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Miscible Flooding for Bitumen Recovery with a Novel Solvent

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Abstract

Steam injection is an effective heavy oil recovery method, however, poses several environmental concerns. Solvent injection methods are introduced in an attempt to combat these environmental concerns. This paper evaluates the effectiveness of a new solvent (VisRed) in the recovery of a Canadian bitumen and compares its results with toluene. While VisRed is selected due to its high effectiveness as a viscosity reducer even at very low concentrations, toluene is selected due to its high solvent power.

Five core flooding experiments were conducted; E1 (Steam flooding), E2 (VisRed flooding), E3 (Toluene flooding), E4 (Steam + Toluene flooding), and E5 (Steam + VisRed flooding). Core samples were prepared by saturating 60% of the pore space with oil samples and 40% with deionized water. The solvents were injected at a 2 ml/min rate, while steam was injected at a 18 ml/min cold water equivalent rate. Produced oil and water samples were collected every 20 min during every experiment. The oil recovery efficiencies of the core flood experiments were analyzed by the emulsion characterization in the produced fluids and the residual oil analysis on the spent rock samples.

The best oil recovery of ~30 vol % was obtained for E2 (VisRed) in which VisRed was injected alone. Although similar cumulative recoveries were obtained both for E2 (VisRed) and E3 (Toluene), the amount of VisRed injected [~1 pore volumes (PV)] was half the volume required by toluene (~2 PV). The produced oil quality variations are mainly due to the formation of the water-in-oil emulsions during mainly steam processes (E1, E4, and E5). The increased amount of the polar fractions in the produced oil enhances the formation of the emulsions. These polar fractions are namely asphaltenes and resins. As the amount of the polar fractions in the produce oil increases, more water-in-oil emulsion formation is observed due to the polar-polar interaction between crude oil fractions and water. Consequently, E1 and E5 resulted in more water in oil emulsions. The cost analysis also shows the effectiveness of solvent recovery over steam-solvent recovery processes.

Introduction

It's not possible to meet the rising oil demand with sole reliance on conventional crude oil resources. Thus, a need arises to develop the unconventional resources (Alhajji, 2002; Meyer & Attanasi, 2003; Reid, 1984; Meredith, 2020).

Heavy oil and bitumen resources are the keys to bridging the gap between increasing carbon needs and depleting conventional oil resources. The untapped heavy oil and bitumen deposits are over five times the remaining conventional crude oil reserves, estimated to be over 6 trillion barrels (Das, 1998; Kovscek, 2006). However, these resources cannot be produced without external help due to their high viscosities. Two common methods to reduce their viscosity include heat transfer or dilution of the oil with light hydrocarbon solvents (Gupta et al., 2005; Stape et al., 2016).

The oldest and the most widely used technique to enhance heavy oil production involves using steam to increase the temperature of the reservoir (Erpeng et al., 2018; Li & Chen, 2015; Bealessio, et al., 2021).This subsequently reduces the viscosity and increases the mobility of the heavy oil resulting in higher oil production (Hernandez & Trevisan, 2007; Stewart & Udell, 1988; Willman et al., 1961). Although this process has many advantages, it also has some operational drawbacks. In this process, a large source of fresh water is required for the generation of steam which incurs several environmental concerns (Collins, 2011; Ng et al., 2019). Steam injection is also not applicable for depths greater than 5,000 feet at which conditions vapor phase of water cannot be obtained (Dou et al., 2007). Apart from the environmental considerations, steam injection also produces poorer quality oil due to severe water-in-oil emulsion formations. Solvent recovery methods were introduced to combat these disadvantages of steam processes.

In 1971, Gates and Caraway tested the effectiveness of several solvents ranging from refinery cuts to chemical compounds to find that low molecular-weight aromatic solvents like toluene, benzene, and xylene proved to be the most effective in recovering heavy crudes (Gates & Caraway, 1971). Butler and Mokrys, 1991 introduced the Vapor extraction (VAPEX) process which has the same operational logic to the Steam Assisted Gravity Drainage (SAGD) process. They suggested the use of solvents instead of heat to mobilize the oil (Butler & Mokrys, 1991; Butler & Mokrys, 1993). The solvent decreases the crudes' viscosity and upgrades the crude by depositing in-situ the heavier ends and extracting a large portion of the lighter ends. Several studies were performed to compare both steam and solvent processes (Stape and Hascakir, 2016; Coelho et al., 2016; Hascakir, 2016). Solvent injections were found to be more energy efficient as they do not consume as much energy as thermal recovery methods (Frauenfeld et al., 2006; Galvão et al., 2014; Jiang et al., 2012). They also consume lower cold water equivalents than steam processes alone, to achieve the same oil recoveries (Doscher et al., 1979; Galvão et al., 2014). However, sole solvent recovery methods are not preferred due to their high cost and toxicity of the injected solvents (Hascakir, 2016). Conventionally used solvents like Benzene, Xylene, and Toluene (BTX) are acutely toxic and have relatively high water solubility and low biodegradability, causing aquifer and groundwater contamination. As a result, they are classified as priority pollutants by the U.S Environmental Protection Agency (Agency, 1986; Tsao et al., 1998). These chemicals are also not safe to handle in an oil field due to their low flashpoints (Al-Taq et al., 2019).

The focus of this paper is to investigate the oil recovery performance of a Canadian Bitumen with steam and steam-solvent processes. A diluted aromatic solvent (VisRed) was used for these experiments, and its efficiency is compared to that of conventional solvents like steam and toluene. Factors like produced oil quality, cumulative oil recovery, and the economic parameters were analyzed to determine the optimum recovery method for Canadian Bitumen.

Experimental Studies

In this study, the recovery performance of a Canadian Bitumen was tested through solvent and solvent-steam processes. The initial oil properties of the sample are listed in Table 1. The sample is classified as Bitumen even though it has an API gravity of 14.3° as its viscosity (~51,000 cP) is more than 10,000 cP at reservoir temperature. Asphaltene content was measured according to a Standard ASTM menthod (ASTM D2007-11) by n-pentane washing.Hence, the asphaltenes mentioned in this work are n-pentane insoluble asphaltenes. The asphaltene percentage for the sample was found to be 43.3%.

Table 1—Characteristics of the Canadian Bitumen used in this study

Properties	Value
Color	Black
Viscosity at 35°C, cP	51395.5
Density of Oil at Room Temperature, *g/cm*^{3}	0.97032
n-pentane insoluble asphaltene, wt.%	43.3

Five core flooding experiments were conducted with two hydrocarbon solvents; VisRed and toluene. VisRed, which is developed by Carbon Chain Technologies Limited, was selected due to its high effectiveness as a viscosity reducer even at very low concentrations. Toluene was selected due to its high solvent power. Experimental conditions are mentioned in Table 2.

Table 2—The list of the experimental conditions used in the coreflooding tests

Properties	Value
Back Pressure, psi	75
Temperature,°C	~ 20
Solvent Injection rate, ml/min	2
Steam Injection rate, ml/min	18
Core cell volume, cc	451

The core pack was prepared by blending Ottawa sand (~39% porosity) with 40% pore volume (PV) of water and 60% PV of oil. The sand grains were first mixed with water in a mixing bowl to coat the grains with a water film to maintain water wetness (Kar et al., 2015). Then, the oil was added to the mixture. This mixture was packed to a core holder with 2.13 in (5.41 cm) inner diameter and 7.84 in (20 cm) length. After the core holder was sealed, it was placed to the experimental setup shown schematically in Figure 1.

As shown in the figure, the bottom end of the core holder is connected via production tubing to a back pressure regulator and separator. Back pressure was kept at 75 psi through nitrogen injection. Production samples were collected every 20 minutes from the outlet of the sample collection section by using separators. A solvent pump was used to pump the solvents (either VisRed or Toluene) into the core holder at 2 ml/min rate at 20°C. A water pump first pumped water into a steam generator, and generated steam was injected to core holder at 18 ml/min cold water equivalent rate at 250°C (Hamm & Ong, 1995; Mukhametshina et al., 2016).

Five coreflood experiments were conducted at the same experimental conditions by just changing the injected EOR (Enhnaced Oil Recovery) fluid type. In the first experiment; E1, Steam was injected alone at 18 ml/min rate, thus, this experiment represents steam flooding process in the lab-scale. In the second experiment; E2, VisRed was injected alone at 2 ml/min rate. In the third experiment; E3, toluene was injected alone at 2 ml/min rate. Therefore, E2 and E3 represent the miscible flooding processes in the lab-scale. In the fourth experiment; E4, steam at 18 ml/min rate was coinjected with toluene at 2ml/min rate. Similarly, in the fifth experiment; E5, steam at 18 ml/min rate was coinjected with VisRed at 2ml/min rate. Hence, E4 and E5 represent the solvent-steam processes in the lab-scale.

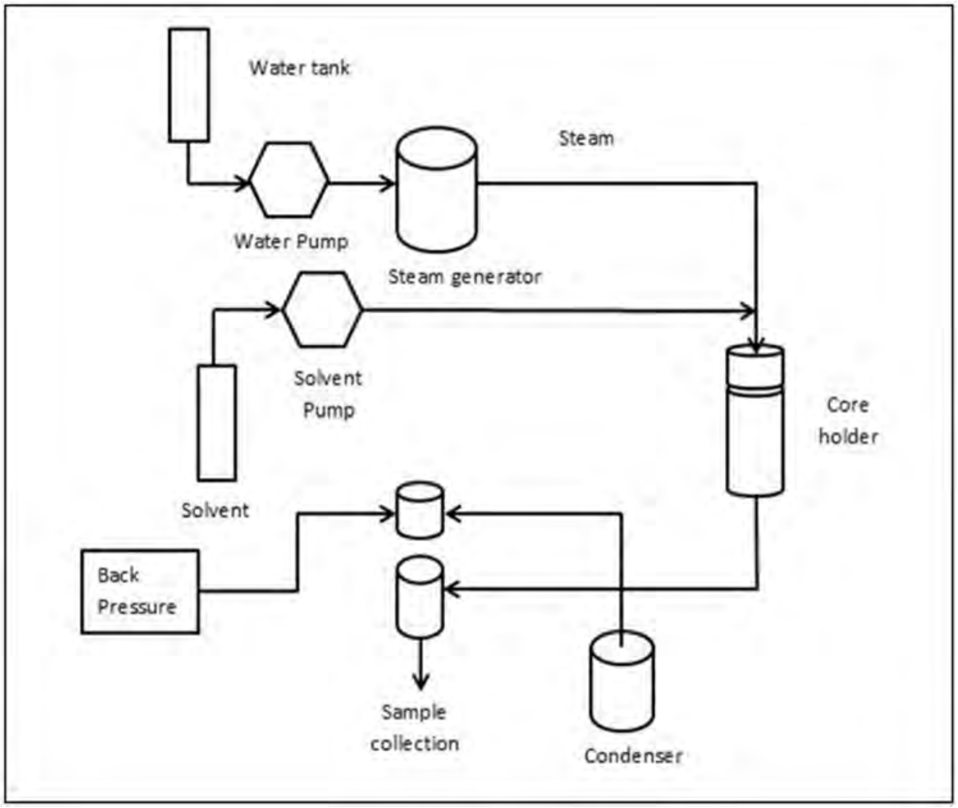

Figure 1—Schematic diagram of the core flooding experiment

After each experiment, the produced liquids collected during each experiment were visualized under the optical microscopy to observe the presence of water-in-oil emulsions in the produced liquids (Mukhametshina et al., 2016).

Mass of all packed (oil, water, and sand), injected (solvent and water), and produced (oil, water, and gas) components were measured. Through mass balance calculations, the amount of residual oil was determined (Kar et al. 2016).

Results and Discussion

The spent rock images from all experiments are provided in Figure 2.

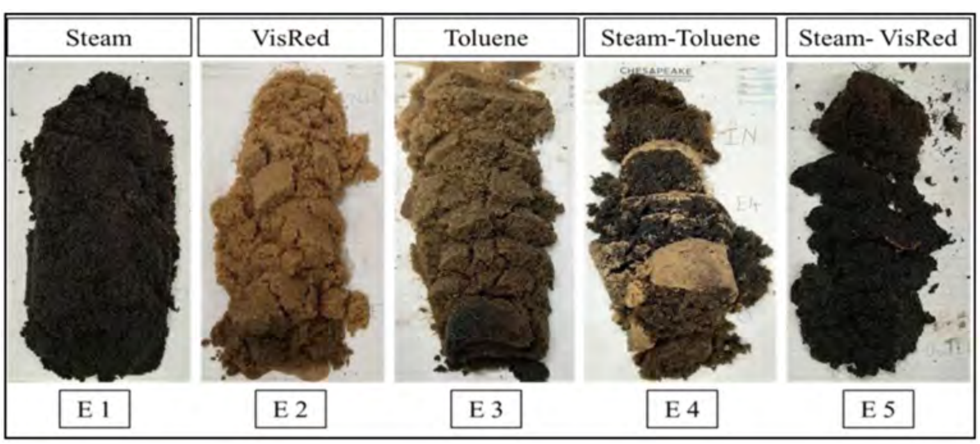

Figure 2—Spent rock images from core flooding experiments. As evident from its color, E2 has the highest oil recovery.

As evident in the figure, the sole injection of VisRed resulted in the lightest color implying the highest oil recovery. However, a co-injection of steam and VisRed yielded the lowest oil recovery, as seen from a very dark post-mortem sample, indicating that VisRed interaction with vapor water results in lower oil recovery.

As summary of the experimental results, the residual oil, the displacement efficiency (volume percent of the whole core), and the total experiment time parameters are provided in Table 3.

Table 3—Post mortem results for core flooding experiments. Initial oil vol % was 60 vol % of the core pack.

Experiment number	Solvent Injected	Residual Oil Saturation vol%	Displacement efficiency, vol.%	Experiment run time, min
E1	Steam	49.6	17.4	196
E2	Visred	42.7	28.9	93
E3	Toluene	42.8	28.7	143
E4	Steam-Toluene	52	13.4	112
E5	Steam-Visred	59.4	0.95	125

While E2 in which the VisRed was injected alone and E3 in which toluene was injected alone provided very similar sweep efficiencies, E2 was conducted in a shorter period of time hence, the VisRed required less pore volumes (PVs) injection than toluene to recover the same amount of oil.

Emulsion characterization was conducted on produced oil samples taken every 20 minutes from each of the core flooding experiments. An image from each of the five experiments on Canadian Bitumen is depicted in Figure 3. The resulting images show that experiments E1 (Steam), E4 (Steam-Toluene), and E5 (Steam-Visred) contain higher water content i.e., stronger emulsion formations indicating lower oil quality.

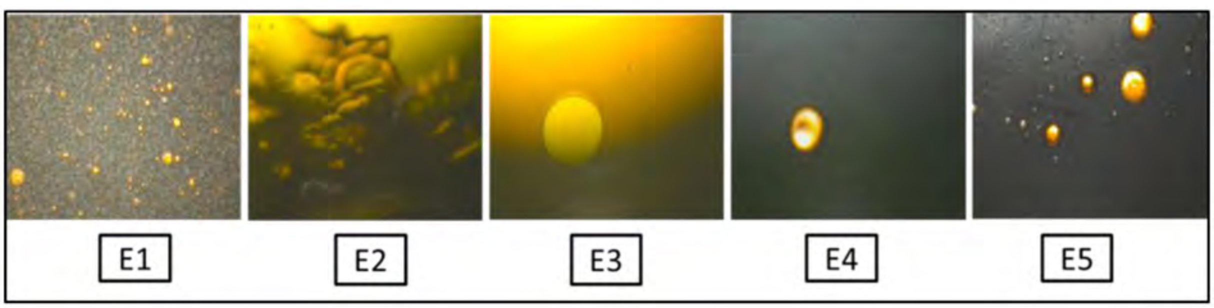

Figure 3—Emulsion characterization results. Experiments E1, E4, and E5 have higher water content and consequently lower oil quality due to higher asphaltene content. These samples will require more processing effort to separate oil from the emulsion.

Emulsion stability is dependent on the existence of polar components and their interactions with emulsion. In this case, the main polar components are water, asphaltenes, and resins (Kar & Hascakir, 2015; Punase et al, 2016). Consequently, stronger emulsion formations are indicative of higher asphaltene content. Experiments involving steam are expected to form stronger emulsions as steam promotes more severe emulsion formations than liquid water (Prakoso et al., 2017; Ng et al., 2018; Prakoso et al., 2018). Additionally, as the stability of emulsion increases, separating oil from the emulsion (emulsion breaking) becomes more difficult and consumes more energy (Kar & Hascakir, 2015; Kar and Hascakir, 2021). Thus, stronger emulsions indicate lower oil quality and result in lower oil recovery. The smaller average size of emulsion droplets result in longer residence time (Kokal, 2005; Kar and Hascakir; 2016). This implies a larger separation setup. Thus, from Figure 3, it is evident that the lowest oil quality was achieved by sole steam injection (E1). On the other hand, images of samples from E2 (VisRed) showed very little to no water content. Hence, produced oil quality was best with a sole injection of VisRed.

We futher checked the economic viability for each injection fluid. Three parameters were evaluated; oil recovery in terms of bbl./acre.ft, the number of pore volumes injected, and the cost of solvent. Cost calculations were determined by taking the cost of toluene and VisRed as 0.055 $/ml and 0.057 $/ml, respectively. As our interest lies in solvent cost, we omit the price of steam in these calculations. These prices were obtained from commercial vendors as of March 2021. Their results are summarized in Table 4.

Table 4—Economic parameters for Canadian Bitumen

Experiment number	Solvent Injected	Oil recovery,bbl./acre.ft	Cost of solvent,$	PVs injected
E1	Steam	454	0	-
E2	Visred	752	0.9	1.1
E3	Toluene	747	0.6	1.6
E4	Steam-Toluene	349	0.7	1.3
E5	Steam-Visred	25	0.7	1.4

Accordingly, both VisRed (E2) and toluene (E3) injections had the greatest oil recoveries whereas a co-injection of steam and VisRed (E5) performed the worst. The table shows that the cost of VisRed injection is higher than that of toluene however, as the amount of pore volume required is almost half of that of toluene, it is still a viable option. Overall, considering oil quality, recovery, PVs required and cost of solvent, sole injection VisRed is the best recovery method for this Canadian Bitumen. This recovery method also reduces the environmental damage by reducing the amount of toxic solvent injected into the reservoir.

Conclusions

In this study, we investigated the effectiveness of a novel aromatic solvent, VisRed for a bitumen recovery. The following conclusions can be drawn from the above results and observations:

1. Experiments involving steam are more likely to have stronger emulsion formations, making it difficult for processing and separation. Stronger emulsion stability is also indicative of higher asphaltene precipitation and consequently lower oil quality.
2. Sole injection of VisRed performed the best, resulting in the highest oil recovery. Visred also produced better quality oil and required lower pore volumes.
3. Co-injections of steam and VisRed reacted adversely and produced almost no oil due to phase trapping in the core sample.

VisRed can be used in smaller volumes than conventional toxic aromatic solvents like toluene for heavy oil recovery. Hence, if oil recovery efficiencies of VisRed are comparable to conventional aromatic solvents, it can reduce the environmental damage caused by these toxic chemicals.

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Nomenclature

API American Petroleum Institute
ASTM American Society for Testing and Materials
BTX Benzene, Toluene and Xylene

cP centipoise
SAGD Steam Assisted Gravity Drainage
TGA/DSC Thermo-gravimetric Analysis/ Differential Scanning Calorimetry
VAPEX Vapor extraction
Vol % Volume percent

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