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The Effects of Combination of Steam Flooding, CO_2 and Cyclic Steam Stimulation Injection Pilot Test in Heavy Oilfield in Sudan

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ABSTRACT - Applications of Enhanced Oil Recovery (EOR) are highly required and needed in Sudan to keep oil supply at stable levels. "FUL" Oilfield in Sudan has shallow reservoir affected by big boundary and bottom water drive with high crude oil viscosity. This research, through a comprehensive analysis of the current producing wells, perforation intervals, CO2 temperature analysis, steam parameters optimization which using two approaches (deterministic and stochastic) were analyzed, using a combination of continues steam flooding, CO2 assisted steam flooding, and cyclic steam stimulation in the pilot test sector. CMG-STARS and CMOST AI simulators software was used in this study. By determining recovery factor (RF) as objective function. It could conclude that: CO2 assisted steam flooding even it could decrease the water cut, but its effect to increase the oil recovery factor is not considerable. Continuous steam flooding has the best oil recovery from these three methods.

Keywords: Heavy-Oil, Enhanced Oil Recovery (EOR), Steam Flood, Recovery Factor (RF), CO2, CSS, CMG, CMOST.

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INTRODUCTION

Hydrocarbons are non-renewable sources of natural energy that are critical to the nation's growth, industry, and economy. They are not only utilized to meet national energy demands, but they are also frequently employed to create revenue and hard currency. (OPEC, 2021). More than two-thirds of oil discovered across the world has yet to be recovered, with 40–70% of the initial oil remaining in place after using conventional production technologies such as primary and secondary recovery. (Boon, 1984)

Sudan is significantly under-explored, even though it has been a producer of oil and gas for many years. Sudan's oil reserves are estimated to be at 6 billion barrels, with 1 billion 700 thousand barrels extracted so far. The country now produces 60,000 barrels per day, with 80,000 barrels per day predicted by 2021. (SMEM, 2020). In Sudanese oil fields, there are six EOR projects: three thermal EOR (two Cyclic Steam Stimulation and one steam flooding), two chemical EOR projects, and one gas/CO2 injection project. The thermal projects are currently being implemented, whereas the chemical and gas projects are being designed and evaluated. (Elbaloula et. al.,2016)

The main objective of this paper is to introduce a new approach, such as CO2-assisted steam flooding and its possibility to enrich the oil recovery, then compare it with the conventional thermal EOR; continuous steam flooding and cyclic steam stimulation.

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Literature Review And Screening

Thermal methos of EOR is to introduce of heat to the oil well. Thermal approaches have been tried since the 1950s, and in terms of field experience and technology, which are the most sophisticated among EOR methods. Heavy oils (10–20° API) and tar sands (10° API) are the best candidates (Prats 1982). Thermal methods have the capacity to reduce the oil's viscosity and so boost the mobility ratio. These techniques are most used in shallow oil wells with high viscosity. Thermal EOR technologies have shown to be extremely successful in the heavy oilfields in the United States, Canada, Venezuela, and Indonesia, as well as in China and Brazil. Thermal technologies account for over 40% of EOR generation in the United States. (Prats 1982). Years of production demonstrate that daily oil production for steam stimulation is nearly three times that of cold wells. (Jones et al. 1995). Wu, 2013 demonstrated that the thermal recovery technique, particularly 4 cycles of Cyclic Steam Stimulation followed by Steam Flooding, can acquire the target block F in the Greater Fula oilfield in Sudan. Elbaloula and Musa 2018 figured out that the thermal EOR projects are highly effective, with doubling the production from 130 barrels per day to 300 barrels per day in the FNE Oil Field and from 280 barrels per day to 440 barrels per day in the Bamboo Oil Field. It is strongly suggested to choose shallow depth, thermal completion, and minimize comingle layer injection or utilize a unique technique for separate layer injection in order to get the most out of the wells.

Elbaloula, et. al., 2020 screened out that the best steam flooding parameters for specific sector in FNE oilfield are a steam injection temperature of 270°C, a pressure of 5–7 MPa, a steam injection quality of greater than 0.6, and a steam injection rate of 1.6 m^3/day/ha/m, with a final recovery ratio of 32.3% to overcome the problems that resulting from applying continuous steam flooding such as breakthrough, channeling, and increasing water cut, other techniques are used. Immiscible carbon dioxide flooding is one of these technique which used to enhance heavy oil, but it isn't a replacement for thermal or miscible EOR. Immiscible carbon dioxide flooding is intended for reservoirs with oils that are too heavy to be miscible with carbon dioxide and are too deep or thin to be economically and practically used using thermal methods. (Reid, 1980). Ali, 1989 mention that pilot testing of the immiscible carbon dioxide process began as early as 1949 in New York state by the Badely Producing corporation. Bagci, 2004 investigated from the effect of continuous CO2 infusion on heavy oil recovery through a one-dimensional physical simulation experiment. CO2 -assisted steam flooding boost recovery by roughly 15.6 percent over steam flooding, according to the data, and the gas-vapor ratio was the primary component impacting ultimate recovery last studies that investigated in this area (using CO2-assisted steam flooding) was pilot test with very limited conditions, that the geometry of reservoir prototype is 60m*60m*40m with physical model dimension is 30cm*30cm*20cm, one injection well and four producer wells, in block J6 Xinjiang oilfield in China. Mean while this study was conducting with larger and unlimited conditions. Changfeng et. Al, 2019

METHODOLOGY

This research was carried out using data processing flow as showed below in Figure 1. Firstly, current wells performance will be evaluated, designing a new spacing well that could be suitable to conduct thermal EOR.

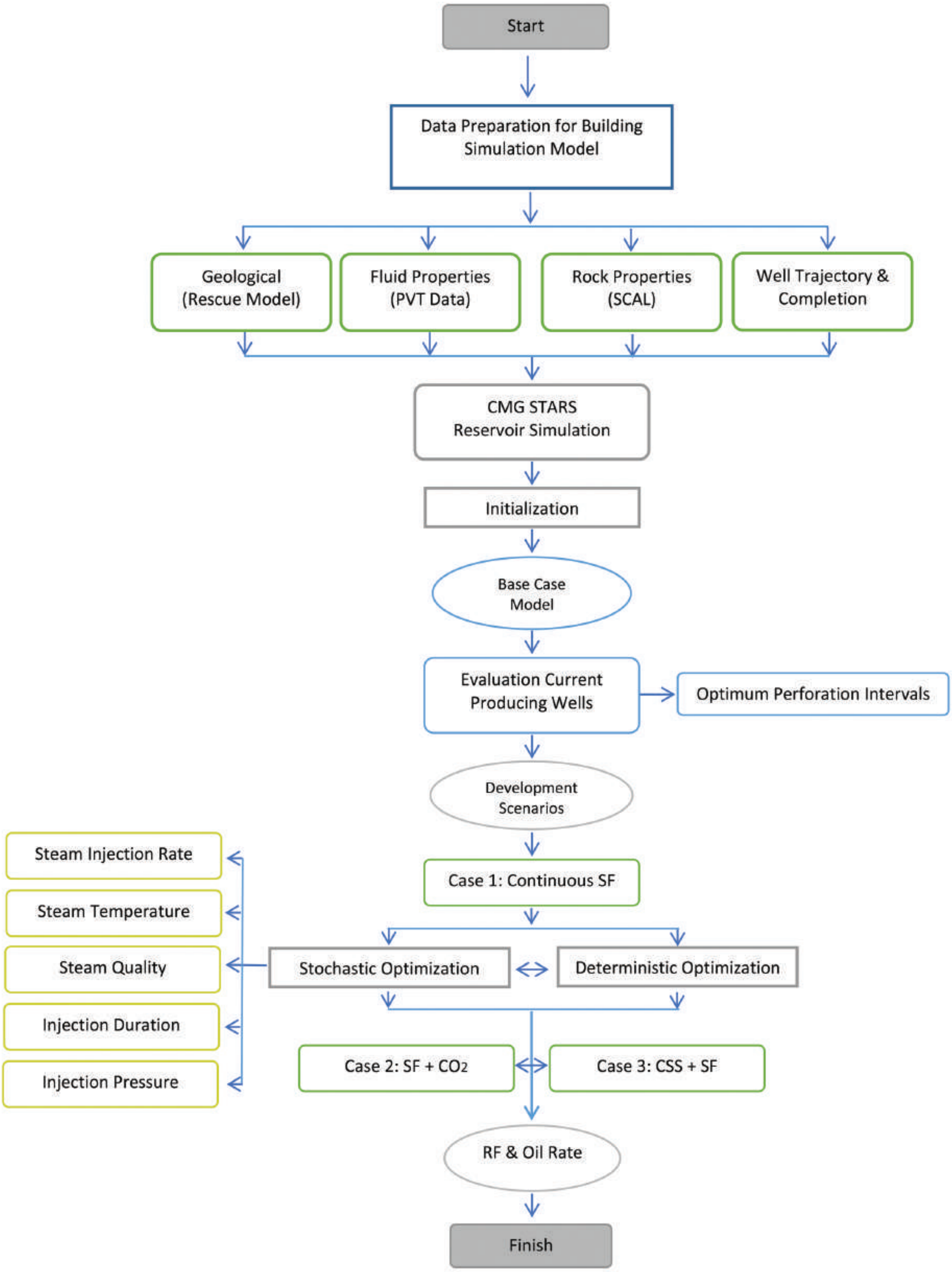

Figure 1
Study workflow

Secondly, feasibility study of implementation of continuous steam flooding as candidate thermal EOR method in this pilot test sector. Thirdly, a comprehensive optimization for perforation intervals was conducted and evaluated, which were optimized manually. Simulation model for F2 reservoir of well have been established in CMG-STARS to compare different perforation percentage cases oil forecast. Four cases have been designed as follows

- Case 1: Perforating region 1 (1/3, 2/3 and 3/3) position of total net pay thickness Figure 2.

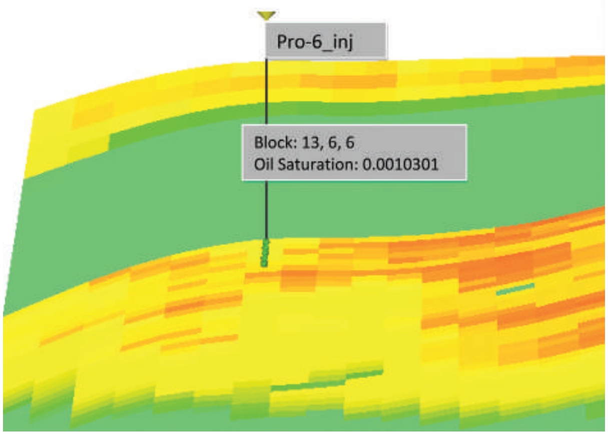

Figure 2
Perforation intervals for region 1 (1/3) position of total net pay thickness.

- Case 2: Perforating region 2 (1/3, 2/3 and 3/3) position of total net pay thickness Figure 3.

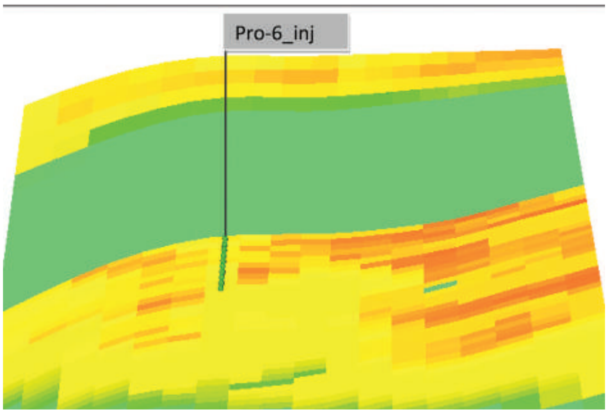

Figure 3
Perforation intervals for region 1 (2/3) position of total net pay thickness.

- Case 3: Perforating region 3 (1/3, 2/3 and 3/3) position of total net pay thickness figure 4.
- Case 4: Combining best perforation intervals for each region.

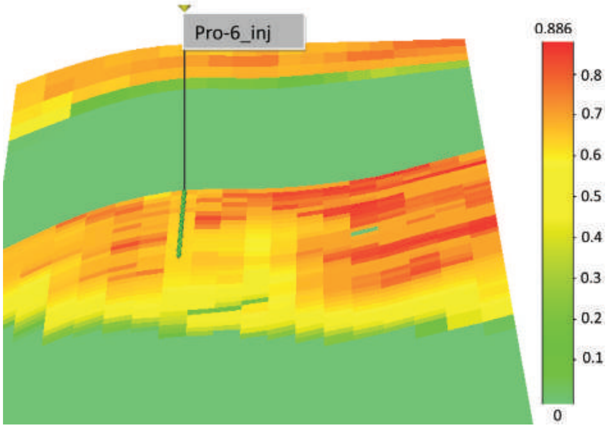

Figure 4
Perforation intervals for region 1 (3/3) position of total net pay thickness.

15 scenarios have been executed for each region (Region 1, Region 2 and Region 3), by perforated the region into three intervals 1/3 upper, 2/3 middle and 3/3 lower from net pay thickness of the region separately, combining best intervals for each region, for both injectors and producers wells, which gives maximum oil recovery factor has chosen as base model to conduct the EOR methods. Finally, three techniques of thermal EOR will be investigated and evaluated, by comparing the results of simulation and forecasting by put oil recovery factor and oil flow rate at the end of simulation period as objectives function of this study. Selected optimum method of thermal EOR executed in the pilot test sector, will be implemented in the entire "FUL" Oilfield.

These methods are:

1. Continuous Steam Flooding.
2. CO2-assisted Steam flooding.
3. Cyclic Steam Stimulation CSS.

Field Overview

- **Field Description**

The "FUL" Oilfield lies about 9 km north of the Fula field in Sudan's Fula Sub-basin. It is structurally subdivided into four main blocks: X-1 Block, X-2 Block, X-10 Block and X-N Block. X-1 Block will be studied in this research. There are three hydrocarbon-bearing formations that have been proven (F2, F3, and F4). With F3 being the primary pay zone it will be the target for this study.

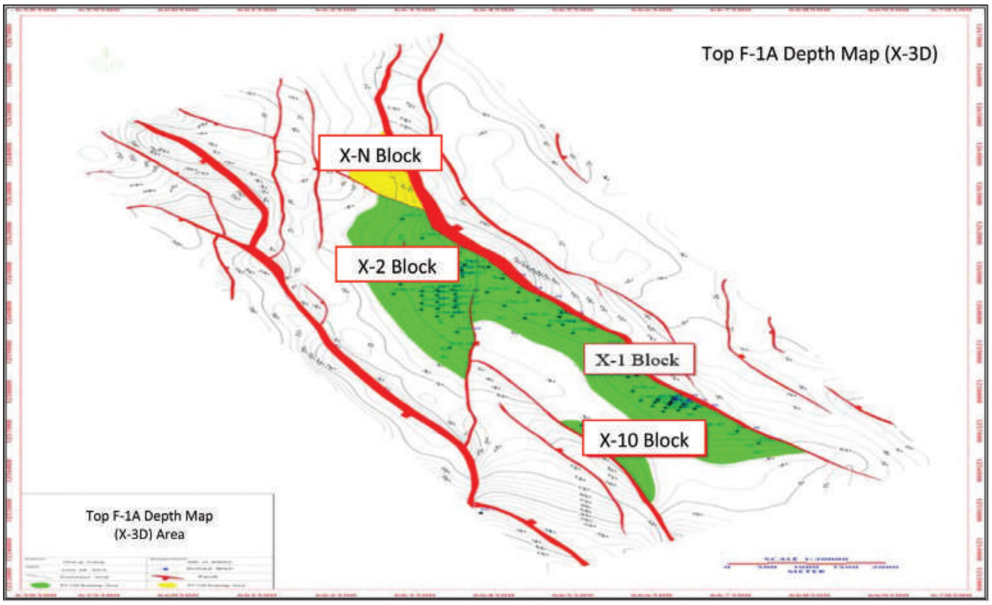

Figure 5
Structure map (Petro-Energy, 2020).

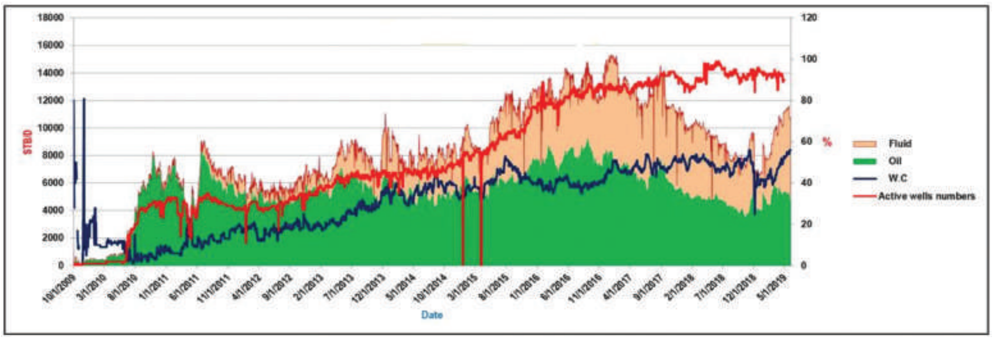

Figure 6
Production performance from 2009-2019 (Petro-Energy, 2019)

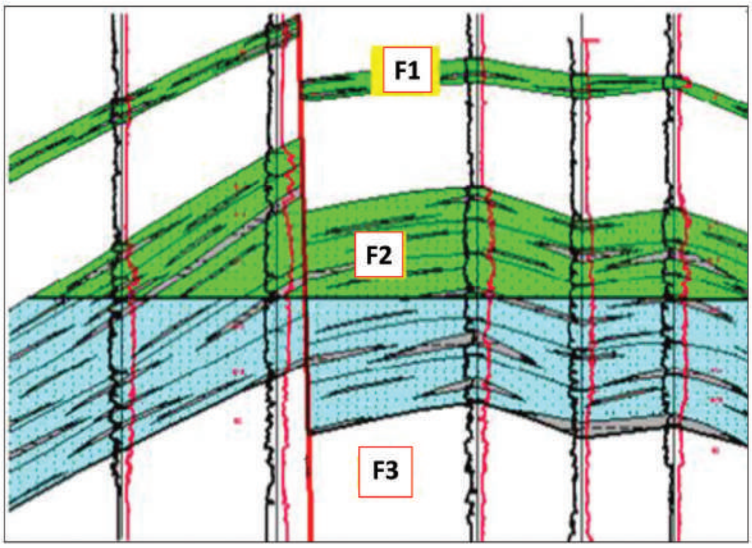

Figure 7
Reservoirs cross section map (Wu et. al., 2013)

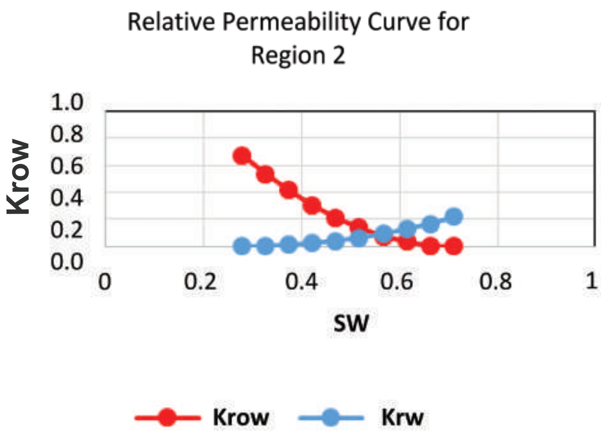

Figure 8
Relative permeability curve for region 2

By March 2018, a total of 117 wells had been drilled, including one horizontal well; 116 wells have been put into operation, of which 21 wells are producing as cold, 82 wells for cyclic steam stimulation. 13 wells for steam flooding. The total original oil in place of 311.1MM STB, estimated ultimate recovery (EUR) is 113.39 MMSTB, cumulative oil produced (N_p) is 18.5 MMSTB and the up-to-date recovery factor of is 5.95%. (Petro-Energy, 2019).The structure map of “FUL” Oilfield is seen in Figure 5.

- **Production History**

“FUL” Oilfield was put into production in October 2009 with cold production, water cut of 52%, , 111 wells were opened with a daily oil production of 5,312 OSTB/D. Highest oil production rate (9,264 STB/D) was on Sep 5th ,2016. Figure 6 shows production profile for the field. (Elbaloula et al, 2020).

- **Reservoir structure**

The Aquifer energy in the F3 is massive and strong, but it is weak in F2. As can be seen from Figure 7 the cross-section map, the whole deposit is a stratified structural (lithology-structural) reservoir with weak to strong aquifer energy in zones below. F3 reservoir has a relatively good quality with porosity ranging from 17 to 40%, permeability ranging from 100 to 11000 mD. The input of relative permeability tables is mandatory for reservoir modelling, and this information is one of the most important factors influencing the recovery factor obtained from the model. Water wet rock is represented in this reservoir. The relative permeability curves for region 2 obtained from “FUL” Oilfield are shown in Figure.

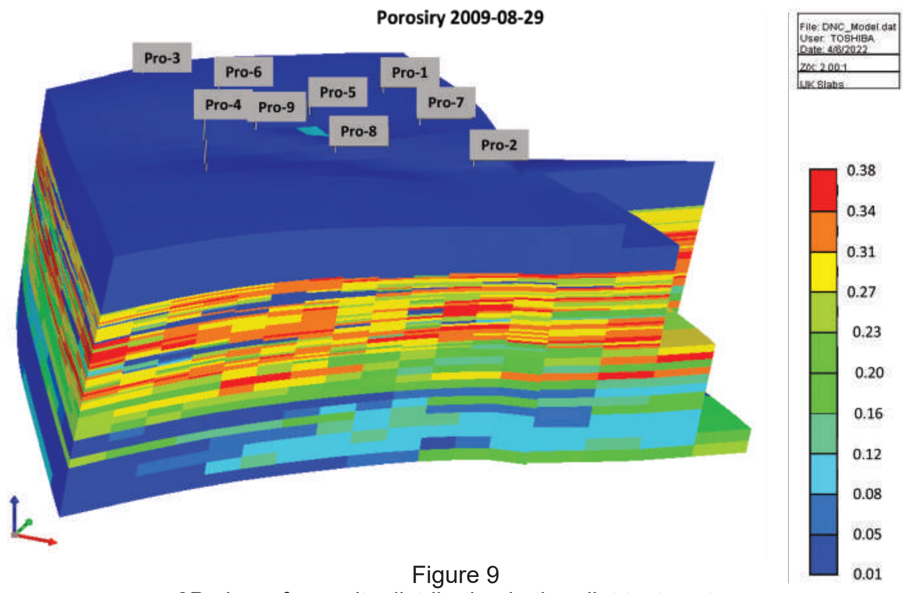

Figure 9
3D view of porosity distribution in the pilot test sector

- **Reservoir Simulation**
  - **Building dynamic model**

CMG software is a dvanced thermal process reservoir simulator has been used which includes options such as chemical/polymer flooding, thermal applications, steam injection, horizontal wells, dual porosity/permeability, directional permeability, flexible grids, fire flooding and many more. The geological model exports essential properties distribution (including elevation, bulk volumes, net to gross, porosity, horizontal permeability, vertical permeability, and water saturation) directly to the simulated dynamic model. Based on fluid gradient, altitudes, and datum pressure, initial reservoir pressure is determined for all grid blocks.

The pilot area has been cut as sector model from the whole "FUL" Oilfield static model and then used for initialization, and prediction using advanced thermal EOR simulator. The grids number of models is 18 × 16 × 58 = 16,704 cell size is dx = dy = 32.5 m, dz = 1.66 m, and vertical formation includes A-D, AY, X1a, X1b, X1c, X1d, X1e and X2.

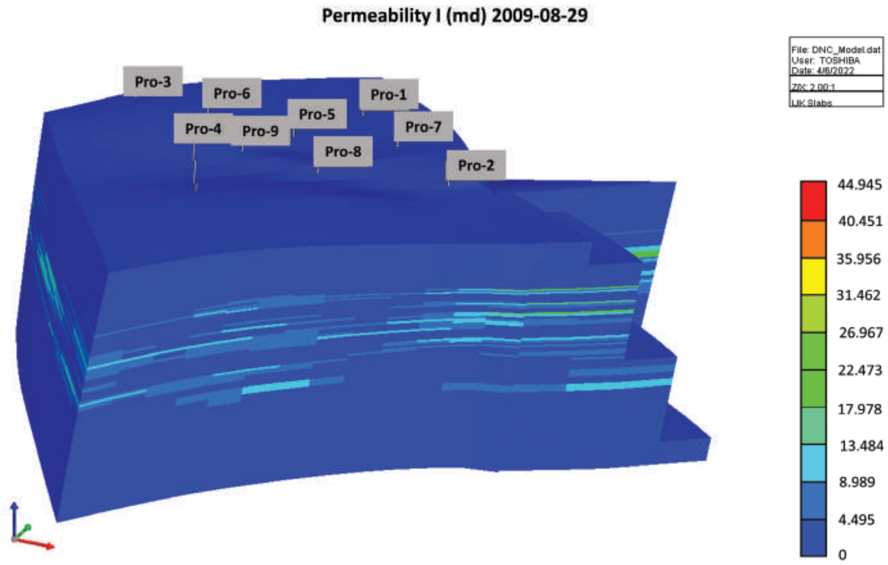

Figure 10
3D view of permeability distribution in pilot sector test.

- **Pilot area selection**

Screening of the "FUL" Oilfield with steam flooding and steam flooding combining with gas injection and CSS were undertaken to determine the optimal location for the pilot; the following aspects are considered:

- The Pilot section must contain a lot of reservoir resources, so the characteristics of the pilot's area may represent the oil field's overall level.
- Sand body between the producer and the injector must have strong connectivity and a uniform oil–water interface, and the interlayer should be completely examined to ensure that the injected steam performs well.
- Now, certain wells' daily oil production is dropping, and the water cut is rather significant. To aid optimization, a dynamic analysis must be carried out.

Figures 9, 10 are show the distribution of porosity and permeability in the pilot test sector respectively.

RESULTS AND DISCUSION

The simulation is started on January 2022 until January 2042; it means that the duration of pilot test is assumed in 20 years. Cyclic steam stimulation technique has conducted in specific wells (Pro-1, Pro-2, Pro-3, and Pro-4), in this SCTR for various times after that the entire SCTR put into production with cold. Current situation of the pilot test SCTR has reviewed and appraised before any pilot test scenarios could be performed out. Some characteristics were examined in this study, including the perforation of currently producing wells, and production performance for do nothing case. From table 1, we can see that current wells with DNC production shows lowest recovery. The oil production is declining rabidly after CSS stopped in 2016 and almost stopp by the end of the simulation period (4 m^3/day), due to high oil viscosity which makes the oil stop to flow to the wellbore and then to the surface. The recovery factor of current wells case is also does not encourage. we have only got 12.20% from original oil in place OOIP in the SCTR. Based on these results, we can say that this scenario is not recommended for this pilot SCTR and will not be profitable. Also, as we've seen from the table of results above, there is no effect that could be considered after EOR design by adding new two wells and convert two wells from producer to injectors, which gives slightly higher recovery 12.57%. The case of implementing continuous steam flooding shows that steam flooding could doubl the recovery factor and increase the performance of wells in the SCTR under study, which gives 25.24%. In the next step, through a comprehensive analysis and optimization of the perforation intervals, injectors and producers' wells will be examined in different cases and scenarios, by conducted three different techniques of thermal EOR, continuous steam flooding, CO2-assisted steam flooding and cyclic steam stimulation combining steam flooding, will be investigated, and analyzed.

Table 1
Recovery factor for different optimization methods

Scenario	Oil Rate (m^3/Day)	Oil Cumulative (m^3)	RF (%)
Current Wells	4.90	0.55×10^6	12.20
EOR Design	4.58	0.57×10^6	12.57
Steam Flood	67.35	1.15×10^6	25.24

Feasibility of steam flooding EOR in pilot test sector

It is recommended that before implementing the EOR scenarios, the EOR approach that will be applied to optimize the pilot test SCTR will be investigated. Four injection wells were employed in this feasibility study of implementation steam flooding as candidate EOR method, with the sensitivity analysis for steam parameters. And compared to the DNC case. Figure 11 and table 1 illustrate the outcomes.

- **Designing of EOR scenarios**

There are three cases under study and evaluation,

1. Case 1: Continuous Steam flooding.
2. Case 2: CO_2-Assisted Steam flooding.
3. Case 3: CSS Combining with Steam flooding.

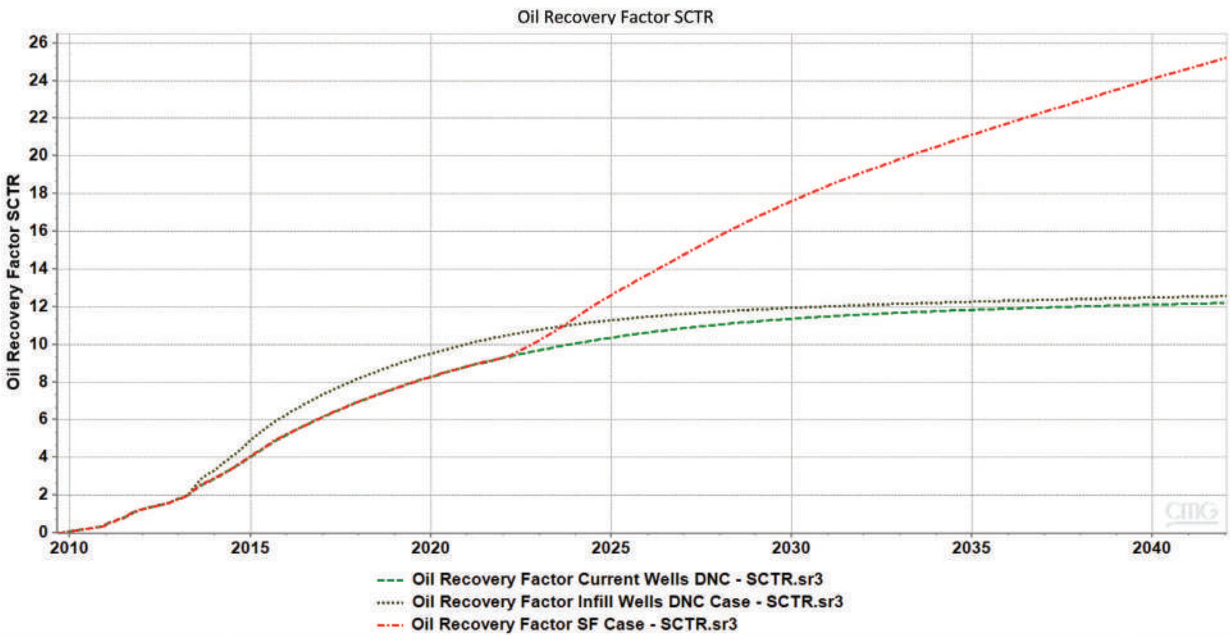

Figure 11
A Comparison between various cases

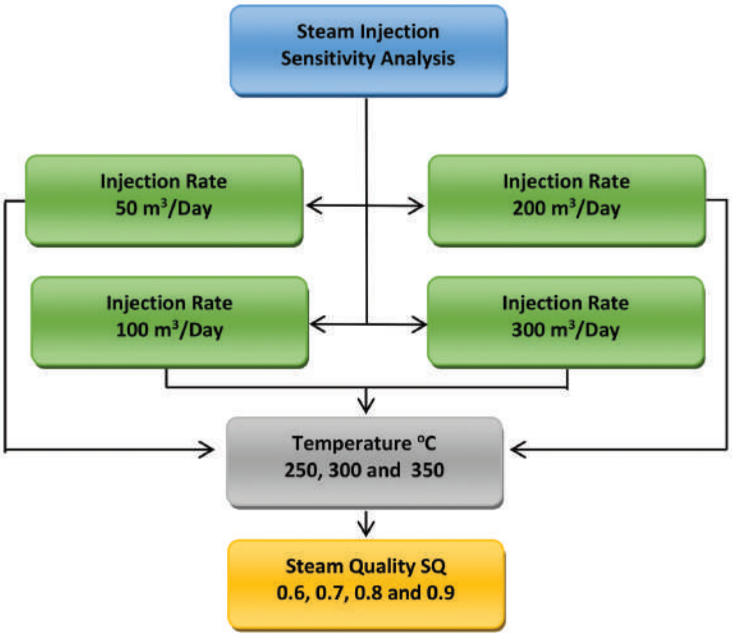

Figure 12
Flow chart of deterministic approach.

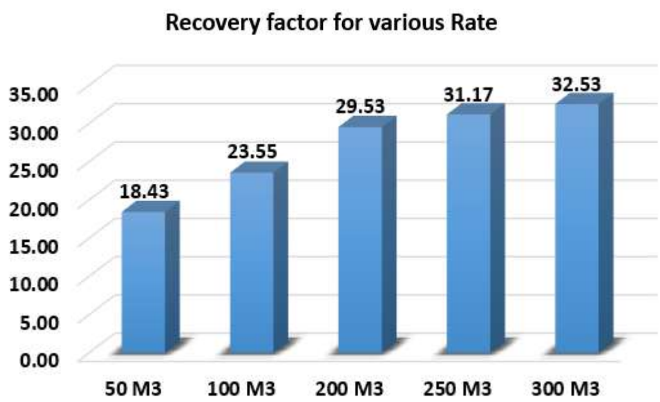

Figure 13
Optimization for steam injection rate of 300 m3/D

- **Continuous Steam Flooding *(Base Case)***

After conducting a comprehensive optimization for the perforation intervals, steam injection parameters that will be used for the development plan of pilot test SCTR case needs to be determined and optimized. Optimization of steam parameters to determine best parameters for steam will be done manually using CMG STARS simulator as the deterministic approach and using CMOST tool as AI to do the optimization for the stochastic approach.

Deterministic Approach for Steam

Before performing the optimization, each of the parameters has to be ranged from a minimum to the maximum values.

So, that value will not exceed the capacity limit for the steam generator/boiler as well as to extend the life of the boiler. The range of each parameter is mentioned in Figure 12. Manual optimization was done for each of the steam parameters manually and it took 60 simulation runs to create. The results of the optimization for various flow rate of steam as oil recovery objective function are shown in Figures 13.

The most dominant parameter is steam injection rate, for each run showed that increasing the steam injection rate will continuously increase the oil production and recovery factor, while increasing the steam Pressure/ temperature and steam quality will slightly increase the oil recovery. The optimum sce-

Table 2
CMOST Model settings and steam parameters

CMOST Model Setting

Study Type	Optimization	Parameters	Min	Max
Number of Experiments	80	Injection Rate, M3/D	50	300
Experiment Duration	2 days 4 hours	Temperature, °C	250	350
Result Obtained	End of Simulation	Steam Quality	0.6	0.9
	Recovery Factor	Injection Pressure, kPa	6550	9307
Objective Function	Cumulative Oil			

nario consists of the following: steam injection rate of 300 m^3/D, the steam temperature of 250 °C, and steam quality of 0.9. With maximum oil recovery factor 32.53 % and highest cumulative oil 1.4 MMm^3.

- **Stochastic Approach for Steam Flooding Optimization**

In this study, CMOST from CMG suits as AI is used to perform the optimization of steam injection parameters to give the highest production performance. By usi ng stochastic approach. The setting used for the CMOST optimization is shown in Table 2. Figures 14,15, and 16 show the result from the CMOST optimization also showed that rate of the steam injection is the most influencing parameter in the optimization. The parameters selected for the optimization are represented by an experience ID No. (77), with high oil recovery factor 31.96%. however, there is a slightly decrease from the manual method. Then, the results could be summarized as following: From the results which is tabulated above, we can choose manual approach as the optimum scenario for continuous steam flooding method, with highest oil recovery factor 32.53% and 45.95% inside pattern. With steam parameters of: steam injection rate of 300 m^3/D, steam temperature 250 °C, steam quality

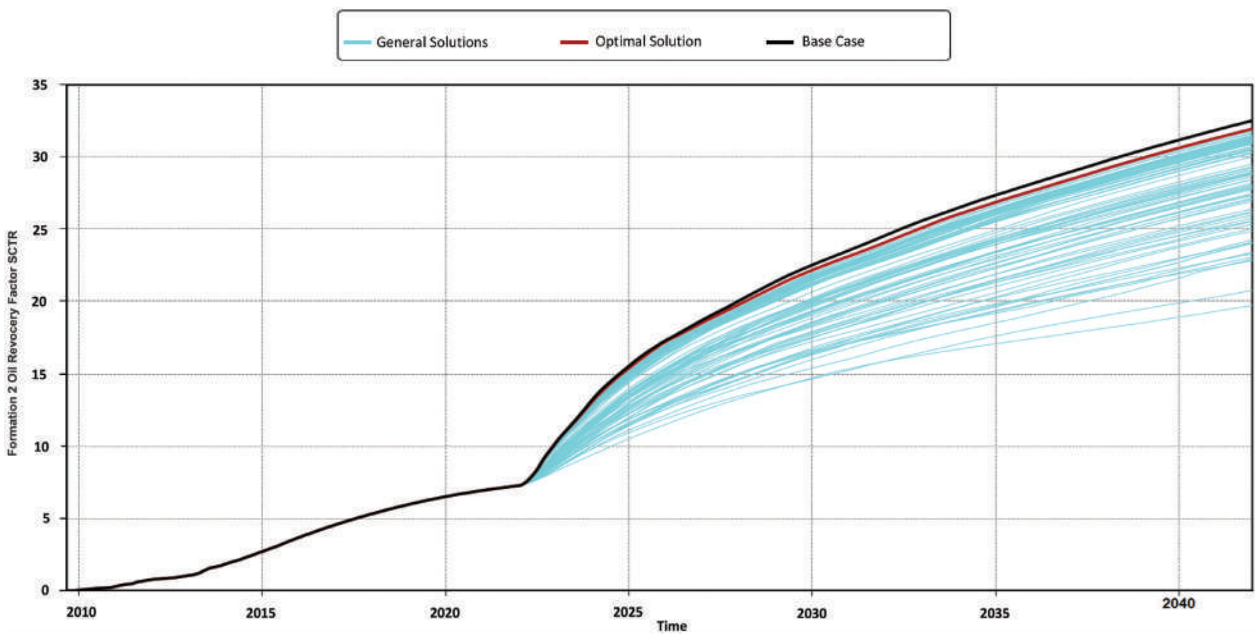

Figure 14
Optimum recovery factor

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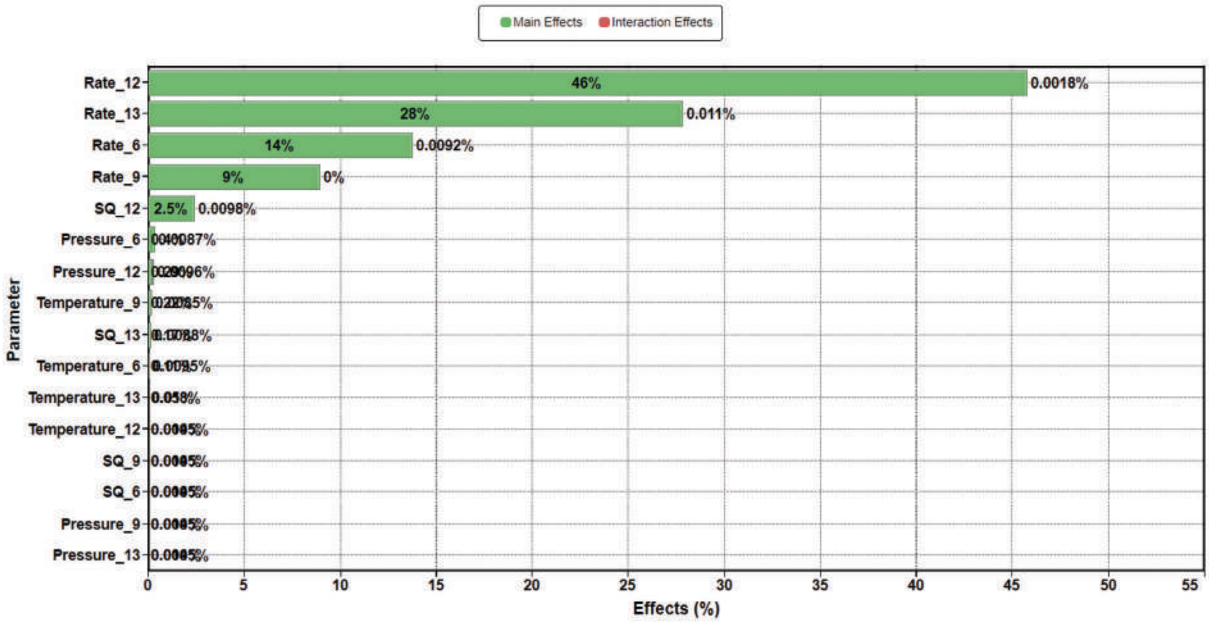

Figure 15
Sobol analysis for R.F objective function

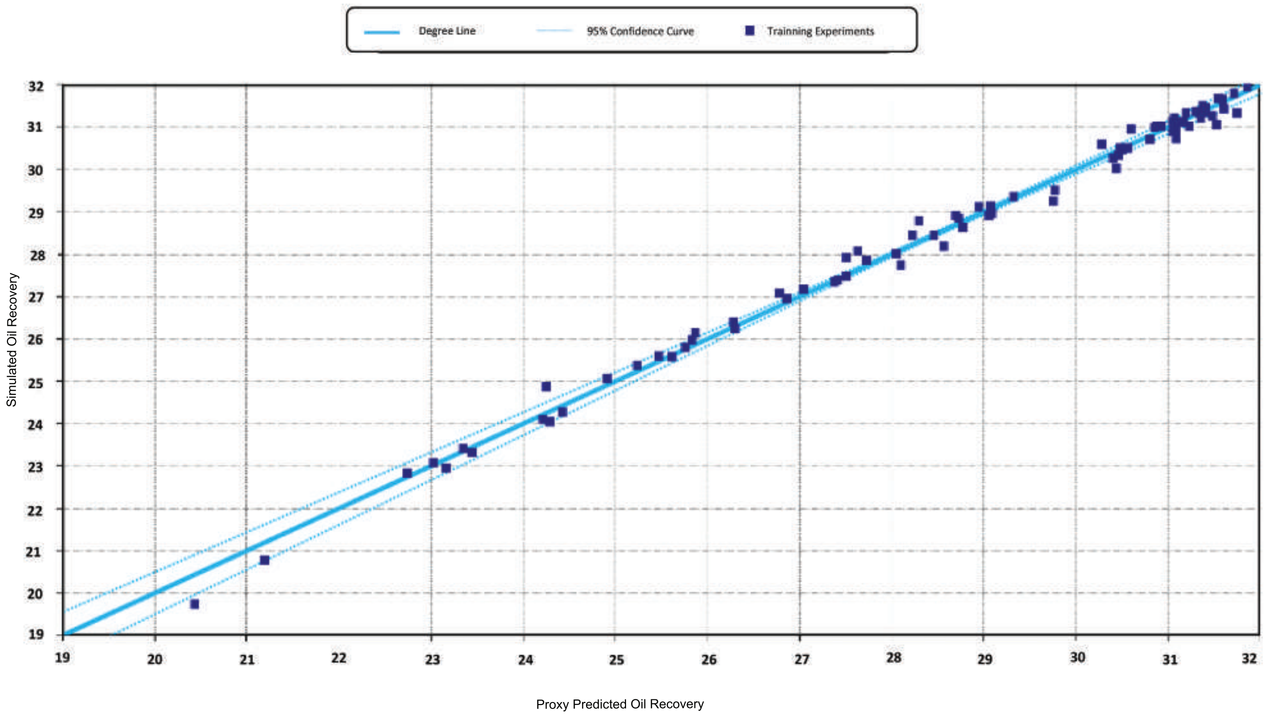

Figure 16
Model quality control for R.F objective function.

0.9, and injection pressure 7928 Kpa.

Temperature distribution of the injector's wells at the end of the simulation period could be plotted as shown in Figure 16.

- **CO_2 Assisted Steam Flooding**

In the later stages of steam flooding, difficulties such as low oil-to-steam ratio, excessive water cut, and steam channelling are common, and with the

Table 3
Optimum results for two approaches

Parameters	R.F, (%)	Cumulative Oil, m^3
Deterministic Approach	32.53	1.48×10^6
Optimum Solution Inside Pattern	45.95	1.39×10^6
Stochastic Approach	31.96	1.45×10^6
Optimum Solution Inside Pattern	44.76	1.2×10^6

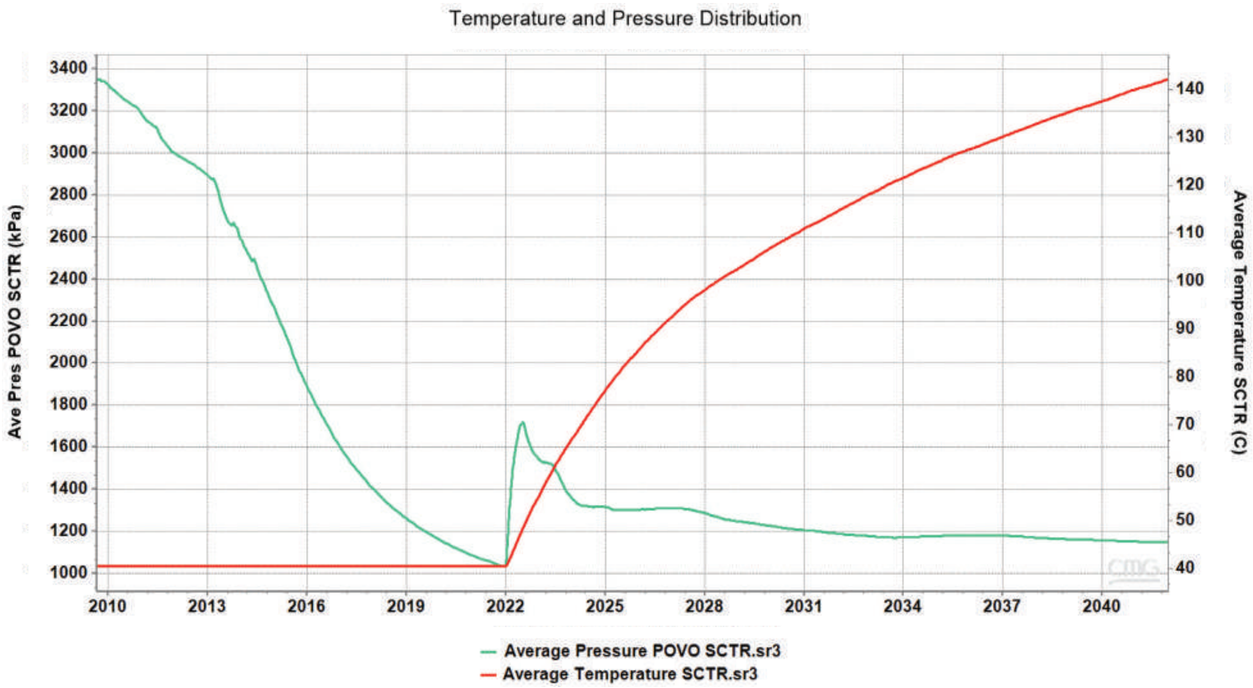

Figure 17
Temperature distribution

economic advantages becoming increasingly poor, the steam flooding must be terminated. As a result, finding novel reservoir development methods is critical. CO_2 could increase oil recovery factor by swelling and lower viscosity the heavy oil in immiscible condition. Conducting CO_2 assisted by steam flooding at late stage of the operation of steam flooding could increase the oil recovery more than 15.6%, based on an experimental study which conducted in J6 block in Xinjiang Chinese heavy oilfield (Changfeng et. al., 2019).

Three scenarios with different late stages of conducting steam flooding will be under study with sensitivity of temperature of CO2, various scenarios will be built.

- Scenario 1: Applied CO2 injection after W.C reach to 85%.
- Scenario 2: Applied CO2 injection after W.C reach to 90%.
- Scenario 3: Applied CO2 injection after W.C reach to 95%.

The characteristic of injected standard CO_2 can be seen in the Table 4 as follow.

CO_2 injection parameters are almost the same as steam injection. Injection pressure in the surface is 1000 psi, and the injection rate is 500 MSCF. The sensitivity analysis of injecting CO_2 in these scenarios would be done by changing its injection temperature. The range of injection temperature sensitivity is about (100 – 600) °F. For comparison, we also simulate a case that use CO_2 injection only

Table 4
The Characteristic of Injected CO_2

Molecular Weight, g/mole	44.01
Critical Pressure, Psia	1073
Critical Temperature, ° F	87.9
Density (32 F, 14.7 psia), Ib/gal	0.12
Specific Gravity (32 F, 14.7 psia)	1.524
Specific Heat (32 F, 14.7 psia)	0.199

started from beginning (2022) with no steam injection. Other technique has conducted by adjusting the perforation intervals after steam channelling when water cut reached 85%, 90% and 95%, after that steam injection was ended. Then the perforation intervals of the injector wells were adjusted by perforating the lower half part of the lower oil layer for CO2 assisted steam flooding stage. The steam assembly around the production well follows the rules of vertical development from top to bottom, and the steam assembly near the production well has a greater vertical distance from the perforated section at the bottom of the reservoir, preventing steam production from the upper reservoir section. Figure 18 and Table 5 below show the simulation result of optimum oil recovery for each scenario. From the results that are obtained, we can figure out that CO2 injection itself (without steam) for scenario 1, scenario 2 and scenario 3 have less recovery factor which has only approximately 15.21%, 15.21 and 15.45 respectively, because the condition of applying CO2 is not suitable for either miscible or immiscible phase, In comparison with CO2 assisted steam flooding have a considered change in the R.F 26.00%, 34.59% and 44.54 respectively. Because there is a little change in the condition of reservoir after applying steam injection. Figure 19 shows the effects of applying CO2 assisted steam flooding in different scenarios Although, decreasing in water cut after injecting CO2 earlier (When W.C is close to 85%) but also there is a decreasing in the oil recov-

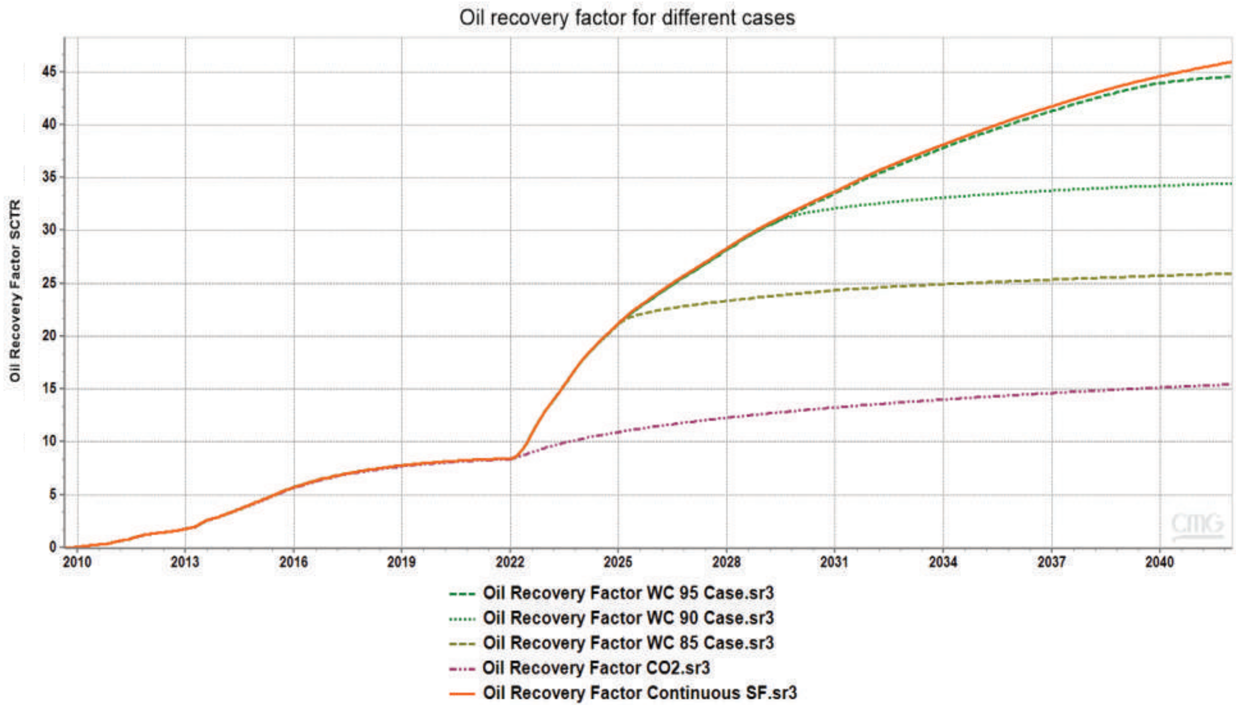

Figure 18
Recovery Factor for the different scenarios

Table 5
The Results of CO2 assisted steam flooding

	W.C (%)	Cum. Oil (M3)	Oil Rate (M3/Day)	R. F (%)
Scenario 1	56.84	0.73×10^6	7.32	26.07
Scenario 2	66.59	0.97×10^6	8.59	34.47
Scenario 3	90.74	1.26×10^6	13.87	44.56

ery. The results could be summarized in Table 5.6 as follow: From the results that tabulated above, we can say that scenario 3 has the best oil recovery for the pilot test sector.

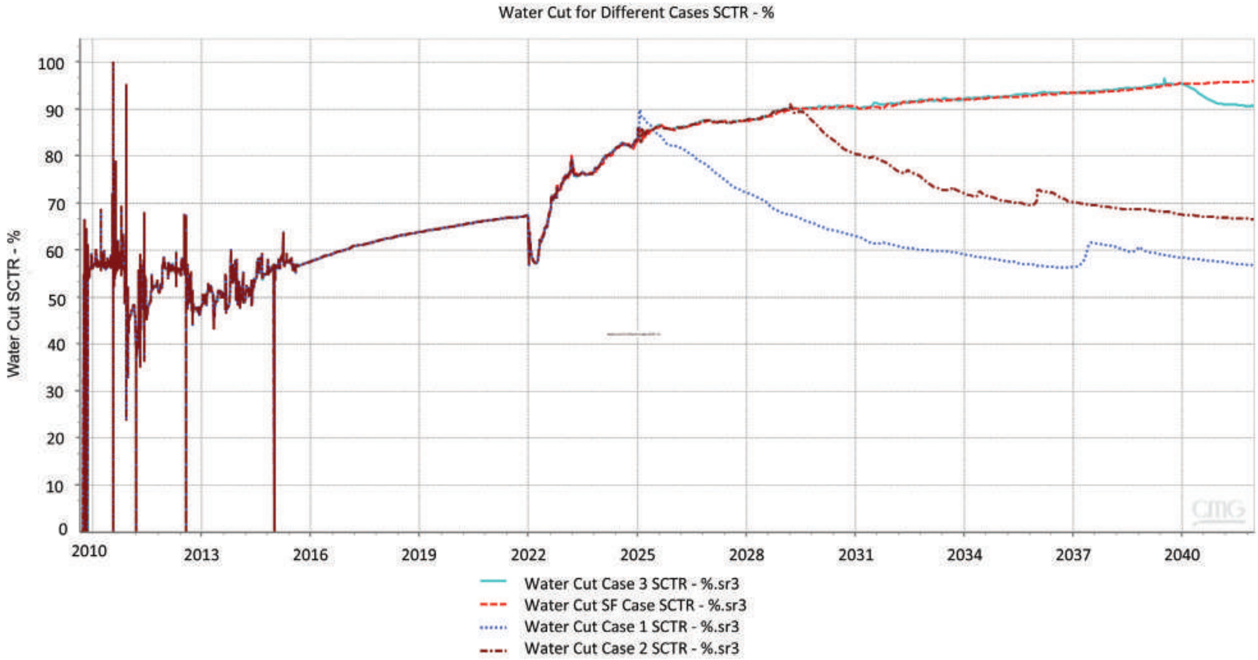

Figure 19
Water cut for different cases

- **CSS Combined with Steam Flooding**

In this case, three cases studied and evaluation, 3 months cyclic period, 6 months cyclic period and 12 months cyclic period. For each case implementation of steam flooding will be after 3 cycles, 4 cycles, 5 cycles and 6 cycles. From the result oil recovery factor, cumulative of produced oil and oil rate determined to compare between them and conclude the technique with the best scenario which give best performance for the sector pilot test, figure 20 shows the oil production rate for this case.

With the same optimum parameters that we have got it from the optimization of continuous steam flooding previously. 12 scenarios will be built, from the literature and field experience, the optimum injection period for CSS is 12 days, followed by soaking period 10 days, then the wells open to produce for 3 months, 6 months and 12 months, according to cyclic period and cases designing followed in this study, after declining the production curve, then the operation will be followed with continuous steam flooding until the end of simulation period in 2042. From the results that have tabulated above, case 1 has the highest oil recovery factor and cumulative produced oil can obtain it by injecting steam after five cycles of 3 months cyclic period case, with 44.05% and 1.2×10^{6} m^3 respectively.

CONCLUSIONS

Over a comprehensive study and evaluation for different cases and scenarios of thermal EOR technique, three EOR methods, continuous steam flooding, CO2-assisted steam flooding and Cyclic Steam Stimulation combined steam flooding were conducted and optimized to select the best case which gives high oil recovery and maximum cumulative oil for the pilot test SCTR.

Oil production at the current wells using do nothing case in the pilot test SCTR gives oil recovery 12.20%. After adding new wells with the same

Table 6
Optimum recovery factor for each case of CSS

Scenario N.O	Operation	Cumulative Oil (m3)	RF (%)
Case 1	5 Cycles + SF	1.24×10^{6}	44.05
Case 2	4 Cycles + SF	1.22×10^{6}	43.23
Case 3	3 Cycled + SF	1.19×10^{6}	42.09

operation of production, slightly increase in the final oil recovery factor just 12.57%. From these results it could say that alter to applying new thermal EOR is necessary.

- Applying a new method such as CO2-assisted steam flooding as pilot test sector and compare it with the previous techniques that have been conducting in the field but in different sector of "FUL", even though CO2-assisted steam flooding might reduce the water cut, it has a little of an impact on the oil recovery factor. over all these methods, continuous steam flooding provides the best oil recovery factor.

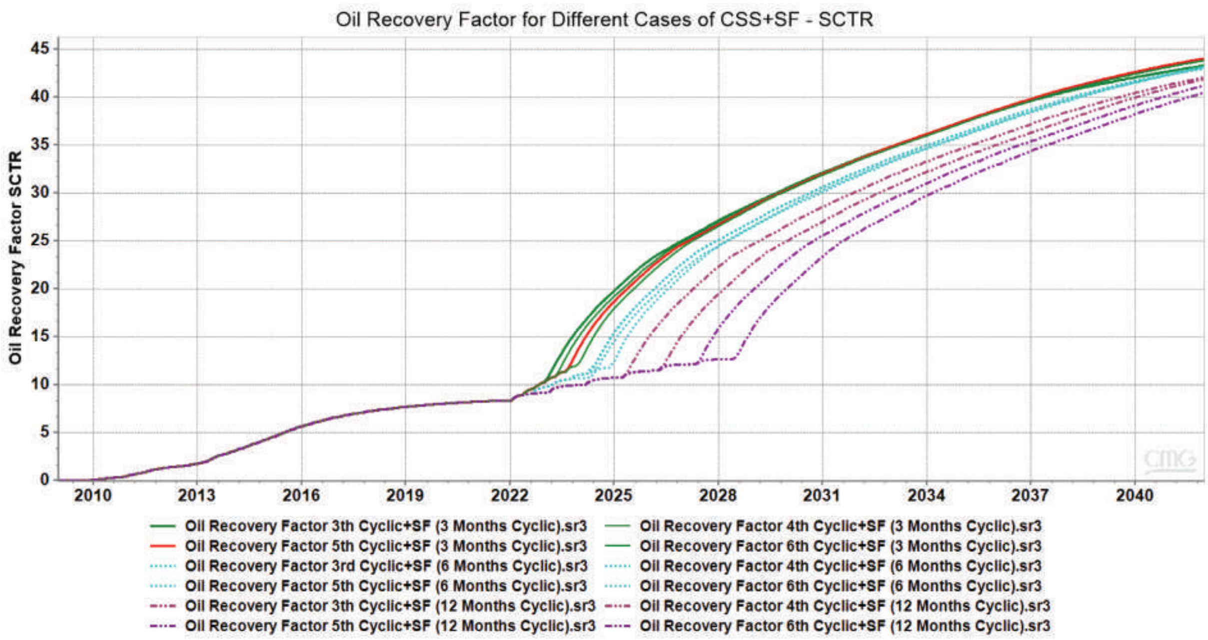

Figure 20
Oil recovery factor (CSS + SF Injection)

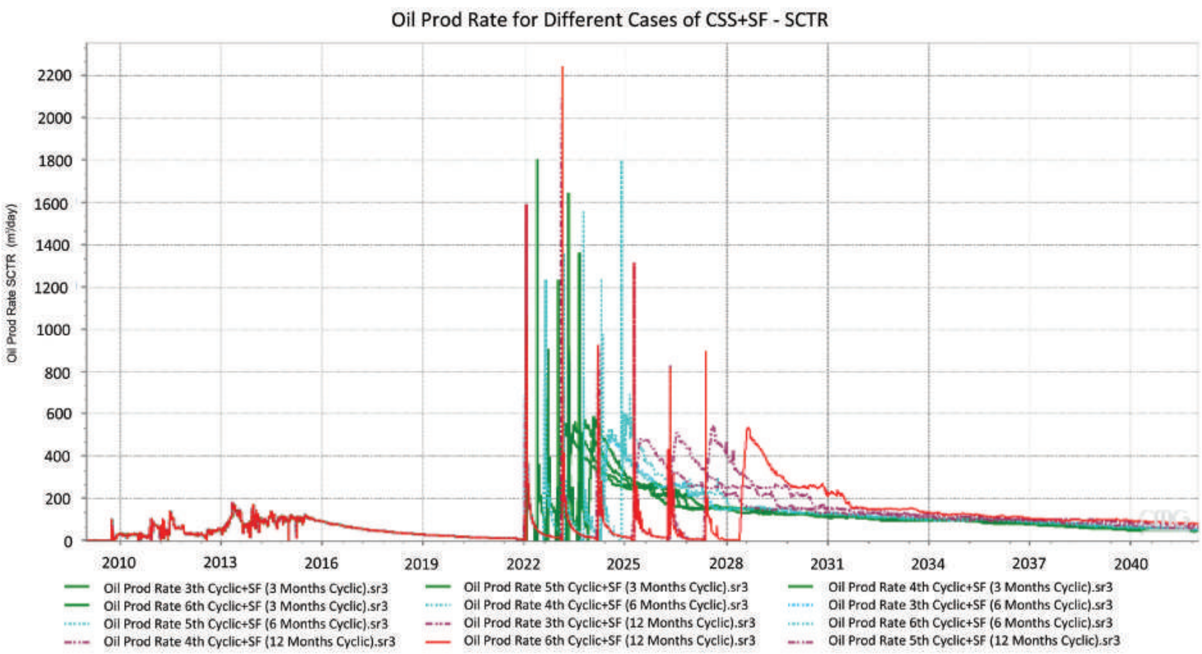

Figure 21
Oil production rate (CSS + SF Injection)

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GLOSSARY OF TERMS

Simbol	Definisi	Unit
CSS	*Cyclic Steam Stimulation*	
SCTR	*Sector*	
CMG	*Computer Modeling Group*	
AI	*Artificial Intelligent*	
RF	*Recovery Factor*	
EOR	*Enhanced Oil Recovery*	
OPEC	*Organization of Petroleum Exportation Country*	
SMEM	Sudanese Ministry of Energy and Mining	
API	*American Petroleum Institute*	
FNE	*Fula North East*	
STARS	*Steam Thermal and Advanced Processes Reservoir Simulator*	
EUR	Estimated Ultimate Recovery	
STB	Stock tank barrel	
F1	Formation 1	
F2	Formation 2	
mD	Millidarcy	
DNC	Do-nothing Case	
OOIP	Original Oil In Place	
SF	*Steam Flooding*	
CO_2	*Carbon Dioxide*	
OP	*Optimization*	
W.C	*Water Cut*	

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