Introduction

Extra-heavy oil is characterized by high viscosity and low API gravity in Block M, Orinoco Belt. But the cold recovery could achieve high initial production rate with horizontal wells due to foamy oil phenomenon. Foamy oil flow describes a form of two phase oil-gas flow in porous media in which the gas phase remains partially or completely dispersed in the oil, when the pressure drops below the bubble point pressure.

The foamy oil cold production belongs to the unconventional solution gas drive, facing the larger errors in using the conventional material balance equation. In order to predict the performance of foamy oil reservoirs, it is essential to establish the material balance equation for these foamy extra-heavy oil reservoirs.

A novel PVT apparatus applicable to foamy oil was developed and adopted in this work. A series of foamy oil PVT tests were conducted. Then the unique PVT behaviour of foamy oil, such as the changes of formation volume factor, oil density and viscosity with pressure were analysed and characterized. Based on the PVT experiments of foamy oil, the properties model of foamy oil were established. Then the material balance equation of foamy oil was obtained, and it was validated through numerical simulation.

Through the material balance equation of foamy oil, the reservoir pressure and the remaining recoverable reserves can be accurately predicted, which is meaningful for reservoir management and optimization.

Experimental setup and process

Experimental material

Dead crude oil or simulated crude oil recombined with methane was mostly used to study properties of foamy oil before. In order to simulate properties of reservoir oil more really, clean degassed crude oil from Block M was saturated with natural gas at the reservoir temperature of 53.7 °C and reservoir initial pressure which is more than 8.5MPa to yield “live” recombined reservoir oil. Components of natural gas contained 10.7% CO2, 0.53% N2, 86.69% C1, 0.33% C2 and 0.19% C4, which were identical to formation dissolved gas. The properties of degassed crude oil, reservoir crude oil and recombined reservoir oil samples were shown in Table 2, which showed that the properties of recombined oil was in highly accordance with that of reservoir crude oil.

Experimental methodology

For conventional crude oil, after pressure drops below the bubble point pressure, the gas rapidly coalesces into larger bubbles and separates almost immediately from the oil phase to form a distinct gas phase. But for foamy oil, the situation is different, the gas bubbles cannot immediately coalesce together to form bubbles large enough to allow gravitational force to separate them from the oil, instead those tiny bubbles remain in the oil phase. After a relatively long time, they start to coalesce to escape from the oil phase.

The coalescence rate of micro-bubbles is affected by time, oil properties, experimental pressure and agitation strength. For foamy oil unconventional PVT test, agitation should be avoided. Conventional and unconventional PVT tests were designed in this paper. In the conventional test, the crude oil samples would be agitated completely and the test was conducted until the oil-gas separation process was finished and in an equilibrium state. On the contrary, in the unconventional test, the crude oil samples would not be agitated. Three complete unconventional PVT tests were carried out with the only variation being the speed of the pressure reduction during the differential liberation experiments. These three unconventional tests were classified as "rapid" (2 hours per depletion step), "mid-rate" (2 days for each depletion step) and "slow" (14 days per depletion step).
Experimental apparatus

A special designed high temperature and high pressure PVT analyzer was adopted to conduct the tests(Figure 1). The characteristics of this equipment are as follows: 1) with a high-temperature and high-pressure-resistant sample cell; 2) with an unique agitation component, which can swing and rotate, guaranteeing sample uniformity and test accuracy; 3) with a visual window in the sample cell; 4) Mercury-free operation, and available for manual control, electric-driven or computer control; 5) with highest experimental pressure of 70MPa and the highest experimental temperature of 200 oC.

Because the formation of foamy oil is very complex and separation process of dissolved gas in heavy oil is slow. As an ancillary equipment, the flash separator was set in the PVT analyzer to enhance the speed of gas-oil separation and to improve measuring accuracy.

Meanwhile, the capillary viscometer was adopted instead of falling-ball viscometer to measure the viscosity of the foamy oil.

Experimental results

The foam oil PVT results are shown in figure 2.
Material balance equation of foamy oil

The material balance equation of foam oil is shown in equation (1-2).

\[
N_p = NB_o \left( e^{\frac{c_{w,OP}}{B_o}} - 1 \right) = NB_o \left( e^{\frac{c_{w,OP}}{B_o}} - 1 \right)
\]

\[
C_{fo} = -\frac{1}{B_{fo}} \frac{\partial B_{fo}}{\partial P} = \frac{1}{\rho_{fo}} \frac{\partial \rho_{fo}}{\partial P}
\]

Application

This material balance equation of foam oil is used for predicting the performance and potential of reservoirs (figure 3).

Conclusions

(1) The PVT test method of foamy oil was different from that of conventional oil because for foamy oil there existed a process during which dispersed gas bubbles generated and coalesced under different pressure conditions, therefore, the PVT test of foamy oil was a non-stable test.

(2) The measurement results showed that the PVT behaviours of foamy oil were quite variable under different pressure depletion rates, and a pseudo bubble-point pressure presented during foamy oil production.
(3) The foamy oil properties model were established based on the PVT tests of foamy oil, and the material balance equation of foamy oil was obtained. This material balance equation was matched and validated through the foamy oil numerical simulation.

(4) A method used for predicting remaining recoverable reserves was developed based on the material balance equation of foamy oil.

Acknowledgements

This work is supported by the China National Key Project of 2016ZX05031-001.

References


