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Physical Properties and Extraction Measurements for the Athabasca Bitumen + Light Hydrocarbon System: Evaluation of the Pressure Effect, Solvent-to-Bitumen Ratio, and Solvent Type

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ABSTRACT: Phase behavior study and solvent-saturated phase properties are of crucial importance for heavy oil in situ recovery methods as well as pipeline transportation, surface upgrading, and refining. In this study, the extraction of light components and liquid–liquid equilibrium (LLE) for Athabasca bitumen/ethane systems were studied at ambient temperature over a wide range of pressure. The impact of the ethane-to-bitumen ratio on the physical properties of the saturated phases as well as the partitioning of solvent in each liquid phase was evaluated. The experiments were conducted using a designed pressure–volume–temperature (PVT) apparatus to obtain LLE properties as well as the extraction yield for bitumen/solvent systems. The experimental results indicated the extraction yield increased with increasing initial solvent concentration at all operating conditions. Comparatively, higher bitumen fractions were extracted at higher pressures, considering a constant initial solvent concentration. Increasing either the pressure or solvent-to-bitumen ratio led to higher light component extraction and resulted in a heavier bitumen-enriched phase. Finally, the extraction yield and solubility data for a bitumen/propane system was experimented and compared with those of a bitumen/ethane system at the same conditions. The results revealed that the propane has a greater ability than ethane to extract components from bitumen.

1. INTRODUCTION

The world production of heavy and extra-heavy oils, such as bitumen, has been increasing as the production of conventional light and medium crudes has been declining. For instance, in Alberta, Canada, Athabasca bitumen represents more than 50% of the total Canadian oil production, and it is estimated that about 3 million barrels per day of synthetic crude oil (SCO) will be produced from Athabasca bitumen in 2015.[1]

Conventional oil recovery methods cannot effectively recover the heavy oil and bitumen, due to their extremely high viscosities. Thus, different recovery processes, such as steam-assisted gravity drainage (SAGD) and vapor extraction (VAPEX) have been invented.[2−4] In practice, thermal-based tertiary oil recovery methods can dramatically reduce the bitumen viscosity. However, their large heating requirement makes 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.

Solvent-assisted processes, such as VAPEX,[4] potentially provide remedies to the limitations outlined above. In a solvent injection process, the solvent injected into the reservoir is largely recoverable with the produced bitumen, and solvents can contribute to in situ upgrading of bitumen to produce higher grades of heavy oil than the original bitumen.

Data on the saturated phase properties and the solubility of bitumen with different solvents are required to simulate the phase behavior of heavy crudes at in situ conditions. In addition, these data are extremely important for production, pipeline transportation, upgrading, and refining. Despite the importance of experimental data for achieving a good understanding of solvent-assisted bitumen recovery processes, there have not been many such studies. There are a number of experimental investigations focusing on the phase behavior of bitumen/solvent systems; however, these studies are confined to conditions where the bitumen and solvent form vapor and liquid phases at equilibrium conditions. The experimental[5−14] and modeling studies[15,16] indicate the possibility of a second liquid under specific conditions.

Liquid–liquid upgrading can have a significant effect on surface upgrading methods and also on the performance of solvent-based recovery processes. The extraction of light components from heavy crudes using solvent was studied elsewhere.[17−25] Ethane as a potential solvent for both in situ recovery and surface extraction has received less attention than other solvents. Only limited experimental data[6−9,22,25−27] for ethane and heavy crudes have been published, with most of these studies considering vapor–liquid equilibrium conditions.

Mehrotra and Svrcek,[6−9] Fu et al.,[26] and Frauenfeld et al.[27] measured the saturated phase properties and solubility of ethane in bitumen. Lim et al.[22] evaluated the differences in the production rate of sand pack saturated with Cold Lake bitumen using subcritical and supercritical ethane. Rose[25] reported some supercritical extraction data for Peace River bitumen/ethane systems. However, no experimental data for the liquid–liquid equilibrium (LLE) or the extraction of bitumen with ethane at ambient temperature have been reported.

In the case of LLE, two phases, solvent-enriched and bitumen-enriched, exist at equilibrium conditions.[12,14,23] The former is mostly composed of solvent and some light components extracted from the bitumen phase. The latter mainly consists of heavy components of bitumen, like asphaltene, that cannot be

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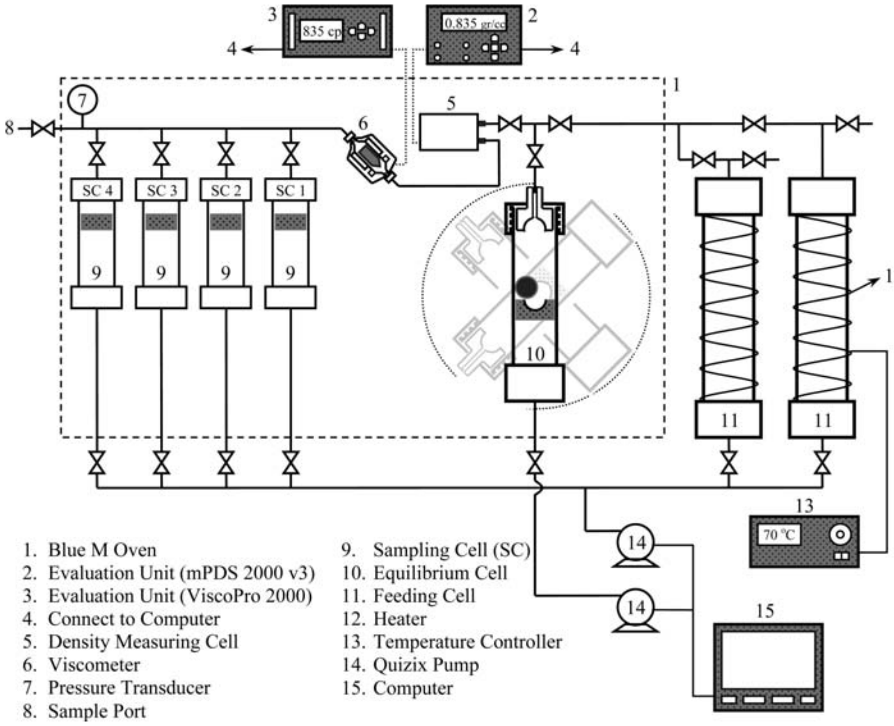

Figure 1. Schematic diagram of the experimental apparatus.

extracted by solvent. The extraction yield depends on the temperature, pressure, and solvent-to-bitumen ratio.

In the present study, the experimental data for LLE, saturated phase properties, and the extraction yield of bitumen using ethane were generated at ambient temperature. The results indicate that both the pressure and the solvent-to-bitumen ratio significantly affect the extraction yield and the properties of two phases. Finally, the experimental results obtained with ethane were compared with our measurements for propane at the same conditions.

2. EXPERIMENTAL SECTION

2.1. Apparatus. The details of the designed experimental apparatus have been described elsewhere.[28] The schematic diagram of the apparatus is shown in Figure 1. It consists of feeding cells, an equilibrium cell, four sampling cells, a density measuring cell, a viscometer, and two Quizix automated pressure activated pumps. The Quizix pumps charge and discharge water to displace the fluids or keep the pressure constant. The equilibrium, sampling, and feeding cells are equipped with the pistons and Viton o-rings to prevent the contamination of the mixture with water.

The equilibrium, sampling, and density measuring cells and the viscometer are placed in a temperature-controlled Blue M oven. The oven is equipped with a temperature controller capable of maintaining the temperature within ± 0.1 K. The two pumps (Quizix pumps) control the system pressure by charging or discharging the fluids. The rocking action of the equilibrium cell with the rolling ball expedites the process of the mixing and reaching the equilibrium. The rocking equilibrium cell has a total volume of about 900 cm^3, which allows for sufficient saturated phase volume for the measurement of physical properties, such as density and viscosity. In addition, it provides ease of phase detection and enough phase volume for further analyses.

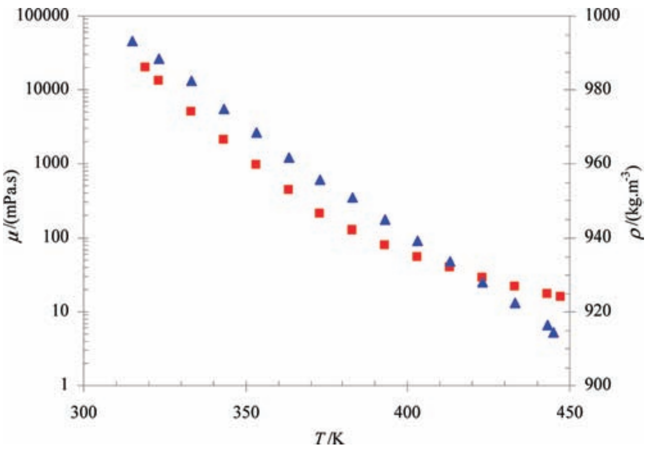

Figure 2. Measured density ρ and viscosity μ of bitumen over wide range of temperature T; ▲, density of bitumen; ■, viscosity of bitumen.

The density measuring cell and viscometer are used for phase detection, and they are installed in series to improve the phase detection. An Anton Paar density measuring cell equipped with a DMA HPM external high pressure unit is used to measure the density of the fluids. The external unit is calibrated using nitrogen and water. The density measurements are precise to ± 0.5 $\text{kg}\cdot\text{m}^{-3}$. The Cambridge viscometer has the ability to measure viscosity in the range of (0.2 to 10 000) mPa·s with an accuracy of ± 1.0 % of full scale. It is factory calibrated, and the accuracy of measurements was tested with pure hydrocarbons and some standard fluids. The average error for the measurements was less than 5 %.

2.2. Chemicals. The ethane (0.99 purity, grade 2) used in these measurements was supplied by Praxair. The bitumen was provided from Athabasca field, and the density and viscosity of

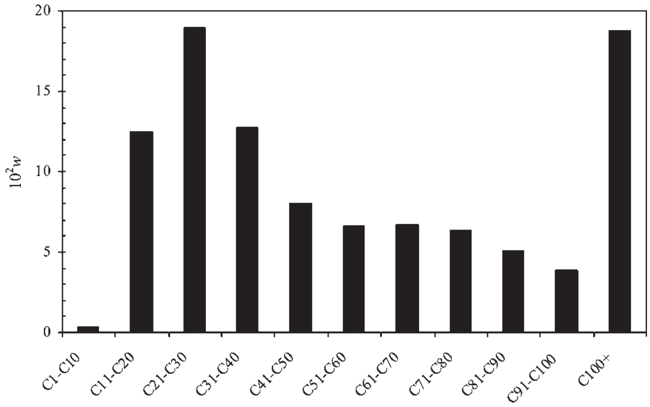

Figure 3. Compositional analysis of bitumen; *w*, weight fraction of components in bitumen.

the bitumen were measured over a wide range of temperature by an Anton Paar density measuring cell and a Cambridge viscometer, respectively. The measured density and viscosity were plotted in Figure 2. In addition, the chemical composition of bitumen was shown in Figure 3.

2.3. Procedure. Prior to each experiment, the entire system was thoroughly cleaned to remove any contaminant. To ensure no contaminants were left inside the system, cells and lines were successively evacuated and flushed with dry helium and ethane.

After cleaning, bitumen was charged into the equilibrium cell using the two Quizix pumps. By measuring the volume and density of bitumen at a constant temperature and pressure, the mass of the bitumen charged into the equilibrium cell was known. The required amount of ethane to have a specific solvent-to-bitumen ratio was then charged into the cell. Thus, the masses of bitumen and ethane inside the equilibrium cell were known. To measure the properties of two liquid phases at a specific temperature and pressure, the experimental pressure and temperature were fixed: the Quizix pumps were kept at a constant pressure with an error of less than ± 5 kPa.

The equilibrium cell was rocked to achieve effective mixing and reach equilibrium conditions for the bitumen/ethane system. During the mixing period, the volume of water, which was charged or discharged to keep a constant pressure in the equilibrium cell, was recorded. When there was no change in the volume, equilibrium was achieved. Thus, the volume change on the mixing of a binary system was the criteria for equilibrium conditions.

Prior to the discharge of the equilibrium fluids, the equilibrium cell was first kept in an upright position (vertical position) for a few hours to obtain single bulk volumes of each phase vertically segregated in the order of phase density. Then, the equilibrium fluids were discharged through the density measuring cell and viscometer, while maintaining a constant temperature and pressure. The pressure was measured by both the in-line and Quizix pump pressure transducers. The uncertainty of pressure measurements was ± 10 kPa.

The phase samples were collected with steady readings of the viscometer and the density measuring cell; any change in viscosity and density indicated a passage of a phase boundary through the measuring instruments. During the discharging of the equilibrium fluids, the volume of each phases was measured using the Quizix pumps. Thus, the volume of each phase at equilibrium conditions was also known. Liquid phases were transferred into sampling cells 1 to 3, and the last sampling cell was used to purge the phase boundary portion and clean the transition between the phases. Saturated samples could be collected through the sampling port for compositional analysis or further studies.

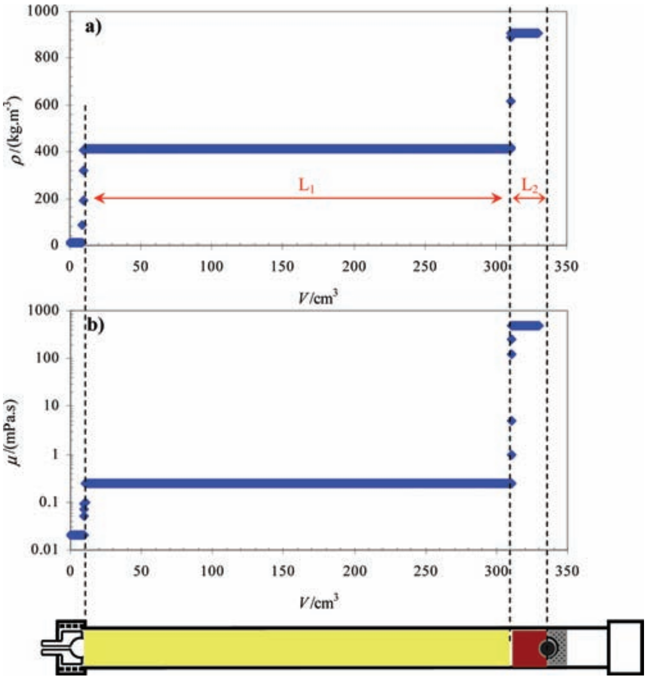

Figure 4. Liquid−liquid phase transition: saturated phase density ρ and saturated phase viscosity μ versus volume V; (a) saturated phase density; (b) saturated phase viscosity.

To measure the solubility of the saturated liquid(s), the collected samples were flashed at atmospheric pressure. The volume of the evolved gas was measured by the Chandler Engineering gasometer (model 2331) with an accuracy of 0.2 % of the reading. The solubility was then calculated having the density of the evolved gas at atmospheric conditions. The density of ethane at atmospheric pressure and temperature was taken from the National Institute of Standards and Technology (NIST) database.[29]

3. RESULTS AND DISCUSSION

The LLE of a bitumen/ethane system at the average temperature of 294.8 K was conducted at three pressures in the range (5 to 9) MPa and four different initial ethane concentrations. (In this study, the terms of initial ethane concentration, solvent-to-bitumen ratio, and feed concentration were used interchangeably; they referred to the overall composition of ethane in the equilibrium cell). The solubility, viscosity, density, and volume of each liquid phase were measured during the experiments.

The procedure to charge the equilibrium cell was described in Section 2.3. The bitumen was transferred directly to the density measuring cell and viscometer. The density and volume of the bitumen were measured to calculate the mass of bitumen charged into the equilibrium cell. As mentioned before, after equilibrium achieved, the change in viscosity and density while transferring equilibrium fluids indicates a passage of a phase boundary through the measuring instruments. Figure 4 illustrates the density and viscosity profile for the experiment at 9 MPa and the ethane feed concentration of 0.8 weight fraction. The density and viscosity of equilibrium phases as well as the volume of each phase at

Table 1. LLE Properties for Bitumen/Ethane Systems at Ambient Temperatures; *P*, Pressure; *T*, Temperature; w_f, Weight Fraction of Ethane in Feed; ρ, Densities; μ, L_2 Viscosity

P	T		$\rho/(\mathrm{kg \cdot m^{-3}})$			μ
MPa	K	$10^2\ w_f$	pure ethane	L_1	L_2	mPa·s
5.09	295.9	20	350	399	854	45.5
5.08	294.8	40	355	397	864	64.8
5.05	294.7	60	355	385	878	115
7.08	294.7	40	376	425	862	67.2
9.08	294.6	40	390	448	859	64.4
9.08	294.3	60	390	431	881	146
9.04	294.7	80	389	414	906	491
9.05	294.3	90	390	404	931	1908

Table 2. Composition and Volume Ratio of Phases for Bitumen/Ethane Systems at Ambient Temperatures; *P*, Pressure; *T*, Temperature; *w*, Weight Fraction of Ethane; $V_1 \cdot V_2^{-1}$, Liquid 1 to Liquid 2 Volume Ratio

P	T		$10^2\ w$		$(V_1 \cdot V_2^{-1})$
MPa	K	feed	L_1	L_2	$\mathrm{m^3 \cdot m^{-3}}$
5.09	295.9	20		17.9	0.150
5.08	294.8	40	91.4	15.7	1.112
5.05	294.7	60	92.9	14.5	3.322
7.08	294.7	40	87.7	16.6	1.113
9.08	294.6	40	84.5	16.6	1.112
9.08	294.3	60	89.0	15.5	3.072
9.04	294.7	80	93.1	13.1	10.779
9.05	294.3	90	96.0	11.6	32.019

equilibrium condition was measured for each experiment. For all experiments, this transition profile was obtained.

Tables 1 and 2 summarize the experimental results. Table 1 summarizes the density of the pure ethane, the ethane-enriched phase (liquid 1, L_1), and the bitumen-enriched phase (liquid 2, L_2). The viscosity of the bitumen-enriched phase was also measured and is given in Table 1. The ethane-enriched phase had low viscosity and was not measured during the experiments.

Table 2 summarizes the ethane solubility in both liquid phases and the volume ratio of the phases at equilibrium conditions. It can be seen from Table 1 that the lighter liquid phase (L_1), that is, the solvent-enriched oil phase, had a much higher ethane concentration than the bitumen-enriched phase. This was because the solvent-enriched oil phase was mainly comprised of the liquid ethane and light components, while liquid 2 was mainly composed of heavy components, in which the solubilities of ethane were much lower than those of ethane in the light components. More details about the experimental results and their trends with pressure and solvent-to-bitumen ratio were discussed in the following sections.

3.1. Calculation of Bitumen Extraction. The experimental results in Tables 1 and 2 indicate that the pressure and initial solvent concentration affected the physical properties of the liquid phases at equilibrium conditions. To find out how these parameters impacted the extraction of the light component from the bitumen at specific conditions, a simple mass balance equation was set up to calculate the fraction of bitumen that was extracted into the lighter liquid (L_1). The extraction yield is of particular importance for supercritical fluid extraction process where the low volatility materials were extracted from various mixtures. The calculation is based on the solubility of ethane in each liquid phase and the volume and density of liquid phases. The general equation for the calculation of extraction yield is:

$$\text{extracted bitumen}(\%) = 100\left(\frac{m_{\mathrm{B},\mathrm{L}_1}}{m_{\mathrm{B},\mathrm{t}}}\right) \tag{1}$$

where $m_{\mathrm{B,L_1}}$ represents the amount of bitumen partitioned in the lighter liquid (L_1), and $m_{\mathrm{B,t}}$ is the total amount of bitumen charged into the equilibrium cell.

To calculate $m_{\mathrm{B,L_1}}$, two methods were considered:

Method 1:

$$m_{\mathrm{B},\mathrm{L}_1} = \rho_{\mathrm{L}_1} V_{\mathrm{L}_1}(1 - x_{\mathrm{C2},\mathrm{L}_1}) \tag{2}$$

and Method 2:

$$m_{\mathrm{B},\mathrm{L}_1} = m_{\mathrm{B},\mathrm{t}} - \rho_{\mathrm{L}_2} V_{\mathrm{L}_2}(1 - x_{\mathrm{C2},\mathrm{L}_2}) \tag{3}$$

where $\rho_{\mathrm{L}i}$ and $V_{\mathrm{L}i}$ are the density and volume of saturated liquid i at equilibrium conditions, $x_{\mathrm{C2,L}i}$ represents the composition of ethane in saturated liquid i, and $m_{\mathrm{B,t}}$ is the total amount of bitumen calculated from the density and the volume of bitumen charged into the equilibrium cell.

Finally, the extraction can also be calculated on the basis of all equilibrium fluid properties as:

Method 3:

$$\text{extracted bitumen}(\%) = 100\left(\frac{\rho_{\mathrm{L}_1} V_{\mathrm{L}_1}(1 - x_{\mathrm{C2},\mathrm{L}_1})}{\rho_{\mathrm{L}_1} V_{\mathrm{L}_1}(1 - x_{\mathrm{C2},\mathrm{L}_1}) + \rho_{\mathrm{L}_2} V_{\mathrm{L}_2}(1 - x_{\mathrm{C2},\mathrm{L}_2})}\right) \tag{4}$$

All of these measurements for the extraction of bitumen were considered in this study for a comparison of the different approaches. The required measured parameters in each approach indicated that the extraction measurements can be calculated even with limited experimental measurements.

3.2. Effect of Pressure. The effect of pressure on the extraction of light components from bitumen was studied. The initial ethane concentration was kept constant (weight fraction of 0.4), which corresponded to 0.654, 0.641, and 0.633 initial ethane volume fractions at (5, 7, and 9) MPa, respectively. The extraction yields calculated from the three different above-mentioned methods are shown in Figure 5. In general, the extraction yields increased with increases in pressure at a constant temperature and initial ethane concentration.

It can be seen from Figure 5 that, at the initial ethane concentration of a 0.6 weight fraction, the extraction yields increased from an average of (0.11 to 0.155) weight fraction with increasing pressure from (5 to 9) MPa. These results confirm that the extent of the extraction yield rose as the ethane concentration in the feed increased. Thus, at the initial ethane concentration of a 0.4 weight fraction, the increase in pressure from (5 to 9) MPa almost doubled the extraction yield, whereas this amount was increased 1.5 times for the initial ethane concentration of a 0.6 weight fraction. The results obtained here can be explained with the following statement: at higher pressures, ethane had a stronger ability to extract the light components from bitumen.

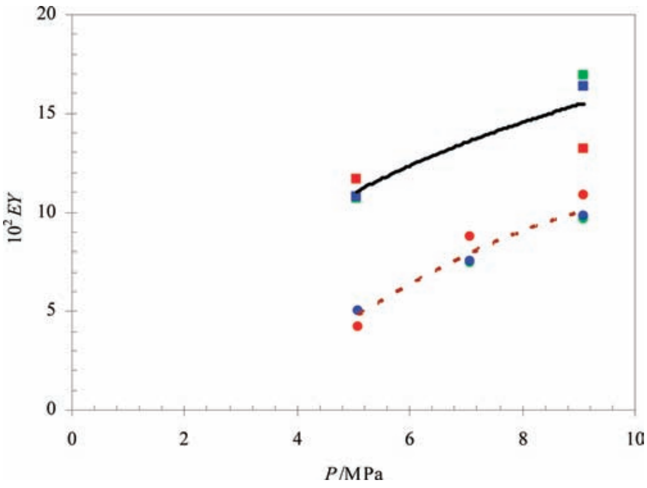

Figure 5. Effect of pressure P on the extraction yield EY of components from bitumen at two feed concentrations of ethane w_f; —, $w_f = 0.6$; · · ·, $w_f = 0.4$; green ●, method 1; red ●, method 2; blue ●, method 3.

The viscosity data in Table 1 indicate that the viscosity of liquid 2 (L_2) remained almost constant with increasing pressure, while the extraction yields favored the heavier phase (L_2). Increasing the pressure increased the light component extraction from the bitumen-enriched phase, resulting in higher viscosity. However, the ethane solubility increased with the pressure and led to lower viscosity. These two phenomena offset each other, and the viscosity of the bitumen-enriched phase remained almost constant.

Generally speaking, the pressure affected the viscosity of liquid 2 in the three ways. First, at a constant temperature, an increase in pressure resulted in an increase in the raw bitumen's viscosity. Second, the bitumen components in liquid 2 became heavier with increasing pressure, due to higher light component extraction at higher pressures. Finally, the viscosity of a liquid decreased with the increasing ethane solubility at higher pressures. The first factor had a small effect on the viscosity; however, the other two factors could result in significant changes in the viscosity. The effect of the first and second factors canceled that of the third. Thus, the viscosity of liquid 2 remained constant.

3.3. Effect of the Solvent-to-Bitumen Ratio. To evaluate the effect of increasing the amount of solvent in the equilibrium cell on the physical properties and extraction yields, the ethane-to-bitumen ratio (equivalently, the initial ethane concentration) was increased at constant pressures of (5 and 9) MPa. The cumulative extraction yields at the two pressures were plotted against the feed concentration and are shown in Figure 6. The maximum extraction yield was obtained at the highest ethane concentration for both pressures. As depicted in Figure 6, the extraction yield increased with increasing ethane concentration. For example, at 9 MPa, the extraction yield increased from about (0.1 to 0.4) weight fraction when the ethane concentration was increased from (0.4 to 0.9) weight fraction. It seems that, at higher pressures, the effect of the initial ethane concentration was more pronounced.

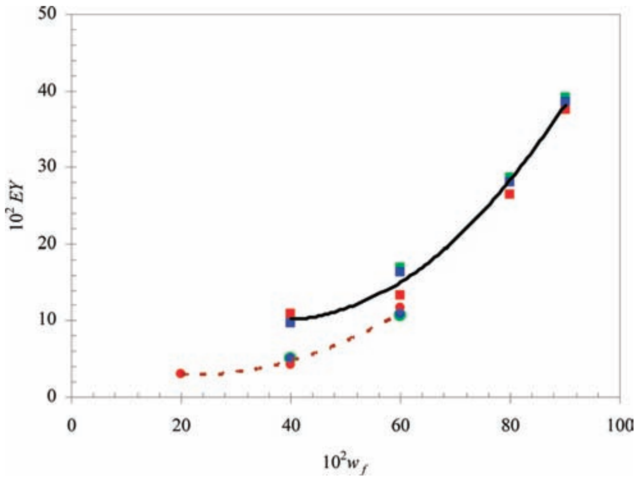

Figure 6. Effect of ethane feed concentration w_f (weight fraction of ethane) on the extraction yield EY of components from bitumen at different pressures P: —, $P = 9$ MPa; · · ·, $P = 5$ MPa; green ●, method 1; red ●, method 2; blue ●, method 3.

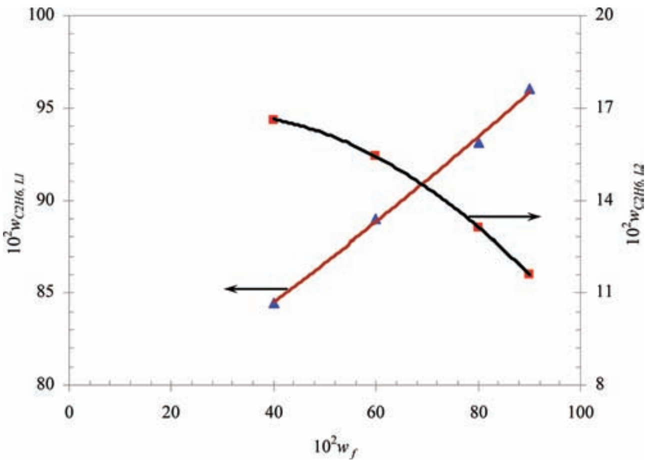

Figure 7. Effect of feed concentration w_f (weight fraction of ethane) on the concentration of each liquid phase at 9 MPa; $w_{C_2H_6,L_1}$, weight fraction of ethane in liquid 1; $w_{C_2H_6,L_2}$, weight fraction of ethane in liquid 2; ▲, liquid 1; ■, liquid 2.

Figure 7 illustrates the solubility of ethane in both liquid phases at a pressure of 9 MPa for four different feed concentrations. As depicted in Figure 7, the solubility of ethane in liquid 1 increased at higher ethane concentrations. This is expected, because when more ethane is added to the system, it goes into the ethane-enriched phase (liquid 1). However, the ethane solubility in liquid 2 was reduced, as shown in Figure 7. This is due to the higher extraction yield at higher feed concentrations, which resulted in a heavier phase and a corresponding lower ethane solubility. As expected, the heavier hydrocarbon had a lower ethane solubility at a constant pressure and temperature. Mehrotra et al.[15] had predicted this behavior by the equation of state modeling of bitumen/ethane mixtures. The solubility of ethane in liquid 1 increased linearly with increasing feed concentration, while the bitumen-enriched phase showed a nonlinear trend.

Figure 8 demonstrates the density of the saturated liquids for four different feed concentrations at a pressure of 9 MPa. As the figure shows, with increasing initial ethane concentration, the density of liquid 1 decreased, whereas the density of the second liquid increased. As the ethane concentration increased, more light components were extracted into liquid 1; thus, the density of the second liquid phase increased. However, the density of liquid 1 decreased and approached the density of pure ethane at the experimental conditions of 294.8 K and 9 MPa, which is

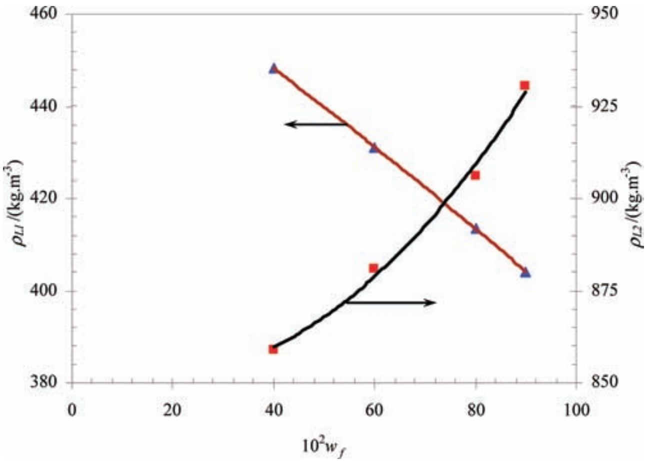

Figure 8. Effect of feed concentration w_f (weight fraction of ethane) on the density of each liquid phase at 9 MPa; ρ_{L_1}, density of liquid 1; ρ_{L_2}, density of liquid 2; ▲, liquid 1; ■, liquid 2; the density of pure ethane at this pressure is 390 kg·m^{-3}.

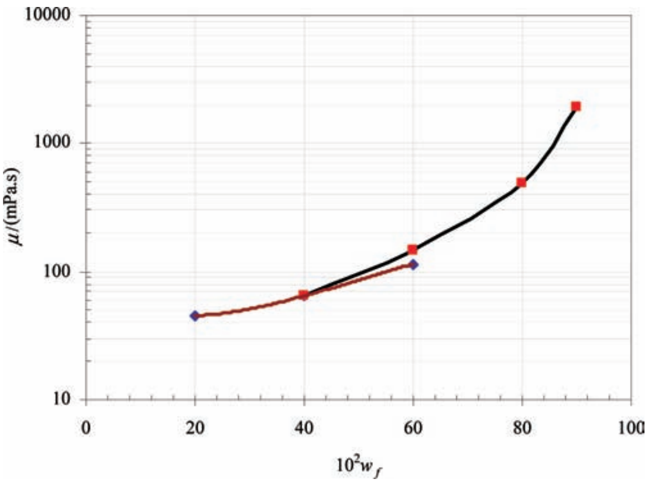

Figure 9. Effect of feed concentration w_f (weight fraction of ethane) on the viscosity of the heavier liquid (L_2) μ at different pressures P; black —, P = 9 MPa; dark red —, P = 5 MPa.

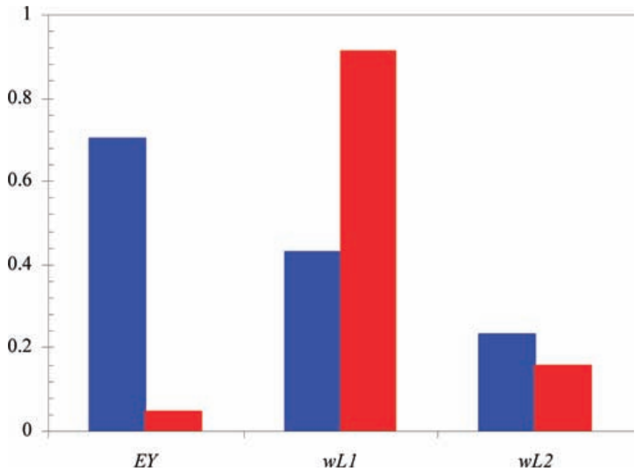

Figure 10. Effect of different solvents on the concentration of each phase and the extraction of light components from bitumen at a constant pressure of 5 MPa, temperature of 294.2 K, and solvent feed concentration of 0.4 weight fraction; EY, extraction yield (weight fraction); wL_1, weight fraction of solvent in L_1; wL_2, weight fraction of solvent in L_2; blue area, propane; red area, ethane.

Table 3. Equilibrium Phase Properties for Bitumen/Solvent Systems at Ambient Temperature, a Pressure of 5 MPa, and a Solvent Feed Concentration of 0.4 Weight Fraction; *w*, Weight Fraction of Solvent; ρ, Densities; μ, L_2 Viscosity

	$10^2\ w$		ρ/(kg·m^{-3})			μ
solvent	L_1	L_2	pure solvent	L_1	L_2	mPa·s
ethane	91.4	15.7	355	397	864	64.8
propane	43.2	23.3	510	715	873	393

390 kg·m^{-3}. This was caused by the large volume of ethane in contact with the bitumen at higher feed concentrations.

The solubility and density of each phase had opposite trends. Increasing the solubility led to the reduction of density. The density reduction for liquid 1 had a linear relationship with feed concentration. Comparatively, the solubility data in Figure 7 and density measurements in Figure 8 indicate that the solubility increased linearly with the feed composition for liquid 1, while the density decreased with a linear trend. For the bitumen-enriched phase, both the solubility and the density had nonlinear behavior with feed concentration.

To illustrate how liquid 2 became heavier with increasing ethane feed concentration and pressure, the viscosity of liquid 2 is plotted versus the feed concentration at two different pressures in Figure 9. The blue dots show the results for 5 MPa, while the red ones are for 9 MPa. The viscosity of liquid 2 increased with increasing pressure and ethane feed concentration. Thus, as stated before, increases in pressure and feed concentration resulted in higher extraction of light components from the bitumen. This led to the increase in the fraction of heavier components in liquid 2 than the original bitumen. Comparatively, at higher pressures, the ethane concentration had a more pronounced effect on the viscosity of liquid 2.

3.4. Effect of Solvent Type. To evaluate the effect of the solvent type on extraction yield and solubility, an experiment at a pressure of 5 MPa and the initial concentration of a 0.4 weight fraction for the bitumen/propane system was conducted. The experimental results obtained for the bitumen/propane system were compared with those of a bitumen/ethane system at the same conditions (pressure of 5 MPa and the initial concentration of a 0.4 weight fraction). Figure 10 illustrates the extraction yields and solubility of the solvent in both liquid phases for ethane and propane solvents. For comparison, the equilibrium phase properties for two solvents are also summarized in Table 3.

The generated experimental results for both systems, bitumen/ethane and bitumen/propane, indicated that the extraction yield for propane was much greater than that of ethane at the same conditions. This is due to the nature of propane, which extracts more components into the solvent-enriched phase (liquid 1) than ethane. The solubility data for both phases confirm that propane extracted more components from the bitumen and had a higher solubility in heavier components. The weight fraction of propane in the solvent-enriched phase was less than that of ethane. This was due to higher extraction by propane compared to ethane. As expected, higher extraction yields led to a heavier second liquid. However, even at this condition, the solubility of propane in this phase was higher than that of ethane with its lower extent of extraction.

4. CONCLUSION

The extraction yields of the bitumen increased with increasing solvent-to-bitumen ratios. The maximum extraction yield was obtained for two pressures at the highest ethane concentration. The extraction yields also increased with increases in the system pressure at a constant temperature and solvent-to-bitumen ratio. The solubility data, as well as the saturated phase properties, density, and viscosity, confirm that liquid 2 became heavier as the pressure and solvent-to-bitumen ratio increased, which corresponded to higher extraction. As anticipated from the viscosity data, liquid 2 was composed of much heavier components than the original bitumen. The extraction yield for propane was much greater than that of ethane at the same conditions. The solubility data for both phases confirmed that propane extracts more components from the bitumen and has a higher solubility in heavier components.

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