A Comprehensive Study on Implementing Enhanced Recovery Schemes in Mature Oil and Gas Fields

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Abstract

This review paper extends comprehensive study on implementing enhanced recovery schemes in mature oil and gas fields, by discussing the existing EOR techniques that were and are currently utilized by many oil giants. The study discusses the kind of tertiary oil recovery techniques are employed in a mature reservoir to get the residual oil recovered, or any hydrocarbon accumulations that were not recovered by conventional primary and secondary oil recovery techniques. A numerical model using Thermal simulator - STARS of CMG Suite 2015 was developed to study the influence of steam flooding in a heavy oil reservoir. The study was carried out in 3 main phases to understand the steam flooding process efficiently along by understanding the screening criteria and the effects of various parameters on the production performance of reservoirs, which includes the effects of injection rates, the kind of composition of injected steam and well pattern and spacing.

Keywords: Enhanced Oil Recovery; Steam Flooding; Thermal Recovery; Review Study; Numerical Modelling

1. Introduction to Enhanced Oil Recovery

Oil perhaps is the main source for current human progress. It is as yet the major wellspring of energy for the world, and is additionally a basic asset for the petrochemical business. Lately, many oil fields all throughout the world have begun to show a decline in oil production and will be unable to fulfill the world's increasing demand of oil.

About two-thirds of the world's daily oil production comes from mature fields, according to a report from IHS Cambridge Energy Research Associates [1]. As most of the mature fields are in their decline phase, an assortment of measures might be utilized, including the utilization of extra innovation to portray, screen, and deal with the producing reservoir, or by improvement in drilling and completions, and implementation of the Enhanced Oil Recoveries to lift the recovery factor. Accomplishing huge expense decrease in field tasks, through innovation application or more viable work cycles and strategic policies, can likewise assume a significant part. [2]

The paper reviews the implementation of the Enhanced Oil Recovery to recover the oil is trapped inside the void spaces of the reservoir that is left and could not be recover via primary recovery that is by the natural reservoir energy or secondary recovery process that is water and gas injection. The oil recovery by these two processes are only 20% - 40%. For enhancing the ability of oil to be produced and recovered up to 30% - 60% Enhanced Oil Recovery (EOR) or Tertiary recovery processes are employed in order to enhance the capability of oil to flow easily. [3][4]

Main EOR technologies that are implemented to revive production (1) Thermal Recovery (2) Chemical Injection and (3) Gas Injection. A detailed work on numerical simulation was carried out to understand the EOR thermal technology. [5][6]

2. Methodology

To achieve the main objective of the study, series of simulation runs were conducted to simulate the production performance of oil wells in different flooding patterns.

The flooding patterns chosen for the simulation run were regular and inverted five and nine arrangements respectively.

Simulation runs were conduct to investigate the effects of the petrophysical properties and operating conditions to examine the most suitable steam flooding pattern for heterogeneous heavy oil reservoir. Effects of injected fluid composition on flood mechanism and injected rate was also recorded and observed to understand the process efficiently.

The simulation results were compared to understand the fundamentals of thermal recovery processes in the mature oil fields.

3. Thermal Recovery Process

Modern oil extraction proceeds for more than a century. As an outcome, exploited reservoirs contain oil that is hard to extract. We can say that the two kinds of oils heavy and viscous, are ruling. Processes of thermal extraction rely on transferring thermal energy from different sources to raise the temperature in the formation. Higher temperature gives for lower viscosity and more powerful development of oil to the production well. It is therefore economically feasible to rise the temperature in the formation if initial oil viscosity is in the region of above 100 cP. We have to stress at this point that when we are talking about steam injection we are exclusively talking about water steam injection as are the most utilized procedures in EOR around the world. [7]

3.1 Different Thermal Recovery Process

(1) Cyclic Steam Stimulation (CSS): This method is called the Huff and Puff technique, comprises of 3 phases: injection, soaking, and production. Steam is first injected into a well for a specific measure of time to warm the oil in the surrounding reservoir to recover around 20% OOIP. It is quite common for wells to be produced in the cyclic steam manner for a few cycles before being put on a steam flooding regime with other wells.

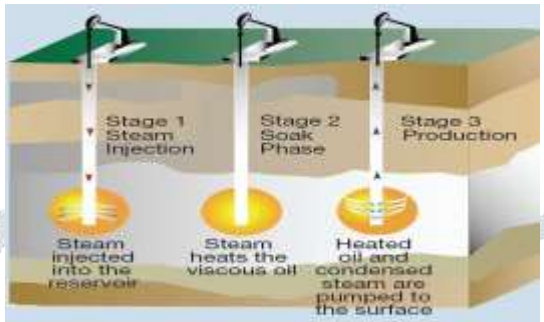


Figure 1: Different Stages of Cyclic Steam Stimulation in Reservoir [13]

(2) Steam-Assisted Gravity Drainage (SAGD): In the SAGD process, two parallel horizontal oil wells are drilled in the formation, one around 4 to 6 meters over the other. The upper well injects steam, and the lower one gathers the heated crude oil or bitumen that streams down because of gravity, plus recovered water from the condensation of the injected steam.

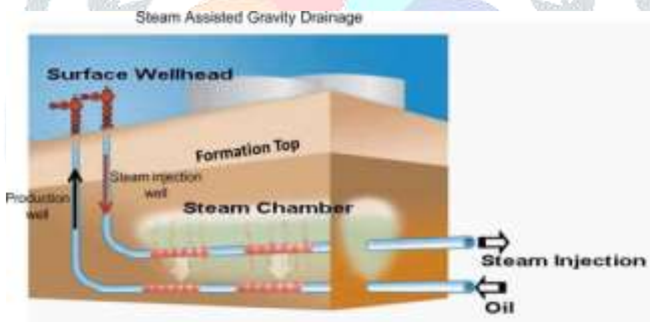


Figure 2: SAGD Process in a Reservoir [14]

(3) In-Situ Combustion (ISC): In-situ combustion is a displacement process for heavy oils in which an oxygen-containing gas is injected into a reservoir where it reacts with crude oil to make a high-temperature burning zone that produces a combustion zone that generates combustion gases and creates a heated front that propagates through the reservoir.

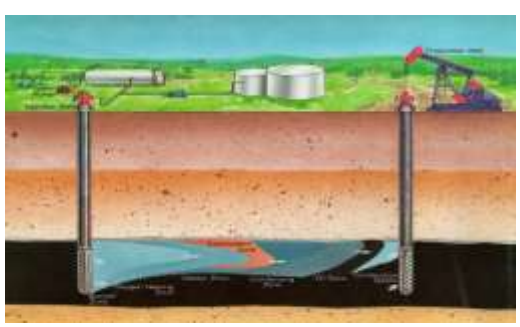


Figure 3: In-Situ Combustion in an Oil Reservoir [15]

(4) Steam Flooding: Like water flooding, SF is one sort of flooding technique by persistently injecting steam to frame a steam zone and uprooting the crude oil by reducing viscosity. Its performance exceptionally relies upon well flooding patterns and geographical conditions. The residual oil saturation can be declined as low as 10% in swept areas, as a rule with oil recovery factors about 50%. Steam is injected from an injection well, and the injected steam frames a steam chamber around the injection well. The steam chamber is extended toward a production well and dislodges the crude oil into a production well with decreasing the viscosity of heavy oil. [8]

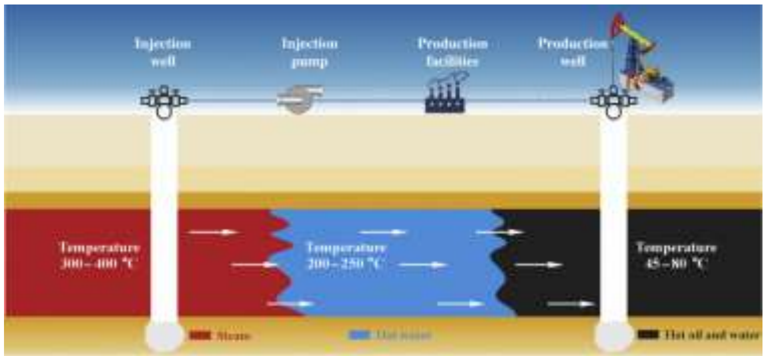


Figure 4: Steam Flooding Process [8]

4. Screening Criteria

The screening criteria for a specific EOR process consist of a list of reservoir parameters and fluid properties such as oil gravity, oil viscosity, reservoir porosity, oil saturation start and end, reservoir permeability, reservoir depth, reservoir temperature, reservoir pressure and pay thickness and their ranges. The criteria recommend minimum to maximum ranges for each parameter, which are likely to lead to a success. The Table 1 shows the screening criteria being used since ages to design flood projects and same parameters used in this numerical simulation study.

Table 1: Screening Criteria for Steam Flooding [9]

Author	Year	°API	μo cp	ø %	S_o start, %	K md	T °F	d ft.	h ft.	kh/μ_o (md-ft/cp)	øS_o
Geffen	1973	>10				**	**	<4000	>20	>20	>0.10
Farouq Ali	1974	12-25	<1000	≥30	1200-1700 bbl/ac-ft	~1000		<3000	≥30		0.15–0.22
Lewin & Assocs	1976	>10	NC		>50	NC	NC	<5000	>20	>100	>0.065
Iyoho	1978	10-20	200-1000	≥30	>50	>1000		2500-5000	30-400	>50	
Chu	1985	<36		>20	>40			>400	>10		>0.08
Brashear & Kuuskraa	1978	>10	NC		42	NC	NC	<5000	>20	>100	>0.065
Taber & Martin	1997	8-25	<100,000		>40	>200	NC	<5000	>20	>50	
Dickson	2010	8-20	1,000-10,000		>40	>250		400-4500	15-150		
Aladasani & Bai	2010	8-30	5E6-3	12-65	35-90	1-15000	10-350	200-9000	>20		

NC = Not critical.
* Requires laboratory test to confirm suitability.

The nature of the reservoir will play a dominant role in the success or failure of any EOR process.

Almost all steam flood projects were conducted in sandstone reservoirs, except a few cases in carbonate or naturally fractured reservoirs. [9]

5. Injection Pattern and Well Spacing

Injection Pattern and Well Spacing plays a vital role in steam flooding EOR processes as it helps to revive the production and to achieve high rates from a heavy oil or matured reservoir by providing good sweep efficiency. The most common well patterns used in past projects are: Five-Spot, Inverted Seven-Spot & Inverted Nine-Spot Patterns. One reason inverted five-spot pattern was often used is that it can be converted to inverted nine-spot pattern or inverted seven-spot pattern. [10] [7]

6. Injection and Production Rates:

In steam flooding processes the injection of steam takes place, for the process to be effective sufficient quantity of heat should be injected as it will ultimately affect the production rates. The actual field data showed an average well injection rate of 1000 bbls/d, and the injection pressure is 959 psi, in a thicker reservoir, the injection rate and steam quality could be lower. In a thin reservoir, the injection rate and steam quality must be high. [7]

7. Steam Quality and Steam Temperature:

Steam quality and steam temperature also plays major role in oil recovery, the previous studies and numerical study of heavy oil suggests that if steam is injected into the reservoir at higher temperature this will results in more energy into the model, hence will improve the ultimate recovery and enhance cumulative oil production. [11]

8. Numerical Study of Model:

A 3-D model was developed to examine the fluid flow patterns and effects of various parameters on the production rates. Thermal Simulator-STARS of Computer Modeling Group (CMG) 2015 was used for the investigation of the numerical model of a heavy oil sandstone reservoir, there are numerous of processes which can be conducted using CMG, such as polymer flooding, surfactant flooding gas and water flooding steam flooding etc.

The simulation work was done to determine the best flooding pattern among: (1) Regular 5 spot pattern; (2) Inverted 5 spot pattern; (3) Regular 9 spot pattern; and (4) Inverted 9 spot pattern.

This simulation work was also carried out to examine the effects of different steam injection rates and the composition of the steam injection fluid. Also the fundamentals of steam flooding were investigated. The above mentioned patterns were investigated keeping all the parameters same using screening criteria mentioned in Table 1 to simulate the reservoir model.

8.1 Simulation Model development:

(1) Grid and Rock Properties: A heterogeneous sandstone reservoir of a matured oilfield was assumed with heavy oil properties. This heterogeneous model was based on the Cartesian system comprising of 35×35×10 (Total Blocks = 12250), along the x, y and z axes respectively. The pattern area for all the flooding pattern was chosen 10 acres with approximate injector-producer well spacing of 142.2 m and with actual block size in X and Y is 5.91671 and block thickness of 4 m. the developed model and its parameters were common for all the cases except few and it is shown in the Figure 5. It is a single porosity model, having average porosity and permeability of 40% and 1200 mD respectively. Formation compressibility was taken as 7.3e-6 kPa^{-1} [11] and Reservoir rock conductivity was taken as 0.628 J/ (m*day*C) [12]. The reservoir temperature was assumed 22°C and the reference pressure was assumed as 8576 kPa.

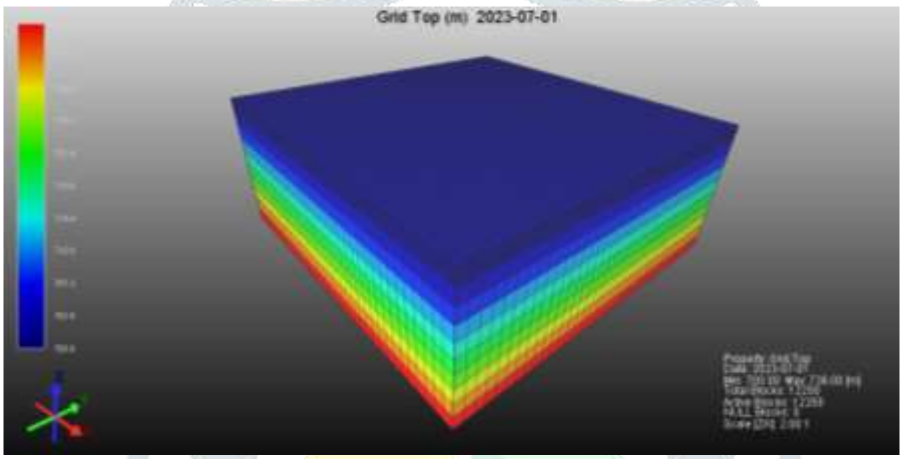


Figure 5: Snapshot of Top View of Simulation Grid Model (Depth)

(2) Fluid Properties: Oil Density & Gas Density was considered as 18.5 API ° and 0.65 respectively based on the screening criteria. Viscosity V/S Temperature relationship was considered on the basis of a laboratory experiment conducted on the behavior of Athabasca bitumen sample obtained from an oil sand reservoir in Athabasca, produced using SAGD method. The experiment was conducted at 300 °C of room temperature. The sample has not been exposed to any solvent. The parameters obtained was utilized in this study to understand the behavior of oil viscosity and a graph is plotted against temperature, shown in the Figure 6. [11]

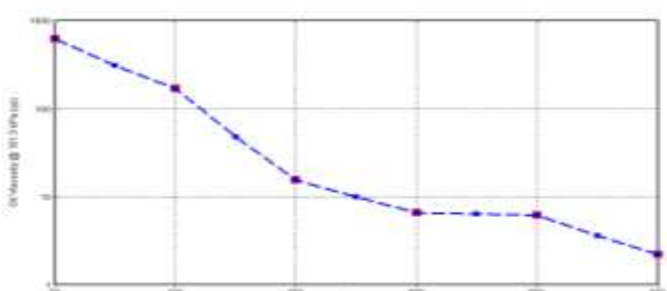


Figure 6: Graph plotted between oil viscosity and temperature, showing decreasing trend in viscosity.

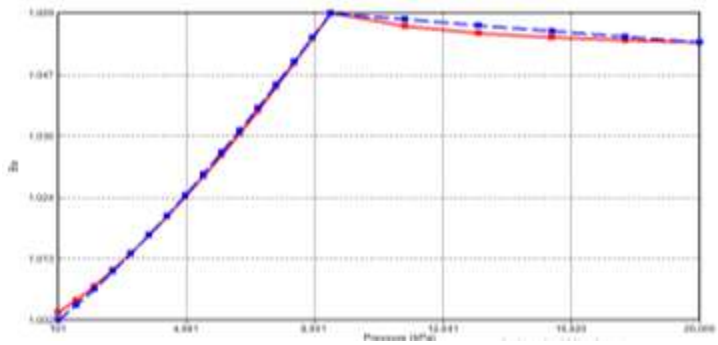


Figure 7: Graph plotted between Formation Volume Factor and Pressure, showing increasing trend in Bo.

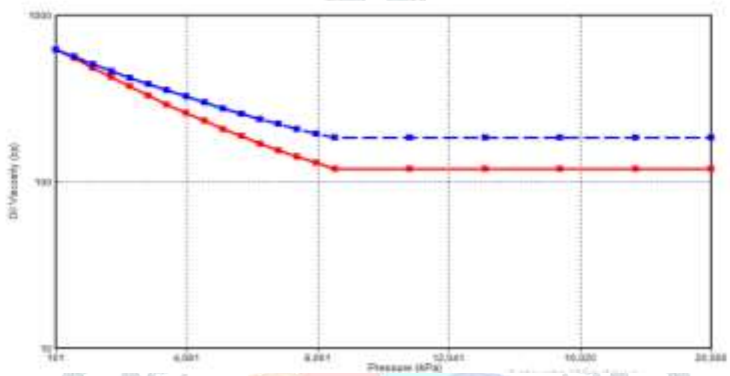


Figure 8: Graph plotted between Oil Viscosity and Pressure, showing decreasing trend in viscosity.

(3) Relative Permeability Data: The relative permeability data is shown in the Table 2 below. The curve plotted in the Figure 10 shows two different curves that shows different trends due to the reduction in the viscosity of oil with the increment in the temperature. The blue curve is plotted between relative permeability of water and water saturation, whereas the red curve is plotted between relative water-oil permeability and water saturation. The Figure 9 shows the relative permeability oil in the absence of gas saturation as a function of $S_{w,}$ in Stone #2 Model. Where the oil saturation keeps decreasing as we are moving to water saturation zone.

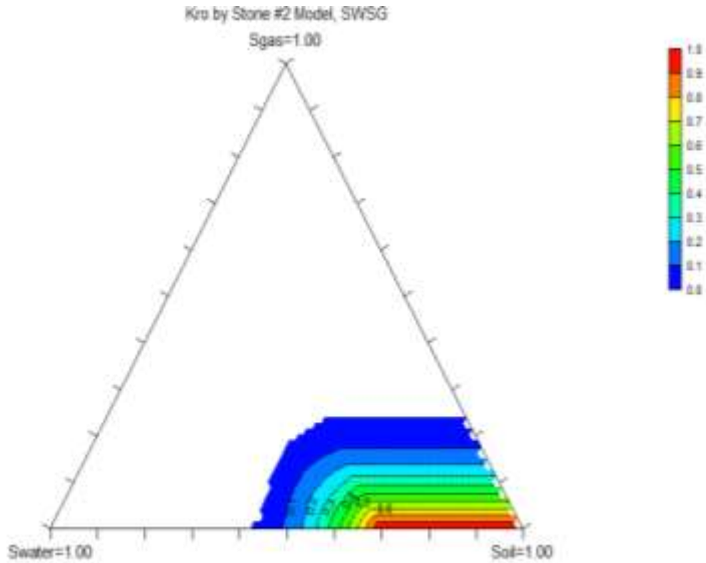


Figure 9: Stone #2 Model

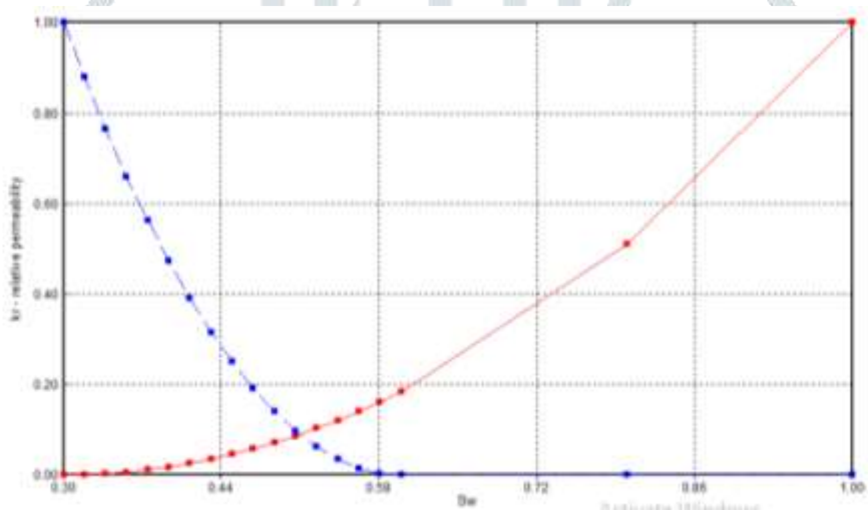


Figure 10: Graph plotted between relative permeability of water and water saturation, whereas the red curve is plotted between relative water-oil permeability and water saturation

Table 2: Relative Permeability Data used in Numerical Study

S_w	K_{row}	K_{rw}
0.3	0	1
0.31875	0.000717	0.878906
0.3375	0.00287	0.765625
0.35625	0.006457	0.660156
0.375	0.01148	0.5625
0.39375	0.017937	0.472656
0.4125	0.025829	0.390625
0.43125	0.035156	0.316406
0.45	0.045918	0.25
0.46875	0.058115	0.191406
0.4875	0.071747	0.140625
0.50625	0.086814	0.097656
0.525	0.103316	0.0625
0.54375	0.121253	0.035156
0.5625	0.140625	0.015625
0.58125	0.161432	0.003906
0.6	0.183673	0
0.8	0.510204	0
1	1	0

(4) Initial Conditions of the Models: The reference pressure was assumed 8576 kPa for the location of the reference depth of 710m. Whereas the water-oil contact depth was chosen as 736m and gas-oil contact depth as 713m. The same image is shown below in Figure 11.

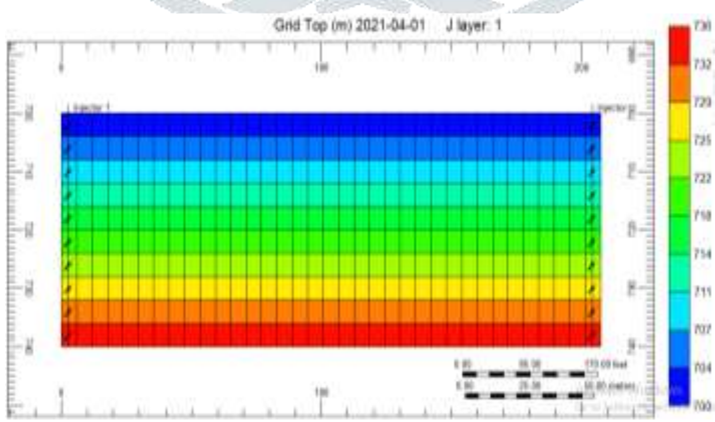


Figure 11: Snapshot of 2-D View of the Model (Reference Depth)

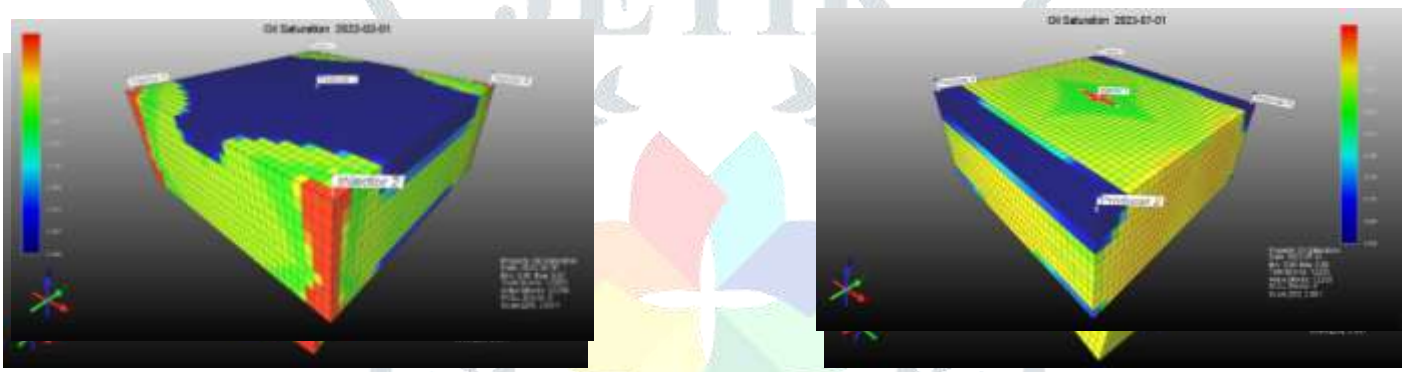
8.2 Numerical Model Simulation:

All the well configurations cases were simulated at the steam injection temperature of 300 °C, Steam quality was taken 90% and the injection pressure was chosen as 5MPa. 4 years of steam flood injection was considered for each case. The models were undergone numerous of simulations for proper examination of all the parameters and to understand the fundamentals, which segregates the simulation process into 3 main phases to investigate: (1) Fundamentals of steam flooding operations; (2) the effects of injection rates to enhance the production rates; and (3) Combination of injected fluid composition effects on the oil recovery and production.

8.3 Visualization of Numerical Model:

After feeding all the parameters, the models were simulated and the effect of steam flooding was recorded by observing oil saturation in each case. The developed models with selected production and injections wells locations with changing oil saturations due to steam flooding is depicted in the images of Figure 12**.**

(a) **(b)**



(c) **(d)**

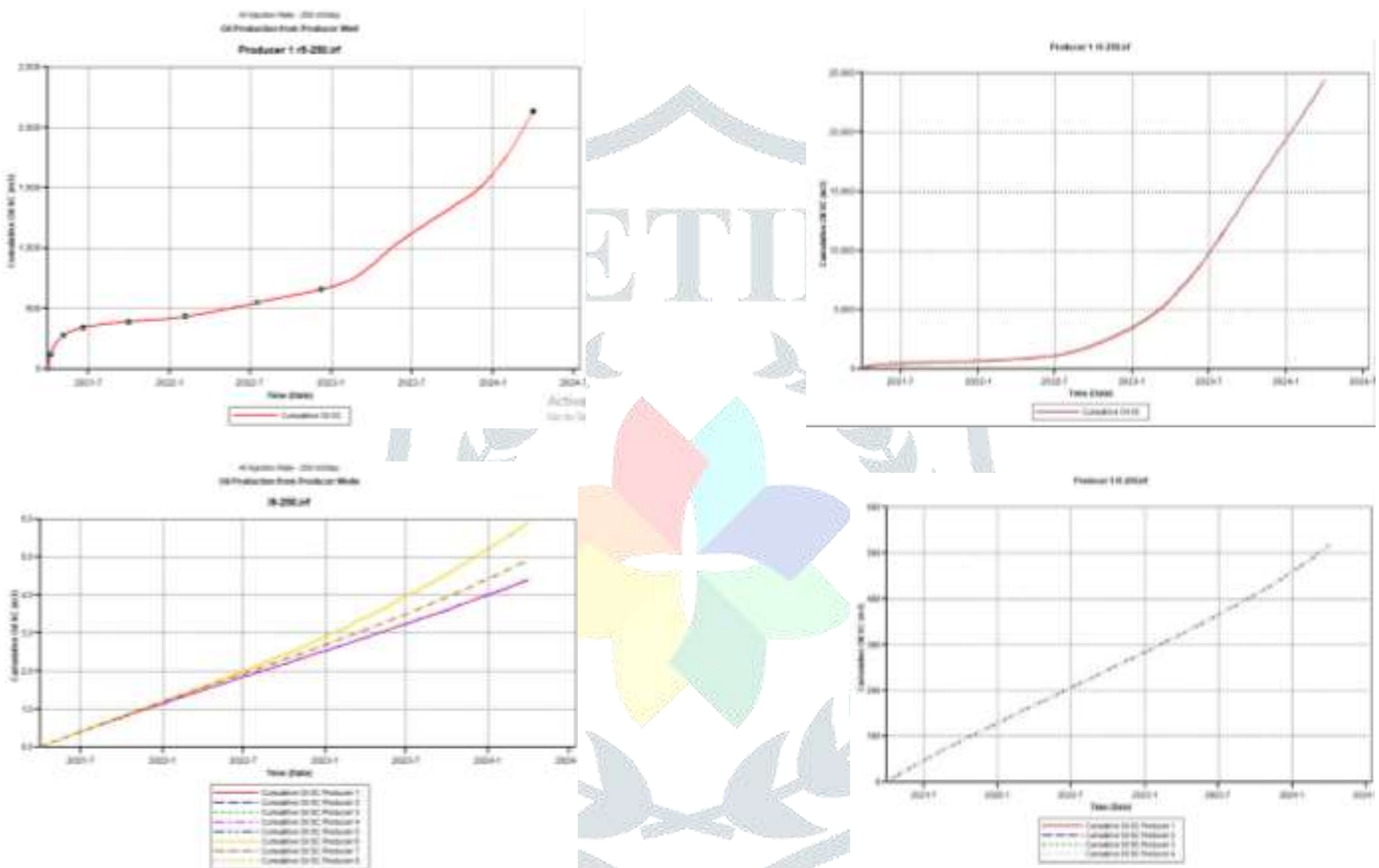
***Figure 12: All the images (a), (b), (c), and (d) illustrates oil saturation at different period and in different well patterns*.**

8.4 Results and Discussions on Numerical Simulations:

Case I:

As discussed before the steam was injected at 300 °C and the steam quality was chosen as 90% with pressure of 5MPa. In first case initially the steam injection rate of all the injectors for each simulation case was taken as 250 m^3/day and the results were recorded then it was changed to 150 m^3/day, while maintaining all other parameters constant such as reservoir pressure and temperature. The simulation was conducted for 4 years and the variation in the oil production rates was observed, shown in the Figure 13**.**

(a) **(b)**



(c) **(d)**

Figure 13: Image (a) shows production rates in well pattern Regular 5. Image (b) shows production rates in Regular 9 spot pattern. Image (c) shows oil production in Inverted 9 spot pattern. Image (d) shows oil production at Inverted 5 spot pattern. (At 250 m^3/day)

In the above four cases Figure 13 in which regular nine well configuration shows oil increment that is highest as compare to other well patterns in this category, this variation in production rates occurs due to higher steam injection rates and number of wells increased in regular nine pattern. At higher injection rates the viscosity will be reduced eventually increasing the recovery rates. The process cost estimation should be kept in mind while designing the project as higher injection rate will require more steam generation.

Case II:

After investigating production rates at 250 m^3/day, injection rates were changed to 150 m^3/day and the results are shown in the Figure 14.

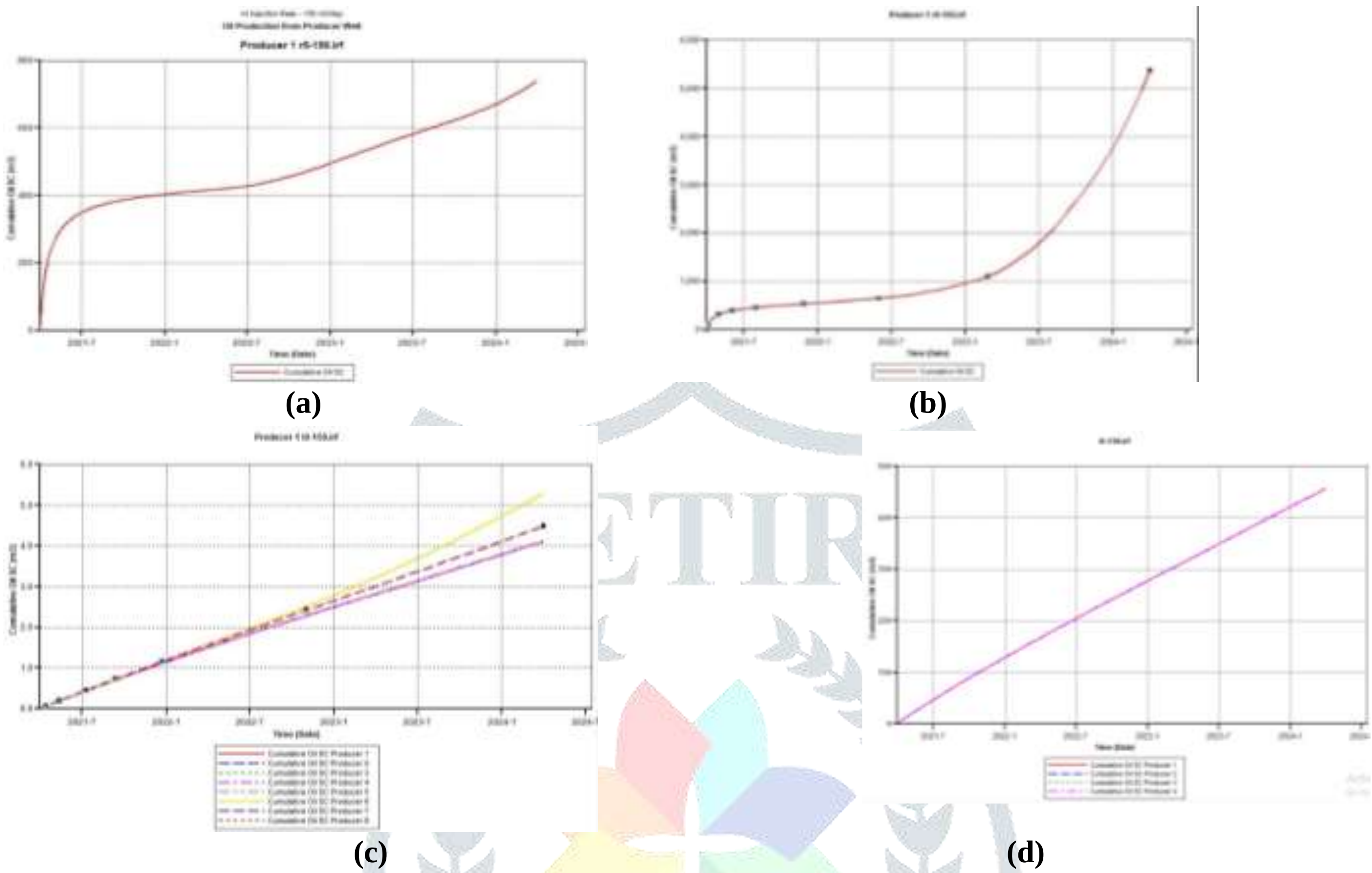


Figure 14: Image (a) shows production rates in well pattern Regular 5. Image (b) shows production rates in Regular 9 spot pattern. Image (c) shows oil production in Inverted 9 spot pattern. Image (d) shows oil production at Inverted 5 spot pattern. (At 150 m^3/day)

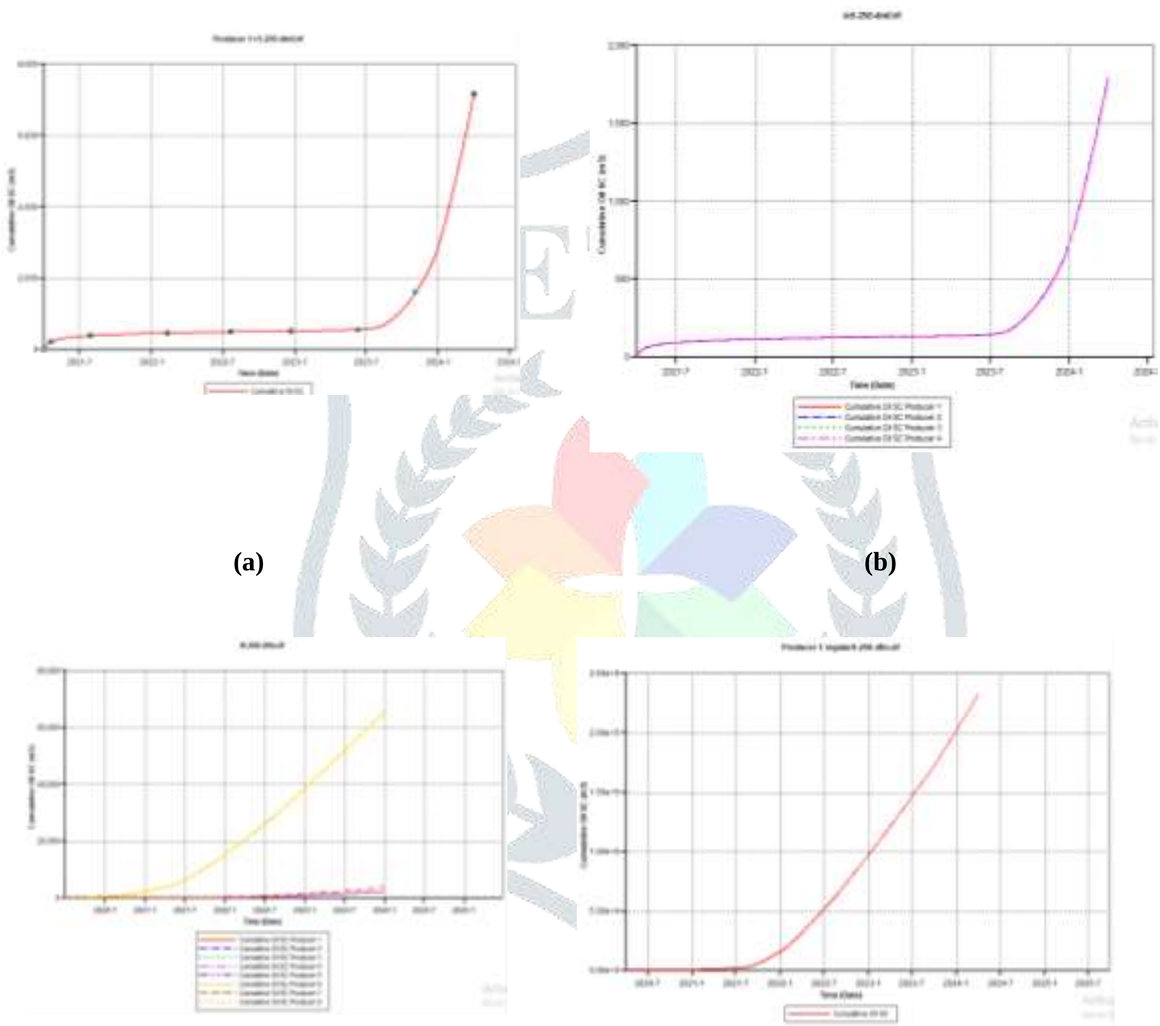
In the above Figure 14 again the regular nine well pattern have the highest production rates as compare to other well patterns, due to more number of producer wells it is possible. But if we compare the case II with I due to reduced injection rates the oil production also declined causing less oil recovery at the end.

Case III:

At this stage after recording the production results both at 250 m^3/day and 150 m^3/day. Now the injected fluid composition was changed and shown in the Table 3 below. For this case the injection rates were kept at 250 m^3/day. The models were again simulated and run, and the production rates were again recorded. Observation is shown below in Figure 15**.**

Table 3: Mole Fraction of Different Injected Fluid Components

S. No	Components	Mole fraction
1	Water	0.5
2	Dead Oil	0.2
3	Solution Gas	0.3
Total		1.0



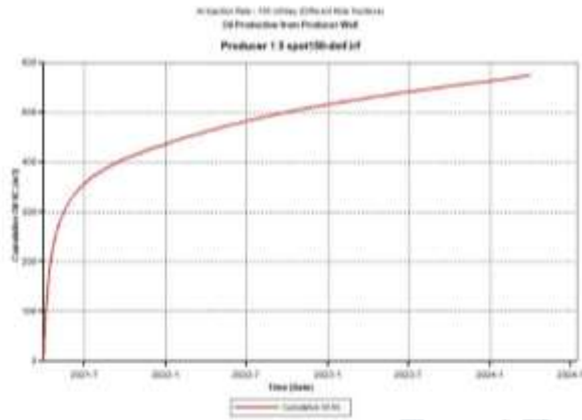
(a) (b) (c) (d)

Figure 15: Image (a) shows production rates in well pattern Regular 5 spot pattern. Image (b) shows production rates in Regular 9 spot pattern. Image (c) shows oil production in Inverted 5 spot pattern. Image (d) shows oil production at Inverted 9 spot pattern. (At 250 m^3/day & different fluid composition)

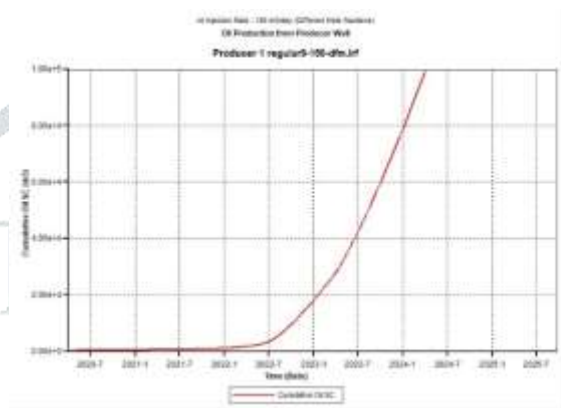
In order to check the effect of changing injected fluid composition, the models were simulated using the parameter mentioned in the Table 3**.** After running the simulation an increasing trend of oil production was observed in all the well patterns if compared with Case I and Case II. This increment in rates occurred due to the utilization of light fluid components (Dead oil and Solution Gas) in injected steam.

Case IV:

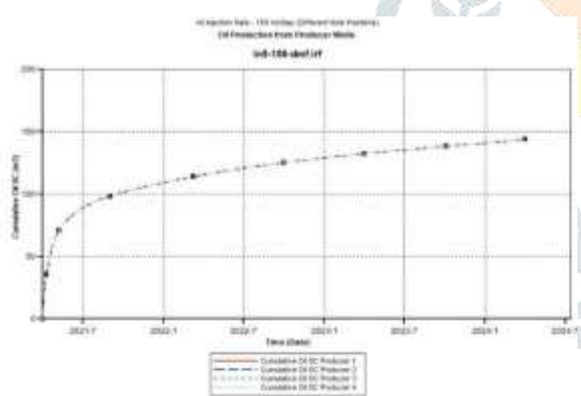
After recording results at 250 m^3/day, now the model simulated at 150 m^3/day with the fluid composition parameters shown in table. The recorded trends are shown in the Figure 16.



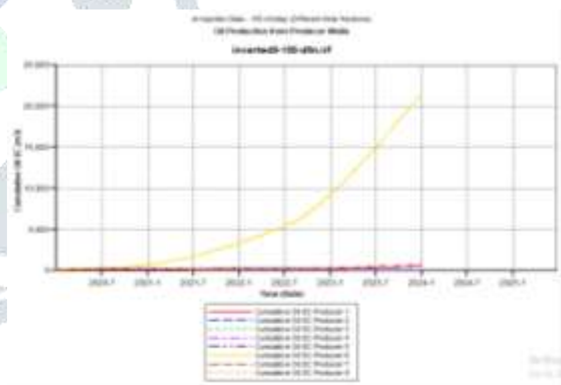
(a)



(b)



(c)



(d)

Figure 16: Image (a) shows production rates in well pattern Regular 5. Image (b) shows production rates in Regular 9 spot pattern. Image (c) shows oil production in Inverted 9 spot pattern. Image (d) shows oil production at Inverted 5 spot pattern. (At 150 m^3/day & different fluid composition)

The above attached Figure 16 also show increment in production rates, which are higher (Except Regular 5 Well Pattern) as compare to Case I and Case II, but still lower as compare to Case III. As discussed in Case I and Case II the injection rate plays a vital role in increment of oil recovery, here at 150 m^3/day injection rates the results are not as satisfied as compared to case III but we can consider this flood design rather than choosing Case I and Case II, based on cost estimation and budget planning of the project.

9. Conclusion

A comprehensive study on literature review of Enhanced Oil Recovery techniques was carried out in order to understand the various oil recovery method used in variety of condition to recover the residual oil and to increase the reservoir potential to produce more oil.

A detailed numerical simulation study was conducted, where 4 cases were taken in which four well flooding patterns was chosen. The initial parameters were similar for each case except few. The well is injected with 250 m^3/day and 150 m^3/day injection rate for all the well patterns and the study was conducted to choose the best pattern among four on the basis of results. Then the Injected fluid composition is changed and again the observation was conducted. The effects of parameters were observed and the following results are concluded:

- At 250 m^3/day the regular nine spot pattern has the highest oil production as compare to other well patterns, where steam with different mole fraction was used as an injected fluid. This implies towards the positive effect of increased injection rate and increment in the number of wells.
- Recovery rates are higher when the fluids are injected at higher rate.
- Light components in contrast with water components can be utilized to increase the flow of injected fluid so that it can enter the void spaces to push the oil out of the trapped zone, ultimately increasing the production performance of the oil fields.

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