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# Insight into heavy oil recovery of cyclic solvent injection (CSI) utilizing $C_3H_8/CH_4$ and $C_3H_8/CH_4/CO_2$

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ABSTRACT

In this study, a sandpack model with porosity and permeability of 32.3% and 9.4 D, and a heavy crude oil with viscosity of 6430 mPa.s were used to represent a typical thin heavy oil formation. First, different ratios of $C_3H_8$ to $CH_4$ stream were prepared and their performance on Cyclic Solvent Injection (CSI) method was examined to quantify the optimum solvent concentration. Second, $CO_2$ was introduced to the optimum quantified $CH_4$-$C_3H_8$ mixture to investigate the extent to which CSI behavior changes by partially replacement of $CH_4$ with $CO_2$.

Results showed that ultimate oil recovery factor (*RF*) increased from 24.3% to 33.4% original oil in place (OOIP) when $C_3H_8$ concentration increased from 15 to 50 mol% in the $CH_4$ stream. CSI tests with higher $C_3H_8$ concentration reached the maximum cyclic recovery with lower number of injection cycles - due to higher solubility of $C_3H_8$ compared with $CH_4$. Solvent utilization factor (SUF) data also confirmed this as lesser volume of solvent with higher $C_3H_8$ concentration was required to produce oil.

Visual observations showed that the produced foamy oil lasted longer with higher concentration of $C_3H_8$ in the solvent (5 min for 15% $C_3H_8$ − 85% $CH_4$ case versus 180 min for 50% $C_3H_8$ − 50% $CH_4$ case). Upon addition of $CO_2$ to the mixture, the solvent apparent solubility increased and foamy oil flow promoted. The highest cyclic $C_3H_8$-$CH_4$ apparent solubility of 0.175 gr. solvent/100 gr. remaining oil jumped to 0.53 gr. solvent/100 gr. remaining oil when 35% mole fraction of $CO_2$ replaced $CH_4$. The highest ultimate oil *RF* of 44.11% OOIP was measured from eight cycle injection of 50% $C_3H_8$ − 15% $CH_4$ − 35% $CO_2$. This solvent also benefited from the longest stability of produced-oil foamy shape with recorded time of 217 min (including production time).

According to the results of this experimental study, it seems that there is an optimum fraction of $C_3H_8$ in $CH_4$ stream injection in heavy oil systems (with viscosity in the vicinity of 6430 mPa s); the concentration beyond which ultimate oil recovery factor does not increase significantly (near 50 mol%). It is speculated that last cycles do not appreciably respond to heavy oil production mainly due to asphaltene getting precipitated within the model.



## 1. Introduction

Role of underground hydrocarbon deposits on meeting global energy demand supply is inevitable and it is vital to precisely identify these commercially exploited minerals that are mainly in the form of liquids underground. The terms “conventional” and “unconventional” reserves are usually used to broadly distinguish the underground fluids (mostly oil). Conventional oil reservoirs offer appealing combination of high quality of oil together with cost-effective methods of extraction. These factors plus relatively low price to refine have motivated petroleum companies to make most of their investment on light oil extraction. However, as these resources are continuously being depleted, unconventional oil exploitation, which had remained on the sidelines for a long time, are being put on agenda to alleviate the confliction between the

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ever-increasing energy consumption and depletion of conventional resources.

Out of wide range of unconventional oil resources (heavy oil, tight oil, and shale oil), Canada is mostly rich in heavy and extra heavy oils. Canada and Venezuela together stand for 55–65% of the word's heavy oil resources [1]. Nonetheless, the majority of Canadian heavy oils are located in reservoirs that have thickness less than 10 m [2]. This poses a risk on the applicability of thermal and gravity-dominated recovery methods in heavy oil reservoirs. In these conditions, Cyclic Solvent Injection (CSI) is considered as a viable method due to its rapid payout and appreciable performance [3].

CSI, which is also termed as huff-n-puff in the literature, is an enhanced oil recovery (EOR) technique that deals with only one well. In this method, solvent is injected to the system for a definite injection time. Then, the well is shut down to allow solvent-oil interaction. At the end, the same injection well is turned into a production well and the solvent-saturated oil together with solvent itself are produced.

In conventional oils, carbon dioxide ($CO_2$) is the mostly implemented solvent in CSI process due to its high solubility, miscibility condition, and environmental consideration (e.g., reducing greenhouse gas emission) [4]. However, $CO_2$ is not always accessible and it causes corrosion problems during implementation. Methane ($CH_4$), on the other hand, is widely available in the field as this gas is produced from the reservoir. However, both $CO_2$ and $CH_4$ bear high saturation pressure. Hence, heavy oils that are usually exposed to low reservoir pressure [5] might not be the ideal candidate for the injection of these solvents. Propane ($C_3H_8$), on the other hand, benefits from low saturation pressure. However, while technically attractive on account of its high solubility and swelling effect, $C_3H_8$ is not the best economic solvent that can be used in large-scale filed applications. It seems that combining $CH_4$ and $C_3H_8$, in different mixing ratios, can be an alternative option for solvent injection that takes advantage of satisfactory saturation pressure, reasonable solvent solubility, and moderate cost EOR process.

Literature shows the importance of $CH_4$ [6–9] and $C_3H_8$ [10–13] in CSI scheme. However, the details of the optimum mixing ratio of these two hydrocarbon solvents are the main knowledge gap that needs to be addressed. In addition, to the best of our knowledge, no published studies examined the potential of particularly these two hydrocarbons (i.e., $CH_4$ and $C_3H_8$) on the recovery performance of CSI scenarios when incorporated at various ratios in the injected $CO_2$ stream. In this regard, this study probes into applicability of different concentrations of $C_3H_8$, $CH_4$, and $CO_2$ on CSI performance. Seven tests are conducted into a sandpack model saturated with 6430 mPa s viscous oil. First solvents with different fractions of $CH_4$-$C_3H_8$ are tested. Then, $CO_2$ is introduced to the optimum $CH_4$-$C_3H_8$ concentration to investigate the extent to which CSI behavior changes by partially replacement of $CH_4$ with $CO_2$. In last, economic consideration is taken into account and high fraction of relatively more accessible component, i.e., $CH_4$, is mixed together with low fractions of relatively expensive components, i.e., $C_3H_8$ and $CO_2$, and the performance of the new solvent on heavy oil recovery is evaluated for the purpose of feasibility study.

In this paper, performance of solvents are compared through measuring cyclic and cumulative oil recovery, solvent apparent solubility, Solvent Utilization Factor (SUF), Solvent Oil Ratio (SOR), and stability of foamy oil flow in each cycle.

## 2. Experiment

Crude oil sample with the viscosity of 132 000 mPa s was provided by Canadian Natural Resources Limited (CNRL). This oil was diluted with kerosene (with oil: kerosene ratio of 6:1) and 6430 mPa s viscous oil was synthetically prepared to represent a heavy oil sample.

A sandpack model with length of 33.50 cm and inner diameter of 4.10 cm was utilized to conduct the CSI tests. Ottawa sand #530 (Bell and Mackenzie Co. Ltd., Canada) was used to fill the physical model and mimic an unconsolidated reservoir. Table 1 represents the particle size distribution of the sand used.

Solvents with different concentrations of $CH_4$-$C_3H_8$-$CO_2$ were purchased from Praxair, Canada to investigate the optimum mixing ratio of $CH_4$-$C_3H_8$ and find out the change(s) in CSI behavior upon partially replacement of $CH_4$ with $CO_2$. In addition, Nitrogen ($N_2$) was purchased from Praxair, Canada to perform leakage test prior to each experiment and sustain pressure in the Back Pressure Regulator (BPR) line (~82 kPa). Table 2 lists the solvents used in this study.

Fig. 1 shows a schematic diagram of the experimental set-up and procedure. The pre-cleaned sandpack model was initially exposed to sandpacking, vacuuming, and leakage testing before being subjected to brine and oil saturation processes. Once the model was vacuumed, brine (2 wt% NaCl) was imbibed into the sandpack model. The negative pressure of the sandpack, with the aid of gravity, caused the model to take the brine inside. The injected brine was considered as the Pore Volume (PV) of the model. The measured PV was divided by the model bulk volume to calculate the model porosity. After that, brine under different injection rate of 0.5–60 $cm^3$/min was injected to the system and pressure difference across the model was recorded. Darcy's equation was used and the model permeability (absolute permeability to brine) was computed. Then, oil under constant injection rate of 1 $cm^3$/min was injected to push the water out of the system, reach connate water saturation, and establish initial oil saturation. The produced brine volume was considered as the original oil in place (OOIP). OOIP was later on used to measure cyclic and cumulative oil recovery factors.

At this time, model was experiencing a relatively high pressure due to brine and oil saturation processes. A sufficient time (24 h) was given to allow the model establish an equilibrium condition at $T = 20\,^{\circ}C$. The above procedures were repeated in each experiment before performing CSI tests.

Thereafter, huff-n-puff test was started. The solvent was first injected into a High-Pressure-High-Temperature (HPHT) transfer cell and its pressure was increased to a desirable value. Then, water was charged from a Teledyne ISCO Model 500HP Syringe Pump to the HPHT transfer cell in order to push the solvent out of the transfer cell and inject the solvent into the system. The volume of the injected brine was considered as the volume of the injected solvent under the constant injection pressure. This recording was later on used to calculate Solvent Utilization Factor (SUF) data. The injection process was continued for $t = 1$ h. Then, system was closed for $t = 24$ h (soaking stage) to allow solvent-oil interaction. After that, production was initiated from the same injection well. The volume of the produced solvent was measured by a gas wet meter (Ritter Drum-Type Gas Meter, Type: TG05/3-1 bar). This

**Table 1**
Particle size distribution of the sand used.

| Component | Composition (wt %) |
| --- | --- |
| $SiO_2$ | 99.88 |
| $Fe_2O_3$ | 0.015 |
| $Al_2O_3$ | 0.05 |
| CaO | 0.01 |
| MgO | 0.003 |
| $K_2O$ | 0.003 |
| $Na_2O$ | 0.007 |
| Other | 0.032 |