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Quantitative evaluation of factors affecting foamy oil recovery in the development of heavy hydrocarbon reservoirs

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ABSTRACT

A series of experiments was conducted to quantify foamy oil recovery under different conditions, including the pressure depletion rate, solution gas-oil ratio (GOR), and oil viscosity. As indicated by the experimental results, at higher-pressure depletion rates, solution GOR, and oil viscosity, the foamy oil ultimate recovery tends to be higher. The foamy oil phenomenon can occur when the pressure depletion rate, solution GOR, and oil viscosity exceed certain values. Based upon experimental results, multiple regression analysis was used to establish a mathematical expression of the relationship between dimensionless foamy oil recovery (R_{eD}) and the main factors affecting it, including the dimensionless pressure depletion rate (Δp_{rD}), the dimensionless solution GOR (R_{sD}), and the dimensionless oil viscosity (μ_D). The computed results showed the weighted values of the effects of $\ln\Delta p_{rD}$, $\ln R_{sD}$, and $\ln\mu_D$ on $\ln R_{eD}$ to be 0.653, 0.211, and 0.136, respectively, which indicates that improving the pressure depletion rate may be the most effective approach to increasing the amount of foamy oil recovered. The uses and limitations of the correlation were validated using verification experiments and are discussed. Suggestions for rendering foamy oil recovery more efficient can provide useful guidance for the development of heavy hydrocarbon reservoirs.

Introduction

The term "foamy oil" is often used to describe a certain type of heavy hydrocarbon produced by solution gas drives, which displays visible foaminess in wellhead samples. It is rendered foamy by natural energy depletion [1]. Unlike conventional heavy hydrocarbon reservoirs, foamy hydrocarbon reservoirs have a pseudo-bubble point and a bubble point. When the reservoir pressure is below the bubble point in those foamy hydrocarbon reservoirs, the solution gas is believed to exist in the form of a gas-in-oil dispersion. The solution gas is slowly liberated but remains trapped by the oil in the form of tiny, dispersed gas bubbles until the pressure drops below the pseudo-bubble point [2,3]. Foamy oil has been found to exhibit

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such special production behaviors as a high oil production rate, low production gas-oil ratio, high oil viscosity, and high primary recovery during the development process [4,5]. The primary recovery factor of typical conventional heavy oil is less than 3%, but that of the foamy oil can reach 8–15%, even 25%, which is about 8 times that of conventional heavy hydrocarbon reservoirs [6–8].

Foamy oil's anomalously high production and primary oil recovery rates have drawn researchers' attention. The factors affecting foamy oil's high recovery rate have become the subject of several investigations and considerable speculation. Many macroscopic factors are believed to affect foamy oil recovery, such as pressure depletion rate, solution GOR, oil viscosity, temperature, initial water saturation, and gravity [5,8–10]. Of course, many microscopic factors such as the number of capillaries, foamy quality number, composition of porous media, and crude oil also exhibit some effects on foamy oil recovery [11–17].

Microscopic factors are outside of the purview of this paper. Rather, this paper focuses solely on discussing the effects of macroscopic factors on foamy oil recovery. It has been reported that the foamy oil recovery effects observed in laboratory depletion experiments are more strongly affected by the pressure depletion rate, solution GOR, and oil viscosity than by the other macroscopic factors named above. Many researchers have conducted depletion experiments on foamy oil to study the effects of these three factors. A general conclusion they have drawn is that foamy oil recovery increased dramatically as the pressure depletion rate, solution GOR, and oil viscosity increased [3,15–22]. However, most of these studies did not show any of the factors affecting the amount of foamy oil recovered or evaluate multiple factors quantitatively.

In this paper, a series of depletion experiments was carried out to quantify the effects of pressure depletion rate, solution GOR, and oil viscosity on foamy oil recovery based on the **control variable method** in detail and the quantitative relationship among them was obtained. Some suggestions for enhancing foamy oil recovery in the development of heavy hydrocarbon reservoirs are presented based upon the experimental results. The conclusions of this study may provide useful suggestions for the development of foam hydrocarbon reservoirs.

Experimental equipment and procedure

Experimental apparatus

The experimental setup for laboratory depletion tests is shown schematically in Fig. 1. An intermediate container was used to transfer the saturated oil sample via the configuring sample container. A long core holder was made by a special steel tube with a diameter of 5 cm, length of 80 cm, and rough wall at a highest working pressure of 32 MPa. A back pressure regulator was used to control the pressure of the outlet of the sand pack; Its maximum control pressure was 70 MPa. An ISCO pump was used for displacing the fluid into the sand pack and pressurizing the system by constant flowing rate. The maximum flowing rate was 25 ml/min, and the maximum pressure was 70 MPa. An electrically controlled thermostatic system was used to ensure the experiments at a constant temperature and the temperature was constant within the range from room temperature to 200 °C. An oil collector was used to measure the amount of oil production. A vacuum pump was used to vacuum the sand pack at the beginning of the experiments [23].

Experimental conditions

The experimental conditions and materials are as follows:

Sand pack

The sand pack was made of clean quartz sand with a grain size between 50 and 75 meshes. Its length was 80 cm, diameter was 8 cm, porosity was 38.8%, the volume of the pore was about 1559 cm^3, absolute permeability was 5.8 μm^2, sand-pack compressibility was 4.7×10^{-4}/MPa, and the irreducible water saturation was 3%.

Water

The water was $NaHCO_3$ type with a total salinity of 12,500 ppm, HCO_3^- content was 2450 ppm, Cl^- content was 10,350 ppm, pH was 7.35–7.75.

Oil

The heavy oil from Zone O-12 of Block MPE-3 in Venezuela was used in the depletion experiments. The viscosity of the dead oil was around 25,460 mPa s. Methane was used as the gas phase in all the experiments. Live oil samples were prepared above the bubble point pressure, and their solution GOR ranged from 10.4 m^3/m^3 to 19.7 m^3/m^3, the density ranged from 0.915 g/cm^3 to 0.996 g/cm^3, and the bubble point pressure ranged from 3.38 MPa to 6.43 MPa at 25 °C.

To study the effects of viscosity on foamy oil recovery, the other five levels of viscosities were prepared by mixing different mass fractions kerosene with the heavy oil. These viscosities of oil samples, called A, B, C, D, E, and F were 25,460 mPa s, 20,180 mPa s 17,840 mPa s, 14,132 mPa s, 9602 mPa s, and 5843 mPa s at 50.5 °C and 0.1 MPa, respectively. The viscosities were measured using a Brookfield DV-II + Pro rotor viscosity meter produced in the United States. To study the effect of solution GOR on foamy oil recovery, six levels of solution GOR were considered, 19.7 m^3/m^3, 17.8 m^3/m^3, 13.2 m^3/m^3, 10.4 m^3/m^3, 14 m^3/m^3, and 15.5 m^3/m^3 (A1, A2, A3, A4, E, and F), respectively. The foaminess of these oils was evaluated before depletion tests. It proved that all the oils can be observed foamy oil phenomena obviously. The properties of the oil samples are listed in Table 1.

A total of 12 depletion experiments were carried out using different oil samples. Oil sample (A1) was used for experiments No. 1, No. 2, No. 3, and No. 4, which were used to study the effect of the pressure depletion rate on foamy oil recovery. Oil samples (A2, A3, and A4) were used for experiments No. 5, No. 6, and No. 7, respectively, which were used to study the effect of the solution GOR on foamy oil recovery by comparing them with experiment No. 1 (the viscosities of live oil samples A1, A2, A3, and A4 are equivalent approximately, so the influence of viscosity can be ignored). Oil samples (B, C, and D) were used for experiments No. 8, No. 9, and No. 10,