pressure of crude oil under different temperature conditions is measured by experiments, and then the measured bubble point pressure was used in the PVT numerical simulation software (PVTsim20) to get the P-T relation diagram of crude oil under reservoir conditions (**Figure 3**). The bubble point pressures at 36℃, 46℃, 56℃, 66℃ and 76℃ were measured. The phase equilibrium model was used to predict the P-T phase diagram of crude oil. As a result, the critical temperature of crude oil was determined to be 424.4 ℃, and the critical pressure was 9.85MPa (Figure 3).

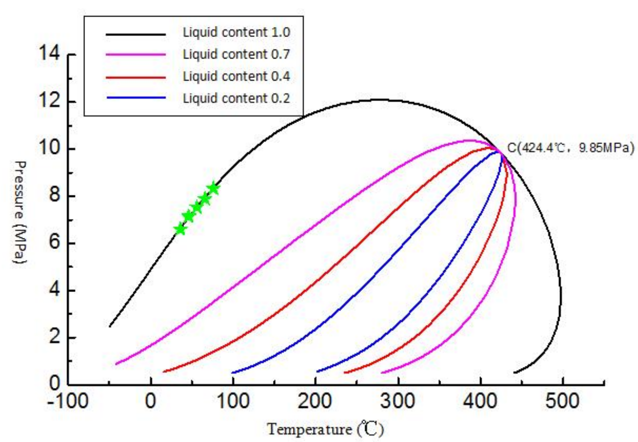


Figure 3—P-T simulation of crude oil.

P-X Diagram And Phase State Characteristics Under Reservoir Conditions. The bubble point pressures of air injected at different concentrations and oxidized gas were investigated. The phase diagram of the bubble point pressure (expansion coefficient)-air (oxidized gas) composition was drawn and given as **Figures 4** and **5**.

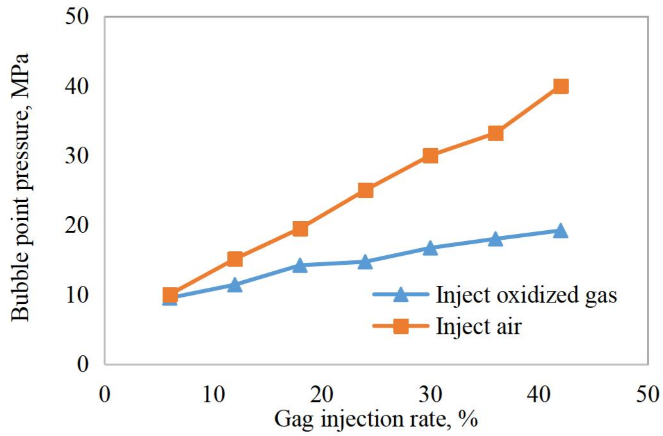


Figure 4—P-X phase diagram of air and oxidized gas with crude oil.

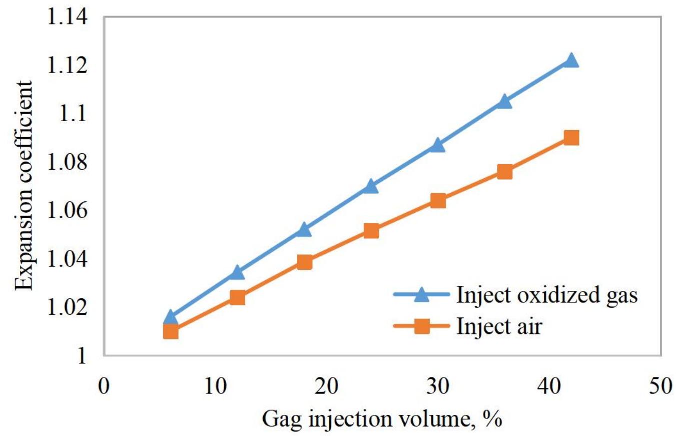


Figure 5—Relationship between the expansion coefficient of the crude oil and the volume of gas injection.

Whether the injected gas is air or oxidized gas, with increasing concentration, the bubble point pressure of crude oil increased, and the rate of increase was relatively stable. It means that the formation pressure continuously increased with the supply of reservoir energy in the gas injection; the injected gas can be partially dissolved in the crude oil, causing the volume of crude oil to expand. The greater the amount of dissolution, the larger the expansion volume. The increase of the elastic potential energy of crude oil was beneficial to the development of crude oil. At the same pressure, the ability of the oxidized gas dissolved in the crude oil was stronger than that in the air, because the methane was the main composition in the oxidized gas. The oxidized gas also contained 2.52% of carbon dioxide and 11.84% of C_2-C_6. The solubility of these gases in the crude oil was stronger than that in the nitrogen.

The Ternary Phase Of Multiple Air Bubble Contact. In the air multiple contact experiment, the contents of CO_2, methane, and C_2-C_6 in the gas phase increase with the increase of contact times under the reservoir temperature and pressure (**Figure 6**). However, due to the low-temperature oxidation reaction between crude oil and oxygen, the medium and heavy components of the crude oil split and the components of the gas-liquid phase tended to be closer, which is conducive to the oil displacement. In the air foam multiple contact experiment, due to the emulsification of the foam system and crude oil in the contact process, its oxidation effect was less than that of the air and crude oil multiple contact (**Figure 7**). The C_2-C_6 produced by oxidation was relatively less, while the C_7-C_{16} was relatively more, so the composition of gas phase tended to approach C_2-C_6 is relatively slow. However, the oil phase composition is closer to C_{7+}, due to the increase of C_7-C_{16} component. Thus, it is more difficult to miscible than multiple air contact.

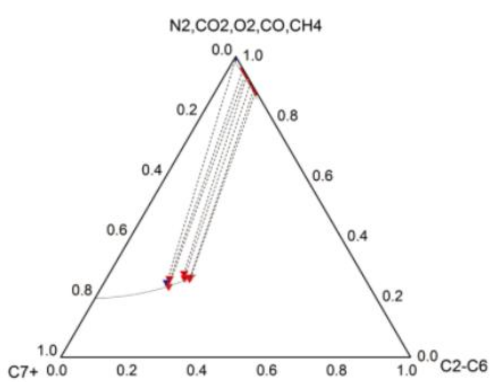


Figure 6—Ternary phase diagram after multiple contact of air and crude oil.

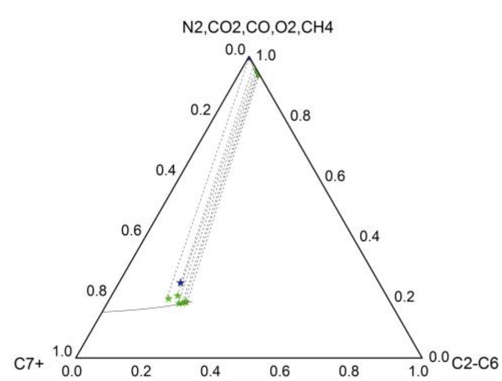


Figure 7—Ternary phase diagram after multiple contact of air bubble and crude oil.

Conclusions

1. According to the physical properties of the crude oil under the reservoir conditions, the simulated oil is configured in the lab. Through the test, the composition of the simulated oil simulate the reservoir state, and the research results were close to the actual development situation.
2. Through PVT experiment, the critical temperature and critical pressure of oil sample determined to be 424.4℃ and 9.85MPa, respectively.
3. The P-X phase diagrams of air and oxidized gas injected under reservoir conditions were studied. With increasing concentration, the bubble point pressure of crude oil continuously increased and the rate of increase was relatively stable.
4. In the process of gas injection, the formation pressure was increased continuously by the supply of reservoir energy. The injected gas can be partially dissolved in the crude oil, making the volume of the crude oil expand. The higher the dissolved volume, the larger the expansion volume and the higher the elastic potential energy of the crude oil, which is conducive to the exploitation of crude oil.
5. Under the same pressure, the ability of gas dissolved in crude oil after oxidation was stronger than that in air. As a result of the emulsification between the foam system and the crude oil in the contact process, its oxidation effect was less than that in the air and the crude oil multiple contact. C_2-C_6 produced by oxidation was relatively less, while C_7-C_{16} was relatively more. Therefore, the trend of the gas phase approaching C_2-C_6 was relatively slow. However, the oil phase composition was closer to C_{7+}, due to the increase in the C_7-C_{16} component. It is more difficult to miscible than multiple air contact.

Conflicts of Interest

The author(s) declare that they have no conflicting interests.

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