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Journal of Petroleum & Chemical Engineering

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Vol: 1 & Iss: 1

Simulation of Cyclic Steam Stimulation for Thermal Enhanced Oil Recovery

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Citation: Dankwa OK, Amoah RA, Appiah TF, Appiah-Adjei F. Simulation of Cyclic Steam Stimulation for Thermal Enhanced Oil Recovery. *J Petro Chem Eng* 2023;1(1): 48-54.

Received: 07 November, 2023; **Accepted:** 10 November, 2023; **Published:** 13 November, 2023

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ABSTRACT

Enhanced Oil Recovery (EOR) is a process whereby certain fluids are injected into the reservoir to enhance oil recovery and cyclic steam stimulation (CSS) is an example under thermal recovery method. This study aimed at stimulating the performance of a reservoir using cyclic steam stimulation. A model was built using the Computer Modelling Group (CMG) software. Reservoir fluid and rock properties data were fed into the model and other necessary steps were followed. After the simulation, the results showed that CSS was very successful and the oil recovery factor increased from 18% to 55% at the end of the five years stimulation period. Sensitivity analysis showed that the higher the permeability, the higher the oil recovery factor and also, the recovery factor increases with grid thickness. The results of the simulation were validated by comparing it to the analytical results and a good match of oil production rates were obtained.

Keywords: Cyclic Steam; Numerical Simulation; Thermal Enhanced Oil Recovery; Production rate; CMG

1. Introduction

Petroleum and natural gas, crucial energy sources, are typically extracted from subsurface pools of hydrocarbons, known as reservoirs, which reside within porous or fractured rock formations. These reservoirs can be broadly categorized as either conventional or unconventional. Conventional reservoirs entail the trapping of naturally occurring hydrocarbons, such as crude oil and natural gas, by impermeable rock formations. In contrast, unconventional reservoirs are characterized by high porosity and low permeability, allowing hydrocarbons to be trapped without the need for a cap rock[1].

The global energy landscape has witnessed significant shifts in recent years, with a growing emphasis on sustainable and unconventional energy resources to meet the escalating demand for energy. As of 2017, the British Petroleum Statistical Review highlighted that the world's petroleum assets amounted to a staggering 1.7 trillion barrels, of which 30% comprised light oil, while heavy oil and other unconventional resources constituted the remaining 70%. However, the effective extraction of heavy oil from reservoirs has been hindered by its inherently low API gravity and high viscosity, resulting in limited primary production[2]. To unlock the vast potential of heavy oil reserves, Enhanced Oil Recovery (EOR) techniques have emerged as a critical field of study, focusing on secondary and tertiary recovery methods to extract the untapped resources.

EOR techniques are categorized based on their primary mechanisms for displacing oil from reservoir rock. These methods primarily seek to overcome the challenges posed by heavy oil's high viscosity. The fundamental mechanisms include reducing oil viscosity, extracting oil with solvents, and altering capillary and viscous forces between the injected fluid and the rock surface. With the ever-increasing global energy demand, unconventional energy resources, such as heavy oil, are being explored as promising alternatives to address this challenge.

One notable EOR technique, cyclic steam stimulation (CSS), has gained prominence as an effective method for heavy oil reservoirs. CSS, also known as "huff and puff" steam injection[3], involves the cyclic injection and production of steam in a single well to raise the temperature across the wellbore, thereby reducing the heavy oil's viscosity. This thermal-enhanced oil recovery method is particularly well-suited for reservoirs located in complex geological formations, such as those characterized by faults and shale barriers. The success of CSS relies heavily on predictive tools for oil production, which are essential for the effective management of reservoirs undergoing CSS[4].

A considerable body of research has been devoted to mathematically modeling the steam injection technique to predict oil recovery. Early efforts in this domain concentrated on the simulation of heat flow and heat loss within the reservoir. In this context, this research project aims to construct a numerical reservoir model and employ it to simulate the cyclic steam stimulation process using Computer Modelling Group (CMG) software. The modeling approach allows to explore the dynamic behavior of the reservoir system in order to manipulate various parameters, thus enabling a comprehensive understanding of the recovery process[5]. The aim was to screen and select the most suitable enhanced oil recovery method for practical implementation and further construct a numerical reservoir model through cyclic steam simulation as a means to enhance oil recovery. Sensitivity analysis of the model was conducted to evaluate the impact of certain parameters on the recovery process.

This study endeavours to contribute to the advancement of understanding and application of EOR techniques, particularly in the context of heavy oil reservoirs, by exploring the potential of cyclic steam stimulation and its associated modelling tools. Through these efforts, challenges posed by heavy oil extraction are addressed, thereby offering sustainable solutions to meet the world's growing energy demands.

2. Literature/Theoretical Underpinning

2.1 Tertiary (Enhanced) Oil Recovery (EOR)

Tertiary (Enhanced) oil recovery is that additional recovery over and above what could be recovered by primary and secondary recovery methods. Various methods of enhanced oil recovery (EOR) are essentially designed to recover oil, specifically described as residual oil, left in the reservoir after both primary and secondary recovery methods have been exploited to their respective economic limits. The categories of oil recovery are shown in Figure 1.

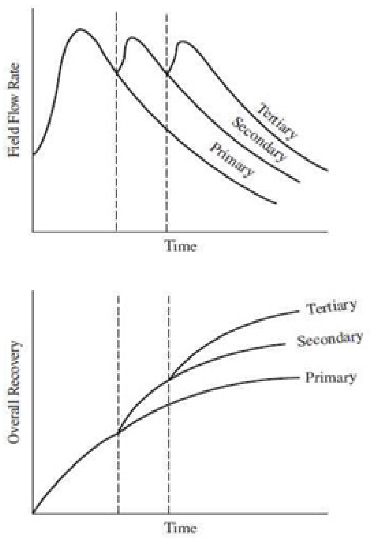

Figure 1: Oil Recovery Categories[6].

During tertiary oil recovery, fluids different from just conventional water and immiscible gas are injected into the formation to effectively boost oil production. Thus, EOR can be implemented as a tertiary process if it follows a waterflooding or an immiscible gas injection, or it may be a secondary process if it follows primary recovery directly. Nevertheless, many EOR recovery applications are implemented after waterflooding[7]. The main goal of EOR processes is to increase the overall oil displacement efficiency, which is a function of microscopic and macroscopic displacement efficiency. Microscopic efficiency refers to the displacement or mobilization of oil at the pore scale and measures the effectiveness of the displacing fluid in moving the oil at those places in the rock where the displacing fluid contacts the oil[8]. For instance, microscopic efficiency can be increased by reducing capillary forces or interfacial tension between the displacing fluid and oil or by decreasing the oil viscosity[9]. Various categories of EOR methods exist.

2.2 Thermal EOR Methods

Thermal methods of enhancing oil recovery mechanisms are known to be the most popular EOR techniques[10] which include cyclic steam stimulation, steam flooding and in situ combustions. These techniques have been tried since the 1950s, and are the most advanced among EOR techniques, taking into account field experience and technology. The prime objective of introducing heat into the heavy oil reservoir is to lower the viscosity of the reservoir fluid. These methods are best suited for viscous oils (10-20 ºAPI) and tar sands (≤10 ºAPI). The heat causes a large reduction in viscosity which also reduces the mobility ratio[11]. Other methods which include fluid expansion, compaction, steam distillation, and vis-breaking may also be applied. Thermal oil recovery techniques have been proven successful in Canada, USA, Venezuela and Indonesia among others.

2.3 Cyclic steam stimulation (CSS)

Cyclic steam stimulation is the introduction of heat into the reservoir and it is a well-known enhanced oil recovery (EOR) technique. CSS is also called huff and puff. It is one of the most common methods used to heat the reservoir to decrease reservoir fluid viscosity. Natural fractures in the reservoir are used to establish effective connections throughout the reservoir, which makes such reservoirs great for steam injection techniques. Cyclic steam stimulation is a single well method and has three stages. The first stage is a steam injection which can normally continue for about a month. The well is then shut-in for a few days for heat to soak the reservoir rock, denoted by the soak period. After the injection and soaking period, the well is put production. The oil rate increases quickly to a high rate, and stays at that level for a short period, and declines over several months[12]. Figure 2 shows the stages of the cyclic steam stimulation process. The focus of this study is on cyclic steam stimulation.

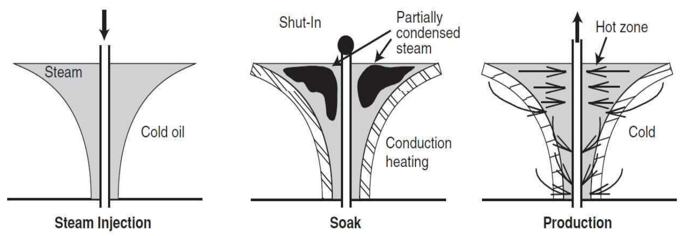

Figure 2: Cyclic Steam Stimulation (CSS)[13].

2.4 Steam Injection Stage

In this stage, steam is injected into the reservoir to increase the temperature. The duration of this stage is generally 3 to 4 weeks depending on the reservoir conditions[14].

2.5 Soaking Stage

After the injection stage, the well is shut in to let the steam soak the reservoir rocks. While the steam diffuses and increases the temperature in the reservoir, the viscosity of heavy oil decreases, and the mobility of the crude oil increases. The duration of this stage is generally 2 to 3 weeks depending on the reservoir conditions[14]. This duration should be selected properly because if it is too short, steam cannot heat the formation and if it is too long, heat can be lost to the formation and the reservoir may cool again.

2.6 Production stage

When the viscosity is reduced to the desired limit, the well is put to production. Production continues until the production rate drops to an economic rate limit as illustrated in Fig. 1.4. After the production rate reaches an economic limit, the whole cycle of injection, soaking, and production may be repeated until it is considered to be non-feasible. Cycles are repeated when the oil rate becomes uneconomic. The steam-oil ratio increases as the number of cycles increase. Near wellbore knowledge is crucial in CSS for heat distribution as well as recovery of the mobilized/ heated oil. CSS is particularly attractive because it has a quick payout, however, recovery factors are low (10-40% OIP). Figure 3 shows the cycles of CSS.

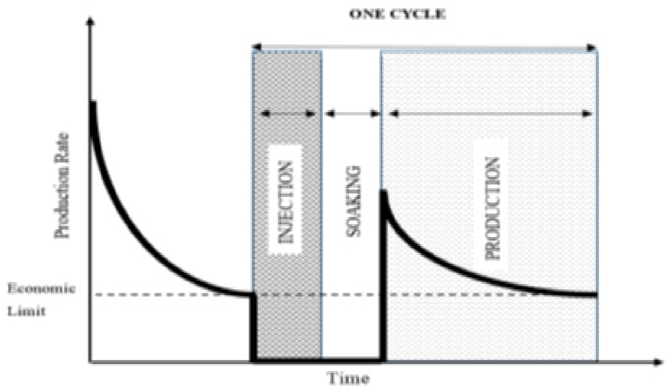

Figure 3: One Cycle of Cyclic Steam Injection with all Stages[15].

3. Methodology

3. 1 Model Construction and simulation procedure

Figure 4 provides a visual representation of the comprehensive procedure employed for the construction and simulation of the numerical reservoir model utilizing the CMG software.

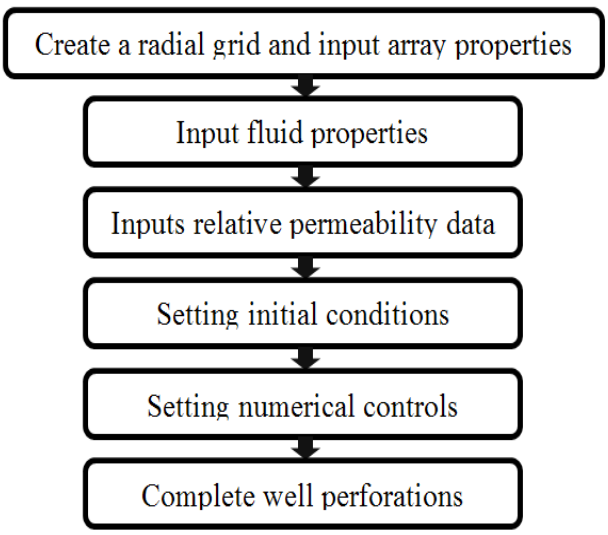

Figure 4: Steps Used in Simulating the Numerical Model.

3.1.1 Data used

The secondary data used for simulation is shown in Tables1 through to 5.

Table 1: Reservoir Input Data[16].

Parameter	Value
Along radius (ft)	25
Angular ('theta' division) (ft)	1
Along K direction (ft)	5
The inner radius of the outermost block (ft)	0.25
The outer radius of the outermost block (ft)	500
Sweep (max 360 degrees) (ft)	3.6*10^2

Table 2: Input grid dimensions[16].

Parameter	Value	
	Grid top	Grid Thickness
Layer 1(ft)	2000	20
Layer 2 (ft)	2020	20
Layer 3 (ft)	2040	20
Layer 4 (ft)	2060	20
Layer 5 (ft)	2080	20
Porosity	0.28	
Permeability (mD)	250	250 80

Table 3: Input Oil Properties[16].

Parameter	Value
Critical pressure (psi)	0
Critical temperature (F)	0
Molecular weight (lb/lbmole)	600
Density(oleic) (lbmole/ft^3)	0.10113
Liquid compressibility (1/psi)	5*10^-6
1st thermal expansion (1/psi)	3.8*10^-4

Table 4: Input Water Components[16].

Parameter	Value
Critical pressure (psi)	3206.2
Critical temperature (F)	705.4
Molecular weight (lb/lbmole)	18.02

Table 5: Water Oil Relative Permeability Data[16].

NO.	S_w	k_{rw}	k_{row}
1	0.25	0.0	0.6
2	0.37	0.000056	0.651
3	0.45	0.000552	0.50625
4	0.55	0.00312	0.325
5	0.60	0.00861	0.2
6	0.65	0.01768	0.1
7	0.70	0.03088	0.05625
8	0.75	0.04871	0.025
9	0.77	0.05724	0.016
10	0.80	0.07162	0.00625
11	0.82	0.08229	0.00225
12	0.85	0.1	0.0

3.2 Completion of the Well Perforation

i. This entails the procedures for completing and perforating the well and it involves several steps as follows:

ii. Well perforations and geometry: This is where the well location is specified either with the block address system or manual perforation. For cyclic steam injection, there must be an injection well and production well located in the same location.

iii. Setting operating constraints for the injection well: The constraints of the well was selected as operate for the two cases, the bottom hole pressure was taken to be 450 psi and surface liquid rate taken to be 1 000 bbl/day. The action was set as continuous repeat for both cases. Other constraints under options were selected as open and shut-in for producer and injector wells respectively.

iv. Entering injected fluid properties: The properties of the injected fluid include steam temperature taken to be 450 F, steam quality to be 0.7 and mole fraction as 1 and 0 for water and oil respectively

v. Setting the duration (injection, soaking, and production): It is obvious that when one of them is open the other one should be closed. Steam will be injected for 10 days, then the well is shut-in and the reservoir is maintained closed for 1 month. After soaking, the well was opened for production close to one year (2021/02/10-2022/01/01) and the cycle is continued for the rest of the five years. The schedule of injection, soaking, and production selected for this project is shown in Table 6.

Table 6: Injection, Soaking, and Production Schedule.

Date(y/m/d)	Injector	Producer	Action
2021/01/01	Open	Shut-in	Steam Injection
2021/01/10	Shut-in	Shut-in	Soaking Period
2021/02/10	Shut-in	Open	Start of Production Period
2022/01/01	Open	Shut-in	2nd Cycle of Injection
2022/01/10	Shut-in	Shut-in	Soaking Period
2022/02/10	Shut-in	Open	Start of Production Period
2023/01/01	Open	Shut-in	3rd Cycle of Injection
2023/01/10	Shut-in	Shut in	Soaking Period
2023/02/10	Shut in	Open	Start of Production Period
2024/01/01	Open	Shut in	4th Cycle of Injection
2024/01/10	Shut in	Shut in	Soaking Period
2024/02/10	Shut in	Open	Start of Production Period
2025/01/01	Open	Shut in	5th Cycle of Injection
2025/01/10	Shut in	Shut in	Soaking Period
2025/02/10	Shut in	Open	Start of Production Period
2026/01/01	Shut in	Shut in	End

3.3 Screening and Selection Procedure

These properties are acquired by using appropriate technologies such as well logging, well testing etc. Table 7 gives the general screening criteria for thermal enhanced oil recovery methods while Table 8 presents the fluid and reservoir properties of a field data from CMG, 2015.

Table 7: Screening Criteria for Cyclic Steam Stimulation (CSS)[17].

Thermal process	Fluid Properties			Reservoir properties				
	Gravity (°API)	Viscosity (cp)	Temp. (F)	Porosity (%)	Perm. (md)	Oil sat. (%)	Lithology	Depth (ft)
ISC/HPAI	19-33	2-660	110-230	17-32	10-1265	50-94	Sandstone	400-8300
Steam	8-30	50-50000	45-290	15-65	100-10000	44-90	Sandstone	200-3600

Table 8: Reservoir and Fluid Properties[16].

Properties	Values
Porosity (%)	36
Permeability (md)	>100
Oil saturation (%)	>45
Oil vis. (cp)	878
Oil gravity (°API)	<20
Temperature (°F)	180
Depth (ft)	2080

3.4 Validation of the Model

Oil production rate was calculated in excel using the equations developed by[18], for vertical CSS wells. The validation was done by exporting the results of the simulation to excel and comparing the plots of the production rate of the simulation results to the production rate results generated in excel using the pressure drop model and inflow equations which is represented in equation 1.

$$q_o = \frac{0.007078KK_{ro}h(p_h - p_w)}{B_o \mu_o ln\left(\frac{r_h}{r_w}\right)} \quad (1)$$

where;

q_o - oil production rate, bbl/day;
k - permeability of the reservoir, md;
k_{ro} - oil relative permeability of the reservoir;
h - the thickness of the pay zone, ft;
p_h - the pressure of the heated zone, psi;
p_w - the pressure of the bottom hole, psi;
B_o - oil formation volume factor, rbbl/STB;
μ_o - viscosity of the oil, cp;
r_h - radius of the heated area, ft; and
r_w - radius of the wellbore, ft.

3. 5 Model Overview

A full reservoir model was built with the help of the CMG software using secondary data. These models consist of five layers and have equal grid sizes with homogeneous porosity system. A well is located at the centre of the reservoir. The models constructed are shown in Figure 5 and a sliced model in Figure 6 which also shows the internal features of the reservoir.

4. Results and Discussion

4.1 Introduction

This section presents the results obtained from the simulation of cyclic steam stimulation, with a focus on several key parameters of interest. The discussion delves into the recovery factor, oil production rate, cumulative oil production, and the oil-to-steam ratio. Additionally, the discussion examines how permeability influences the recovery factor and cumulative oil production. The ensuing sections provide a detailed presentation of the outcomes derived from this study.

4.2 Screening and Selection Results

Tertiary oil recovery techniques are normally applied after thorough investigation and studies of the properties of the reservoir. Fluid and reservoir properties such as gravity, viscosity, temperature, porosity, permeability, oil saturation, lithology and depth are screened through the general screening criteria under Table 2 to select an enhanced oil recovery technique which is presented in Table 4. The selection was done using a light-blue and a black color. Light-blue represents applicable while black represents not applicable. After thorough screening process, cyclic steam stimulation was found to be the appropriate method for implementation.

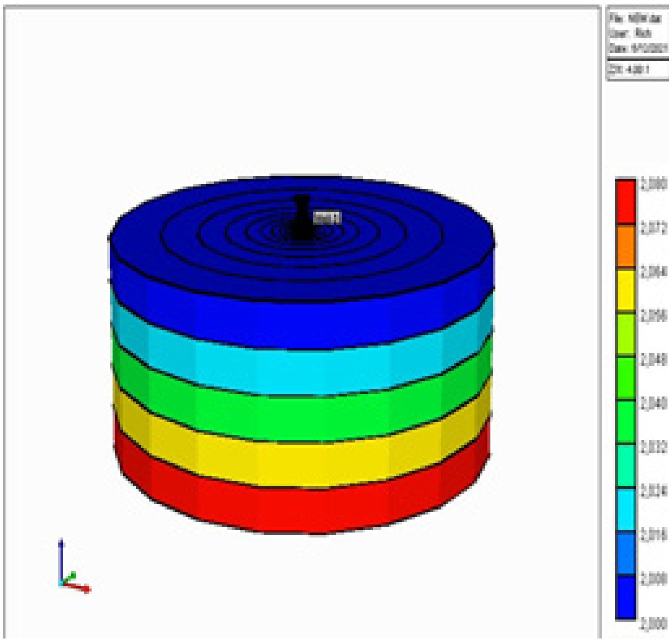

Figure 5: A 3D Cylindrical Model of CSS Reservoir.

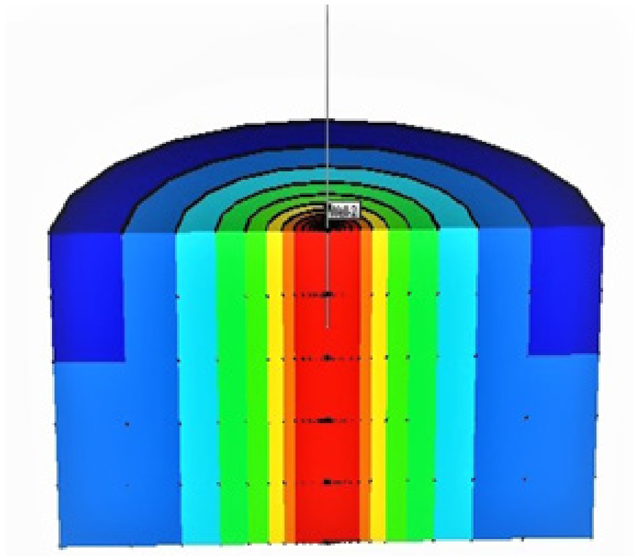

Figure 6: A Cut-3D Model of the CSS Reservoir.

Table 4: Screening and Selection Procedure.

	Selection process	
	Steam	**ISC/HPAI**
Porosity (%)		
Permeability (md)		
Oil saturation (%)		
Oil viscosity. (cp)		
Oil Gravity (° API)		
Temperature (°F)		
Depth (ft)		

Not Applicable   Applicable

4.3 Cumulative Oil Production

A plot of cumulative oil versus time is presented in Figure 7. The cumulative oil production gives the total amount of oil produced at a given period of time. The amount of oil produced at the end of the second cycle of injection in the simulated model is 18 000 bbl as against 5 000 bbl using the natural energy drive. The increase in cumulative production by 13 000 bbl (98%) during the second cycle of injection can be attributed to the role the steam played in reducing the viscosity of the crude oil in the reservoir rocks making it easier to flow to the wellbore.

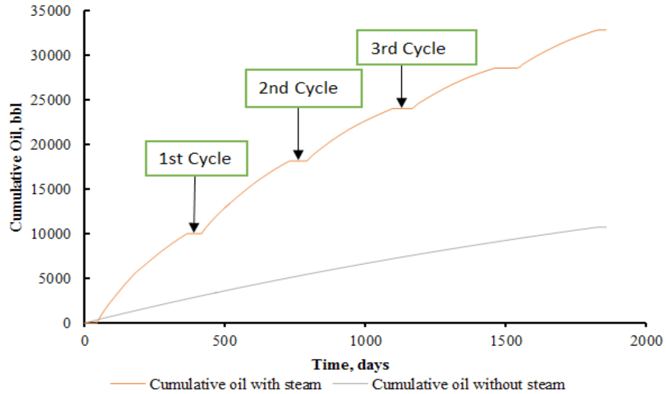

Figure 7: A Plot of Cumulative Oil Production versus Time.

4.4 Oil Production Rate

The results of the rate at which oil is produced before and after stimulation are plotted in Figure 8. The rate at which oil is produced from the reservoir per day using the natural energy is 7 bbl/day at the second cycle of injection due to the viscous nature of the oil in the reservoir. The production rate increased with the help of steam to 25 bbl/day which saw an improvement of 18 bbl/day of oil. That represents an increment of 97%. The improvement reduced as the temperature in the reservoir reduced due to heat lost by conduction to the surrounding rocks during production. Considering the two cases illustrated on the graph, the indication is clear that viscosity reduction plays an important role in the production of oil in heavy oil reservoirs.

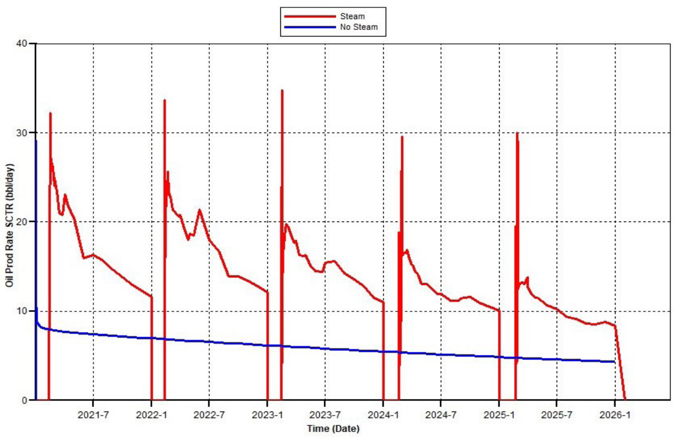

Figure 8: A Plot of the Oil Production Rate Versus Time

4.5 Results on Oil Recovery Factor

The recovery factor for the five years of production increased from 18% to 55% in Figure 9 when steam was injected into the wellbore which lowered the viscosity of the oil and made it easier to flow to the surface. Numerous projects carried out on CSS shows that the recovery factor could only increase significantly up to the fourth cycle of steam injection. Further injection of steam did not have an effective improvement.

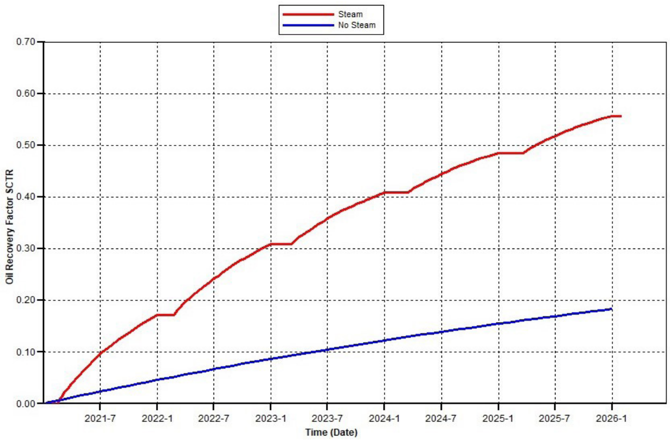

Figure 9: Oil Recovery Factor Versus Time.

4.6 Oil Steam Ratio

Oil steam ratios are indicative of the amount of steam needed to produce a given barrel of oil in a reservoir at a given time. Figure 10 shows the ratio is higher at the beginning of the process and therefore little amount of steam is needed at the beginning.

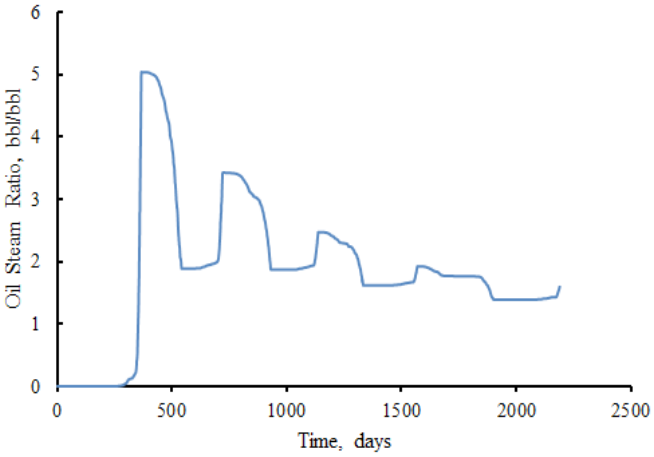

Figure 10: A Plot of Oil Steam Ratio versus Time.

The oil steam ratio was between 5.25 and 1. The ratio decreased as the injection cycles continue because more of the steam is injected, there is high chances of some of the steam condensing which later increases water cut.

4.7 Sensitivity Analysis on Oil Recovery Factor

The results of the sensitivity analysis (robustness) of the model in given ranges of permeabilities (250 md to 450 md) on recovery factor is presented in Figure 11. There was absolutely no significance if there were wide pore spaces which have not been interconnected. When the permeability was increased, there was an increased in oil recovery factor which was due to the increase in the interconnectivity of the pore spaces of the reservoir. The higher the permeability of the reservoir, the higher the oil recovery from the reservoir as shown in Figure 11.

4.8 Sensitivity analysis on cumulative oil procedure

The thickness of the grids of the model was also tested with values ranging from 15 ft to 30 ft in Figure 12. The greater the grid sizes, the higher its possibility to contain much crude oil. The cumulative production versus time curve in Figure 12 shows that as the grid sizes increases the cumulative oil production increases. This therefore establishes the fact that bigger grid sizes improve oil recovery as there is high chances of more oil being contained in bigger sized reservoirs than smaller sized reservoirs.

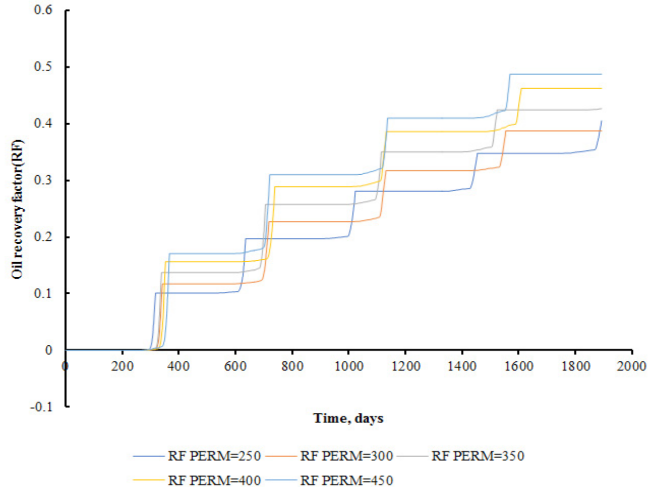

Figure 11: A Plot of Recovery Factors with Different Permeabilities versus Time.

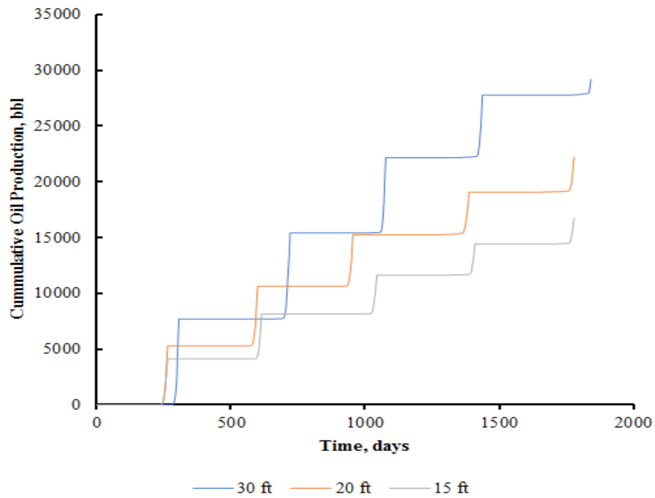

Figure 12: Comparison of Cumulative Oil Production with Different Grid Thickness.

4.9 Comparison of Oil Production Rate in STARS and Analytical Model

In Figure 13, the results of the comparative analysis between oil production rates from the CMG STARS reservoir simulator and the qo (analytical) model are presented. Calculations were conducted using Excel. The numerical modeling with CMG STARS aligns more closely with real-world observations, emphasizing its superiority in capturing reservoir dynamics. Discrepancies arise from underlying assumptions in the production rate equation and numerical model approximations. This underscores the importance of selecting the appropriate modeling technique, advocating for reservoir simulators in scenarios demanding accuracy and comprehensive representation. Subsequent sections explore these findings further.

5. Conclusion

This project developed and performed screening criteria for cyclic steam stimulation to improve oil recovery in heavy oil reservoirs using CMG software. From the findings of this work the following conclusions:

- Cyclic steam stimulation improved the oil recovery from 18% to 55%.
- The cumulative oil and oil production rate saw an increment of 98% and 97% respectively.

- Screening and choosing the best enhanced oil recovery method is crucial since it gives efficient and effective results.
- The oil recovery factor increases with increasing permeability of the reservoir.
- Viscosity reduction plays an important role in the recovery of oil in heavy oil reservoirs, The lighter the oil, the higher the oil recovery from the reservoir.

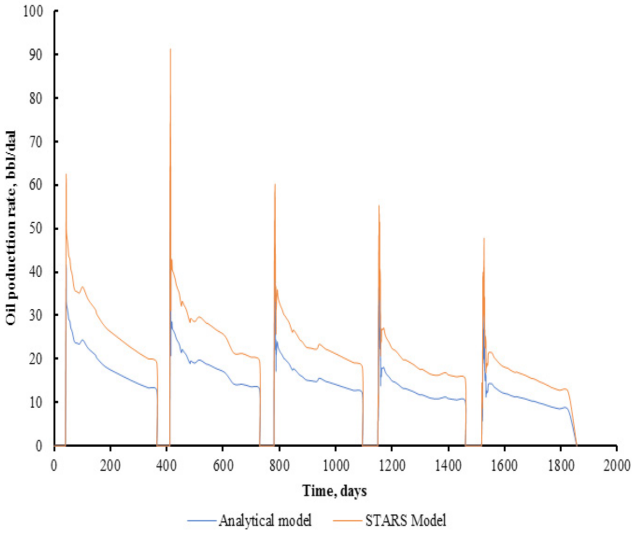

Figure 13: Comparison of Oil Production Rate in STARS Model and Analytical (qo) Model versus Time.

6. Future Research

The optimum injection time, and soaking time should be chosen to obtain effective results of cyclic steam stimulation; and

In-situ combustion should also be considered as an alternative for CSS implementation.

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