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Feasibility study of enhanced foamy oil recovery of the Orinoco Belt using natural gas

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ABSTRACT

Foamy oil behavior contributes significantly to the anomalously high primary recovery of heavy oils observed in the Orinoco Belt, Venezuela. However, once below the pseudo-bubble pressure, disappearance of this phenomenon results in a rapid increase in the produced GOR and a fast decline in oil production. This paper presents the results of a laboratory investigation, including asphaltene precipitation studies, pressure–volume–temperature (PVT) studies of foamy oil–natural gas mixtures and coreflood tests, for evaluating the feasibility of the natural gas injection process for enhanced heavy oil recovery with foamy oil characteristics. Firstly, asphaltene precipitation tests were carried out to investigate the likelihood of asphaltene deposition problems in MPE3 reservoir during the gas injection process. The natural gas dissolution tests characterized the natural gas diffusion process in the foamy oil, and a new method for determining the natural gas diffusion coefficient in foamy oil was developed on the basis of experimental data. Thereafter, foamy oil swelling tests examined the effects on viscosity reduction and foamy oil swelling of the presence of natural gas. Finally, coreflood tests were carried out to investigate the effects on oil recovery of injection mode and their different process parameters. The results indicate that significant amounts of natural gas could dissolve in the oil, which would cause oil swelling, viscosity reduction and artificial foamy oil formation. Core-flooding tests show that the natural gas huff-n-puff process could increase oil recovery 7.8% compared to the primary pressure depletion process, indicating a greater potential for recovering heavy oil. However, the asphaltene instability could potentially nullify any expected benefits of improved oil recovery with natural gas.

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1. Introduction

The Orinoco Oil Belt is located along the southern margin of the Eastern Venezuela Basin. Within it lies one of the largest heavy oil deposits in the world, roughly 1.3 trillion barrels of oil-in-place (Gipson et al., 2002). The heavy oil in this area differs greatly from other heavy oils in the world such as high density (934–1050 kg/m^3), high sulfur (average 35,000 mg/L), and low viscosity (generally lower than 20 Pa s). One of the biggest differences is that, once below the bubble-point pressure, the producing gas–oil ratio (GOR) does not increase sharply, and the rate of pressure drop is low. Relatively high primary recovery factors have been reported from some reservoirs of this area (Mu et al., 2009; Li et al., 2012). For example, the MPE3 reservoir in this area has a STOOIP of 283×10^4 t, of which around 8–12% has been produced through horizontal wells cold production with foamy oil mechanism. The production of one horizontal well can be up to 200 t/d, but the producing GOR is around the original gas–oil ratio. However, in 2012, the producing GOR of the MPE3 reservoir increased sharply, to a level that exceeded 41.1 m^3/m^3, which was 2.6 times of the original gas–oil ratio. The average decline rate of production wells was 1.8%. The reason for this phenomenon is that the gas bubbles trapped in the oil begin to coalesce together to form a free gas phase as the reservoir pressure inclined, which resulted in the disappearance of the foamy oil phenomenon. For this reason, EOR methods are needed for restoring the foamy oil mechanism and increasing the oil recovery.

Among various enhanced oil recovery (EOR) methods, such as gas miscible/immiscible injection, chemical flooding and thermal technologies, there is increasing interest in produced natural gas injection process in MPE3 reservoir because the process is relatively cost effective with small investment requirements and low operating costs. What is more, this method proves to be successful in some foamy oil reservoirs (Garcia, 1983; Guan et al., 2008; Li et al., 2008). It should be noted that Meneven conducted successful a natural-gas-injection project in OM-100 Reservoir of the Oveja Field, located in Eastern Venezuela. Thus, the high viscosity (low API gravity) of a reservoir crude is not necessarily a limiting factor in the successful application of conventional gas injection.

The mechanisms involved in the production of oil during gas injection process for conventional oil reservoir have been mentioned

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Nomenclature

D	diffusion coefficient (m^2/s)
V	volume (m^3)
C	mass concentration of solute (kg/m^3)
$C(x,t)$	solute concentration at position x at time t (kg/m^3)
K	defined by Eq. (8)
m	mass of solute (kg)
u	velocity (m/s)
r	rate of reaction (kg/m^3 s)
J	mass transfer by the mechanism of molecular diffusion ($kg/m^3 s$)
t	time (s)
x	coordinate direction (m)
S	cross-section area of diffusion cell (m^2)

in the literature (Srivastava and Huang, 1997; Faríasa et al., 2009; Benyamin et al., 2012). For example, laboratory measurements were carried out by Shayegl (1996) to determine the influential mechanisms, such as relative permeability hysteresis and repressurization for applying the gas huff-n-puff process in a medium-gravity oil reservoir in Saskatchewan. Later, Srivastava and Huang (1997) reported that the important mechanisms for Senlac oil recovery by gas injection are oil viscosity reduction and oil swelling. However, according to the best of our knowledge, none of the available experimental data and methods is reported for determining the influential mechanisms of natural gas injection process for the foamy oil reservoir.

The investigation of asphaltene precipitation problems before implementing a gas injection project for any reservoir is now becoming a regular menu as a part of gas injection studies (Cenegy, 2001; Rogel et al., 2001; Asomaning, 2003). That's because the gas injection process can cause a number of changes in the flow and phase behavior of the reservoir fluids and can significantly alter formation properties. These modifications during natural gas injection could lead to asphaltene precipitation and deposition causing formation damage problems by altering wettability, porosity and permeability reduction in the reservoir, and also plugging of the wellbore and piping in production facilities, which can adversely affect the productivity of the reservoir during the course of oil recovery (Ebtisam et al., 2010).

The purpose of this work is to investigate the potential for applying the natural gas injection process in heavy oil reservoirs after primary production in the Orinoco Belt, Venezuela. Asphaltene precipitation studies were conducted to evaluate the asphaltene onset pressure and quantify the precipitation of asphaltene by contacting various molar concentrations (13%, 19%, 30% and 51%) of natural gas with the reservoir fluid. Subsequently, natural gas dissolution tests were carried out to characterize the process of natural gas solution in foamy oil at four pressures, and a new method was developed for determining the natural gas diffusion coefficient in foamy oil on the basis of experimental data. Besides, Foamy oil swelling tests were conducted to determine the influential mechanisms such as viscosity reduction and foamy oil swelling of the presence of natural gas. As a final point, corefloods were performed to examine the effect on oil recovery of three injection mode (continuous gas coreflood, intermittent gas coreflood and gas huff-n-puff coreflood).

2. Experimental section

2.1. Materials

Crude oil from the MPE3 reservoir in the Orinoco Belt, Venezuela, was supplied by China National Petroleum Corporation. The crude oil was recombined with methane gas and carbon dioxide at the reservoir temperature and pressure (54.2 °C and 8.65 MPa, respectively) to yield recombined reservoir oil with a gas–oil ratio of approximately 15.58 m^3/m^3 for use in the laboratory tests. Table 1 lists the fluid characteristics of the resulting dead oil and recombined oil. The bubble pressure of the recombined reservoir oil was estimated by a relative volume versus pressure curve, which was obtained from a instantaneous liberation in a conventional PVT test. Pseudo-bubble pressure is the pressure at which coalescence of the gas bubbles exists and gas becomes a free phase movable, which means that the foamy oil phenomenon immediately disappears at this pressure. Thus, foamy oil phenomenon exists when the reservoir pressure is within the range of the bubble pressure and pseudo-bubble pressure. Pseudo-bubble pressure was estimated likewise but from a pressure-volume curve obtained from non-conventional method (Bennion et al., 2003). It is believed that non-conventional method simulates more realistically heavy and extra heavy oil field behavior. The so-called "non-conventional" method is that the PVT cell is not shade during the depletion process, avoiding a rapid artificial nucleation of the gas micro bubbles and hence forming a separated gas phase. During the non-conventional test, the time between two depletion steps affects the pseudo-bubble pressure

Table 1
Summary of fluid sample.

Flash data	
GOR (m^3/m^3)	15
Dead oil density (g/cm^3)	1.013
Viscosity study (MPa s)	
@50 °C	24,715
@65 °C	5559
@80 °C	1620
@95 °C	644
Composition monophasic (mol%)	
CO_2	2.8
N_2	0.13
C_1	22.43
C_2	0.08
C_3	0.04
C_4	0.04
C_5	0.12
C_6	0.49
C_{7+}	73.87
Total	100
Molecular weight	418.76
Recombined oil properties	
FVF (m^3/m^3)	1.173
Density (g/cm^3)	0.957
Bubble pressure (MPa)	4.95
Pseudo-bubble pressure (MPa)	
@60 min for each depletion step	3.44
@12 h for each depletion step	2.74
@1 days for each depletion step	1.89
SARA analysis (wt%)	
Saturates	19.8
Aromatics	51.2
Resins	18.9
Asphaltenes	8.8
Inorganics	1.3

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