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Comparative analysis of pure CO_2 and CO_2 enhanced polymer flooding: a numerical modelling approach

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Abstract

In this research, the mechanism of pure CO_2 flooding and that of CO_2 enhanced polymer flooding were studied, and their efficiencies as they relate to recovery efficiency, displacement sweep efficiency, oil cumulative recovery, etc., were compared. CMG software was used for the modelling of the EOR techniques herein and STARS simulator was the platform of choice. The results obtained from the simulation studies have shown the CO_2 enhanced polymer flooding to have superior overall oil recovery efficiency of 53% as against the 33% obtained from the pure CO_2 flooding model, thanks to the mobility improvement from the polymer addition. Moreover, the pure CO_2 flooding has less oil displacement sweep efficiency ranging between (40-45%), on the other hand, the CO_2 enhanced polymer showed a significant improvement (70-75%). In the aspect of cumulative oil production, we were able to achieve 1.6 million barrels of oil from the CO_2 enhanced polymer, greater than the 930 thousand barrels recorded from the pure CO_2 flooding. Judging from the results of our analysis, it can be concluded that CO_2 enhanced polymer flooding should be deployed on a larger scale for medium to low viscosity oil reservoirs, as against the use of pure CO_2 flooding. Furthermore, CMG software has been shown to be effective and efficient software for modeling EOR processes.

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Keywords: CO_2 enhanced polymer flooding, CO_2 sequestration, Numerical reservoir modeling and simulation, Oil recovery factor, Chemical flooding

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1. Introduction

Enhanced oil recovery involved the use of different materials like water, chemicals, carbon-di-oxide (CO_2) and liquids of varying kinds and viscosity to help oil flow to production well and to the surface with ease. The ultimate gain from enhanced oil recovery (EOR) is to produce more oil, especially from matured oil fields whose pressure has ultimately dropped significantly, while other techniques like CO_2 sequestration serve the additional purpose of reducing carbon emission. Other techniques involve the use of two or more methods of EOR mentioned above, called the hybrid enhanced oil recovery techniques [1]. The EOR method that makes use of chemicals like polymer, surfactant, nanomaterials, alkaline, or polymer-surfactant-alkaline are referred to as the chemical EOR processes.

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The recent global demand for cleaner energy has made it extremely paramount to devise a means for simultaneously addressing the energy and carbon emission problems. This paves a way for research in areas of enhanced oil recovery that will utilize more than one method of EOR (hybrid EOR). In this research the hybrid EOR that will be deployed involves the use of CO_2 and Polymer (CO_2 enhanced polymer flooding). It is a well-known idea that CO_2 dissolves in both oil and reservoir water, as such increase the volume of the oil phase and improves sweep efficiency, while simultaneously sequestering CO_2 into the reservoir. Hence, prevent carbon emission, which ultimately ameliorates global warming. On the other hand, polymers help improve the viscosity of the displacing phase, and as such improves displacement at a high rate. The polymer EOR technique is one of the under explored techniques but with limited deployment for the EOR process, although over the past years there has been serious deployment and have yielded results. It is highly believed that the alliance of CO_2 and polymer will bring results ultimately, this research will also serve as a bedrock for other research to emerge in this direction [1, 2].

In keeping with the carbon peak and carbon neutrality policies, CO_2 flooding can serve as a very effective oil displacement and geological storage solution at the same time. It also offers other application benefits. However, CO_2 will channel in the reservoir due to an unfavorable mobility ratio and gravity overriding, thus limiting the development impact. Thus, enhancing CO_2 flooding further requires a practical and affordable way to mitigate gas channeling. Through adsorption and retention, polymers can decrease the permeability of beneficial channels, decrease the fluidity of injected fluids, and eventually increase the swept volume. Having an appropriate resistance coefficient and residual resistance coefficient is a need for the effective application of polymers. These coefficients are often used to assess the injectivity performance of polymer solutions [3].

Gas flooding is one method that has been effectively used. Since the 1960s [4], gas flooding operations have been a profitable component of extended oil recovery (EOR) in both conventional and unconventional reservoirs. However, if the gases are incompatible with the application circumstances, they might make the technical feasibility less likely. Ideally, CO_2 helps release oil through several ways, including enhancing microscopic efficiency, reducing oil density, and lowering interfacial tension (IFT) at the miscible state. Currently, flooding with CO_2 has been identified as a useful technique to lessen greenhouse gas emissions and global warming. However, a few issues, including gas fingering, operational parameters, and pressure depletion rates, remained unresolved [4]. The difficulty is in attaining the field incremental recovery, which ranges from 5 to 10% oil originally in place (OOIP), even with the effectiveness of CO_2-water alternating gas (WAG). The gravity segregation effect, the water blocking phenomenon, and the WAG mobility control are to blame for this poor productivity. Furthermore, the technique encountered considerable difficulties in increasing sweep efficiency in highly permeable zones. Water prevented the remaining oil from coming into touch with CO_2 because of the gravity segregation effect, which occurs as the injected fluid moves towards the production wells. WAG mobility control is impractical in high- or medium-viscosity oil. Because the oil and water mobilities in very viscous oil reservoirs are low, the mobility ratio will be large [4]. It is important to note, if mobility ratio M is greater than 1 viscous fingering will ultimately occur. Due to the above reasons the introduction of CO_2 and chemical alliances like polymer, surfactant, and alkaline or nanoparticles becomes inevitable.

Injecting carbon dioxide (CO_2) has developed into an enhanced oil recovery (EOR) technique that is used all over the world. The International Energy Agency (IEA) estimated that there are around 3 × 1011–6 × 1011 bbl of oil resources in the globe that are appropriate for the development of CO_2 enhanced oil recovery technology. This amounts to 14%–28% of the world's present total recoverable oil resources. There are several examples of effective use of carbon dioxide injection to enhance oil recovery in China, Russia, America, and Canada [5].

The enhanced oil recovery process

The process of producing oil from subterranean reserves revolves around recovery. Many problems with the world's energy supply will be resolved if the average global recovery factor from hydrocarbon reserves can be raised above the present levels. At the moment, oil is produced on a daily basis from old or maturing oil fields, and the replacement of reserves is not keeping up with the rising need for energy. The global average recovery factor for hydrocarbon reservoirs is currently between 30 and 40 percent. Advanced secondary and enhanced oil recovery (EOR) technologies can take advantage of this difficulty to potentially improve the demand-supply balance. This article provides a broad review of EOR technologies, emphasizing their possibilities and problems [6]. The price of oil and general economic conditions have a direct bearing on the deployment of EOR. Due in large part to the high cost of injectants, EOR is capital and resource intensive as well as costly. An argument is made that advanced secondary recovery, or improved oil recovery, technologies are a better initial alternative before full-field deployment of enhanced oil recovery (EOR). The timing of EOR is also essential. Only long-term capital and human resource commitments, research and development, a risk-taking mindset, and a goal of ultimate oil recovery rather than quick oil recovery may lead to the realization of EOR potential. Even if EOR technology have advanced throughout time, there are still big obstacles to overcome.

There have occasionally been haphazard and interchangeable uses of the words EOR and IOR. Improved oil recovery, or IOR, is a broad phrase that refers to increasing oil recovery using whatever means possible. For instance, operational techniques like horizontal wells and infill drilling enhance vertical and area sweep, increasing oil recovery. The idea of enhanced oil recovery, or EOR, is more narrowly defined and can be thought of as an IOR subset. A decrease in oil saturation below the residual oil saturation (Sor) is implied by EOR. Oils that are immobile or almost immobile due to high viscosity (heavy oils and tar sands) and oils held due to capillary forces (after a waterflood in light oil reservoirs) may only be recovered by reducing the oil saturation below Sor.

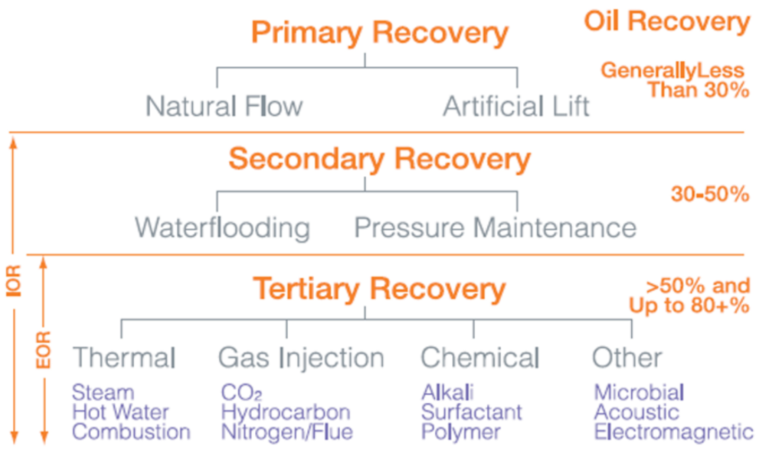

Figure 1: Summary of Enhanced oil recovery process [6].

Since they are successful in lowering residual oil saturation, miscible procedures, chemical floods, and steam-based techniques are considered EOR techniques [7]. The objective of EOR differs significantly depending on the kind of hydrocarbon. EOR is often used for light oil reservoirs following secondary recovery operations, with an approximate 45% OOIP objective. The majority of output from such reservoirs comes from enhanced oil recovery (EOR) techniques since heavy oils and tar sands do not respond well to primary and secondary recovery techniques.

Figure 1 shows the summary of different EOR techniques that are deployed under primary, secondary, and tertiary oil recovery methods. The natural history of oil production from the beginning to the point when it is no longer cost-effective to produce from the hydrocarbon reservoir is followed by primary, secondary, and tertiary (EOR) recovery techniques. EOR procedures make an effort to recover oil that is not possible using secondary techniques. Recovery particularly EOR is strongly correlated with both the price of oil and general economic conditions. Around one-third of the initial reservoir content is recovered globally on average by traditional (primary and secondary) recovery techniques. This suggests that a significant goal for EOR two-thirds of the resource base has been set. Using state-of-the-art EOR and IOR technologies in conjunction with best-in-class reservoir management techniques can increase the recovery factor [8].

Thermal EOR: Thermal EOR techniques, which increase the temperature of the oil and lower its viscosity by introducing heat into the reservoir, are typically used on heavy, viscous crudes. The two most often used techniques for thermal recovery are in-situ combustion and steam (or hot water) injection. Steam flooding, steam aided gravity drainage (SAGD), and cyclic steam stimulation (huff and puff) are three popular techniques utilizing steam injection. When air is injected into the oil during in-situ combustion, the oil ignites, producing combustion gasses that improve recovery as well as internal heat.

Miscible Gas EOR: Another well-liked EOR technique is gas injection, particularly CO_2, which may be used in both carbonates and sandstones for light oil reserves. It is anticipated to become more popular for two reasons: the removal of a greenhouse gas and enhanced oil recovery via miscibility. The majority of the more than 100 commercial CO_2-EOR projects are located in the US's west Texas carbonates in the Permian Basin. A contributing factor in their success has been the inexpensive natural CO_2 that is readily available from surrounding farms and ponds. Weyburn-Midale in Saskatchewan, Canada, is another significant CO_2-EOR project. Here, CO_2 is pumped over the border from a gasification plant in North Dakota. Due to environmental concerns, several more CO_2-EOR projects are being considered (sequestration).

Chemical EOR: The main objective of chemical flooding or enhanced oil recovery (EOR) is to increase oil recovery through one or more of the following methods: (1) mobility control, which involves adding polymers to decrease the injected water's mobility; and (2) interfacial tension (IFT) reduction, which involves the use of surfactants and/or alkalis. The 1980s saw a lot of research and pilot testing conducted, as well as a number of projects launched, mostly in the US. As a result, none of those initiatives was profitable at all. China has been the only country in the previous ten years where chemical EOR, particularly polymer, has proven effective. Chemical EOR has gained fresh momentum because to its success in China and the current rise in oil prices.

Hybrid EOR: As primary and secondary techniques of oil extraction are exhausted due to the depletion of natural oil sources; the oil industry is now compelled to concentrate on tertiary recovery technologies. Chemical EOR (CEOR), one of the Enhance Oil Recovery (EOR) methods, is becoming more well-known. The complexity of extraction techniques is rising despite research attempts to use CEOR to boost recovery. The chemicals that are now employed in CEOR, such as surfactants, polymers, and alkali, no longer work as well due to changes in crude oil characteristics and high salinity, temperature, and pressure in the reservoir. Precipitation, degradation, and other issues have a negative impact on the effectiveness of EOR chemicals in these conditions. Ref [8] said qualities that could endure the impacts of harsh reservoir conditions and changes in the properties of crude oil are greatly enhanced by the synergistic effects between the hybrid components. Thus, the purpose of this work is to evaluate current developments in

CEOR hybrid technologies. It also covers the fundamental idea, uses, progress, and constraints of various hybrid materials that are employed in CEOR processes. Ref. [9] stated that it has been extensively studied that using surfactant and preformed particle gel (PPG) flooding simultaneously on the oil recovery enhancement is a better improved oil recovery strategy than polymer flooding. This research develops a numerical model to simulate the deep effects of PPG/polymer/surfactant hybrid chemical enhanced oil recovery strategies in sandstone reservoirs. Furthermore, the model that has been proposed takes into account the control of gel particle conformance after polymer flooding in order to enhance oil recovery. The developed model is validated and its reliability evaluated using two sets of experimental field data from Shengli oil field (PPG-surfactant flooding after polymer flooding) and Daqing oil field (PPG conformance control after polymer flooding). By blocking very permeable channels, produced gel particles, polymers, and surfactants can mobilize stored oil via porous media to increase the oil recovery factor. This is possible because of the deformation, swelling, and physicochemical features of gel particles. Consequently, PPG compliance control is crucial to improving oil recovery. Additionally, a comparison of the suggested model with experimental field data of PPG/polymer/surfactant flooding in the Shengli field showed that the two are in good agreement. As a result, rather than using simple chemical recovery strategies, the coupled model of surfactant and PPG flooding following polymer flooding performances has produced greater recovery factor.

CO_2 Enhanced polymer flooding

The application of polymer-assisted CO_2 flooding in low-permeability reservoirs is studied extensively in this paper using a systematic study approach. The viscosity properties are first optimized to increase, rheological, salt resistant properties and temperature of the polymer solution. Subsequently, core experiment is deployed to evaluate injectivity performance, resistance increasing ability, and profile-improving effect of the solution, in which case concentration is optimized at optimum level. Lastly, the performance of the enhanced oil recovery (EOR) using polymer-assisted and water-assisted CO_2 flooding were compared in Ref. [10]. CO_2 flooding is very efficient in the development of low permeability reservoirs and can contribute greatly to net-zero emission of CO_2. Although, because of unfavorable viscosity ration and effect of gravity override, CO_2 channeling is bound to happen, and will consequently affect displacement and storage effects. The finding demonstrates that the temperature-resistant polymer surfactant (TRPS) has some viscosity-increasing properties, good temperature resistance properties, and the ability to react with CO_2 to greatly enhance the viscosity of the solution. Although, TRPS exhibits strong injection performance and resistance-boosting capabilities. The concentration of the TRPS solution, injection rounds, and enhanced permeability all cause a rise in the resistance raising factor (η and η') of TRPS-assisted CO_2 flooding. Compared to water-assisted CO_2 flooding, the EOR impact of TRPS-assisted CO_2 flooding is 8.21% greater. The first and second rounds are the most effective, while the third injection round is the best. Data supporting the practical use of polymer assisted CO_2 flooding in low-permeability reservoirs may be obtained from the study presented in Ref. [10].

According to Ref. [11], polymer-alternating gas has been successful in increasing oil production in high permeability zones. Although, some practical aspects affecting its field application were ignored. Hence, this research focuses on bridging the gap of using many different EOR techniques such as CO_2 flooding, water flooding, polymer flooding, water alternating gas, and polymer alternating gas. STARS-CMG numerical simulator is deployed to predict behavior and characteristics of fluid in the reservoir. He uses the design pattern of single injection-single producer (PI) in a homogeneous highly permeable reservoir. To viscosify water, and improve overall sweep efficiency, the use of polymer in water-alternating gas has become a norm. The order of the oil incremental recovery findings was as follows in comparison to flooding with water < 3% CO_2 flooding < (6.8%) water-alternating gas < (11.6%) polymer flooding < (15%) polymer alternating gas. The reduction of water cut % (83%), which is the main indicator of the polymer's influence on improving the water alternating gas, is evident. The uninform u-shape indicates that the improved sweep efficiency was facilitated by the polymer's regulated conformity. In addition, the lowest gas oil ratio of 51.7 M ft3/bbl. was the consequence of the notable delayed gas breakthrough. The finding of a low gas oil ratio suggests that CO_2 may be captured in the reservoir, which provides strong support for the continued use of CO_2 as a green resource.

Ref. [12] examined the effects of water flooding and polymer flooding on reservoir performance using a three-dimensional water-and-oil model and a black-oil simulator. In the oil and gas industry several techniques can be deployed to recover hydrocarbon from the sub-surface of a reservoir. Particularly, water flooding is employed as a conventional method, which can recover at least 10-40% of the oil in place. Polymer flooding involves the injection of polymer into the reservoir to increase water viscosity and hence, improve the viscosity of injected fluid to reservoir fluid to a more favorable value. As thus, vertical sweep efficiency is improved with polymer when compared to conventional water flooding. The performance of the reservoir is merited from results such as; production rates, water cut, cumulative outputs, and oil recovery parameters.

2. Methodology

The water-wet system model employed in this study is a heterogeneous, non-fractured, slightly compressible system that is increased by CO_2 flooding. In every scenario, the simulation is scheduled to run for 5000 days (about 13 and a half years). to calculate the sweep efficiency for oil displacement, recovery factor, and cumulative oil output. CMG Builder was utilized extensively in the Model's creation, where data was entered into pertinent software components. To construct a Model of Choice, one must first decide which kind of simulator to use, when to start the simulation, what kind of unit system to use, and what kind of porosity model to use. all before the Builder's graphical user interface was launched. For this project the same reservoir and grid parameters

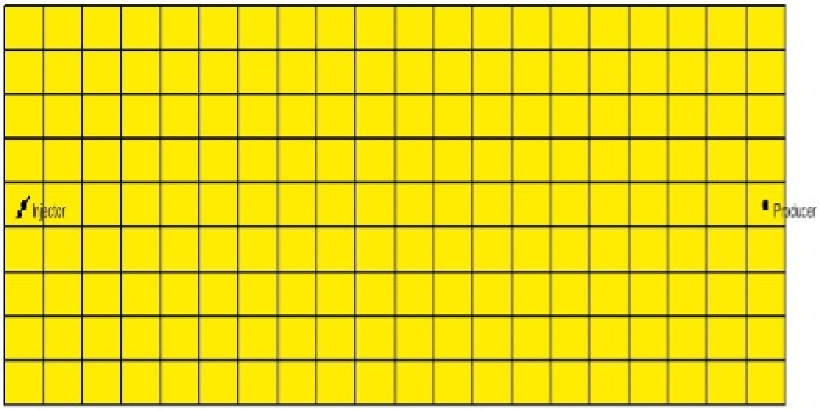

Figure 2: 2D areal view of the reservoir grid showing the injector and producer for the pure CO_2 flooding model.

are used to first run a single CO_2 flood model, and thereafter replicated to inject CO_2 and Polymer to subsequently compare their efficiencies. In order to run an effective model, the following sections of the builder to be outlined below must be populated with data to accomplish desired outcome.

- Input / Output control section
- Reservoir
- Component
- Rock and fluid
- Initial conditions
- Numerical
- Wells and recurrent sections respectively

2.1. *The pure CO_2 flooding model*

he pure CO_2 flood system is designed and run on same grid system to later compare its results to a later CO_2 enhanced polymer flooding to be constructed. A complete explanation of all the sections of the builder as outlined above would be explained.

In this case, the simulation model is allocated using the Grid and the properties of the array. The Cartesian grid system, 20×9×6, is used to design the grid model [13]. This means that there are 1080 grid blocks total-20 grids in the I-direction, each with a block width of 150 feet; 9 grids in the J-direction, each with a block width of 100 feet; and 6 grids in the K-direction, which corresponds to the number of layers. The first layer out of the six is selected as the reference, the grid thickness is taking as 10 ft, and our porosity which is heterogeneous for each layer as follows (0.2, 0.15, 0.08, 0.2, 0.1, 0.1). The permeability for I, J, and K directions are all taking to be 200mD respectively.

Figure 2 shows the aerial view of the reservoir after completing all the important segments of the CMG builder platform. The reservoir pressure is taking as 2000 psia, while the temperature as 120 F to model effectively the reservoir parameters with a reference pressure of 14.7 psia. In essence, the component section is used to simulate the viscosity, fluid type, and other fluid parameters. Alternatively referred to as the PVT data in literature. For the sake of CMG software, all fluid types-hydrocarbon and non-hydrocarbon-are referred to here as components. Two components were employed for this basic case: water and heavy oil. Water was introduced first, and its key characteristics were as follows: molecular weight of 18.015 lb/lbmole, critical pressure of 3208.23 psi, and critical temperature of 705.182 F. However, an oil type that has a molecular weight of 100 pounds per pound mole is also chosen. The following CO_2 parameters were included in the library of the CMG software: molecular weight of 44.01 lb/lbmole, critical temperature of 87.89 F, and critical pressure of 1069.8 psi. Our rock-fluid behavior, rock relative permeability, water-oil/water-gas/liquid saturation, contact types, and capillary pressures are all modeled in the rock-fluid portion. The initial condition, which is chosen immediately after the rock-fluid section is included, establishes the start of the simulation or initial state. Numerical conditions, on the other hand, provide parameters that govern the numerical operations of the simulator, including time-stepping, the iterative solution of non-linear flow equations, and the solution of the linear equations that follow. The first need for this research is not to do calculations for

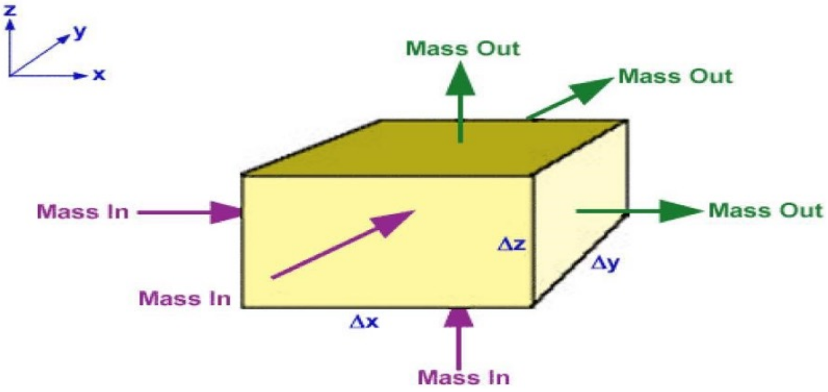

Figure 3: Showing 3D control elemental volume for the mathematical modeling.

vertical equilibrium (VERTICAL OFF). The isothermal option is enabled with model formulation ZT (temperature flash algorithm), linear solver iteration, and linear solver orthogonalization 150 under numerical conditions. The minimum timestep size (DTWELL) is 0.001day. In order to obtain lowest error for the linear solver, the maximum average scale residual for all equations is set to TIGHT and the model convergence tolerance is set to total residual. In essence, the simulation has a 5000days (about 13 and a half years) period, and the model is constructed with a single injector (I1) and single producer as depicted in Figure 2. To inject pure CO_2, I1 is configured to have a maximum BHP of 4300 psi and a surface gas rate of 1000000 ft3/day. The producer comes last and runs at a minimum BHP of 2000 psi.

2.2. The CO_2 enhanced polymer flooding model

The distinguishing feature between the pure CO_2 flooding and that of the CO_2 enhanced polymer flooding is in the component composition which inculcated the addition of polymer and that of the wells and recurrent section where there is polymer injection. The polymer is added via the process wizard available on the component drawdown, which is an add-in to most recent versions of the CMG software. Under the process wizard drop down single polymer flooding is selected and all the geochemistry is defaulted as no real data or laboratory information is available. After this selection, a polymer of good quality is added under the available components. Using a maximum BHP for the injector to be 5000 psi a little above the reservoir pressure to enable a seamless injection and 1000000 ft^3/day surface gas rate. The injection stream pressure is 1800 psi to inject little water to enable a polymer injection of 10% and CO_2 injection of 80% respectively. Same Producer constraint is maintained as that of the pure CO_2 flooding model for fair comparison. Although, it is important to stress that for a good reservoir model, it comprises of both geological and mathematical modeling.

2.3. The governing numerical solution method

Along with the computer program and geological model, the mathematical and numerical model is the final essential component for reservoir modeling and simulation. The geological model is the one that was created using computer algorithms and software-in this case, CMG as previously described in the process. Ref. [14] stated that Mass conservation, flow equations, and techniques for solving them are all part of the mathematical model. Examine an elemental control volume for both inward and outward mass flow, as shown in Figure 3; for the purpose of this research only the mass conservation would be highlighted. The Flow Equations and Numerical solution methods was highlighted in Ref[15].

2.3.1. Mass conservation

The principle of mass conservation is taking as follows;

$$[Mass\ in] - [Mass\ out] + [Source/Sink] = [Mass\ accumulated/depleted]. \tag{1}$$

Source/sink = Injection (IN (+)) or Production (OUT (-)).

Mass rate:

$$m_{f,x} = q\rho_{f,x}, \tag{2}$$

$$\left[\left(m_f\right)_x \Delta t\right] - \left[\left(m_f\right)_{x+\Delta x} \Delta t\right] + Q_f^* \Delta t = \left[\Delta x \Delta y \Delta z \left(\emptyset S_f \rho_f\right)_{t+\Delta t} - \Delta x \Delta y \Delta z \left(\emptyset S_f \rho_f\right)_t\right]. \tag{3}$$

Let

$$m_{f,x} = m_{f,x}^* \Delta y \Delta z = m_{f,x}^* A_x = \rho_f V_{f,x} A_x, \tag{4}$$

Table 1: The data used for the geological modelling the representing grid and array property.

Grid property	Unit	Value
GRID dimension (I J K)	-	20 9 6
K-direction	-	Down
I-block width	ft	20*150
J-block width	ft	9*100
Thickness	ft	10
Grid top	ft	0
PERM-I CON	mD	200
PERM-J CON	mD	200
PERM-K CON	mD	200
POR	%	(20, 15, 8, 20, 10, 10)
Porosity ref. Pressure	psi	14.7
Compressibility	psi$^-1$	1E-6
Porosity ref. Temperature	F	77
Reservoir Pressure	psi	2000
Reservoir Temperature	F	120

$$\rightarrow \left[\left(\rho_f V_{f,x} A_x\right)_{x+\Delta x} - \left(\rho_f V_{f,x} A_x\right)_x\right] + Q_f^* = \frac{V_b\left(\left(\emptyset S_f \rho_f\right)_{t+\Delta t} - \left(\emptyset S_f \rho_f\right)_t\right)}{\Delta t}, \tag{5}$$

where q= flow rate, in ft^3/day, ρ = fluid density, lb/ft^3,$m_{f,x}$= fluid mass rate, lb/day, $f \cdot x$ = fluid phase in terms of x, $\emptyset$ = Porosity, S = saturation, A = Area, V_b = bulk volume.
$m_{f,x}^*$ = mass flux, which is product of the fluid density and velocity, in lb/ft2*day.
V_f = velocity of the fluid phase, ft/day, Q_f^* = mass flow rate of well, lb/day.
Dividing eq. 5 by the bulk volume Vb and recall;

$$\left[\frac{\partial f}{\partial x} =_{x\rightarrow 0}^{lim} \frac{f(x+\Delta x) - f(x)}{\Delta x}\right].$$

Take the limit as Δx, Δt → 0,

$$-\frac{\partial}{\partial x}\left(\rho_f V_{f,x}\right) + \frac{Q_f^*}{V_b} = \frac{\partial}{\partial t}\left(\emptyset S_f \rho_f\right). \tag{6}$$

Multiplying eq. 6 by V_b resulted to;

$$-\frac{\partial}{\partial x}\left(\rho_f V_{f,x} A_x\right)\Delta x \ + \ Q_f^* = V_b \frac{\partial}{\partial t}\left(\emptyset S_f \rho_f\right), \tag{7}$$

$$A_x = \Delta y \Delta z.$$

Convert Q_f^* volumetric flow rate as;

$$Q^*\,(lb/day) = q_{fsc}\,(STB/day) \cdot \rho_{fsc}\,(lb/SCF) \cdot 5.615\,(SCF/STB)\,.$$

Eq. 7 is the general form of the continuity equation for any kind of phase.
For oil: $-\frac{\partial}{\partial x}\left(\rho_o V_{0,x} A_x\right)\Delta x \ + Q_o^* = V_b \frac{\partial}{\partial t}\left(\emptyset S_o \rho_o\right)$.
For water: $-\frac{\partial}{\partial x}\left(\rho_w V_{w,x} A_x\right)\Delta x \ + Q_w^* = V_b \frac{\partial}{\partial t}\left(\emptyset S_w \rho_w\right)$.
For gas: $-\frac{\partial}{\partial x}\left(\rho_g V_{g,x} A_x\right)\Delta x \ + Q_g^* = V_b \frac{\partial}{\partial t}\left(\emptyset S_g \rho_g\right)$.
We can introduce formation volume factor → $B_f = \frac{\rho_{fsc}}{\rho_f}$ $in\ rb/STB$ in terms of the phase density as;

$$\rho_f = \frac{\rho_{fsc}}{B_f}. \tag{8}$$

3. Results

For the purpose of modelling the entire research work. Table 1. parameters would be used; the acronym CON signifies that the property represents the entire grid. It can be seen that we have six different porosity values for the six layers available in the grid system respectively. It can be seen that our top layer, being zero (0) is our reference layer, for the system modeling. Tables 2 and 3

Table 2: Fluid density data for the pure CO_2 flooding model, showing a three (3) component system, where we have (water, Oil, and CO_2) for the modeling of the pure CO_2 flooding.

Component	Molecular weight (lb/lbmole)	Mole Density (lbmole/ft3)	Mass Density (lb/ft3)	API	Compressibility (1/Psi)	Thermal Expansion (1/F)	Critical Pressure (Psi)	Critical Temperature (Fahr)
Water	18.02	3.464	62.4	9.9	0.00	0.00	3280.2	705.18
Oil	100	0.1451	55	29.0	0.00	0.00	0.00	0.00
CO_2	44.01						1069.8	87.89

Table 3: Fluid density data for the CO_2 enhanced polymer flooding model, showing four component systems comprising of polymer as the fourth component. The properties of the polymer include critical pressure, critical temperature, and molecular weight.

Component	Molecular weight (lb/lbmole)	Mole Density (lbmole/ft3)	Mass Density (lb/ft3)	API	Compressibility (1/Psi)	Thermal Expansion (1/F)	Critical Pressure (Psi)	Critical Temperature (Fahr)
Water	18.02	3.464	62.4	9.9	0.00	0.00	3280.2	705.18
Oil	100	0.1451	55	29.0	0.00	0.00	0.00	0.00
CO_2	44.01						1069.8	87.89
Polymer	8000		62.4				3197.8	705.56

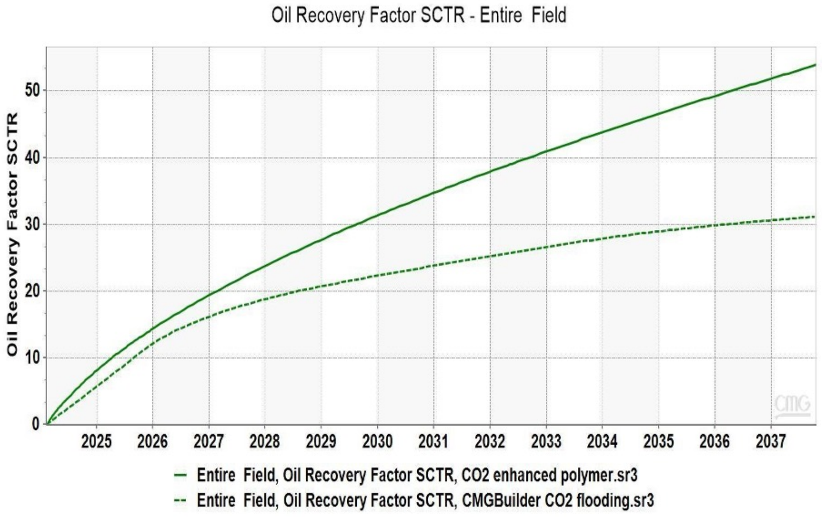

Figure 4: Oil recovery factor from the two models. The recovery factor for the CO_2 enhanced polymer flood is shown in thick green line, while that of pure CO_2 flood in dash green line.

show the data used for the fluid system/ different components used in the research work, Table 2 shows the data (components) for the pure CO_2 flooding while Table 3 for the CO_2 enhanced polymer flooding.

The research focuses on oil recovery factor, cumulative oil production, and volumetric sweep efficiency of both models in Ref. [16]. The result of the findings is compared side by side with one another to make conclusion and to derive which flooding techniques provided superior results in each case.

It is thought that enhanced oil recovery functions in reservoirs when natural energy has run out and the system can only produce a small amount of economically viable oil. Oil dissolving, viscosity reduction, and improvement of flow characteristics, such as surface, interfacial tension, wettability, etc., are facilitated by CO_2 injection. However, due to mobility problems encountered the performance of CO_2 is significantly reduced, hence, it necessitates the introduction of other substances like chemicals, nanoparticles for better performance. In this case the substance added to CO_2 is polymer in a process called (hybrid EOR process) to improve the overall efficiency of the process [17]. EOR techniques, which sequester CO_2 in subterranean reservoirs, can be used to mitigate the escalating trends in carbon emissions and global warming. Millions of cubic feet of CO_2 may be sequestered via EOR process as was the case herein.

Figure 4 compares the oil recovery factor for the two different models i.e., the pure CO_2 flooding and CO_2 enhanced polymer flooding. Based on the result obtained from this research it can be seen that the pure CO_2 flooding although with a good oil recovery

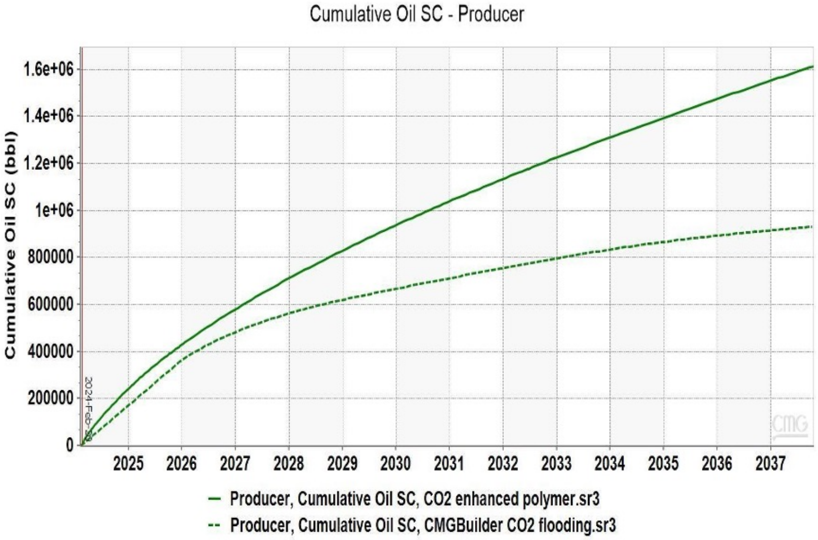

Figure 5: Cumulative oil Productions. The cumulative oil production for the CO_2 enhanced polymer is shown in dark green line, and that of pure CO_2 in dash green.

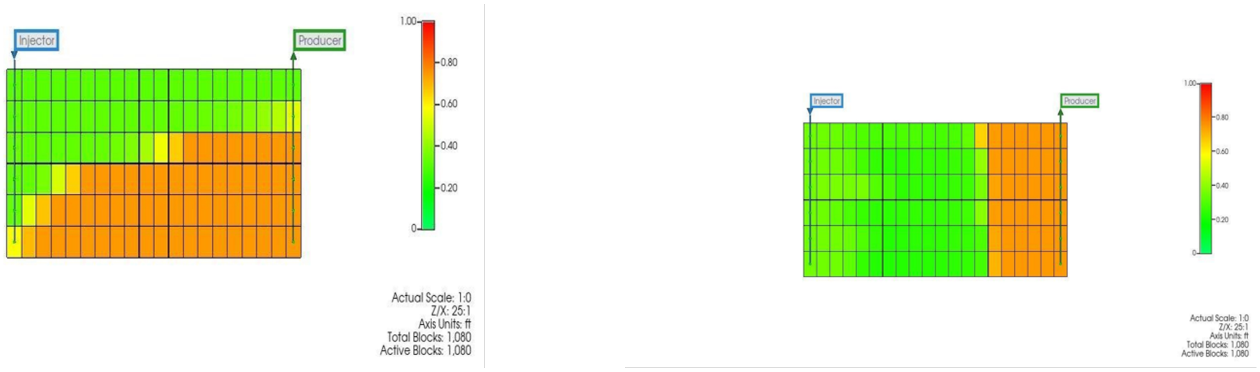

Figure 6: (a) Oil displacement efficiency after 10 years for the pure CO_2 flooding process. (b) Oil displacement efficiency after 10 years for the CO_2 enhanced polymer flooding process.

of 33%, more work should be done to achieve better performance. A good EOR process should yield an overall recovery above 50%. This is due to low mobility ratio from pure CO_2 flooding process since gravity segregation and water blocking pores due to low viscosity of CO_2. In the other model, CO_2 enhanced polymer flooding yielded an overall recovery of 53%. On comparison the CO_2 enhanced polymer flooding possesses superior oil recovery of around 20%, which is evident of the function of the polymer used during the EOR process. Figure 5 depicts the cumulative oil production achieved from the two different EOR techniques deployed herein.

In the aspect of cumulative oil production which is another important factor to be considered to rate the overall performance of an EOR process, the pure CO_2 flooding produced an overall cumulative oil of 930000 bbl. of oil thanks to pressure maintenance from the CO_2 injection well. On the contrary the CO_2 enhanced polymer flooding produced a cumulative oil of 1.6 million bbl. of oil over the years of simulation (5000 days). The incremental cumulative oil production is evident of the performance of our added polymer solution.

Figure 6(a) and 6(b) are very essential as they depicted one of the important parameters for measuring the performance of an EOR technique i.e., the displacement sweep efficiency. Finally, in the aspect of oil displacement sweep efficiency the pure CO_2 flooding has provided around (40-45%) which is not very bad since it is over a period of ten years from the start of the simulation. Although there is room for improvement since the displacement is not up to the desired range, when we deployed the CO_2 enhanced polymer flooding an increase oil displacement sweep efficiency of (70-75%), thanks to the polymer addition. Conclusively, the result has shown an improved performance in the CO_2 enhanced polymer flooding when compared to pure CO_2 flooding.

4. Additional insights to the research

In this research we study the mechanism of pure CO_2 flooding and CO_2 enhanced polymer flooding, and some important parameters like cumulative oil production, oil recovery factor, and oil displacement sweep efficiency were studied and analyzed, before deriving conclusion from them thereafter. Ref. [18] enhanced oil recovery is the process of adding some substances like steam, chemicals, and other substances into the reservoir to improve the production of hydrocarbon to the surface. EOR is the most sought technique deployed in the hydrocarbon industry to optimize oil recovery. This research analyzed and compared two different enhanced oil recovery methods using CMG STARS simulator to model the process. The first model constructed using the same constraint highlighted during this research work, is pure CO_2 flooding, which shows a very good performance when compared to other techniques. Ref. [19] stated that however, the method recorded lower performance when compared to the CO_2 enhanced polymer flooding, which is the second constructed model. It is a common knowledge that CO_2 dissolves in oil and therefore, reduces its viscosity and improve its movement to the production well, on the other hand the addition of polymer improves the viscosity of the displacing phase (water and CO_2) therefore, leading to more oil at the producer.

5. Conclusion

The introduction of EOR to hydrocarbon process industry significantly aided production of hydrocarbons, with aim of cushioning global energy deficit. The techniques range from injecting substances to improve oil recovery or to sequestering CO_2 underground to reduce the emission of carbon to the atmosphere according to Ref. [20]. Based on the above established facts the following conclusions to be outlined below can be carved out from this research.

1. The overall oil recovery factor recorded in the pure CO_2 flooding is in the range of 33% which is not adequate for commercial deployment, while the CO_2 enhanced polymer flooding recorded an improvement of 53% overall oil recovery factor. This has superseded a similar research result by Ref. [21]. This success recorded shows the efficiency of this research work and effectiveness of CMG software for modeling EOR processes.
2. The CO_2 enhanced polymer flooding has shown an increment when compared to the pure CO_2 flooding in the aspect of cumulative oil production. The CO_2 enhanced polymer recorded 1.6 million barrels of cumulative oil while the pure CO_2 injection recorded 930 thousand barrels. Ref. [22] stated that he has conducted similar research and recorded results close to the ones obtained herein.
3. The oil displacement sweep efficiency, which is also an important aspect that signifies the efficiency of an EOR process, has shown pure CO_2 flooding with around (40-45%) displacement over a period of ten years. However, the CO_2 enhanced polymer recorded an improvement to the aforementioned with (70-75%), thanks to mobility improvement gained from the polymer addition [23].
4. The efficiency of CMG software and STARS simulator for modeling EOR projects has been shown, during this research.

The research based its conclusion on three parameters during the work viz; cumulative oil, oil recovery factor, and oil displacement sweep efficiency. In all the parameters, we can see the CO_2 enhanced polymer flooding recorded a superior performance when compared to the pure CO_2 flooding in Ref. [24]. Hence, the aim of the research work is achieved since the CO_2 enhanced polymer provided better results when compared to pure CO_2 flooding, in addition to the benefits accrued through sequestration.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request. As most of the data are generated from the modelling process from Computer Modelling Group Software (CMG).

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