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Super Critical Fluid Extraction of a Crude Oil Bitumen-Derived
Liquid and Bitumen by Carbon Dioxide and Propane

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ABSTRACT

Supercritical fluid extraction of complex hydrocarbon mixtures is important in separation processes, petroleum upgrading and enhanced oil recovery. In this study, a paraffinic crude oil, a bitumen-derived liquid and bitumen were extracted at several temperatures and pressures with carbon dioxide and propane to assess the effect of the size and type of compounds that makeup the feedstock on the extraction process.

It was observed that the pure solvent density at the extraction conditions was not the sole variable governing extraction, and that the proximity of the extraction conditions to the pure solvent critical point affected the extraction yields and the compositions of the extracts. Heavier compounds reported to the extract phase as the extraction time increased at constant temperature and pressure and as the extraction pressure increased at constant temperature and extraction time for both the paraffin crude-propane and the bitumen-propane systems. This preferential extraction was not observed for the bitumen-derived liquid. The non-discriminatory extraction behavior of the bitumen-derived liquid was attributed to its thermal history and to the presence of olefins and aromatics in the liquid.

Phase behavior calculations using the Peng-Robinson equation of state and component lumping procedures provided reasonable agreement between calculated and experimental results for the crude oil and bitumen extractions, but failed in the prediction of the phase compositions for the bitumen-derived liquid extractions.

INTRODUCTION

Supercritical fluid extraction (SFE) has found application in solvent extraction, separation processes and in the upgrading of petroleum feedstocks. The SFE concept is also of interest in enhanced oil recovery processes since the performance of these processes depends on the extraction of oil components by a solvent that is typically in a supercritical state. There are several potential SFE applications related to oil sands production, bitumen upgrading and bitumen analysis:

- o Upgrading the bitumen and bitumen-derived liquids by rejection of the asphaltenes

using techniques similar to the ROSE¹⁻³ process.

- o Recovery of the bitumen using SFE in mining-surface recovery schemes.
- o Use of dense gases as recovery agents or as additives in the production of heavy oils by in-situ recovery methods.⁴
- o Use of SFE as an analytical tool for understanding the nature and thermodynamic behavior of oil sand bitumens.

Two phases, the lighter extracted phase and the heavier oleic phase, usually resulted when the solvent was contacted with the feedstock. The

extracted phase was removed continuously as fresh solvent was introduced into the SFE system. Thus, the nature of the solute and the compositions and phase properties of all the relevant phases changed, continuously. The process operated at thermodynamic equilibrium and the phase compositions of the extracted phases were analyzed.

In this investigation, the extraction of three different feedstocks: a paraffinic crude oil, a bitumen-derived liquid produced in a fluidized-bed pyrolysis reactor and a native bitumen from the Whiterocks oil sands, was carried out with two typical SFE solvents, carbon dioxide (CO_2) and propane (C_3H_8). The intent was to study the extraction process as a function of the density of the feedstock (heaviness of the material) and its chemical composition.

EXPERIMENTAL METHODS AND MEANS

Experimental Apparatus

The SFE system was custom-built for the University of Utah by Autoclave Engineering, Inc. A schematic of the apparatus is presented in Figure 1. Central to the system was a temperature controlled 300 cm^3 extractor rated to a pressure of 37.2 MPa at 617 K . The extractor was equipped with a magnetic-drive packer-less stirring device. Solvent was charged to the extractor and the system was brought to the desired pressure using a high-pressure liquid pump. Pressure control was achieved by incorporating a back pressure regulator in parallel with the pump. The pump-head was cooled by a circulating cooling bath to ensure that the solvent was maintained in the liquid state at the pump-head.

Fig. 1 Schematic of the Supercritical Fluid Extraction System

Once the initial equilibrium state was attained the solvent, carbon dioxide or propane, was continuously fed to the extractor. Commercial grade propane which contained 96% propane and 4% C₁-C₄ hydrocarbons was used in this work. A heated metering valve was used to transfer the extract phase from the extractor to the separator. The separator was held at the ambient pressure so that the solvent vaporized. The solvent which separated from the extract phase was vented through a flow totalizer. The totalizer measured the cumulative volume of the vented solvent. The hydrocarbons in the separator were collected and weighed.

In all the experiments, a known amount of oil or bitumen was charged to the extractor and the extraction process was begun. After approximately 25 liters of solvent (at room temperature) had flowed through the totalizer the oil in the separator was collected and weighed. The extracted oil was removed from the separator after each additional 25 liters of solvent had passed through the system. When the amount of oil extracted became small, relative to the initial amount extracted, the extraction was stopped, the extractor was depressurized, and the residue was weighed and analyzed. In each extraction sequence, seven to eight extract samples were collected. Each sample corresponded to an extraction window of 25 liters of carbon dioxide or propane vented through the totalizer or about 20 minutes of extraction time.

Feedstock Characterization

Properties of the feedstocks used in this study are listed in Table I. The bitumen-derived liquid was produced from the Whiterocks (Utah) oil sands in a fluidized-bed

Table I
Feedstock Characterization

	Paraffinic Crude Oil	Bitumen Derived Liquid ^a	Native Bitumen ^b
Properties			
Specific Gravity (288/288 K)	0.808	0.945	0.980
Gravity, °API	43.6	18.2	12.9
Conradson Carbon Residue, Wt%	0.02	3.2	9.5
Pour Point, K	293	277	327
Viscosity, cps	1.78288K	1768294K	870,0008311K
Asphaltenes ^c , Wt%	0.1	3.0	5.9
Maltenes ^c , Wt%	99.9	97.0	94.1
Elemental Analysis^d			
C, Wt%	86.13	87.13	86.97
H, Wt%	13.68	11.39	11.28
N, Wt%	0.16	1.16	1.35
S, Wt%	0.03	0.32	0.40
H/C Atomic Ratio	1.91	1.57	1.56
M.W., g/mol	348	319	700
NI, ppm	-	17	87
V, ppm	-	<1.0	2.9
As, ppm	-	3.5	3.1
Simulated Distillation			
Volatility, Wt%	100.0	76.9	32.5
IBP, K	309	417	520
IBP-477 K, Wt%	35.5	4.5	0.0
478-616 K, Wt%	37.6	24.4	5.6
617-811 K, Wt%	26.9	48.0	26.9
>811 K, Wt%	0.0	23.1	67.5

- ^a Bitumen-derived liquid from fluidized-bed pyrolysis
^b From Whiterocks Utah oil sand deposits
^c As determined with pentane
^d C,H,N,S analysis normalized to 100%

pyrolysis reactor. The reactor temperature ranged from 773 to 813 K at a retention time of 17.2 minutes during the production run. The bitumen was toluene-extracted from the Whiterocks oil sands. The API gravities indicated that the bitumen-derived liquid was heavier than crude oil and that the bitumen was the heaviest of the feedstocks. The carbon number distributions of the three feedstocks confirmed the gravity data. Gas chromatographic - mass spectrometric analyses conducted as part of the present and previous investigations^{5,6} indicated that the crude oil was predominantly paraffinic, that the bitumen-derived liquid contained olefins and significant amounts of aromatics and that the native bitumen was mainly comprised of naphthenes and naphtheno-aromatics with long alkyl side chains. Thus, the feed

materials used in this study are diverse with respect to both the size and type of compounds.

RESULTS AND DISCUSSION

Mass recoveries in excess of 95 wt% of the material initially charged to the extractor were obtained in all the experiments. The losses were attributed to material trapped in dead spaces in various parts of the apparatus. Two sets of experiments were performed at identical conditions to assess the experimental reproducibility and confirmed that the experiments were reproducible to within 99%.

Initial experiments performed with hexadecane and CO₂ demonstrated that the system operated at thermodynamic equilibrium; the phase behavior data obtained for hexadecane-CO₂ matched the data in the literature⁷.

Extraction of the Paraffinic Crude Oil with CO₂

Extractions were performed at a series of temperatures and pressures. The initial oil charge to the extractor was 80 g in all the experiments. The effect of pressure on the extraction yields at a constant temperature of 311 K is shown in Figure 2. It has been demonstrated that the extraction of complex hydrocarbon mixtures such as crude oil by CO₂ is governed by the density of pure CO₂ at extraction conditions^{8,9}. Pure CO₂ densities at the pressure and temperatures used in these extraction experiments are listed in Table II. It is clear that at a temperature of 311 K, as the pressure increases, CO₂ density also increases. It can be seen from Figure 2 that the increase in extraction yields with pressure can

be linked to this increase in CO₂ density.

Figure 2: Extraction Yields as a Function of Pressure for the Crude Oil - CO₂ System at 311 K.

Table II
Density of Carbon Dioxide^a at Experimental Conditions
Conducted in Extractions²²⁰

(Unit: g/cm ³)					
Temperature	297 K	304 K	311 K	319 K	366 K
PRESSURE					
5.5 MPa	-	-	0.1348	-	-
7.6 MPa	-	-	0.2550	-	-
10.3 MPa	0.8385	0.7664	0.6672	0.2821	0.2099
17.2 MPa	-	-	0.8254	-	0.4170
24.0 MPa	-	-	0.8840	-	0.5798
30.9 MPa	-	-	-	-	0.6867

^a Density of carbon dioxide at 86.9 MPa (12.6 psia) and 297 K (75°F) is 0.00165 g/cm³.

Extraction yields as a function of temperature at a pressure 10.3 MPa are shown in Figure 3. The extraction yields were practically identical for the three temperatures (297 K, 304 K and 311 K) in the proximity of the critical temperature of CO₂. The yield decreased

Figure 3: Extraction Yields as a Function of Temperature for the Crude Oil - CO₂ Systems at 10.3 MPa.

significantly at a higher temperature (339 K). This decrease in yield was due to a phase transition from a liquid-liquid (L-L) like system to a liquid-vapor (L-V) like system at the higher temperature. The vapor-like extract phase has been reported to extract considerably less oil than the liquid-like extract phase^{8,9}. The density of pure CO₂ decreased about 20% as the temperature increased from 297 to 311 K at a constant pressure of 10.3 MPa. This density decrease was approximately the same as that observed when the pressure was changed from 17.2 MPa to 10.3 MPa at 311 K. However, the difference in extraction yields observed as the pressure decreased (Figure 2) was not observed as temperature increased (Figure 3). This led to the presumption that density was not the sole controlling parameter that determined extraction efficiency of CO₂.

Compositional information for the extract phases was obtained using simulated distillation (SIMDIS). The compositional plots (Figures 4-6, 9-12, 15-17) are cumulative carbon number distributions. The earlier

extracts contained lighter components and the latter extracts contained progressively heavier compounds in all the experiments. An example of this trend is shown in Figure 4 for the extraction at 10.3 MPa and 311 K.

Figure 4: Composition as a Function of Time for the Crude Oil - CO₂ Extracts at 311 K and 10.3 MPa.

Comparison of the carbon number distributions of the middle extracts at three different pressures and a fixed temperature (Figure 5) confirmed the extraction of heavier hydrocarbons as the pressure increased. These observations are consistent with continuous crude oil-CO₂ extraction experiments reported by Orr, et al.⁹. Examination of the carbon number distributions of the middle extracts obtained at three temperatures close to the critical temperature of CO₂ indicated that there was little or no difference in these fractions (Figure 6). This compositional nondiscrimination despite a considerable density change seems directly related to the extraction temperature and its proximity to the critical temperature of CO₂. This temperature effect has not been reported in previous continuous extractions studies. The

Figure 5: Compositional Changes as a Function of Pressure for the Crude Oil - CO_2 extractions at 311 K.

Figure 6: Compositional Changes as a Function of Temperature for the Crude Oil - CO_2 Extractions at 10.3 MPa.

middle extract at 339 K exhibited the presence of considerably more light components due to the L-L to L-V transition. Thus, the compositional information for the extracts was consistent with the extraction data.

Extraction of the Bitumen-Derived Liquid

In all the experiments, 95 g of the bitumen-derived liquid was initially changed to the extractor. The extraction yields as a function of pressure for the two solvents are plotted in Figure 7. The extraction yields for propane were considerably higher than for CO_2 due to the greater affinity of propane for the hydrocarbon components of the bitumen-derived liquid. The cumulative yields with CO_2 increased linearly in a manner analogous to the extraction of a pure hydrocarbon component (such as hexadecane) exhibiting L-L phase behavior with CO_2 .

Figure 7: Extraction yields for the Bitumen-Derived Liquid with CO_2 and Propane as Function of Pressure of 311 K.

The effect of temperature on the extraction yields at a constant pressure of 10.3 MPa for the propane extraction is shown in Figure 8. An explanation of the extraction data was attempted on the basis of the density of pure propane at the extraction conditions (Table III).

Figure 8: Extraction Yields for the Bitumen-Derived Liquid with Propane as a Function of Temperature at 10.3 MPa.

Table III
Density of Propane* at Experimental Conditions
Conducted in Extractions

(Unit: g/cm³)

Temperature	311 K	339 K	380 K	408 K	422 K
Pressure					
5.5 MPa	0.5082	-	0.2585	-	-
10.3 MPa	0.5267	0.4782	0.3825	0.3093	0.2672
17.2 MPa	0.5503	-	0.4416	-	-

* Density of Propane at 86.9 KPa (12.6 psia) and 297 K (75°F) is 0.00157 g/cm³.

The propane densities in Table III were calculated using the Peng-Robinson equation of state (EOS).¹⁰ The density varied by only about 10% when the pressure was increased from 5.5 MPa to 17.2 MPa while it changed by over 30% when the temperature was increased from 311 K to 408 K. The effects of temperature and pressure on the extraction yields appeared to be similar (Figures 7 and 8). This again led to the conclusion that density was not the only parameter that controlled the extraction of complex hydrocarbon mixtures by dense gases. Apparently, the individual

extraction temperatures and pressures and their values relative to the pure solvent critical values affect extraction. For example, at a constant pressure of 10.3 MPa, the yields were highest at 380 K, a temperature close to the critical temperature of propane. An understanding of relevant thermodynamic properties near the solvent critical point would be required to rigorously explain this phenomena.

The compositional variation of the extracts as a function of time for the CO₂ extractions is plotted in Figure 9. There was essentially no

Figure 9: Compositions as a Function of Time for the Bitumen-Derived Liquid - CO₂ Extracts at 311 K and 10.3 MPa.

preferential extraction of the bitumen-derived liquid unlike that which was observed for the crude oil. The same trend was observed for the compositional variation as a function of pressure. The bitumen-derived liquid behaved effectively like a single component in these extractions, except that the composition of the extracted phases was different from the original composition of the bitumen-derived liquid. The linear cumulative extraction yield curve was consistent with this behavior.

The nondiscriminatory extraction of the bitumen-derived liquid by propane as a function of time (Figure 10), temperature (Figure 11) and pressure (Figure 12) clearly demonstrated that these compositional trends were features of the chemical nature of the bitumen-derived liquid. This unusual behavior was attributed to the presence of olefins and

Figure 10: Compositions as a Function of Time for the Bitumen-Derived Liquid - Propane Extracts at 380 K and 10.3 MPa.

Figure 11: Compositional Changes as a Function of Pressure for the Bitumen-Derived Liquid - Propane Extracts at 380 K.

Figure 12: Compositional Changes as a Function of Temperature for Bitumen-Derived Liquid - Propane Extracts at 10.3 MPa.

aromatics in the bitumens-derived liquid which were produced during the pyrolysis process. The dealkylation reactions and the cleavage of alkyl linkages between aromatic and naphthenic clusters at pyrolysis temperatures could have produced a more homogeneous hydrocarbon mixture which was reflected by the behavior of the bitumen-derived liquid in the SFE experiments. The bitumen contains naphthenic and naphtheno-aromatic compounds with long alkyl side chains. The cleavage of these side chains could have led to the formation of similar-sized compounds whose solubilizing effect caused the bitumen-derived liquid to act as an integrated unit. Despite the lack of compositional differences in the extracts, the cumulative extraction curves for the bitumen-derived liquid were not linear. This was attributed to changes in extract phase densities as a function of time and extraction conditions. The fact that heavier compounds were found in the propane extracts was consistent with the greater extraction yields with propane. Both of these trends were expected.

Extraction of the Native Bitumen

For CO₂ extractions, 99 g of native bitumen was charged to the extractor. The extractions were performed at 367 K and pressure of 10.3 MPa, 17.2 MPa, 24.0 MPa and 30.9 MPa. At the highest extraction pressures, practically no oil was extracted.

For those propane experiments, 50 g of the native bitumen was initially charged into the extractor. The effect of pressure on extraction yields at 380 K is presented in Figure 13 and the effect of temperature on the extraction yields at 10.3 MPa is presented in Figure 14. The absolute yields, compared to the propane extractions of the bitumen-derived liquid were lower; however extraction trends were similar. The extraction appeared to be most effective when the extraction temperature was in the proximity of the critical temperature of propane. Thus, the propane density could not be used as a single parameter to

Figure 13: Extraction Yields for the Native Bitumen with Propane as Function of Pressure at 380 K.

Figure 14: Extraction Yields for the Native Bitumen with Propane as Function of Temperature at 10.3 MPa.

explain the differences in extraction yields. The compositional variations as a function of time were evaluated by reviewing the carbon number distributions of the first, middle and the last extracts for the experiments at 10.3 MPa and 380 K (Figure 15). The middle and the last extracts contained compounds heavier

Figure 15: Composition as a Function of Time for the Native Bitumen Propane Extracts at 380 K and 10.3 MPa.

than the first fraction. This trend was similar to the CO₂ - crude oil extractions and highlights the unusual nondiscriminatory extracts of the bitumen-derived liquid. The carbon number distributions as a function of pressure (Figure 16) indicated that heavier compounds were extracted at higher pressure. No significant compositional changes were observed as a function of temperature (Figure 17).

Figure 16: Compositional Changes as a Function of Pressure for the Native Bitumen-Propane Extracts at 380 K.

Figure 17: Compositional Changes as a Function of Temperature for the Native Bitumen-Propane Extracts at 10.3 MPa.

MODELING THE EXTRACTION PROCESS

Equations of state have been used to represent the phase behavior of complex hydrocarbon mixtures. Preliminary phase behavior calculations were performed using the Peng-Robinson EOS.¹⁰ There are two options for the phase behavior calculations using EOS; the component lumping method and the continuous thermodynamics approach. The component lumping technique was selected for the initial attempt to model these systems.

The 35-component crude oil system determined by simulated distillation was lumped into 6 pseudocomponents using Whitson's¹¹ lumping procedure. Four fractions of the bitumen-derived liquid generated by the SIMDIS analysis were adopted directly as pseudocomponents in the phase behavior calculations. The native bitumen had about 35% of the material that boiled below 811 K. Based on the boiling point curve up to 811 K, an extrapolated curve extending to 1100 K was obtained. This extrapolated curve was divided into five pseudocomponents with each corresponding to 20 wt% of the bitumen. The pseudocomponent representations of each of the three materials are presented in Table IV. Once the pseudocomponents were assigned, the pseudocritical properties of each pseudocomponent were computed. The mean boiling point and molecular weight of each component were used for the estimation of critical properties for the crude oil. A Watson characterization factor of 11 was used for all the fractions to estimate pseudocomponent specific gravities for the bitumen-derived liquid and the bitumen. Kesler-Lee¹² correlations were used to calculate the critical properties in all cases. A set of interaction parameters that decreased with carbon

Table IV
Boiling Point Distributions of Pseudocomponents Generated
for Representing Three Different Feedstocks

	Boiling Point Range (K)	Wt. %
Crude Oil		
Pseudocomponent 1	109 - 447	24.3
Pseudocomponent 2	448 - 468	9.0
Pseudocomponent 3	469 - 489	4.6
Pseudocomponent 4	490 - 508	4.1
Pseudocomponent 5	509 - 575	20.6
Pseudocomponent 6	> 575	41.4
Bitumen-Derived Liquid		
Pseudocomponent 1	417 - 477	4.5
Pseudocomponent 2	378 - 616	24.4
Pseudocomponent 3	617 - 911	48.0
Pseudocomponent 4	> 911	23.1
Native Bitumen		
Pseudocomponent 1	520 - 689	20.0
Pseudocomponent 2	690 - 786	20.0
Pseudocomponent 3	787 - 857	20.0
Pseudocomponent 4	858 - 931	20.0
Pseudocomponent 5	> 931	20.0

number were used for the CO₂ - hydrocarbon systems. In the propane case, interaction parameters that increased with carbon number were used. The choice of these interaction parameters was arbitrary and they were adjusted until the most reasonable agreement was found between calculated and experimental results. Details of the lumping procedure and the pseudocomponent properties for the three feedstocks have been reported elsewhere.⁷

The initial extractor charge was used to calculate the overall feed compositions and a flash calculation was performed at the system conditions. It was assumed that for the first extraction window, the extract phase composition was given by this initial flash. The amount of solvent exiting and the amount of oil extracted during the first extraction window were determined experimentally. These amounts, along with the composition of the extracted oil, determined by SIMDIS, were used to reconstruct the extract phase composition inside the extractor at the given conditions. This provided the comparison between the calculated

and experimental extract phase compositions. The phase density of the extract phase was calculated by the Peng-Robinson EOS. The amount of material withdrawn during the first extraction window and the density of the extract phase were used to compute the volume of the extract phase withdrawn during the first stage. It was assumed that this volume was replaced by fresh solvent at the system conditions for the next window. A material balance on the solvent and the oil components yielded the overall mixture composition for the flash calculation for the next extraction stage. This procedure was repeated for all the extraction stages.

A comparison of the experimental and calculated extract phase compositions for the crude oil - CO₂ extraction at 10.3 MPa and 311 K is presented in Table V. The agreement

Table V
Comparison of the Experimental Carbonic Phase and Residual
Oil Compositions with the Phase Behavior Calculations
for Crude Oil-Carbon Dioxide Extraction
at 10.3 MPa and 311 K

(Unit: Mol%)									
	First Extraction Window		Middle Extraction Window		Last Extraction Window		Residual Oil		
	F	C	F	C	F	C	F	C	
CO ₂	95.7	96.1	97.6	97.2	98.8	97.7	-	-	
F1 Oil	1.9	2.4	6.8	1.9	0.4	1.1	33.3	27.8	
F2 Oil	0.3	0.3	0.2	0.2	0.1	0.2	5.6	5.8	
F3 Oil	0.3	0.2	0.2	0.2	0.1	0.1	4.7	5.1	
F4 Oil	0.2	0.2	0.2	0.1	0.1	0.1	4.3	4.6	
F5 Oil	0.9	0.5	0.6	0.4	0.4	0.4	17.5	22.2	
F6 Oil	0.7	0.4	0.4	0.4	0.2	0.4	34.7	34.6	

F^e experimental data
C^e data predicted from phase behavior calculation by
Peng-Robinson equation of state

F1 Oil: C₁-C₂ fraction of extracted oil
F2 Oil: C₃ fraction of extracted oil
F3 Oil: C₄ fraction of extracted oil
F4 Oil: C₅ fraction of extracted oil
F5 Oil: C₆-C₇ fraction of extracted oil
F6 Oil: C₈-C₉ fraction of extracted oil

between the calculated and experimental results was reasonable considering the uncertainties of modeling such a complex process. Phase behavior calculations for the

propane - bitumen-derived liquid system at 10.3 MPa and 380 K are compared to the experimental values in Table VI. The EOS model predicted

Table VI

Comparison of the Experimental Extracted Phase Compositions with the Phase Behavior Calculations for Bitumen Derived Liquid-Propane Extraction at 10.3 MPa and 380 K

(Unit: Mol%)

	Initial Overall Compositions	First Extraction Window E / C		Middle Extraction Window E / C		Last Extraction Window E / C	
C ₂ H ₆	82.7	90.2	94.3	95.1	99.6	97.7	99.7
F1 Oil	3.3	1.1	2.5	0.8	0.0	0.2	0.0
F2 Oil	5.2	3.7	2.4	1.9	0.0	0.9	0.0
F3 Oil	7.1	4.7	0.7	2.4	0.3	1.1	0.2
F4 Oil	1.7	0.3	0.1	0.1	0.1	0.1	0.1

E^{*} experimental data
C^{*} data predicted from phase behavior calculation by Peng-Robinson equation of state

F1 Oil: extracted oil fraction(b.p. range: 417 - 477 K)
F2 Oil: extracted oil fraction(b.p. range: 478 - 616 K)
F3 Oil: extracted oil fraction(b.p. range: 617 - 811 K)
F4 Oil: extracted oil fraction(b.p. range: > 811 K)

a complete depletion of lighter components from the bitumen-derived liquid by the time of last extraction. However, it was observed experimentally that heavier components extract equally efficiently from the bitumen-derived liquid. Current phase behavior models were not capable of predicting the unusual extraction behavior of the bitumen-derived liquid. Examination of the experimental and calculated values for the native bitumen - propane extractions at 10.3 MPa and 380 K (Table VII) indicated reasonable agreement between the two values. Thus, the EOS models with component-lumping performed reasonably well for typical extraction predictions; however, the models breakdown when dealing with unusual behavior like that of the bitumen-derived liquid.

Table VII

Comparison of the Experimental Extracted Phase Compositions with the Phase Behavior Calculations for Whitetocks Bitumen-Propane Extraction at 10.3 MPa and 380 K

(Unit: Mol%)

	Initial Overall Compositions	First Extraction Window E / C		Middle Extraction Window E / C		Last Extraction Window E / C	
C ₂ H ₆	95.0	98.9	98.4	99.2	99.3	99.6	99.7
F1 Oil	1.6	0.6	1.2	0.4	0.4	0.1	0.1
F2 Oil	1.1	0.4	0.3	0.3	0.3	0.2	0.1
F3 Oil	0.9	0.1	0.1	0.1	0.1	0.1	0.1
F4 Oil	0.8	0.0	0.0	0.0	0.0	0.0	0.0
F5 Oil	0.6	0.0	0.0	0.0	0.0	0.0	0.0

E^{*} experimental data
C^{*} data predicted from phase behavior calculation by Peng-Robinson equation of state

F1 Oil: extracted oil fraction(b.p. range: 520 - 689 K)
F2 Oil: extracted oil fraction(b.p. range: 690 - 786 K)
F3 Oil: extracted oil fraction(b.p. range: 787 - 857 K)
F4 Oil: extracted oil fraction(b.p. range: 858 - 931 K)
F5 Oil: extracted oil fraction(b.p. range: > 931 K)

CONCLUSIONS

The conclusions drawn from this study were as follows:

1. Pure solvent density was not the only parameter that controlled extraction efficiency. Factors such as the proximity of the extraction temperature to the critical temperature of the pure solvent appeared to affect the extraction yields.
2. As expected heavier compounds were extracted as extraction time and extraction pressure increased in the crude and bitumen extractions. However, no preferential extraction was observed in the bitumen-derived liquid extracts. This was attributed to the presence of olefins and aromatics in the bitumen-derived liquid and to its thermal history.

3. EOS model and component-lumping methods can be used to describe a typical extraction sequence. However, this approach is incapable of handling unusual extraction behavior like that exhibited by the bitumen-derived liquid.

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