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Recovery of Heavy Oil – A Numerical Study of Critical Parameters

Samarth D. Patwardhan[1], Steffi Calmiano[2], Ali A. Al-Aizari[2], Aman Batar[2], G. Suresh Kumar[1]

1. Department of Ocean Engineering, IIT - Madras, Chennai, India.
2. Department of Petroleum Engineering, MIT Pune, Pune, Maharashtra, India.

Presenting Author E-mail: *samarth.patwardhan@mitpune.edu.in*

Abstract

Heavy oil forms a significant percentage of the overall unconventional energy basket, almost double in volume compared to conventional oil reserves. With depleting conventional oil reservoirs, heavy oil holds great potential in meeting the future energy demand. Some of the methods that are employed for recovery of heavy oil include steam injection, in-situ combustion, polymer flooding, and steam assisted gravity drainage. In steam injection, steam is injected into the reservoir to reduce the oil viscosity, and enhance its ability to flow towards the production well. Modelling and designing an optimum steam injection operation requires an accurate characterization and representation of the reservoir, to better understand the dynamic impact of the chosen operational parameters. This paper presents a critical review of the steam injection process, by taking into account all the significant technological developments that form a part of the same. Further, this work utilizes a commercially available thermal simulator to build a numerical model, and run a series of simulations to quantify the effect of certain parameters on the well productivity. Studies have been conducted on the simulation of heavy oil recovery using steam flooding, and effect of steam quality and injection rate are known to significantly affect the well performance. Due to the complexity of recovery from heavy oil reservoirs, a comprehensive sensitivity analysis is deemed significant in order to determine the appropriate production approach. With the help of sensitivity analysis, the simulations further assess the impact of other important design parameters that affect well performance. Some of the parameters under consideration in this study include but are not limited to injected steam temperature, oil saturated formation thickness, formation heterogeneity, relative permeability, and completion strategy. Data for this work has been derived from literature, and the results help enable better decision making from a production standpoint, to assess their future economic implications.

Introduction

Heavy oil is characterized by high viscosity and an inability to flow under normal reservoir conditions. It’s available worldwide in significant quantities, with the largest reserves of heavy oil located in Venezuela which equates the conventional reserves of Saudi Arabia. Heavy oil has gained significance nowadays due to the depletion of conventional oil reservoirs and advancement in technology. Thermal oil recovery mechanisms have been widely used in heavy / light oil reservoirs to enhance / improve oil recovery because of their ability to positively change the reservoir and fluid properties for more efficient production. Once the steam is injected into the reservoir, it leads to the reduction of oil viscosity and enhances the oil displacement towards the production wells. Since the viscosity is highly sensitive to temperature, it reduces significantly with an increase in temperature. The distribution of the remaining heat into the reservoir depends on the reservoir properties such as permeability and thickness, steam quality, thermal conductivity, and volumetric heat capacity especially in multi-layered reservoirs. Also, the steam flooding efficiency depends on the oil saturation values. The efficiency of displacing and production performance increases as the oil saturation increases. The conduction phenomenon causes the oil to get produced to the surface, whereas, convection leads to oil getting displaced in the steam zone. The steam injection rate per the entire reservoir in heavy oil reservoirs depends on the reservoir thickness, permeability, and well spacing.

Many studies have been done to investigate the feasibility of steam flooding in heavy / light oil reservoirs. Experimental and modelling work has been done by Alajmi(5)to study the formation of oil bank into the reservoir due to the steam injection. He concluded that the oil bank depends on the initial oil viscosity, and steam quality. Yartsos(6) studied the influence of steam injection on oil saturation distribution in the reservoir. He concluded that the rapid reduction in oil saturation depends on the steam quality and injection time. Prats(7) studied the effect of steam injection on heat distribution and concluded that it depends on the thermal conductivity, volumetric heat capacity, and reservoir thickness. Haghigi et al.(8) has used two numerical simulators separately to study the steam performance in light and heavy oil reservoirs. He concluded that the light oil reservoir is more sensitive to the steam flooding than the heavy oil reservoirs. He also found that the oil viscosity reduction in heavy oil reservoir is the main factor affecting the oil recovery; however, all the main parameters such as the thermal conductivity, oil saturation and volumetric heat capacity play critical roles when it comes to production. Ashrafi (9) performed experimental and simulation work to study the steam flooding in heterogeneous heavy oil reservoirs. The PVT data for this work was obtained through the experimental work and was further used in a thermal reservoir simulator. He concluded that there is an optimal value of steam temperature and quality for more efficient performance. Also, he discovered that the shale barriers could impede the oil flow and increase the residual oil saturation considering the reservoir permeability. Moussine(10) in his research conducted a numerical simulation of gas & steam mixture for injection process. He concluded that gas-steam injection efficiency depends on formation permeability, oil saturated thickness and the shut in time between injection and production stages. Bahonar(11) studied the feasibility of steam injection in a highly fractured carbonate reservoir using reservoir simulation. He concluded that production increase from a steam injection operation depends on steam quality, perforation intervals, capillary pressure and injection and production rates. Haskakir(12) conducted various sensitivity studies for relative permeability curves compiled from literature for diatomaceous reservoirs. He also studied other parameters like steam temperature, pressure, quality, and bottom-hole pressure for injectors and producers. He concluded that while all the above parameters affect productivity, relative permeability is the most sensitive parameter. Al-Mudhafer(13) conducted a simulation study to investigate the viability of steam flooding in a heterogeneous light oil reservoir having infinite aquifer support. He states that the incremental oil recovery is due to factors such as wettability, changing interfacial tension, vaporization, viscosity reduction and thermal expansion. Cheng Zan(14) in his work conducted simulation studies of steam flooding processes in thin, extra heavy oil reservoirs, focussing on well patterns. He conducted experiments run under three different well configurations; vertical injection-vertical production, horizontal injection-vertical production, and vertical injection-horizontal production and observed that maximum recovery was obtained during vertical injection – vertical production well configuration.

Work performed by others, and reported in the literature helped us identify a set of parameters which affect the steam injection operation. Some of the parameters are: oil saturated formation thickness, oil viscosity, formation heterogeneity, imbibition stage duration time, steam quality, different strategies for perforating, capillary pressure, well spacing and well type, pattern type and size, steam injection and oil production rate, initial oil viscosity, thermal conductivity, volumetric heat capacity, thickness, injection, soaking, production period, steam temperature, pressure, relative permeability, porosity and BHP. The parameters were classified after identification into controllable and uncontrollable parameters and were investigated and studied according to the viability of the commercial simulator.

Objectives

The work in this paper is directed towards a study related to reservoir and fluid properties' sensitivity with time and its consequent effect on the production performance of a well completed in a heavy oil reservoir. Understanding the fluid flow behaviour in a heavy oil reservoir can only be attained either through experimental work, or through reservoir simulation. Validating the results of an experimental study through simulation has proved to be the most appropriate method. The importance of heavy oil as a source of energy has been increasing tremendously as well as the complexity of its efficient production is much more than that of a conventional oil reservoir. Therefore, this notion became a source of inspiration for us to take up the simulation study of a heavy oil reservoir. This work includes working on a reservoir simulation model, which aptly describes a heavy oil reservoir. The work has been carried out by collecting data from available literature. Post creation of the apt reservoir model, sensitivity cases for various influencing parameters were analysed and subsequent performance prediction was done from a recovery standpoint.

Simulations

The main reservoir parameters that are used for this study is given below in Table 1. The data required to build this model has been derived from literature. The following values were utilized to build the reservoir model. The values aptly represent the characteristics of a common heavy oil reservoir.

Table1: Reservoir Properties

PROPERTY	VALUE
Reservoir Area	10 acres
Porosity	30%
Permeability(I direction)	400 mD
Permeability(J direction)	400 mD
Permeability(K direction)	40 mD
Porosity reference pressure	8576 KPa
Formation Compressibility	$1.8e^{-5}$ 1/KPa
Reservoir Temperature	37.7778 C
Bubble point pressure	8576 KPa
Oil density	21 API
Gas density	0.65
Water-oil contact depth	526 m
Gas-oil contact depth	504 m
Water salinity	10000 ppm
Volumetric heat capacity	$2.35e^{+6}$ J/(m*day*C)
Thermal conductivity	$1.5e^{+5}$ J/(m*day*C)
BHP for injector	12000 KPa
Surface water rate for injector	250 m^3/day
Steam Quality	80%

A reservoir model was created in a commercially available simulator, and following were the results obtained from the simulation runs:

Figure 1 shows cumulative oil production of 8500 m^3 over a period of 5 years. The oil rate and water cut graphs show opposite trends i.e. oil rate increases when water cut decreases and vice versa. The sudden peak in GOR is due to the production of lighter gas containing oil which moves towards the producer earlier than the heavier oil during the course of production. Eventually, the GOR reduces as heavier oil starts getting produced. To find out the most optimum values of the key parameters in both the above cases, a sensitivity check was run, as shown in Figure 2.

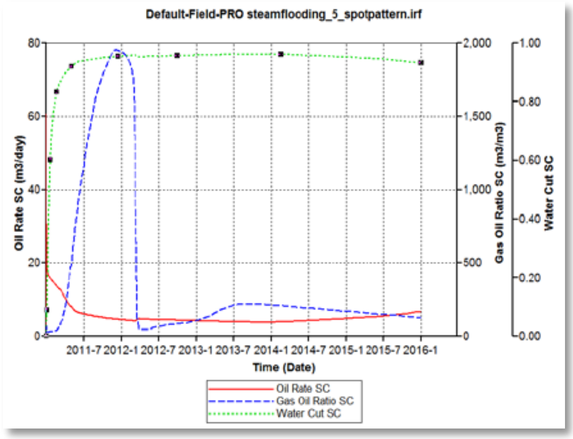

Figure 1: Steam flooding plots vs. time

Sensitivity analysis involves evaluation of ranges of behaviour for different values of key reservoir parameters. Sensitivity cases can help identify critical parameters, define probable ranges of behaviour, and in designing programs for gathering more data or for monitoring key aspects of reservoir performance. Various sensitivity runs were performed in order to attain our basic objective of optimizing parameters for production and also to study the effect of changes in the parameters that affect the production profile.

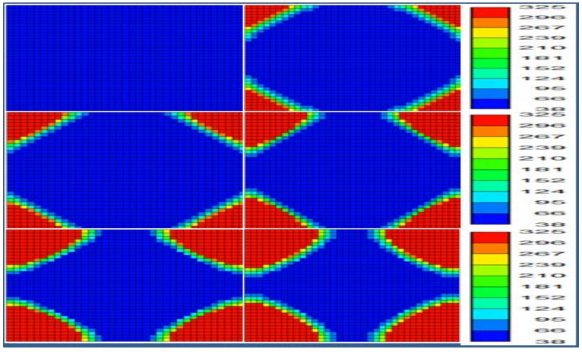

Figure 2: Steam flooding temperature (^{0}C) profile

Following were the sensitivity parameters, which were investigated through this simulation model while keeping the remaining parameters constant:

- Effect of steam quality
- Effect of steam temperature

- Effect of reservoir permeability
- Effect of reservoir porosity
- Effect of perforation intervals

Effect of steam quality: As the steam quality increases the oil recovery increases proportionally. This happens because, as the quantity of steam decreases, the latent heat available to increase the temperature of oil also decreases. In these runs, the steam quality was changed from 60% to 100%. This also explains why we get maximum oil recovery for 100% steam quality. All the curves in Figure 3 show a smooth trend indicating stable continuous flow conditions.

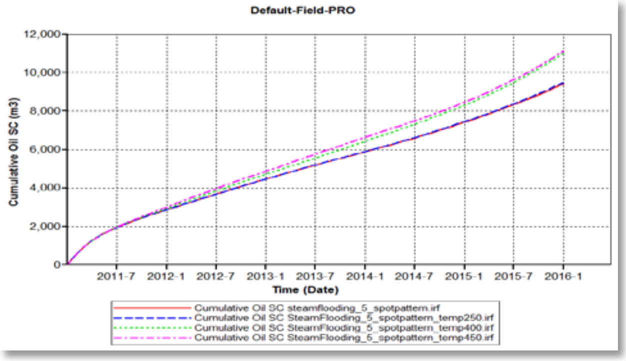

Figure 4: Cumulative oil vs. time for different values of steam temperature

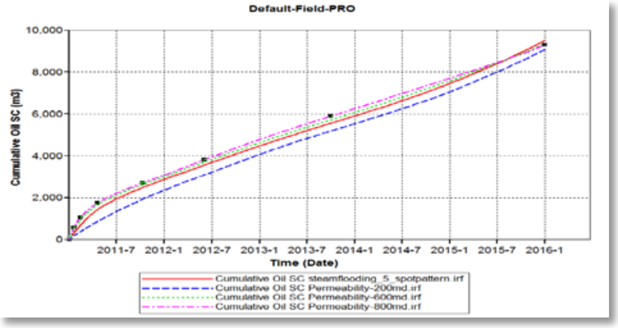

Figure 5: Cumulative oil vs. time for different values of reservoir permeability

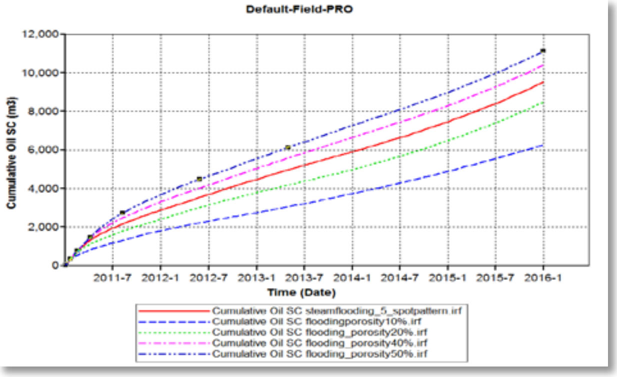

Figure 6: Cumulative Oil SC vs. time for different values of reservoir porosity

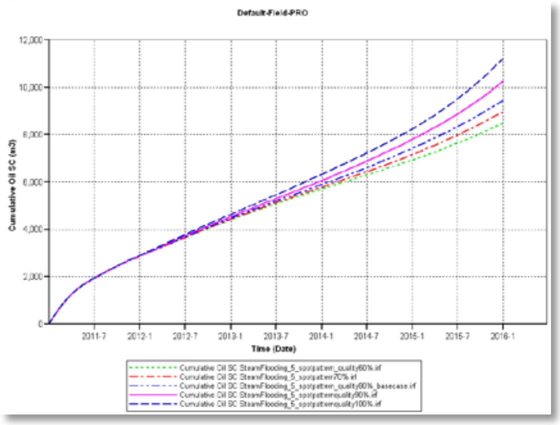

Figure 3: Cumulative oil vs. time for different values of steam quality

Effect of steam temperature: Values of temperature which were examined are 200,250,400,450˚ F. As shown in Figure 4, the higher the temperature of injected steam more is the oil recovery. As steam flooding is a continuous process and does not include any shut-in or soaking period, all the heat supplied tries to travel towards the producer and thus heats the oil. It does not dissipate into layers other than the production interval, or the dissipation is considered negligible.

Effect of reservoir permeability: Lower the reservoir permeability the less is the recovery because the steam is unable to percolate to all the parts of the reservoir to heat the heavy oil. Reservoir permeability was varied to observe its effect on overall production. Values of permeability which were investigated are 200,400,600,800 mD. It was seen from Figure 5, that a minimum permeability of 400 mD will ensure substantial percolation of steam, leading to a good recovery.

Effect of reservoir porosity: An increase in the porosity directly affects the cumulative oil production. Various simulations were run to see the effect of a change in porosity on overall production. Porosity was changed from 5 % to 50 %, and it was seen that lower porosity values give minimum recovery as the steam finds it difficult to propagate through the entire reservoir. As evident from Figure 6, as the porosity increases, the production of oil also increases.

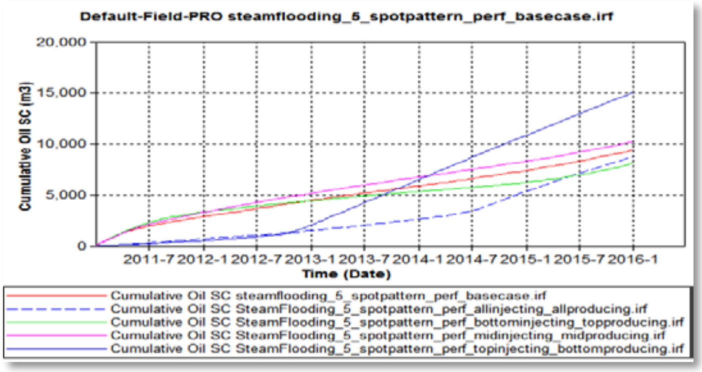

Figure 7: Cumulative Oil SC vs. time for different perforation intervals

Effect of perforation intervals: The effect on the reservoir is highly dependent upon the amount of steam being injected through the number of perforations open. When top layers perforations are used for injection, gravity drainage comes into picture in the course of production and give maximum recovery as observed from the Figure 7.

Effect of changes in Relative Permeability End Point: These runs included changing values of K_{rwro}, which is the relative permeability to water at the residual oil saturation, and K_{rocw}, which is the relative permeability to oil at the connate water Saturation. The results in Figure 8 show that larger the K_{rwro}, lesser is the cumulative oil production. This is due to the fact that an increase in the K_{rwro} increases the water mobility which in turn implies that water flow is increased. This causes the water to flow more easily towards the producing well. The results show that larger the K_{rocw}, greater is the recovery of oil. Lower K_{rocw} implies that all values of K_{ro} are reduced at all oil saturation conditions. This implies lower oil phase mobility, which in turn leads to reduced oil production.

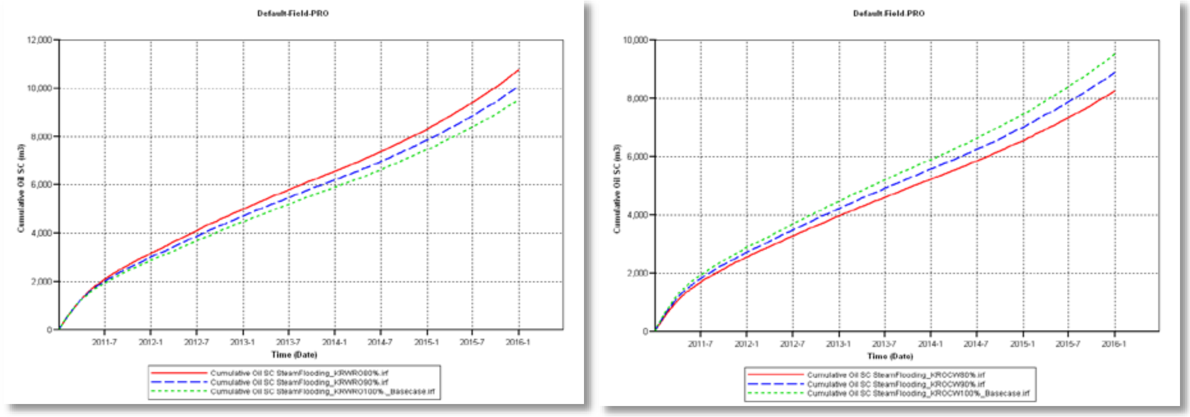

Figure 8: Cumulative Oil SC vs. time for different values of K_{rwro} and K_{rocw}

Conclusions

Based on the simulation results and the parametric investigations performed in this study, following conclusions are provided:

1. Higher the steam quality less is the latent heat required which results in proportional increase in the oil recovery as the quality increases.
2. An increase in the injected steam temperature in the steam flooding process gives high oil recovery which states that the heat dissipation is negligible due to the continuous process.
3. It was observed that a minimum value of 40 mD permeability was required to ensure sustainable percolation of the injected steam throughout the entire reservoir leading to a higher recovery.
4. Lower porosity values give minimum recovery as the steam finds it difficult to propagate through the entire reservoir. Higher the reservoir porosity gives direct increase in the oil recovery.
5. It was shown that the gravity drainage comes into picture when injecting the steam through the top layers perforations hence maximum recovery is obtained.
6. Changes of the relative permeability end points directly affect the mobility of oil and water hence affect the cumulative oil production. Greater the K_{rwro} (relative permeability to water at the residual oil saturation) results in an increase in water mobility therefore the oil production is decreased. Larger K_{rocw} (relative permeability to oil at the connate water Saturation) increase the oil recovery as the mobility of oil is enhanced.

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