Experimental study on phase behavior of heavy oil-solvent mixture system

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Abstract. Phase behavior research is of great significance for formulating oilfield development plans. In this paper, an experimental procedure was proposed to investigate the phase behavior of a solvent mixture (5 mol\% CO\textsubscript{2} + 45 mol\% CH\textsubscript{4} + 55 mol\% C\textsubscript{3}H\textsubscript{8}) with Venezuela Orinoco heavy oil. The measured physical properties of the heavy oil–gaseous solvent system include the bubble point pressure, swelling factor, density and viscosity of the liquid phase as a function of gas mole fraction. The experimental results show that as the gas molar fraction increases from 10\% to 30\%, the bubble point pressure and swelling factor of the heavy oil–solvent mixture system increase accordingly; as the dissolved gas content in the heavy oil increases, the viscosity and the density of the system is reduced, but the reduction is getting smaller and smaller.

1. Introduction

Heavy oil reserves are becoming more significant with the increasing global demand. Some solvent-based techniques appear to be highly promising for the exploitation of heavy oil reservoirs, especially for complex heavy oil reservoirs that are economically unsuitable for thermal recovery methods. Plenty of mechanisms for enhancing oil recovery in solvent-based techniques include viscosity reduction, swelling effect, solution gas drive and foamy oil flow\cite{1-2}. Han Buxing et al. found that increasing pressure can increase the solubility of CH\textsubscript{4} in the heavy oil and reduce the viscosity of heavy oil\cite{3}. Wang Shoulong et al. have shown that the dissolution of CO\textsubscript{2} can effectively reduce the viscosity of heavy oil\cite{4}. Boustani et al. pointed out that the dissolution of C\textsubscript{3}H\textsubscript{8} has a significant viscosity-reducing effect on heavy oil and improves the oil mobility\cite{5}. Peng et al. have studied and compared two solvents: the pure CO\textsubscript{2} and CO\textsubscript{2}–C\textsubscript{3}H\textsubscript{8} mixture. The CO\textsubscript{2}–C\textsubscript{3}H\textsubscript{8} mixture was found to be substantially more effective than CO\textsubscript{2} alone in terms of oil viscosity reduction and swelling\cite{6}. In this study, CO\textsubscript{2}–CH\textsubscript{4}–C\textsubscript{3}H\textsubscript{8} mixture was used with a molar ratio of 1:8:11. The bubble point pressure, swelling factor, density and viscosity of heavy oil–solvent mixture under different gas mole fractions were studied.

2. Experimental section

2.1. Materials

The crude oil samples used in the experiments were Venezuela Orinoco heavy oil. Density and viscosities for the dead oil, which were measured at three temperatures and ambient pressure, are presented in Table 1.
|                     |                     |                |
|---------------------|---------------------|----------------|
| Density (g/cm³)     | 1.013               |                |
| Viscosity (mPa.s)   |                     |                |
| 50 °C               | 24715               |                |
| 65 °C               | 5559                |                |
| 80 °C               | 1620                |                |
| Saturates           | 19.8                |                |
| Aromatics           | 51.2                |                |
| Resins              | 18.9                |                |
| Asphaltenes         | 8.8                 |                |

2. Experimental set-up
The setup is shown schematically in Figure 1.

![Experimental set-up diagram](image)

Figure 1. Schematic of experimental set-up

2.3. Experimental procedure
The experiments included the following steps: 1. Check device for air tightness using nitrogen; 2. Vacuum the experimental instrument and then preheat it; 3. A certain amount of heavy oil and gaseous solvent mixture is injected into the PVT cell, and the amount of solvent mixture that needs to be injected is calculated by the real gas state equation. The stirring switch is turned on to ensure that the fluid system reaches the liquid-gas equilibrium state. 4. Increase the volume of the PVT cell to reduce pressure. Each stage is reduced by 0.1-1 MPa. When the fluid system reaches equilibrium, the volume and pressure of the PVT cell are recorded. 5. After the bubble point pressure measurement is completed, the PVT cell pressure is stabilized to the bubble point pressure, and then the oil sample therein is transferred to a rolling-ball viscometer and a densitometer to measure the viscosity and density values under the bubble point pressure, respectively.

3. Results and analysis
Different pressure-volume data were obtained by injecting different molar fractions of solvent mixture (10-30 mol%) into the heavy oil, and the pressure-volume curves are plotted in Figure 2. The data corresponding to the inflection point in the figure is the bubble point pressure and the volume of the
system under the bubble point pressure. The bubble point pressure considerably increases as the mole fraction of solvent mixture increases. As the gas mole fraction was increased to 30%, the bubble point pressure of the system reached 5.67 MPa, which means that there is more energy in the solution gas drive process to make the heavy oil flow.

![Pressure-volume curve with varied gas molar fractions](image)

Figure 2. Pressure-volume curve with varied gas molar fractions: (a) 10 mol%, (b) 15 mol% (c) 20 mol% (d) 25 mol% (e) 30 mol%

The dissolution of solvent mixture into the oil resulted in noticeable swelling of the oil. This increase of oil volume can make discontinuous oil droplets trapped in a porous medium merge with the flowing oil stream in some solvent-based techniques. The extent of increase in oil volume is indicated by the swelling factor, which is defined as the ratio of the volume of the heavy oil-solvent mixture system at reservoir temperature and bubble point pressure to the volume of the dead oil itself at the same pressure and temperature.

The measured swelling factor curve, as depicted in Figure 3, rose almost linearly as the molar fraction of the solvent mixture increased. The experimental results show that 1.2% to 4% expansion of the oil was realized in the gas molar fraction range of 10 mol% to 30 mol% at the reservoir temperature of 54.2°C. However, the magnitude of swelling for heavy oils is not as drastic as for light/medium
oils, which can often be swelled by more than 50% of their original volume due to significant solvent dissolution[6].

Viscosity reduction is one of the most important mechanisms for enhanced heavy oil recovery[7]. Reducing the density and viscosity of heavy oil can effectively increase the relative permeability of the oil phase and improve the flow capacity of the heavy oil. It is worthwhile to mention that viscosity reduction is closely related to the amount of solvent gas dissolved in the heavy oil[8].

The density and viscosities of the heavy oil-solvent mixture systems with varied molar fractions of solvent mixture at bubble point pressures are plotted in Figure 4. It is observed that as the dissolved gas content in the heavy oil increases, the viscosity and density of the system decrease. And the viscosity of oil reduced significantly even at a relatively low gas molar fraction during the early stage. It may be concluded that when solvent-based technique is used to explore heavy oil reservoirs, gas solvent can effectively reduce the density and viscosity of heavy oil, improve the flow capacity of heavy oil, and thus improve the recovery of heavy oil reservoirs. However, when the molar fraction of the solvent is increased to a certain extent, the magnitude of the viscosity and density reduction gradually decreases.

4. Conclusions
(1) As the gas molar fraction increases from 10% to 30%, the bubble point pressure of the heavy oil-solvent mixture system rises from 1.57 MPa to 5.67 MPa.
(2) As the dissolved gas content in the heavy oil increases, the swelling factor of the heavy oil-solvent mixture system increases almost linearly, and 1.2% to 4% of the oil expands in the gas molar fraction range of 10 mol% to 30 mol%.
(3) As the dissolved gas content in the heavy oil increases, the viscosity and density of the system decrease, but the magnitude of the reduction gradually decreases.

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