Managing of Hybrid Steam-Solvent Injection Distribution for Maximizing Recovery Factor in Heterogeneous Reservoir

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Abstract

Steam Assisted Gravity Drainage process has been done and successfully implemented for the producing of the Canadian heavy oils and bitumen. Although it is commercially proven, but it still uses high energy intensity and has high environmental impact. To reduce those side effects, hybrid steam-solvent is proposed as one of the alternative processes in order to reduce the problems.

There are some challenges in reservoir heterogeneity correlated with steam-solvent injection. In conventional process, spreading of steam-solvent is able to be controlled using bottom-hole pressure injection and liquid production rate. In heterogeneous reservoirs however, each part of the horizontal well will have different optimum operation conditions.

This paper presents a strategy for hybrid steam-solvent optimization using ICVs (interval control valves) to maximize energy efficiency. To provide an overview of this phenomenon, the synthetic reservoir model is built from McMurray Formation. Bitumen saturation distribution and rock properties are created using geostatistic method and validated using several wells. The reservoir models were run using several operating conditions to achieve the most realistic interpretation. Sensitive variables are steam injection pressure, length grouping of perforations, managing of perforation openings, and solvent concentration. Afterwards, steam efficiency and solvent affectivities are evaluated during 15 years of project life.

Simulation results show that the managing of steam injection will increase heat efficiency up to 7.4% compared with conventional perforations. Furthermore, in the hybrid steam-solvent injection, the recovery factor will be better 8% compared to without adjustment in solvent concentration of 10% volume. Finally, retention of solvent injection can also reduce until 30% by this managing of processes.

Introduction

The Alberta oil sands is third rank after Saudi Arabia and Venezuela, in terms of proven global crude oil reserves. In 2011, Alberta's total proven oil reserves were 170.2 billion barrels, or about 11 percent of total global oil reserves (1,523 billion barrels). Almost all of Alberta's proven oil reserves are found in Alberta's oil sands. Alberta's total oil reserves are 168.7 billion barrels, or about 99 percent comes from the oil sands. As of January 2013, there were 127 operating oil sands projects in Alberta, where only five of these projects are mining projects. By 2021, crude bitumen production is expected to be more than double to 3.7 million bbl/day (Alberta's Government report, 2012).

Typically, the bitumen characteristic is high viscosity at the reservoir conditions. The bitumen viscosity will become less than 10 cp, if the bitumen is heated more than 200 ^{o}C. A large amount of energy is needed to increase temperature from reservoir condition (around of 15 ^{o}C) to around 200 ^{o}C. To increase temperature, usually the heat needed comes from burning natural gas to make steam. Effect of this process, the greenhouse gas emissions will increase (Gates and Chakrabarty, 2008, Deng et al. 2010).

In 2002, Alberta passed the Climate Change and Emissions Management Act (CCEMA) signaling its commitment to manage greenhouse gas emissions in the province. In 2010, seven oil sands mining and upgrading facilities accounted for 28.7 Mt (22.9 percent of total GHG emissions in Alberta). In 2010, Nineteen oil sands in-situ facilities accounted for 18.7 Mt (15.3 percent of total GHG emissions in Alberta) (Alberta's Government report, 2012).

To minimize energy intensity and environmental impact, the hybrid steam-solvent injection has been developed in field (Gupta and Gittings; 2006,Jasper et al.,2011). Combining of steam-solvent will reduce bitumen viscosity significantly. The small amount of solvent is mixed with steam and injected to the reservoir, and as a result, the solvent vapor goes to up side with steam. In the boundary of chamber, solvent will be distillated and dissolved in the bitumen. Consequently, the bitumen viscosity will reduce, which is caused by two cases, i.e. dissolved solvent and heat from steam. Figure 1 shows this phenomenon, where there are some solvent dissolved to the bitumen. When the solvent is added to the steam, the good solvent should be condensed at the same condition with water phase. Figure 2 shows the comparison temperature of solvent vaporization and steam in different conditions. Hexane is the solvent which has the closest temperature vaporization with steam in temperature of 215 °C and pressure of 2200 kPa (Nars et. al, 2003).

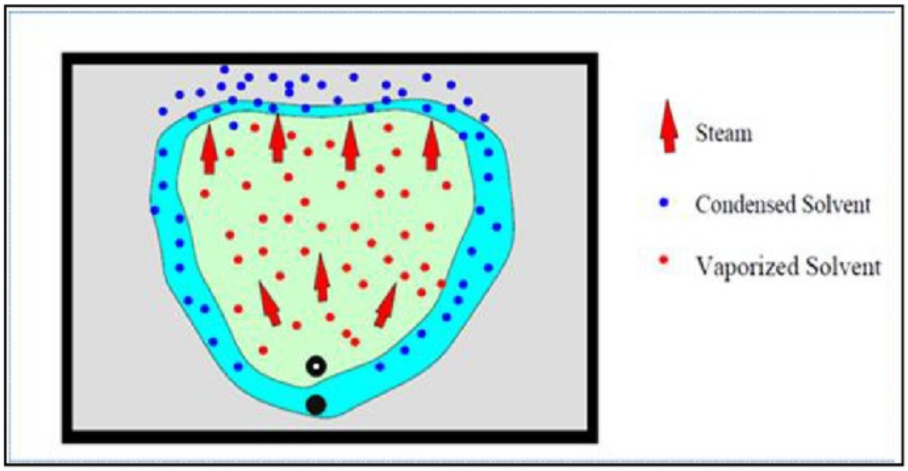

Figure 1. The concept of ES-SAGD (Nars, 2003)

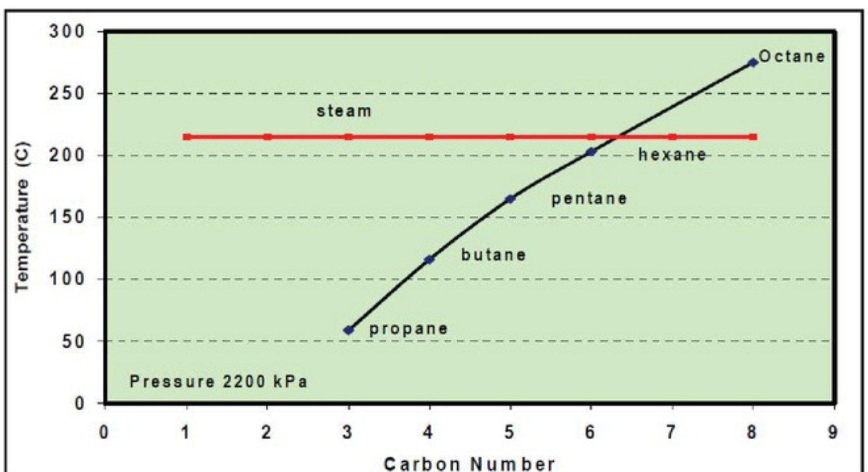

Figure 2.Comparison of solvent vaporization temperature with steam temperature (Nasr et al. 2003).

There are several experimental studies about hybrid steam-solvent injection, particularly in 2D experiment model. Small amount of solvent injected at different solvent composition (C1 until C8) will accelerate the production rate. The highest production rate can be obtained by injecting hexane and diluents (Nars and Ayodele, 2006). On the other hand, reservoir properties and operating condition will have an effect on recovery (Ardali et.al. 2012). The low pressure and the suitable concentration (mostly at low concentration) will have an advantage compared with high pressure (Hosseininejad et al, 2009; Ayodele et. al, 2009). Especially for hexane, it will still have a benefit at pressure ranged from 1500 kPa until 3500 kPa (Hosseininejad et al, 2012).

In the 3D numerical simulation process, the hybrid steam-solvent injection is more complicated compared with the conventional recovery method (pure steam injection). There are several simulation studies that have been done to investigate different aspect for hybrid steam-solvent in field scale. Generally, solvent type and concentration, steam-solvent injection strategy, and operating condition are significant parameters in the oil recovery.
In reservoir simulation, there are very sensitive variables correlated with steam-solvent injection process. The solvent solubility in oil phase is representative in K-value of each component in reservoir simulation model. The density and viscosity are calculated using combined term, so the viscosity of liquid, mixed solvent, and bitumen are also mostly determined using correlations.
Shu W.R. in 1984 investigated that mixing of solvent and bitumen will reduce viscosity drastically when using small concentrations of solvent. However, if the concentration of solvent increases, the effectiveness of the solvent to reduce bitumen viscosity will also decrease.
In the operating condition, the early stage injection steam-solvent will be beneficial compared with in the late stage. Stopping of steam-hexane co injection in the certain point will be favorable to reduce solvent usage and the process will not change the oil production rate significantly. Finally, adjusting of operating parameters such as the start time of injection, the duration of injection period and solvent concentration will improve solvent efficiency (Jiang, 2012),
The hybrid solvent injection is proven useful in reducing energy intensity and environmental impact. The bitumen will be more mobile by both of the steam-solvent injection process. The four majors of strongly effect of a suitable hybrid steam-solvent process are operating condition, reservoir fluid composition, the heavy oil viscosity, and the petrophysical properties of the reservoir (Hosseininejad et al, 2009, Ardali et al, 2012).
Optimizing in the heterogeneous reservoir will have a difficulty correlated with divert permeability. Part of reservoir in the length of well will have optimization individually. Here, it needs a distribution of steam in different pressures. The high permeability regions will need a low injection pressure but the low permeability zones will need a higher injection pressure. Even though experiments and simulation studies have been done for several cases, but it still remains unclear in the managing of steam-solvent distribution in heterogeneous reservoirs in order to reach optimum operating conditions.
This research will focus in the managing of steam-solvent distribution in different petrophysical properties. This case is typically in heterogeneous reservoir. In the homogeneous reservoir, the optimum condition can be achieved by controlling steam-solvent injection pressure, solvent concentration, liquid rate production, and timing of stop injection solvent. For the heterogeneous reservoir case, in the length of well with the same rock properties, it will have individual optimum conditions. Based on this phenomenon, managing of steam-solvent distribution in the wellbore is very important. The base case model in this research is the SAGD process using average operating condition. It means that the length of horizontal well pair is operated with the same operating condition. Afterwards, the SAGD process is optimized using ICVs to improve heat efficiency. As the main research, how to manage the hybrid steam-solvent injection distribution using ICVs will be demonstrated in this research.

Reservoir Model

The thermal reservoir simulator, STARS Version 2011, by Computer modeling Group, was applied to construct reservoir model and investigation performance of hybrid steam-injection. The reservoir model which representing a generic in McMurray Formation is selected for this research as described in Table 1. The model is built with three-dimensional numerical simulations and one well pair in the center of the model.
In previous work, building this model uses geostatistic method to get porosity, permeability, and oil saturation distribution and validated with several wells data. The model wasa no gas cap, no bottom water drive and the geomechanics process was ignored in this model. Due to limited data, the heterogeneous model only included porosity, permeability, and oil saturation, whereas the other parameters were assumed homogeneous in reservoir such as heat loss, heat capacity, and fluid properties. The ratio of horizontal and vertical permeability is 0.7.
Figure 3 shows the porosity, permeability, oil saturation distribution, and oil per unit area total in 3 dimension displays. The porosity distribution is very contras in every each reservoir section. In the left part of reservoir is really good but the right part become gradually tight. It is similar with the distribution of permeability and oil saturation in the reservoir. Consequently,the oil per unit area total which is distributed from the left to the right becomes wane .The production well is above 2 meters from bottom reservoir and the injection well above 5 meters from production well. The thickness of reservoir is 30 meters, width is 110 meters, and length is 750 meters. The grid numbers are 30 x 44 x 15 (i,j,k) and the grid size is 25 m in i, 2.5m in j, and 2m in k direction. To generate details in the wellbore, the refined grid blocks was implemented in the near wellbore with 12.5 m x 1.25 m x 1 m. The initial pressure is 2260 kPa and determined from normal gradient hydrostatic pressure in the depth 215m (in the injection well position).
The model was run until one year without well activity in order to know the stability of the model and the balance of equilibrium. If the model does not change in oil saturation or fluid characteristics after a one year run, the model will continue to be used for the next steps in simulation, the preheating process. Preheating is the making of connections between horizontal injection well and the production well using line heater. Preheating period is about 4 months and the temperature in both of the wells is set at 230 °C. During the preheating process, the heat will be transferred by conduction to the

surrounding wells, and then, both wells will be connected hydrodinamically. After preheating, the wells are switched to become injection and production wells.

Table1. Key reservoir simulation used in this study

Reservoir Properties	Value
Initial reservoir temperature, °C	12
Initial reservoir pressure at injection well depth, kPa	2260
Depth of injection well	215
Bitumen viscosity at 100 °C,cp	260
Bitumen viscosity at steam injection temperature, cp	5.7
Bitumen viscosity correlation (CMG manual,2011)	A = 2.3693E-5 B = 6046.7035
k_v/k_h	0.7
S_{orw}	0.15
S_{wc}	0.15
S_{org}	0.001
Sgc	0.3
Krwro	0.5
Krocw	0.3
Krogc	1
Krg(sorg)	1
Three phase relative permeability model	Stone's model 2
Reservoir, underburden/overburden heat capacity, kJ/m^3°C	2,600
Reservoir, underburden/overburden thermal conductivity, kJ/m day °C	660
Bitumen thermal conductivity, kJ/m day °C	11.5
Hexane K-value correlation, k-value = $\frac{kv_1}{p} e^{\frac{k_{v4}}{T+k_{v5}}}$ (CMG Manual, 2011 and Gates, 2008)	Kv1 = 1.01E+6 kPa Kv4 = -2,697.55 °C Kv5 = -224.37 °C

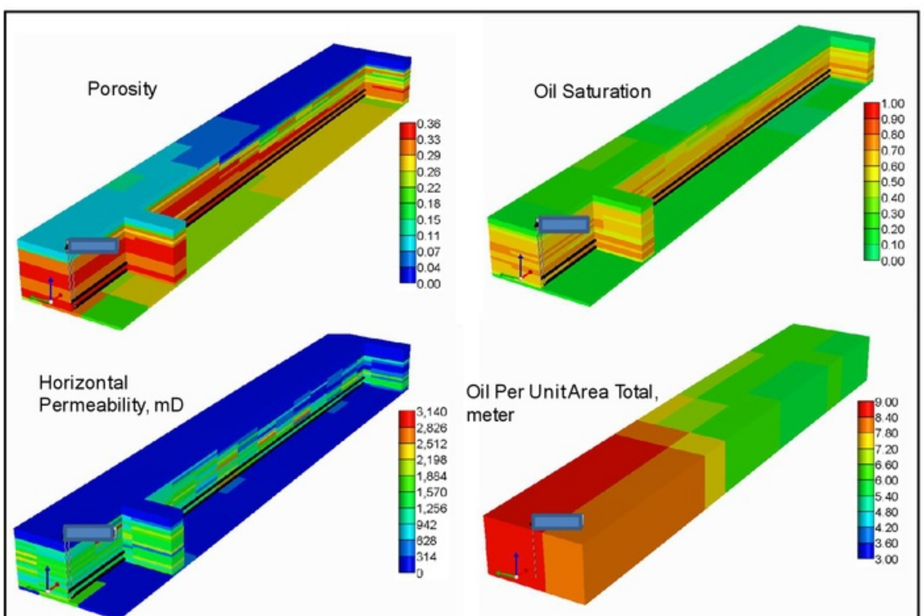

Figure 3. View of reservoir simulation model porosity, permeability, oil saturation, and initial oil per unit area-total.

In this research, the steam injection uses constant pressure in sand face with a steam quality of 0.9. To get optimum conditions, sensitivity of the steam injection pressure and liquid production rate has been made. In the production well, the maximum steam rate is set to 5 m^3/day to prevent steam losses from the steam chamber. The reservoir simulations were run for 15 years of project life.

In the investigation of hybrid steam-solvent injection, hexane is used. The hexane characteristic is close with water and it will condense in 200 ^{o}C with pressure 2200 kPa (Nars et. al, 2003). The managing of hybrid steam-solvent distribution in the length of horizontal well uses a close and open perforation and also changes the operating conditions. To interpret ICVs work in the model, the closed perforation of the model indicates a close on valve (the ICVs), while the open perforations indicates an open ICV valves.

Result and Discussion

Pure Steam Injection

The optimization of SAGD process used the same operating condition in the length of horizontal well. The sensitivities of injection pressure is between 2200 – 2700 kPa with different pressure of 100 kpa and the sensitivities of production rate is between 250- 600 m^3/day with different rate 50 m^3/day. The aim of this way is to make optimum operating condition using steam trap control (Gates and Leskiw, 2008). In this case, the optimum operation should be high recovery factor, low cSOR and low injection pressure. Result of this work exhibits that injection pressure is 2500 kPa, liquid production rate is 400m^3/day, the cSOR is between 2.9 until 4.2. Furthermore, this model is called base case model.

The next step is to manage steam distribution in the length of horizontal well injection. Because of heterogeneous reservoir, the part of reservoir in the length of horizontal well will have optimum condition individually. So the length of injection and production well will be divided into 4 parts due to divert permeability. It will be applied in different operation conditions. Figure 4 shows the temperature distribution from the top view and oil per unit area-total in the end of production period in the base case model. In the Figure 4, the temperature distribution is not uniform in the length of reservoir due to heterogeneous reservoir, then the oil per unit area-total indicates that the bigger prospect is in red color.

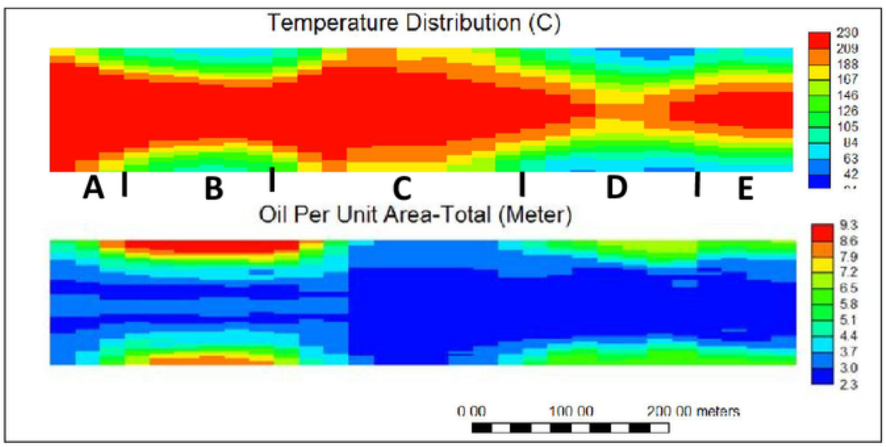

Figure 4. Temperature Distribution and Oil Per Unit Area-Total in the end project

In the high permeability, the steam will be easier to penetrate compared with in low permeability. So to manage steam distribution, the high permeability zone will be closed periodically, otherwise the low permeability zone will be opened continuously. In the end of the project life (Base case model), it is reflected that the length of perforation is divided into 2 zone classification, those are high penetration steam (zone A and C) and low penetration steam (zone B, D, and E). To disperse steam evenly in the reservoir, the open and close perforation uses ICVs. Furthermore, the operating condition and managing of this process is shown in Table 2.

The adjustment process does not continue but it repeats with base case operation within three months cycle started from the beginning and the other case is from peak production. The first adjustment is operated the same as the base case but the zone A and C perforation injections are closed. The second adjustment is to change the operating condition but the open-close in injection-production perforation is the same with a first adjustment. Result of this process can be seen in Figure 5.

Here, the factors for evaluating the successful operation are the temperature and oil saturation distribution. Figure 5 shows that the temperature distribution after adjustment is almost uniform compared with before adjustment. Infact, the oil saturation will reduce and recovery factor will increase in the end of project life (Figure 6b).

As can been seen that if the adjustment is from the beginning, the production rate goes down and CSOR will increase. This indicates that the adjustment of steam distribution will be effective after the peak production because the steam chamber will grow up in the high permeability regions. In this process, the higher permeability regions are prioritized to drain first. After the steam penetrates the high permeability regions, then the ICVs will be switched to penetrate the low permeability regions, therefore making a uniform steam chamber.

On the other hand, the efficiency of the low permeability region is lower than the high permeability region. Therefore, if the operation is switched to penetrate in the low permeability, the CSOR will increase. However, it must be done because the steam should be distributed in this zone to drain the bitumen. Generally, the low permeability reservoir will have lower oil saturations, so it is still reasonable that in this zone, the steam efficiency will be lower than the other part due to wane reservoir quality.

Table 2.
The scenario model for adjustment of steam injection

Region	Base case operation		Adjusment 1		Adjusment 2	
	Injection well	Production well	Injection well	Production well	Injection well	Production well
A	open	open	Close	open	close	open
B	open	open	Open	close	open	close
C	open	open	Close	open	close	open
D	open	open	Open	open	open	open
E	open	open	Open	open	open	open
Operating condition	Pressure : 2500 kPa	Liquid rate : 400 m^3/day	Pressure : 2500 kPa	Liquid rate : 400 m^3/day	Pressure : 2700 kPa	Liquid rate : 450 m^3/day

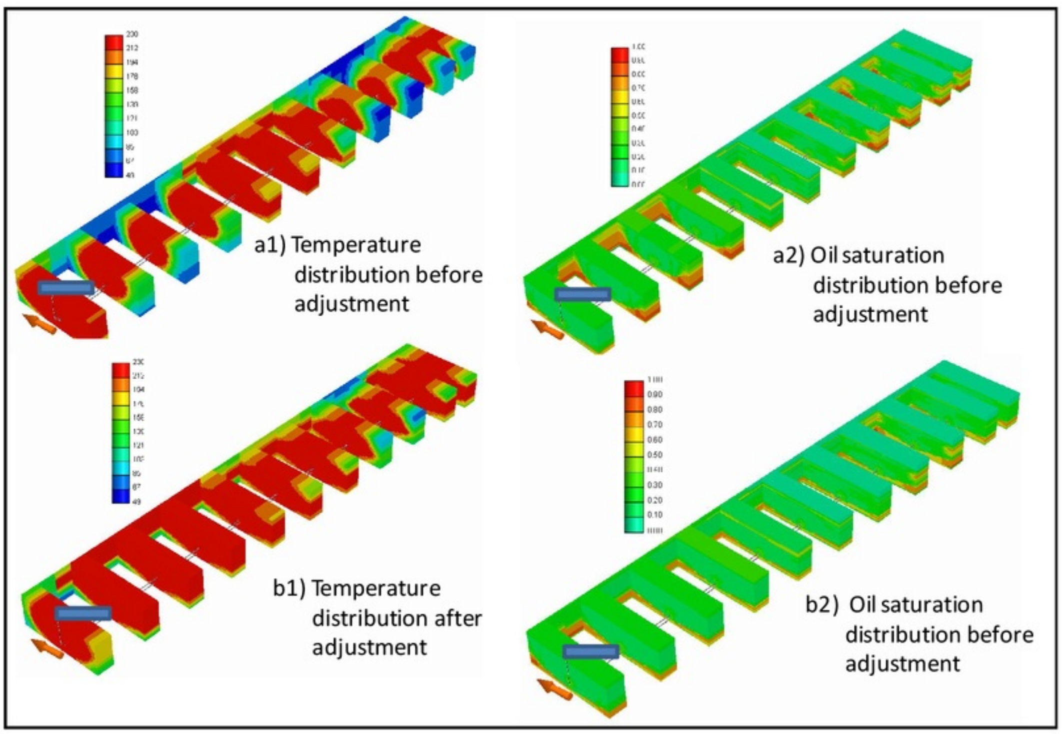

Figure 5. Comparison of temperature and oil saturation before (a) and after (b) adjustment

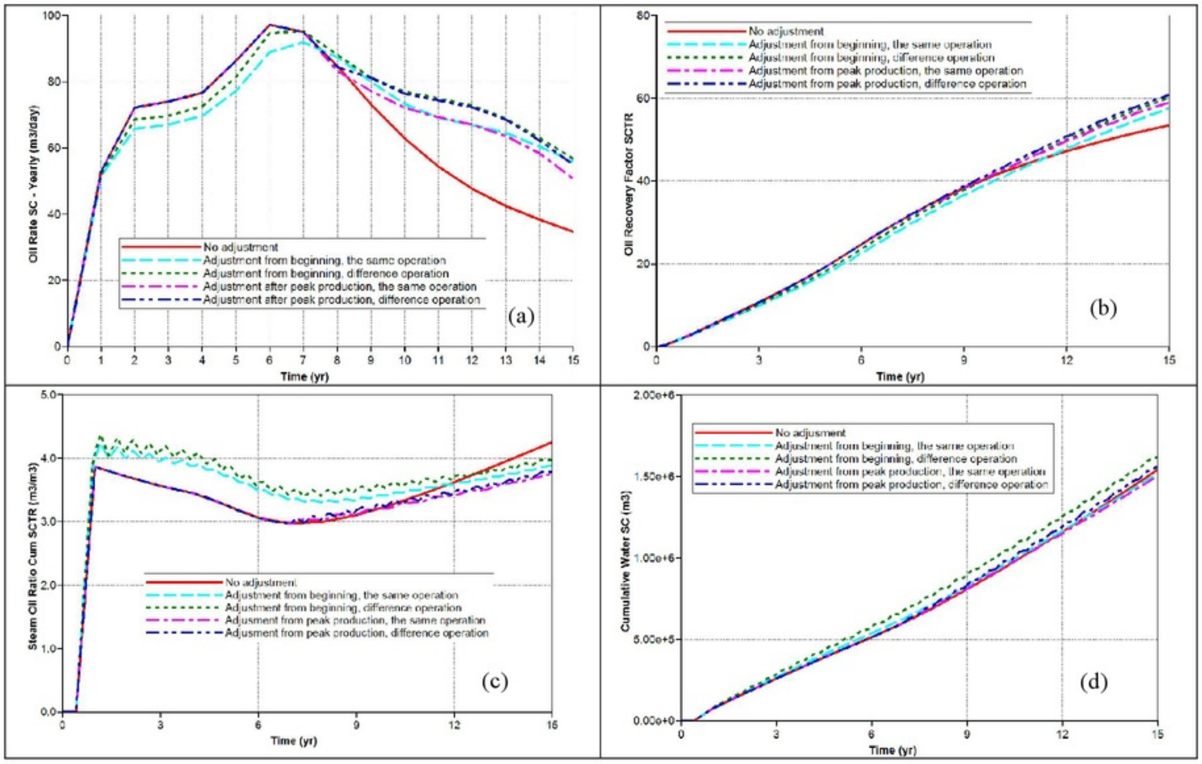

Figure 6. [(a) Oil rate, (b) Recovery factor, (c) cSOR, (d) Cumulative Water Injection) vs Time

Managing of hybrid Steam-solvent Injection

The managing of hybrid steam-solvent injection distribution is to improve effectiveness of solvent in heterogeneous reservoir. Figure 7a shows that RF will increase 8% after steam-solvent injected with 10% of volume using adjustment compared with no adjustment even though the steam and solvent quantities are the same in volume. The sensitivity of solvent concentration between 10% and 15% of volume are not significantly different from the beginning until peak production, but slightly different with concentration solvent of 5% volume. In this case, the amount of solvent can penetrate to bitumen depends on steam chamber volume. Smaller steam chamber will cause less solvent distributed into the bitumen. The addition of solvent concentration at this stage will be not totally effective because the solvent will limit movement to the upside reservoir and it will condense together with steam, then it goes down to production well. Besides, if the addition of solvent is too large, its effectiveness will reduce because the mixture of solvent and bitumen viscosity will meet the exponential line (Shu W.R, 1984).

On the other hand, added solvent on the steam will reduce energy injection due to steam volume reducing in the same operation pressure injection. Figure 7b shows that the solvent concentration of 10% volume will save energy 14% compared with pure steam. Then, the solvent concentration of 5% volume will save energy 7% compared with pure steam and also the concentration solvent of 15 % volume will save energy 19 %. The addition of solvent concentration will reduce energy intensity because the solvent will take a part of volume in the steam.

Furthermore, managing of hybrid steam-solvent distribution will affect in reducing solvent retention. Figure 7c shows that the solvent retention in the hybrid steam-solvent injection without adjustment is 30% higher than with adjustment in the solvent concentration of 10% volume. Nevertheless, the steam concentration of 15% volume has also smaller solvent retention compared with steam consentration of 10% volume with without adjustment at the end of project life.

On the other part, increasing of solvent concentration will reduce percentage of solvent retention. Figure 7d presents the solvent concentration of 5% volume will have higher percentage of sovent retention compared with the solvent concentration of 10% and 15% volume, but both solvent concentratios of 10% and 15% have almost silimar percentage of solvent retention. Here, it can be estimated that too small amount of solvent concentration (round of 5% volume) is less satisfactory to improve oil recovery.

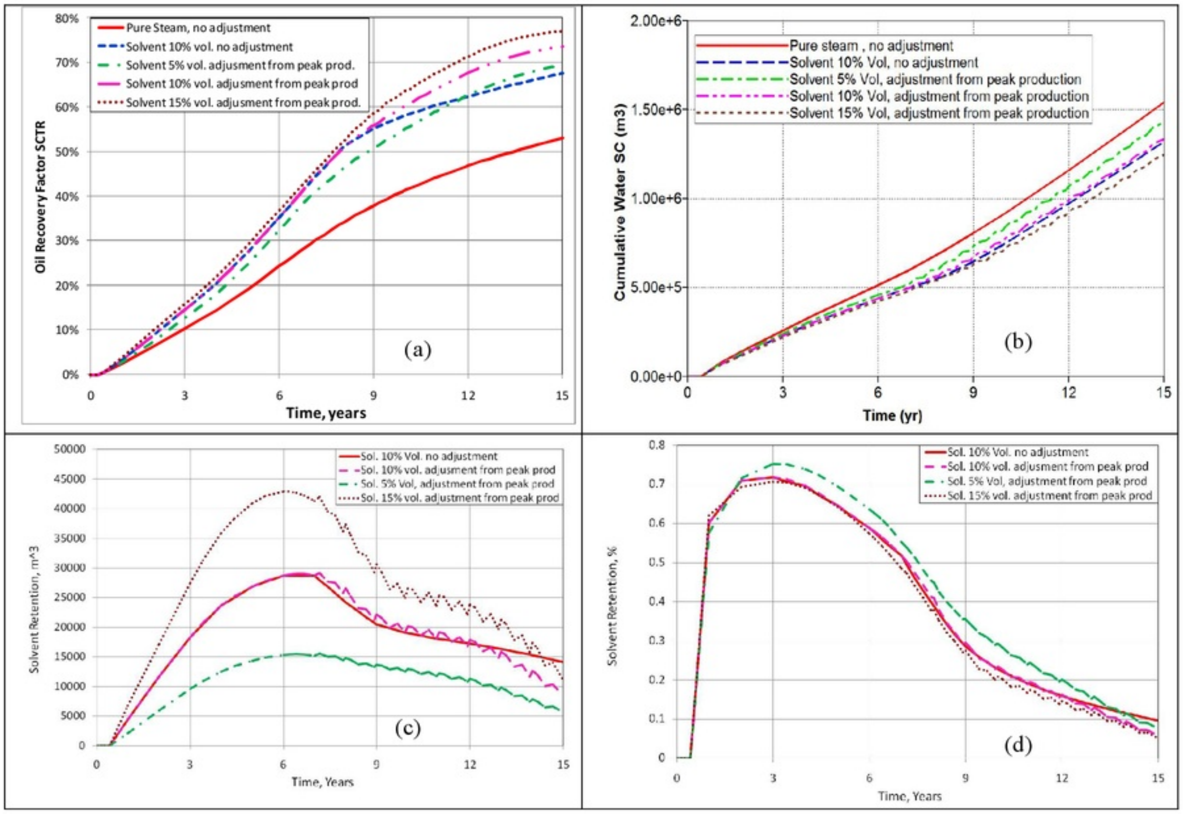

Figure 7. [(a) Oil recovery, (b) cumulative water injection and (c) solvent retention] vs time

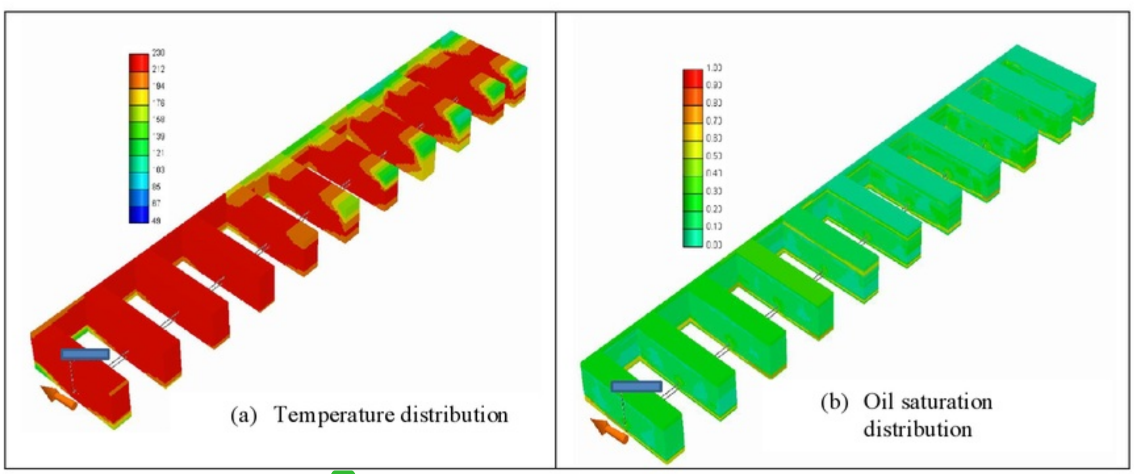

Figure 8. Temperature and oil saturation distribution in the end of project life

Figure 8 shows the temperature and oil saturation distribution in the end of the project life. It reflects that the effect of solvent is able to make the steam penetrate easier into the reservoir. The mechanism of this phenomenon is that solvent becomes condensed in the boundary of the steam chamber (together with steam) and solvent mixes with bitumen, which causes the bitumen to move into the production well due to viscosity reduction. (T. Nars, 2003). Consequently, the temperature distribution will be more spread out in the reservoir. Therefore the temperature distribution will affect oil depletion, so the more heat spreads in the reservoir the more oil will be produced. Due to very large heterogeneity in the zone D and E, the steam chamber will be smaller than the other parts. Even though the process has used ICVs to manage hybrid steam-solvent distribution, but this case is still leaving the issue particulary in the hetergeneous reservoirs.

Conclusion

This study demonstrated that adjustment of steam injection will increase energy efficiency. In the pure steam injection process, the recovery factor increases around 7.4% compared with no adjustment. Managing of hybrid steam-solvent injection in length of horizontal well will increase recovery factor 8% compared with no adjustment in solvent concentration of 10% volume. Furthermore, solvent retention will reduce 30% after using solvent managing. Therefore it was proven that the managing of hybrid steam-solvent injection is very important in the SAGD project and if implemented correctly will contribute significant advantage towards production.

Nomenclature

ICVs	Interval control valves
BHP	Bottom hole pressure
SAGD	Steam assisted gravity drainage
RF	Recovery factor
cSOR	Cummulative steam oil ratio

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