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An Investigation of Hybrid Steam-Solvent Injection for Increasing Economy and Reducing CO_2 Emission

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The hybrid steam-solvent injection scheme has been applied but limited results have been reported in the literature. The optimum solvent concentration to maximize economics and to reduce the CO_2 emission is still in question. A synthetic reservoir model was developed using real field data to study such an injection. Results indicate that the optimal solvent concentration is 5.0% by volume fraction and as the concentration increases the CO_2 emission reduces. The optimum case has 21% gain in the net present value discounted by 12% per annual and 9.1% reduction in the CO_2 emission comparing to the pure steam injection.

Keywords: hybrid steam-solvent injection, solvent concentration, net present value, CO_2 emission, bitumen

1. INTRODUCTION

The Alberta oil sands rank third in proven global crude oil reserves, right after Saudi Arabia and Venezuela. Its total proven reserve was estimated to be 170.2 billion barrels, or about 11% of total global reserves in 2011. About 99% of this comes from oil sand. By 2022, crude bitumen production is expected to be 3.8 million bbl/day (Government of Alberta, 2013). (Government of Alberta, 2013). The bitumen viscosity will reduce to less than 10 cp if the bitumen is heated to more than 200°C. To increase the temperature, heat is used by burning natural gases to produce steam and the greenhouse gas emission will increase (Gates and Chakrabarty, 2008; Deng et al., 2010).

In 2002, Alberta passed the Climate Change and Emissions Management Act (CCEMA) (Government of Alberta, 2012) signaling its commitment to manage greenhouse gas emissions in the province. However, in 2010, 19 in situ oil sands facilities still accounted for 18.7 Mt or 15.3% of total greenhouse gas emission in Alberta (Government of Alberta, 2013). To increase the oil production while minimizing energy usage and environmental impact, hybrid steam-solvent injection has been developed. Such the injection has increased the production of about 57% while more than 70% of the solvent retention was recovered from the reservoir (Gupta and Gittins, 2005, 2006).

In the hybrid steam-solvent process, a small amount of solvent is mixed with the steam and is injected into the reservoir. As a result, the solvent vaporizes together with the steam. In the boundary of the steam chamber, the solvent will be distilled and dissolved into the bitumen. Consequently, the bitumen viscosity will be greatly reduced due to two factors (i.e., dissolved solvent and the heat

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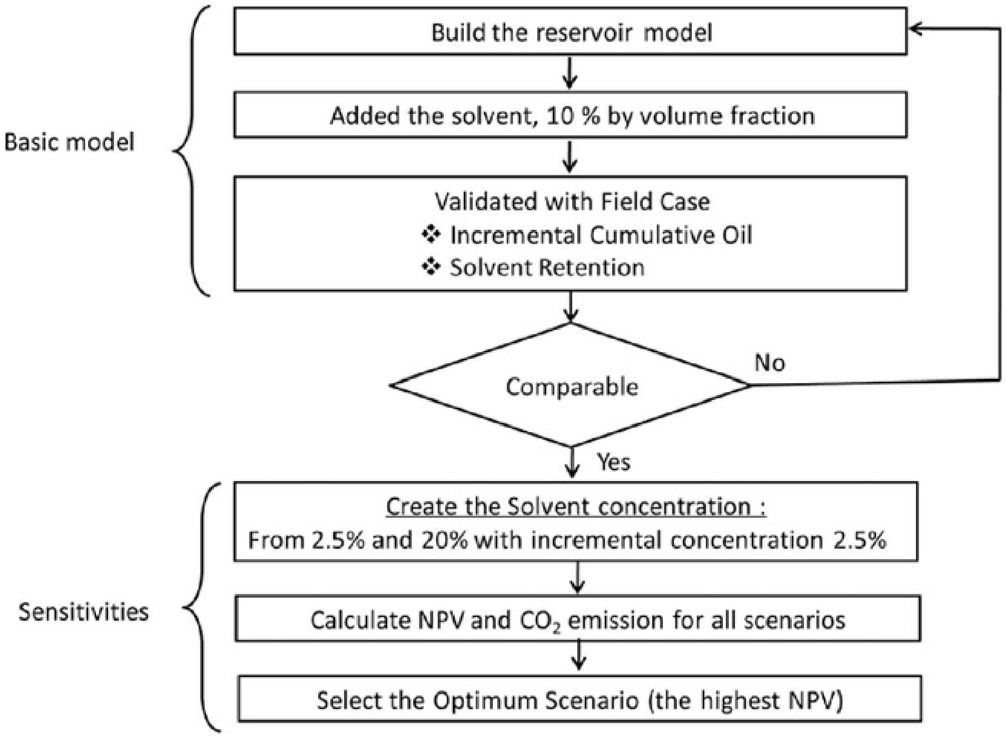


FIGURE 1 Flowchart of the optimization algorithm based on NPV.

from the steam). A good solvent should be condensed at the same condition with water phase. Hexane is a solvent which has the closest vaporization temperature to steam, which is 215°C at pressure of 2200 kPa (Nasr et al., 2003; Nasr and Ayodele, 2006). On the other hand, Shu (1984) investigated that mixing of solvents and bitumen will reduce the viscosity drastically at small concentrations of solvents. In conclusion, if the solvent concentration increases, the bitumen viscosity will decrease exponentially.

There are several considerations in steam-solvent injection process including solvent price, solvent retention, and solvent effectives. Adding solvents into steam will be favorable because the cumulative cost per unit volume will decrease of approximately 13% compared to pure steam process (Frauenfeld et al., 2009). In this research, the hybrid steam-solvent injection was applied to the McMurray formation in Canada. Steam efficiency, solvent effectiveness, economic value, and CO_2 emission at different solvent concentrations were observed.

2. OPTIMIZATION OF SOLVENT CONCENTRATION

Figure 1 displays the optimization process used in this work. At first, a basic reservoir model is built. The results of reservoir simulation are compared to field performances reported by EnCana. To make this model comparison possible, the operating condition is varied. In the second step, nine scenarios are built by varying the solvent concentration. In each of those scenarios the net present value (NPV) is observed. Following standard term of CO_2 emission from gas fuel (U.S. Environmental Protection Agency, 2004), the amount of CO_2 emission generated is observed. The NPV and CO_2 emission

TABLE 1
Key Reservoir Simulation Parameters Used

Reservoir Property		*Value*
Initial reservoir temperature, °C		12
Initial reservoir pressure at injection well depth, kPa		2,105
Depth of injection well, m		215
Bitumen viscosity at 100°C, cp		260
Bitumen viscosity at steam injection temperature (220°C), cp		5.7
Bitumen viscosity correlation		$A_{visci} = 2.3693E\text{-}5$
$[\mu_i = A_{visci} \cdot \exp(B_{visci}/T_{abs})]$ (CMG, 2012)		$B_{visci} = 6046.7035$
k_v/k_h		0.7
Residual oil saturation (s_{orw})		0.15
Connate water saturation (s_{wc})		0.15
Residual oil for gas-liquid (s_{org})		0.01
Connate gas saturation (s_{gc})		0.05
k_{rw} at reducible oil saturation		0.3
k_{ro} at connate water saturation		1
k_{ro} at connate gas saturation		1
k_{rg} at residual oil saturation		1
Underburden/overburden heat capacity, kJ/m^3 °C		2,600
Underburden/overburden thermal conductivity, kJ/m-day °C		660
Bitumen thermal conductivity, kJ/m day °C		11.5
Hexane K-value correlation,	$K\_value = \frac{Kv_1}{p} e^{\frac{K_{v4}}{T+K_{v5}}}$	$K_{v1} = 1.01E+6$ kPa $K_{v4} = -2{,}697.55$°C $K_{v5} = -224.37$°C

Source: Gates and Chakrabarty (2008), Computer Modeling Groups (2012).

equations are the following:

$$NPV = \sum_{t=0}^{N} \frac{NCF_t}{(1+i)^t} \tag{1}$$

$$CO_2 \text{ emission (kg)} = 50 \times \text{heat employed (GJ)} \tag{2}$$

3. RESERVOIR MODEL

The thermal reservoir simulator, STARS Version 2012 is used to construct the reservoir model. The reservoir model is described in Table 1. The model did not have gas cap and bottom water drive. The geomechanics were ignored. Figure 2 illustrates the permeability, porosity, and oil saturation distribution in a 3-D form. The left part of the reservoir (Cross Section A) is very permeable while the right part (Cross Section C) is gradually tighter. The distributions of porosity and oil saturation in the reservoir follow the similar pattern. The production well is 2 m above the bottom of the reservoir and the injection well is 5 m above the production well. The thickness of the reservoir is 30 m, the width is 110 m, and the length is 750 m. The total grid number is 30 × 44 × 15 (i, j, k) and the grid size is 25 m in i-direction, 2.5 m in j-direction, and 2 m in k-direction.

The preheating period lasts about six months and the temperature in both of the wells is set to be 220°C. During this process, the heat will be transferred via conduction mechanism to the

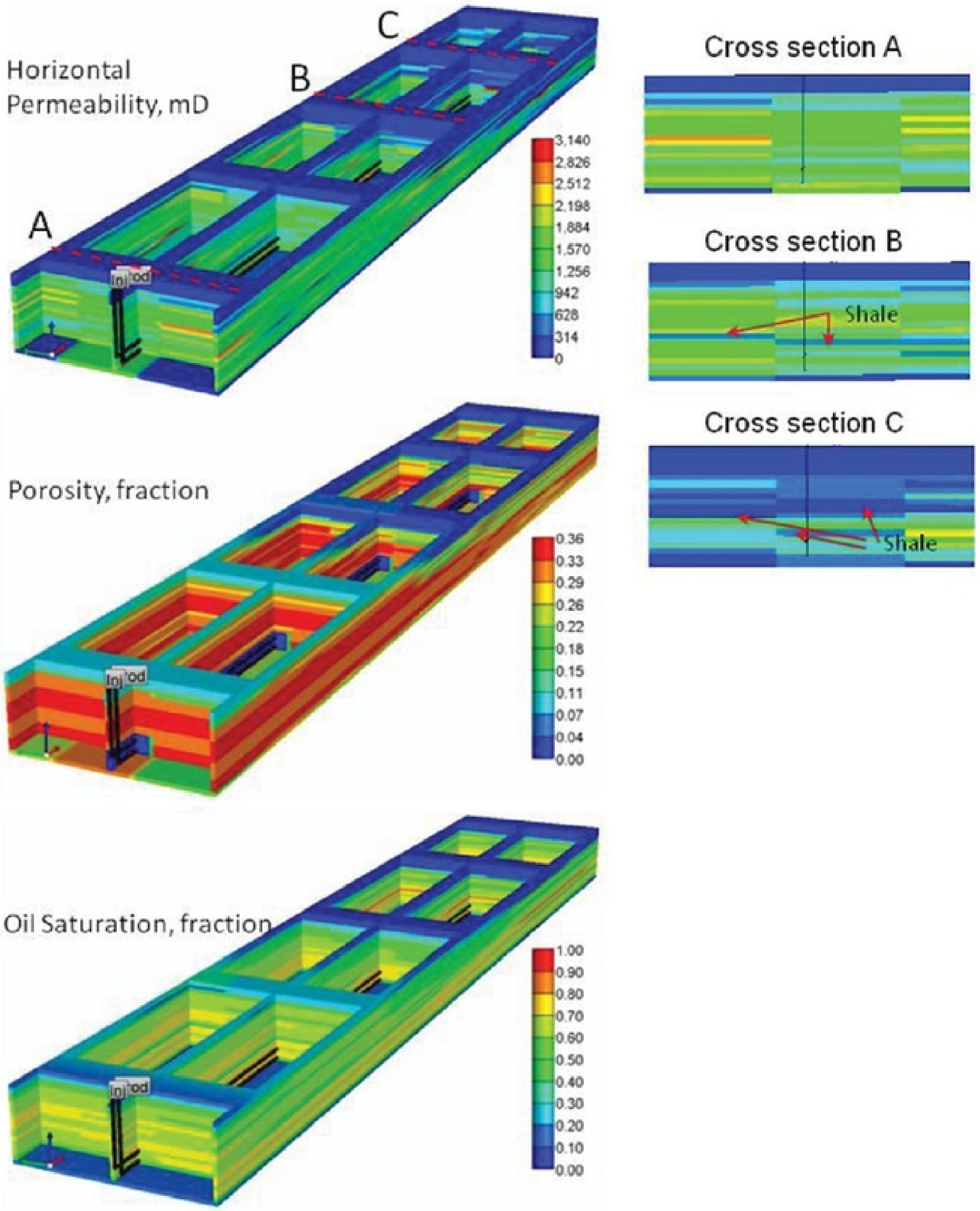
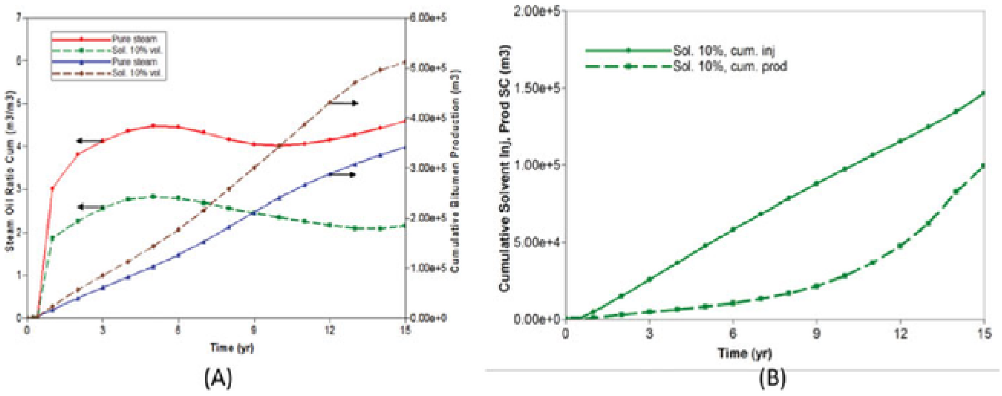


FIGURE 2 3D view of reservoir model permeability, porosity, and oil saturation.

surrounding wells and both the production and injection wells will be connected hydrodynamically. After preheating, the wells are switched to become injection and production wells. The steam injection is operated at constant pressure at the sand face with a steam quality of 0.9. To prevent steam losses from the chamber, a maximum steam production rate is set to 5 m^3/day. In all cases, the reservoir simulation project life is set to 15 years. A sensitivity analysis for solvent concentration using hexane is conducted.



(A) (B)

FIGURE 3 (A) cSOR and cumulative bitumen production for the pure steam and 10% solvent concentration system; (B) cumulative solvent injection and production for 10% solvent concentration injection scheme.

4. RESULT AND DISCUSSION

4.1 Reservoir Simulation

Figure 3A displays the cumulative steam oil ratio (cSOR) and cumulative bitumen production versus time of pure steam and 10% solvent concentration scenarios, respectively. The cumulative bitumen production of the solvent injection case is 50% bigger than that of the pure steam injection case. The percentage of solvent retention is approximately 30% at the end of the project (Figure 3B). This phenomenon is comparable to a documented field case performance in EnCana (Gupta and Gittins, 2005, 2006). To achieve this performance, the operating conditions of injection pressure and liquid production rate are 2300 kPa and 400 m^3/day, respectively.

In the pure steam process, during the first year to the fifth year, the cSOR increases because the steam chamber is still growing up and the effectiveness of the steam has not been maximized yet due to shale barriers in the reservoir (Figure 4). After the steam chamber reaches the top, the bitumen production will be at peak and consequently, cSOR will be decreased. After that, when the steam chamber has been matured, the cSOR will slowly increase due to the decrease of ultimate recovery. Zone A has relatively little shale breaks compared to Zone B and Zone C. Therefore, the performance of steam chamber in Zone A is better than those of Zone B and Zone C. Besides that, the heat will be dispersed if solvent is added. At the end of project life, the steam chamber will be wider in the steam-solvent process compared with that of the process utilizing only pure steam. This indicates that the effectiveness of steam-solvent is better even though the energy used is slightly lower.

The amount of solvent that can penetrate to bitumen depends on the steam chamber volume. The smaller the steam chamber, the less solvent will penetrate into the bitumen. Addition of solvent concentration at this stage is not effective because the solvent has limited movement to the upside of the reservoir and it will condense together with steam. As a result, it goes down to the production well. If the addition of solvent is too much, its effectiveness will greatly reduce because the mixture of solvent, and bitumen viscosity follows an exponential trend (Shu, 1984).

There are two terms in hybrid steam-solvent injection process. The first is energy efficiency, which is defined as the sum of enthalpy from steam injection utilized for getting the bitumen production per unit volume (cumulative energy oil ratio [cEOR]). The second is solvent efficiency, the amount of solvent that is needed to be injected to obtain the bitumen production per unit volume (cumulative solvent oil ratio [csOR]). As can be seen in Figure 5, to obtain 1 m^3

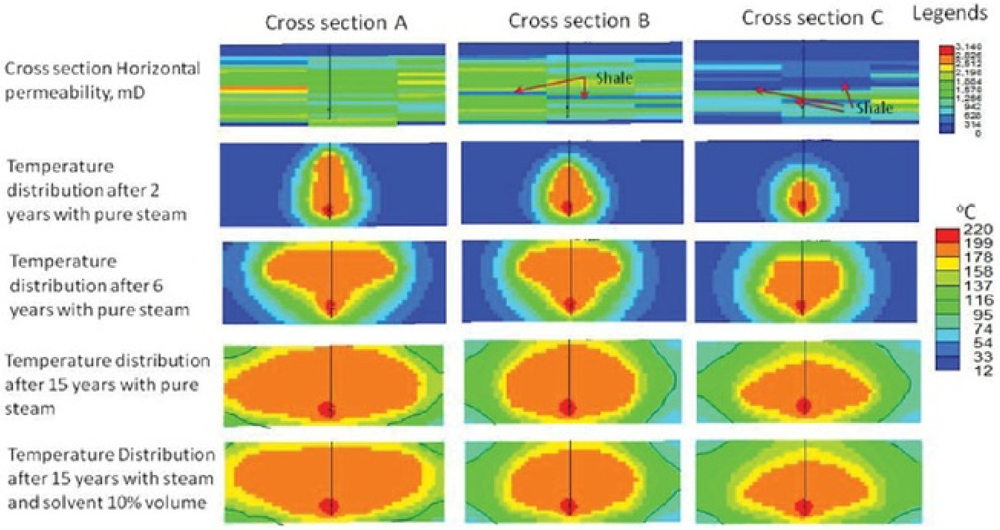


FIGURE 4 Cross section of horizontal permeability and temperature distribution in Zones A, B, and C.

of bitumen in pure steam process, it will need 11.7 GJ of energy. While in the hybrid steam-solvent injection, at solvent concentration of 2.5%, the energy required will be reduced to approximately 9 GJ/m^3. If the solvent concentration increases, the cEOR will decrease while the csOR will increase.

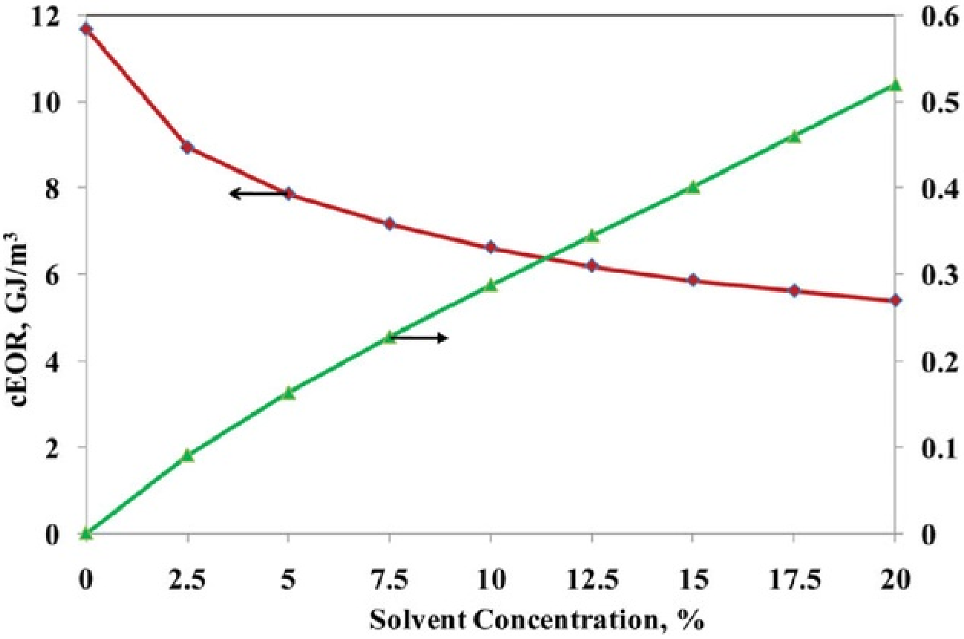


FIGURE 5 The relationship between energy efficiency and solvent efficiency.

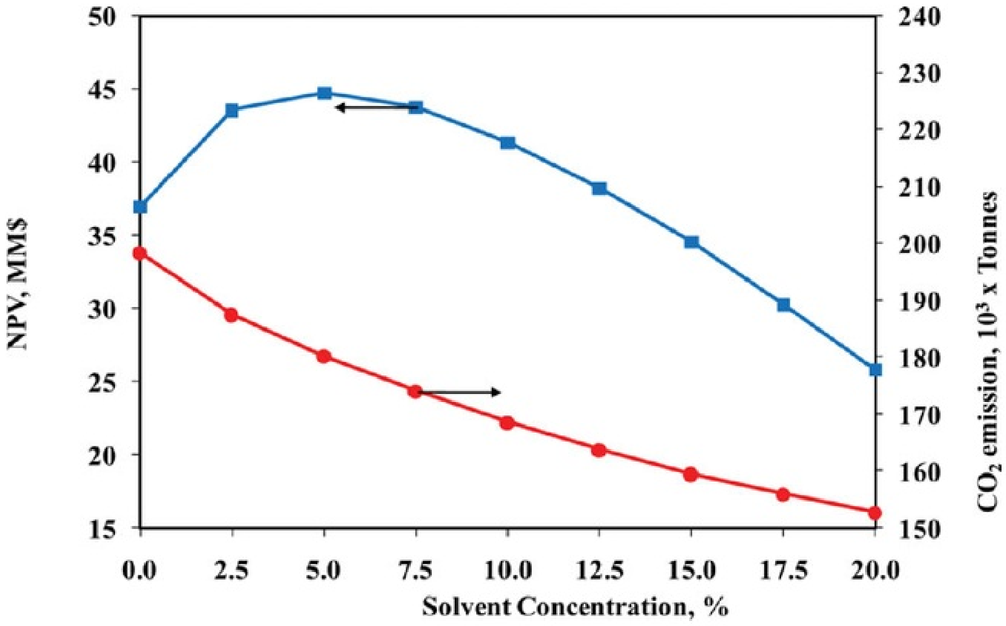


FIGURE 6 The relationship between NPV and CO_2 emission.

4.2 Economic Analysis and CO_2 Emission

The economic analysis used a common set of general assumptions in SAGD projects. Two wells cost and exploration costs are assumed to be \$1.35E6 and \$0.2E6, respectively. Steam generation capital cost is \$2.05E6 for a 430 m^3/day-capacity generator. Water treatment capital cost is \$2.45E6 for a 400 m^3/day-capacity plant. Solvent capital cost is \$100k. Solvent handling cost is \$20k/year/well, and solvent recompression cost is \$0.17/std m^3 (Frauenfeld et al., 2006). The natural gas cost is assumed to be \$4.33/GJ. The other assumptions include water treatment cost is \$1/barrel of water production, the fixed cost is assumed to be 0.9 MM \$/year, the interest rate is 12% per annual, bitumen price is \$70/barrel, and the hexane price is 1.5 times of bitumen price. The net cash flow calculation (NCF) is:

$$
\begin{aligned}
\text{NCF} = {} & [\text{Net revenue}] - [\text{Well cost} + \text{exploration cost}] - [\text{steam generation cost}] \\
& - [\text{water treatment capital cost}] - [\text{solvent capital cost}] \\
& - [\text{solvent handling cost}] - [\text{solvent recompression cost}] \\
& - [\text{natural gas cost} + \text{water production treatment cost} + \text{solvent usage cost}] - [\text{fixed cost}]
\end{aligned}
$$

Figure 6 shows that NPV of the pure steam process is lower than that of hybrid steam-solvent injection process at concentration range from 2.5% to 12.5% volume. The NPV in which the solvent concentration is 5.0% by volume fraction is the highest and the cEOR and csOR are 7.86 GJ/m^3 and 0.16 m^3/m^3, respectively.

Figure 6 shows that the CO_2 emission can be reduced by adding solvent to the steam. At solvent concentrations of 5.0% to 7.5% CO_2 emission will be decreased to approximately 3.4% but NPV will only be decreased approximately 1 MM\$. At the solvent concentration of 2.5%, there is a dramatic NPV difference compared with pure steam. Additionally, it will also greatly affect on the CO_2

emission. Nevertheless, starting from solvent concentration of 2.5%, the NPV will be influenced. Larger concentration of solvent will generate larger impact on reducing CO_2 emission.

Furthermore, even though the CO_2 emission will start to be influenced even from small solvent concentration (2.5%), it will be slightly affected by continuing added solvent concentration. Economically speaking, the solvent concentration more than 5.0% will reduce the NPV. However, it will be more environmentally favorable. If the NPV is a major priority, the solvent concentration of 5.0% becomes the best case that it can reduce CO_2 emission and increase the NPV approximately 18.05×10^3 tonnes and 7.76 MM$, respectively. On the other hand, if the CO_2 emission is a major priority (for example: it must be reduced to 15% CO_2), the solvent concentration should be 10.0% by volume fraction. At that concentration, NPV will be 41.36 MM$, approximately 7.5% decrease compared to the maximum NPV but it will still be higher than that in the pure steam process (i.e., approximately 12%). Finally, if the solvent concentration is higher than 5.0%, the economic criteria and CO_2 emission will be contradictive.

5. CONCLUSIONS

This study demonstrated that the hybrid solvent injection method will have advantages compared to pure steam injection method. High solvent concentration will result in low CO_2 emission and high recovery factor, but optimum condition will be achieved at solvent concentration of 5.0% by volume fraction. If the solvent concentration is larger than 5.0%, the economical and CO_2 emission will be contradictive. In this investigation, the cEOR and csOR of 7.86 GJ/m^3 and 0.16 m^3/m^3, respectively, had the most profitable NPV. The solvent concentration of 5.0% increased the NPV by 21% (7.76 MM$) and decreased the CO_2 emission by 9.1% (18.05×10^3 tonnes), respectively, when compared to those of the scenario of utilizing pure steam.

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NOMENCLATURE

NPV = net present value
NCF = net cash flow
i = discount rate
n = project's economic life in years
SAGD = steam assisted gravity drainage
cSOR = cumulative steam oil ratio
cEOR = cumulative energy oil ratio
csOR = cumulative solvent oil ratio
GJ = gigajoule
$ = U.S. Dollars

SI Metric Conversion Factors

bbl × 1.5899 = m^3
cp × 1.0 = Pa.sec
1 tonne = 1000 kg

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