Fuel 111 (2013) 12–19

Contents lists available at SciVerse ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Experimental study on the stability of the foamy oil in developing heavy oil reservoirs

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HIGHLIGHTS

- The HTHP visualized experimental system was used to study the foamy oil stability.
- A serial of experiments were evaluated the performance of the foam stability.
- The foamy bubbles exist much longer at the actual reservoir conditions.
- The results were used to guide the development of Block MPE-3 in Venezuela.

ARTICLE INFO

Article history:
Received 2 May 2012
Received in revised form 7 March 2013
Accepted 13 March 2013
Available online 30 April 2013

Keywords:
Foamy oil
Heavy oil
Experimental study
Pressure decline rate
Porous media

ABSTRACT

In the process of natural energy depletion, foamy oil is characterized of high oil viscosity, low production GOR, high daily production rate; relatively slow production decline rate and high primary recovery factor (compared with conventional heavy oil). The stability of the foam becomes the dominant factor that determines the life of the 'foamy oil'. To quantify the main factors affecting the stability of the foam, a high-temperature–high-pressure (HTHP) visualized experiment model for foamy oil stability test was developed. A serial of experiments were conducted to evaluate the performance of the foam stability under different conditions, including temperature, dissolved gas oil ratio, pressure decline rate and the pore sizes. As indicated by the test results, the stable foamy oil exists only if the reservoir temperature is lower than 70 °C. The initial dissolved gas oil ratio was higher than 4.23 m^3/m^3 and the pressure depletion rate was higher than 0.0018 MPa/min. It was also concluded that as the pore sizes of the porous media becomes closer to the actual reservoir pore size, the foam can last longer, which indicates that the "foamy oil" will exist for a long time during the reservoir development. The experimental results above have been used to guide the development of Block MPE-3 in Venezuela.

1. Introduction

The term "foamy oil" is often used to describe certain heavy oils produced by solution gas drive which display obvious foaminess in wellhead stable samples collected in many heavy oil reservoir developed by natural energy depletion in Canada and Venezuela. These heavy oil reservoirs acquired higher primary recovery than expected as the reservoir pressure declines [1–6].

In the production of foamy heavy oil, the dissolved gas was believed to exist in the form of a gas-in-oil dispersion instead of instant liberation to be free gas. Though very little ingeneration is available to describe the actual microscopic characteristics of the gas-in-oil bubbles, the oil phase mobility was very much enhanced due to the influences of the gas bubbles dispersion [7,8]. Compared with conventional heavy oil reservoir, Foamy oil has exhibited such special production behaviours as: high oil viscosity, low production gas oil ratio, high oil production rate, slower production decline rate, higher primary recovery [3,6,9,10]. The primary recovery factor of typical conventional heavy oil is 0–5%, while that of the foamy heavy oil can reach 5–25% [4,5,11].

As foamy oil phenomenon greatly affects the production performance of some heavy oil reservoirs developed by natural energy depletion, many researchers have explained its mechanisms. Smith [1,2], explained this phenomenon in detail and characterized foamy oil flow as a fluid characteristic of large volumes of tiny gas bubbles highly dispersed in the heavy oil. Later, a large amount of experimental and theoretical investigations was carried out to better understand this gas-in-oil flow behaviour [1,2].

It was suggested by some researchers that the reservoir flow mobility in the wellbore vicinity can be enhanced by the foamy oil behaviour when the pressure gradient was established [13]. Gas in the reservoir always exists at three statuses, namely dissolved gas, dispersion gas and free gas. A comparison was con-

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0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.03.021

ducted on different indices between foamy oil solution gas drive and regular solution gas drive [5] and the mechanism of gas bubbles nucleation, growth and flow are thoroughly studied. To better understand the foamy oil phenomena, two categories of mechanisms were suggested: firstly, geomechanical effects, such as sand dilation and development of wormholes; secondly, the property of the reservoir fluid, such as gas and heavy oil themselves are the main contributors to the high production rate [4,12,14–17]. In order to better describe the dynamic behaviour of the production wellbore, a semi-analytical model was also developed based on the relationship between the heavy oil cold production reservoir and wormholes [18].

Conventional heavy oil reservoirs with dissolved gas only have one bubble point. During the process of natural energy depletion, dissolved gas will liberate from oil quickly when the reservoir pressure dropped to the bubble point, causing the production gas oil ratio to increase and resulting in much higher oil viscosity. However, some heavy oil reservoirs (typically the Orinoco Heavy Oil Belt in Venezuela) have exhibited the foamy oil production behaviour during their cold production process: high oil viscosity (underground viscosity 10,000–50,000 mPa s), high daily production rate (100–250 t/d), and slower production decline rate (12% per year). The primary recovery factor could expect to be more than 10% if the foamy oil effects can be maximized [19].

Studies have showed that gas bubbles are nucleated and trapped in dispersion for a relatively long time when the reservoir pressure dropped below the bubble point in these foamy oil reservoirs [20–23]. Compared with conventional heavy oil, foamy oil reservoir has a pseudo-bubble point and a bubble point. When the bubble point is reached, the solution gas will be liberated but remain trapped by the oil in the form of dispersed tiny gas bubbles. The oil viscosity is much reduced because of the trapped gas bubbles [24]. This is the expected period when the foamy oil takes effect and a lower production GOR will be observed. After the pressure drops to between the bubble point and pseudo-bubble point, the gas bubbles will grow and coalesce, and become free gas eventually after the pressure drops below the bubble point. When the gas is released from the oil, the oil viscosity increases and the production will drop quickly.

Many researchers [25–28] have suggested that during the foamy oil period, which is when the reservoir pressure is between bubble pressure and pseudo-bubble pressure, the recovered production accounts for approximately 70% of whole production during natural energy depletion phase, while the fractions are only 20% and 10% when the reservoir pressure are above the bubble point and below the pseudo bubble point respectively. Much higher primary recovery can be obtained when developing a foamy oil reservoir [4,29]. Therefore, it is of great practical significance to use the foamy oil for maximizing the effect of natural energy depletion on production.

The stability of the trapped gas bubbles, in other words, the lifespan of the bubbles, is the dominant factor of the foamy oil effects. One-dimensional core depletion experiments were conducted by some researchers [30] to investigate the temperature effects. In those experiments, the temperatures ranged from 22 °C to 175 °C. They concluded that a relative higher recovery ratio could be obtained at moderate reservoir temperatures and the maximum accumulative production was achieved when the reservoir temperature was 70 °C. However, the effects of both high-temperature-low-viscosity and foamy oil phenomenon on accumulative oil production were not quantified. Maini [31] investigated the effect of oil viscosity and pressure decline rate on recovery using a 2-meter sand pack and different oil samples. It was concluded that the solution gas drive recovery increases with pressure decline rate. When pressure declines rapidly, the effect of oil viscosity on recovery may be ignored.

Heavy oil samples from two different blocks in Venezuela were tested by Andarcia et al. [15] for core depletion. The results indicated that oil viscosity was not the only parameter affecting the foamy oil behaviour. Akin et al. [32] used X-ray and CT-scan technique in their experiments at a microscopic scale to determine the critical gas saturation which causes foamy oil phenomenon under HTHP conditions. Javadpour et al. [33] drew a conclusion from network modeling that the lifespan of foamy oil increases linearly with the rock's porosity/surface area ratio. However such nonstable processes as the micro bubbles' growth, coalescence and breakup, etc. cannot be reflected from analytical models.

Ostos and Maini [34] conducted core depletion tests at different pressure decline rates and concluded that high pressure depletion rate promotes higher recovery, and foamy oil phenomenon mainly occurs when pressure declines rapidly. But this conclusion was only based on oil production data from outlet end, failure to observe the lifespan of the foamy oil and to obtain the lowest pressure gradient which causes the foamy oil phenomenon. Another core test was performed by Chen and Maini [35] to pursue the correlation between initial gas oil ratio and primary oil recovery. According to this test, the accumulated production tends to become less with lower initial gas oil ratio. However, only production data is insufficient to quantify the existing time and the contribution of foamy oil under different initial gas oil ratio.

George1et al. [36] designed a 2D transparent silicon-glass model to study foamy oil mechanism and concluded that oil viscosity had significant influence on bubbles' coalescence from beginning to the end of the reservoir life. Bravo et al. [37] studied the oil permeability performance for gas saturated heavy oil under pressure gradients. They analyzed the effect of pressure on oil relative permeability under varying capillary forces, which is very helpful in understanding foamy oil mechanism. Wang et al. [38] used a sand-pack (with a dimension of 42.5 cm long, diameter of 2 cm, and total volume of 133.518 cm^3) to test the influence of the oil viscosity on the bubble's stability. And it was proposed that oil viscosity, solution gas content, temperature and pressure decline rate all have effects on the foamy oil stability, among which pressure decline rate is regarded as the most important factor.

Bondino et al. [39] established a mathematical model and conducted a serial of core tests to study on how pressure depletion rate affects the foamy oil in porous media. This study provided a better understanding for the gas bubbles nucleation. Peng et al. [40] conducted a series of pressure depletion tests at reservoir temperatures with different live crude oils and mineral oils to investigate the role of oil composition during heavy oil solution drive. They compared the morphology of gas bubbles, pore pressure, critical gas saturation and oil recovery. They pointed out that oil chemistry may play a role in the solution gas drive processes. Chen and Qin [41] used a 2D visualized micro experiment device to observe the foamy oil behaviour in real porous media structure.

A HTHP visualized experimental apparatus was developed to study foamy oil stability in this paper and the heavy oil samples from Block MPE-3 in Orinoco Belt in Venezeula were used. The main factors (temperature, initial solution gas oil ratio, pressure depletion rate, and pore size) affecting foamy oil stability are studied in detail. The experimental data of foamy oil expansion height and foam lifetimes were acquired and analyzed to quantify the stability of foamy oil.

2. Experiment equipment and procedure

2.1. Experimental apparatus

The HTHP visualized experimental setup (Fig. 1) for foamy oil stability tests is composed of the oil sample injection system, oven,