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Full Length Article

Phase behavior of C_3H_8–CO_2–heavy oil systems in the presence of aqueous phase under reservoir conditions

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ABSTRACT

Phase behaviors including phase boundaries, volumes, and compositions of reservoir fluids during solvent(s)-assisted heavy oil recovery processes have been experimentally and theoretically determined in the presence of an aqueous phase. More specifically, a water-rich aqueous phase (A), an oil-rich liquid phase (L), and a solvents-rich vapor phase (V) can coexist under certain reservoir conditions. The phase boundary between AL and ALV on a pressure–temperature phase diagram, i.e., three-phase bubblepoint pressure, has been measured for C_3H_8–CO_2–water–heavy oil systems at temperature ranging from 298.15 K to 383.15 K. The phase volumes of A + L and V at thermodynamic equilibrium state have been determined at temperatures of 321.55 K and 344.95 K, respectively. Moreover, the fluids in both L and V phases are sampled in an isobaric manner to perform the compositional analyses by using gas chromatography (GC) method. Meanwhile, two heavy oil samples are theoretically characterized as the multiple pseudocomponents. The Peng–Robinson equation of state (PR EOS) together with two recently developed alpha functions for water and non-water component(s) is applied as the primary thermodynamic model. A previously developed binary interaction parameter (BIP) correlation for CO_2–water pair is combined with the van der Waals' mixing rule to improve the phase behavior prediction for water-contained system. A volume translation method proposed by Peneloux et al. (1982) is then incorporated to correct the calculated phase volume. Without tuning any parameters, the developed water-associated and water-free mathematical models are found to be able to accurately reproduce the measured phase boundaries in the presence and absence of the aqueous phase, respectively. The three-phase bubblepoint pressure is found to be reduced in the presence of water. More accurate prediction can be achieved by considering the effect of aqueous phase. Finally, the GC analyses and flash calculations demonstrate that CO_2 is more easily to be vaporized than alkane solvent (i.e., C_3H_8) when phase splitting occurs for a C_3H_8–CO_2–water–heavy oil system.

1. Introduction

Heavy oils are typically composed of complex organic compounds and characterized by high density and viscosity [4]. The total original oil in place (OOIP) of heavy oil resources in known accumulations is estimated to be 3396 billion barrels distributed in 192 basins worldwide [35]. Such tremendous heavy crude reserves may enable the rapidly increasing world energy demand to be fulfilled while the conventional oil resource has been depleting. It is a great challenge to recover heavy oil resources economically and efficiently because of the rapid depletion of reservoir energy. Viscosity reduction is the key to enhance heavy oil recovery [14]. Generally, two methods can be used to substantially reduce the viscosity, i.e., thermal method and solvent-assisted method. The former, e.g., steam flooding and steam assisted gravity drainage (SAGD), requires a thick payzone to reduce the heat losses and abundant high quality steam which leads to excessive unfavorable greenhouse gas emissions [13,11]. Thus, the latter, e.g., vapor extraction (VAPEX) [51] and cyclic solvent injection (CSI) [17], has attracted increasing interest for enhancing heavy oil recovery recently.

Since innumerable components contained in reservoir fluids cannot be individually identified, it is necessary to characterize the heavy oil prior to thermodynamic modeling [33,53]. A gamma distribution function with three parameters (i.e., the shape of the distribution α, the minimal molecular mass in C_{7+} group η, and the molecular mass of C_{7+} group M_{C7+}) to split the plus fraction has been developed [55,56], which can be easily transformed into an exponential distribution function [34,38] when α is set to be 1. Azinfar et al. [3] characterized a bitumen by utilizing a residue curve map where the results from

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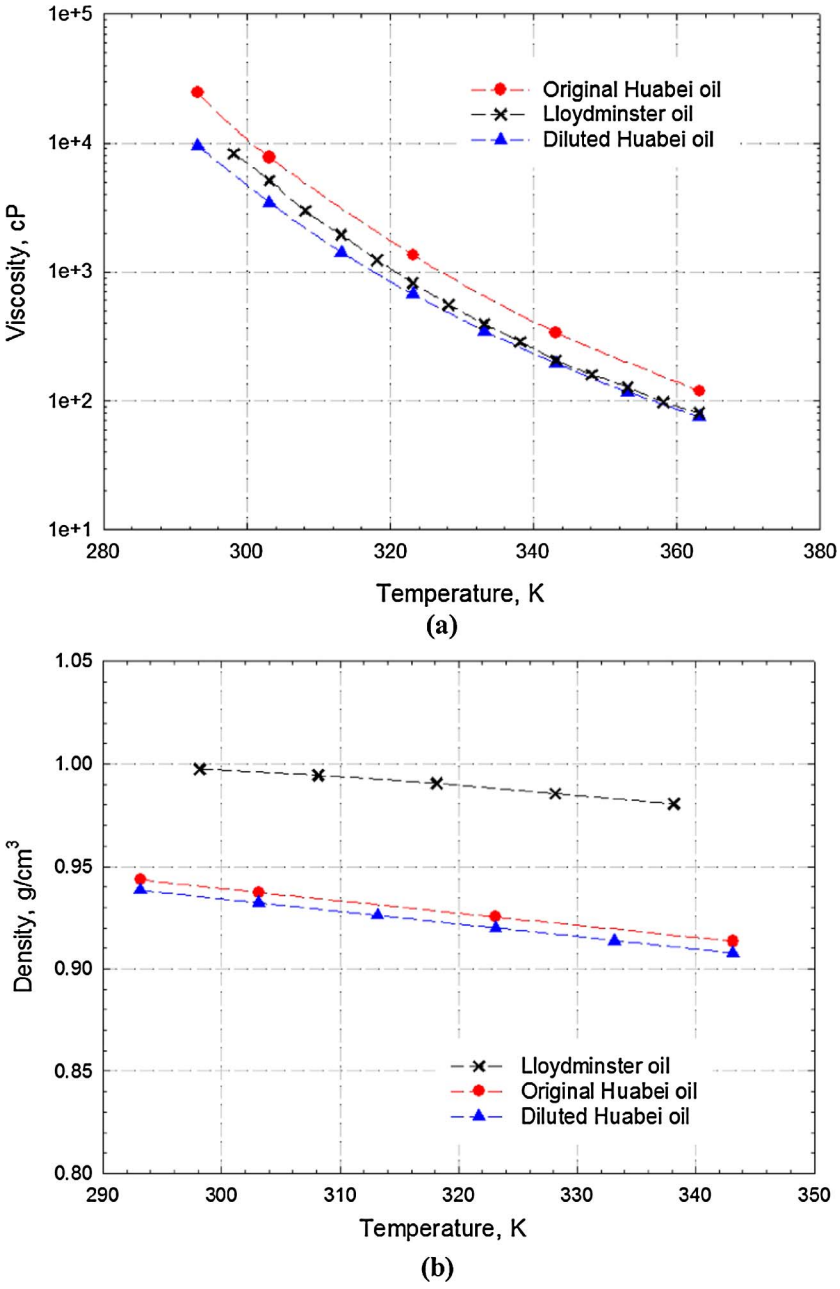

Fig. 1. (a) Viscosities and (b) densities of Lloydminster heavy oil, original Huabei heavy oil, and diluted Huabei heavy oil as a function temperature.

simulated distillation assay is used. In general, it is reported that characterizing reservoir fluid as five to eight pseudocomponents is adequate for simulation purpose [53]. One the basis of van der Waals equation of state [52], the Peng-Robinson equation of state (PR EOS) [39] have been successfully applied in various petroleum fluids including heavy oil due to their accurate prediction for liquid phase [18]. Mehrotra et al. [36] utilized the PR EOS to compute the phase behavior of the Athabasca and Peace River bitumen with CO_2 and C_2H_6. Kokal and Sayegh [20] reproduced the solubility and density data with volume-translated PR EOS for a bitumen–solvent mixture. Castellanos Díaz et al. [5] predicted the saturation pressures of CO_2–Athabasca bitumen systems at elevated temperatures with a good accuracy. Li et al. [24–26] accurately predicted the two- and three-phase boundaries for alkane solvents–CO_2–heavy oil mixture by incorporating a modified alpha function in the PR EOS. The solubility of CO_2 in bitumen has been predicted by applying Krichevsky-Ilinskaya equation without characterizing the bitumen to pseudocomponents [63] and a cubic-plus-association equation of state (CPA-EOS) by lumping bitumen into a single component [64].

Water is inevitably existing in the reservoir and commonly produced along with the crude oil. In addition to the connate water and bottom water, the injected water accounts for a significant part of it [9]. For instance, the EOR process of water-alternating-gas (WAG) method requires regularly water injection, resulting in a solvent(s)–water–crude oil mixture in the reservoir [62]. Recently, taking advantages of both thermal and solvent-based methods, the co-injection of solvent and steam has seen its promising applications, e.g., expanding solvent-steam assisted gravity drainage (ES-SAGD) [10]. Gao et al. [15] measured multiple phase boundaries for *n*-butane/bitumen/water mixtures where excessive *n*-butane exists in the system. Zirrahi et al. [65] have used the CPA EOS to predict the solubility of water in petroleum fractions, heavy oils, and bitumens at high temperatures up to the critical temperature of water. However, few attempts have been made to quantify the phase behavior of alkane solvent(s)–CO_2–heavy oil systems in the presence of water under reservoir conditions. This is attributed to the following two reasons: (1) it is a challenging task to conduct the