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Enhanced solvent dissolution into in-situ upgraded heavy oil under different pressures

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Abstract

During a solvent-based heavy oil recovery process, asphaltene precipitation may occur when a solvent is dissolved into heavy oil under certain reservoir conditions. Thus, such an in-situ upgraded heavy oil with a lower asphaltene content is less viscous and easier to be recovered. In this paper, enhanced solvent dissolution into the in-situ upgraded heavy oil is studied. First, three heavy oil samples with different asphaltene contents are tested to model the upgraded heavy oils to rather different extents. Then the propane solubilities in these three heavy oil samples and the viscosities of the three heavy oil–propane systems are measured at five equilibrium pressures ranging from 200 to 800 kPa. Also, the propane diffusivities and oil-swelling factors of the three heavy oil–propane systems are measured by applying the newly developed dynamic pendant drop volume analysis (DPDVA) method in the same pressure range. The detailed experimental results show that the asphaltene content in heavy oil strongly affects propane dissolution into the heavy oil. The propane solubility in the maltenes is found to be the highest, which results in the largest oil-swelling factor among the three heavy oil samples tested. Expectedly, the viscosity of the heavy oil–maltene system is the lowest and accordingly the propane molecular diffusivity in the maltenes is the largest. The in-situ upgrading of heavy oil during a solvent-based recovery process greatly enhances further solvent dissolution into heavy oil and reduces its viscosity.

Keywords: Solvent-based heavy oil recovery; In-situ upgrading; Asphaltene precipitation; Heavy oil–solvent system

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1. Introduction

Depletion of conventional petroleum reserves and increase of hydrocarbon fuel demands require effective and economical recovery of unconventional heavy oil and bitumen resources. The Western Canada contains tremendous heavy oil and bitumen with estimated original-oil-in-place (OOIP) of 2.5 trillion barrels [1]. Nevertheless, heavy oil and bitumen cannot be effectively recovered by using some conventional oil recovery methods due to their extremely high viscosities. The cold heavy oil production (CHOP) is a major recovery process, in which heavy oil and bitumen are produced with sands under solution–gas drive [2]. After the cold production, there is still 85–95% of the OOIP unrecovered at the economic limit [3]. In practice, thermal-based tertiary oil recovery methods, such as steam-assisted gravity drainage (SAGD) process [4], are often applied because they can dramatically reduce the heavy oil viscosity. However, large heating requirement makes the thermal-based methods ineffective and uneconomical for many Canadian heavy oil reservoirs with thin pay zones, underlying bottom water, overlying gas caps, low rock conductivities, large vertical fractures, and high water saturations [5].

In the past, a number of studies have been conducted to explore the potential of non-thermal enhanced oil recovery (EOR) methods for the heavy oil reservoirs. Solvent-based recovery processes, such as vapor extraction (VAPEX) [6–9] and cyclic solvent injection [3,10], are among the most promising heavy oil recovery methods under investigation. In the VAPEX process, for example, gaseous condensable solvents [11], in conjunction with carrier gases [12], are used to extract heavy oil from the reservoir formations. The major oil recovery mechanism in this process is significant viscosity reduction of heavy oil through sufficient solvent dissolution and possible asphaltene precipitation. The solvent-based heavy oil recovery

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processes can eliminate several major technical problems associated with the thermal-based EOR methods, such as source water supply, formation heat losses, and produced water treatment [7].

In the solvent-based heavy oil recovery processes, solvent dissolution into heavy oil plays a dominant role in determining the subsequent heavy oil recovery rate. The molecular diffusivity and solubility of a solvent in heavy oil are the two most important parameters to quantify the solvent diffusion rate and dissolution amount respectively, both of which strongly depend on the physicochemical properties of the heavy oil–solvent system and the operating pressure and temperature as well. On the other hand, it has long been found that the heavy oil properties are largely determined by its heaviest and most polar components, i.e., asphaltenes [13,14]. When certain solvent is made in contact with heavy oil at a sufficiently high reservoir pressure, asphaltene precipitation occurs so that the heavy oil in the reservoir is in-situ upgraded. Such an in-situ upgraded heavy oil has a lower viscosity and a higher API gravity [7,15]. In the literature, several experimental studies report that asphaltene precipitation has been observed to occur in different VAPEX physical models [15–17]. However, it is unknown whether such an in-situ upgrading process enhances further solvent dissolution into heavy oil under the practical reservoir conditions.

In this paper, three heavy oil samples with different asphaltene contents of 0.0 wt.% (i.e., the maltenes), 7.0 wt.% (the reconstituted oil), and 14.5 wt.% (the original oil) are tested to model the heavy oils that are in-situ upgraded to rather different extents. These heavy oil samples are saturated with propane at five different equilibrium pressures in the range of $P = 200$–800 kPa and $T = 23.9\,^{\circ}\mathrm{C}$. It is found that the following properties of three heavy oil–propane systems with different asphaltene contents are rather different even at the same equilibrium pressure. In general, the propane solubility is higher and the oil-swelling factor is larger in the heavy oil sample with a lower asphaltene content. Consequently, the viscosity of the heavy oil–propane system is lower, whereas its molecular diffusivity is larger if the heavy oil contains a lower asphaltene content. In addition, a commercial phase behavior simulation module with the Peng–Robinson equation of state (P–R EOS) is used to predict the propane solubilities in different heavy oils at different equilibrium pressures. Finally, some existing empirical correlations are applied to analyze the overall relationships among the propane concentration, oil-swelling factor, viscosity, and molecular diffusivity.

2. Experimental

2.1. Materials

The original heavy oil is collected from the Lloydminster area, Canada. The density and viscosity of the cleaned field heavy oil sample are equal to $\rho_{\mathrm{oil}} = 988\,\mathrm{kg/m^3}$ and $\mu_{\mathrm{oil}} = 24{,}137$ mPa s at the atmospheric pressure and reservoir temperature of $T = 23.9\,^{\circ}\mathrm{C}$, respectively. The compositional analysis result of this heavy oil obtained by using the simulated distillation is given in Table 1. It can be seen from this table that there are no light components under C_{12} and that there is a large fraction of heavy components with $C_{50+} = 47.50$ wt.%. Given the measured asphaltene content of $w_{\mathrm{asp}} = 11.5$ wt.% (*n*-heptane insoluble) [18] or $w_{\mathrm{asp}} = 14.5$ wt.% (*n*-pentane insoluble) [19], it is obvious that the carbon numbers of most asphaltenes in this heavy oil are much larger than C_{50}. The purities of propane (Praxair, USA) and *n*-pentane (Fisher Scientific, USA) used are 99.5 and 99.9%, respectively.

Table 1
Compositional analysis result of the original heavy oil with the asphaltene content of $w_{\mathrm{asp}} = 14.5$ wt.% (*n*-pentane insoluble)

Carbon number	wt.%
C_1	0.00
C_2	0.00
C_3	0.00
C_4	0.00
C_5	0.00
C_6	0.00
C_7	0.00
C_8	0.00
C_9	0.00
C_{10}	0.00
C_{11}	0.00
C_{12}	0.86
C_{13}	1.14
C_{14}	1.33
C_{15}	1.74
C_{16}	1.75
C_{17}	2.01
C_{18}	2.08
C_{19}	2.13
C_{20}	1.87
C_{21}	2.28
C_{22}	1.50
C_{23}	2.24
C_{24}	2.08
C_{25}	1.66
C_{26}	1.56
C_{27}	1.80
C_{28}	1.85
C_{29}	1.56
C_{30}	1.50
C_{31}	1.93
C_{32}	1.78
C_{33}	1.04
C_{34}	1.02
C_{35}	1.47
C_{36}	1.40
C_{37}	0.87
C_{38}	0.85
C_{39}	1.35
C_{40}	1.23
C_{41}	0.62
C_{42}	0.61
C_{43}	1.10
C_{44}	0.80
C_{45}	0.80
C_{46}	0.57
C_{47}	0.72
C_{48}	0.72
C_{49}	0.68
C_{50+}	47.50
Total	100.00