Enhanced oil recovery by CO_2 injection in carbonate reservoirs

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Abstract

The majority of carbonate reservoirs have low porosity and permeability in general because of having a high amount of matrixes that make a heterogeneous reservoir, however high permeable layers are fractured. This study shows the effect of carbon dioxide injection on the oil recovery factor using an ECLIPSE 300 compositional reservoir simulator for 3D modelling and the change of carbonate components reaction during CO_2 injection in experimental work. In addition, a high recovery factor has been recorded during miscible CO_2 injection compared to immiscible injection. Water alternative gas (WAG) has been used as an enhanced oil recovery (EOR) method to overcome an unfavourable mobility ratio of CO_2 flooding. Miscible CO_2 injection with the aid of WAG has also had a great impact on the dissolution of carbonate components in dissolving calcite and dolomite components. Consequently, CO_2 flooding has a relatively low recovery factor without any EOR techniques such as gravity stable displacement, WAG or mobility control. CO_2 injection below minimum miscibility pressure (MMP) reduces CO_2 emission, while it takes too long time to maintain reservoir pressure. On the other hand, CO_2 flooding above MMP improves pressure maintenance; causes oil swelling, and increases the oil density.
Keywords: miscibility, MMP, CO_2 and WAG injections, carbonate reactivity.

1 Introduction

Increasing the amount of greenhouse gases, especially CO_2, in the atmosphere has resulted in climate change and aggravation of global warming which are big concerns for human beings in recent years [1]. In addition, there are number of ways which are mentioned by the authors to reduce the amount of CO_2 in the

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atmosphere, one of them is CO_2 geological sequestration in oil reservoirs. Researchers have discussed that this method cannot only minimise the concentration of CO_2 in the atmosphere, it can also improve additional oil recovery by CO_2 flooding as a method of Enhanced Oil Recovery (EOR) [2, 3].

It has been stated that CO_2 flooding has been started for some decades [4]. Worldwide CO_2 injection have been applied as an EOR method at 76 sites and 67 among them are in the US (50 of these in the west Texas and New Mexico) and the rest in Turkey, Canada and Trinidad [2].

CO_2 flooding has been introduced as injecting a big volume of CO_2, roughly 30% or more of the hydrocarbon pore volume (PV) as shown in Figure 1 [4].

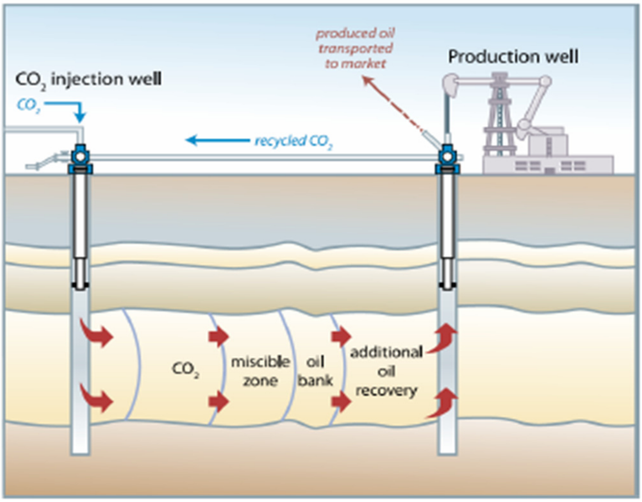

Figure 1: CO_2 flooding process.

Moreover, the main mechanisms of recovery oil by CO_2 injection are identified as; reducing viscosity of oil; swelling the crude oil; lowering the interfacial tension between the oil and the CO_2/oil phase in the near miscible regions; It also produce miscibility since it has lower MMP: and Solubility process [5]. It has been estimated that 40% of the worldwide oil reservoirs are carbonate reservoirs which mostly contain about 1.6 trillion barrel in place of heavy oil [6]. Most of the carbonate reservoirs have been recognised as having heterogeneous, vugs, cavities and comprising fracture in their structures. Having very low permeability and porosity matrix of carbonate reservoirs makes it difficult for the oil to flow through it during primary and secondary recovery methods and it results in very low oil recovery [7].

It is also revealed that water injection is not appropriate candidate to recover oil in the carbonate reservoirs because they are commonly (80%) mixed-wet or oil wet and it causes high water relative permeability [8]. Subsequently, carbonate reservoirs have been selected as good candidates for CO_2 enhanced oil recovery, since CO_2 can obtain miscibility with the oil at low minimum miscibility pressure

300 bars [9]. Although, immiscible CO_2 flooding is not operative in carbonate reservoirs, it is more effective than water flooding in these reservoirs [4]. On the other hand, sometimes early CO_2 breakthrough and poor macroscopic sweep efficiency are resulted in due to viscous fingering and gravity override which are caused by unfavourable CO_2 mobility and reservoir heterogenic in carbonate reservoirs [6]. The injection specified volumes, or slugs, of water and gas alternately is a developed technique to overcome this problem and the method is these called the water-alternating-gas (WAG) process [10].

WAG process has been introduced as a control method to improve vertical sweep efficiency and solve gas fingering because the mobility of each face can be declined by simultaneous flow of the two phases (water and CO_2) and the stability of flood front can improve. The author also mentioned that at immiscible condition with CO_2, WAG can improve oil recovery efficiently and this experienced in some oil fields for both miscible and immiscible processes, for instance, Lick Creek, Kuparuk River, Brage and Gullfaks and in some countries (USA, Canada and recently in Norway) [11].

The aim of this paper is to show the effect of CO_2 flooding on improving the recovery factor and changing porosity and permeability in the carbonate reservoirs. In addition, using of WAG flooding as a control method to minimise fingering and mobility control.

2 Miscibility and minimum miscibility pressure (MMP)

During CO_2 injection, miscibility between the injected gas (CO_2) and residual oil can be created at a higher pressure (at a constant temperature and composition). The pressure which can develop miscibility between the two phases is called minimum miscibility pressure (MMP) which is schematically shown in Figure 2 [12].

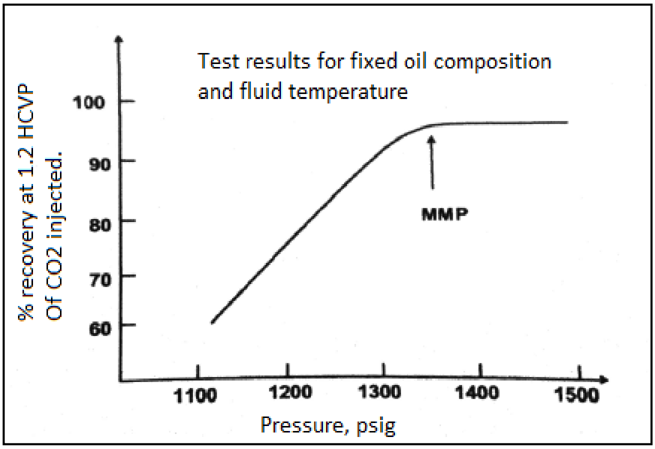

Figure 2: Schematic illustration showing minimum miscibility pressure for CO_2 for a fixed oil composition (Skarrestad and Skauge, 2011 [12]).

CO_2 is not miscible in the first contact with the reservoir oil, however, dynamic miscibility with the oil can be obtained when CO_2 pressure is high sufficient (depends on oil composition and reservoir temperature). Based on this theory, Vaporization occurs at temperatures where the fluid at the displacement front is a CO_2-rich gas, and extraction occurs at temperatures where the fluid at the displacement front is a CO_2-rich liquid [13].

It has been argued that the main factors which impact on miscibility pressure are: 1) high density of CO_2 results in dynamic miscibility as it can dissolve the C_5-through-C_{30} components in the hydrocarbons oil reservoir. 2) Higher miscibility pressure can be attained as a result of high (constant) temperature. 3) Having large percentage of C_5-through-C_{30} fraction causes reducing miscibility pressure. 4) Light components in hydrocarbon crude oils, such as (methane and C_2 through C_4) do not have impaction on the achieving MMP [14].

It has been evidenced that pressure is the principal criterion during CO_2 injection since CO_2 pressure need to be significant to impact on the hydrocarbon components [15]. In order to make distinguish between the two CO_2 flooding (miscible and immiscible) processes, the Minimum Miscibility Pressure (MMP) needs to be known.

The relative values of the reservoir pressure and MMP can be used to distinguish the immiscible and miscible CO_2 injection processes. Furthermore, dynamic miscibility of CO_2 injection can be attended, if reservoir pressure is above MMP. In order to reach dynamic miscibility, reservoir pressure can be increased, although, reservoir fracturing is the big concern of this concept [15].

If MMP is unknown, immiscible CO_2 injection can be achievable, when the oil gravity and the injected pressure are lower than 25^o API and 1450 psi, respectively. Otherwise, if the pressure greater than 3600 psi and oil gravity is higher than 40^o API, then, miscible CO_2 displacement will be practicable [16].

Temperature is another important principle in the successfulness of CO_2 flooding and achieving miscibility since the solubility and density of CO_2 decrease with increasing temperature. Therefore, MMP necessary for given oil have to be increased with normal rising temperature in the reservoir.

3 Simulational strategy and scenarios

Three dimensional (3D) models were constructed in order to analyse CO_2 behaviour in a carbonate reservoir as shown in Figure 3. There were applied different features of the carbonate reservoir in terms of characterize rock properties (permeability, porosity, compressibility) and fluid properties (viscosity, density) of a typical carbonate reservoir. The compositional reservoir simulator (Eclipse 300) model was applying to predict and monitor the effect of CO_2 injection on field oil efficiency and the reservoir behaviour using five spot models involve four injectors (A,B,C,D wells)and single producer (Well P) as illustrated in Figure 3.

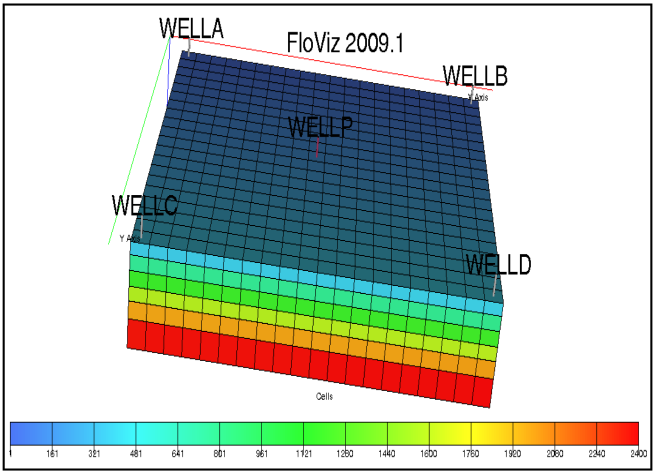

Figure 3: FloViz visualization shows well locations.

CO_2 gas injection was set up to inject under reservoir condition and the wells were located based on the five spot systems. In addition, WAG flooding was performed on the same system in order to compare their results with the two CO_2 flooding processes. The model consisted of four injectors and single producer wells with 20 x 20 x 6 cells. The model included several low porous and permeable layers of the hydrocarbon reservoir. The initial reservoir pressure was about 4000 psi at 5390 ft at temperature of 219°C. The input porosity is ranged about 0.07 to 0.18 with changeable permeability according to X, Y and Z directions. In addition, the model consists of seven numbers of comments (MC_1, MC_2, M C_3, MC_4, MC_5, CO_2, and N_2). The total injection and production period was about 20 years, and the other input data are listed in Table 1.

Table 1: Input parameters to study of the carbonate reservoir.

Parameter		**Value**
No. of global cells		2400 (20 x 20 x 6)
Porosity		0.07 to 0.18
Permeability (x,y,z) [mD]		10 to 77
Initial reservoir pressure [Psia]		4000
Initial oil saturation		0.7
Initial water saturation		0.2
Depth [ft]		6109
Bottom hole pressure [Psia]		3000
Injection rate	CO_2 [MSCFD]	10
	Water [STBD]	200
Oil density [lb/ft^3]		49
Water density [lb/ft^3]		63
CO_2 density [lb/ft^3]		0.117

The oil-wet characteristic is considered in the carbonate rock reservoir for fluid and rock properties by the oil-water relative permeability curve as shown in Figure 4.

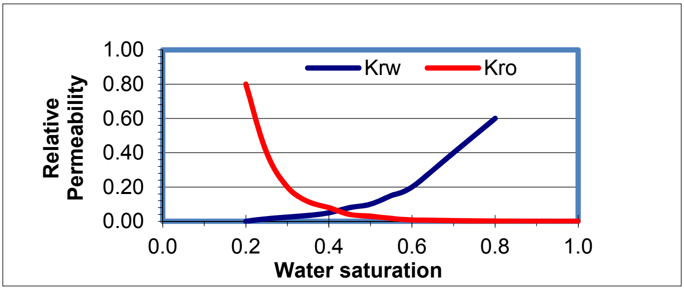

Figure 4: Relative permeability curve for oil–wet (carbonate reservoir).

There was assumed that the reservoir fluid involve oil, gas and water, but, without free gas and solution gas. The gas existing in the reservoir represents only CO_2 gas. When CO_2 gas is injected into the reservoir, CO_2 becomes immiscible with oil at the first contact [7].

4 Geochemical interactions between CO_2, reservoir rocks and pore-waters

Various chemical reactions are another concern of injecting reactive gas (CO_2) into the reservoirs. When, CO_2 is injected into the reservoirs, chemical reaction can occur as a result of interaction between CO_2, cup rocks and reservoir rocks and CO_2 dissolution into pore-water. In addition, the interaction between CO_2, water and the rocks might have positive or deleterious impact on the capacity of CO_2 storage and injectivity process. The carbonate reactivity and its interaction with the rock and pore-water are illustrated in Figure 5 [17, 18].

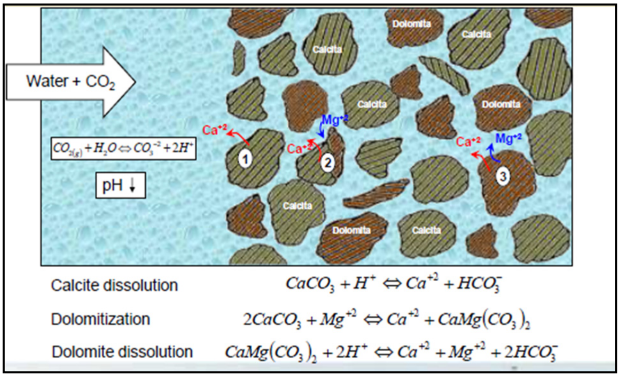

Figure 5: Shows rock fluid interaction (Sengul, M., 2007 [5]).

There have been discussed that several trapping are produced as a consequences of the chemical and mineralogical reactions of CO_2 storage in the deep underground with water and rocks. The mechanisms of the CO_2 trapping are shortened in Table 2 and they are introduced hereafter [7].

Table 2: Possible trapping mechanisms associated with the deep underground storage of supercritical CO_2.

➢ Physical trapping	Increasing
CO_2 'bubble': dense supercritical CO_2 phase	importance with
➢ Chemical trapping	time
• Solubility trapping: CO_2 (aq) or H_2CO_3	⇩
• Ionic trapping: HCO_3^-, $CaHCO_3^+$, $NaHCO_3$	
• Mineral trapping: $CaCO_3$ (calcite), CaMg $(CO_3)_2$(dolomite)	
$MgCO_3$ (magnetite), $FeCO_3$ (siderite), $NaAlCO_3\,(OH)_2$ (dawsonite)	

Physical trapping is produced by buoyant supercritical CO_2 'bubble', however, reaction between formation water and CO_2 could create solubility trapping. Moreover, decreasing PH and enhancing solubility trapping associated with interaction of the dissolved CO_2 and minerals in the host formation results in ionic trapping. In addition, mineral trapping could be induced as a consequence of reaction between dissolved CO_2 and non-carbonate calcium-rich minerals [7].

It has mentioned that permeability and porosity modification is a big consequence of reaction between CO_2, reservoir rocks and pore-water, the change can delay the process of CO_2 injection or enhance its migration out of the storage volume. For instance, mineral precipitation around the target zone might block the pathways of injection flow and high injection rate maintenance is required, although, injectivity around the wellbore might increase rapidly as a result of calcite dissolution. The main factors that aid geochemical reactions are fluid chemistry, precise mineralogy, temperature and pressure of the host formation and time [19].

5 Results and discussion

It can be noticed that the field oil efficiency increased significantly during miscible CO_2 injection. Whereas, there is a moderated increase during immiscible CO_2 injection, because miscible CO_2 helps the oil as a pressure support to dissolve and expand, and then go through the reservoir matrix and the production well. Figure 6 shows the effect of oil recovery with respect to the amount of CO_2 gas injected into the field. It can be clearly seen that as CO_2 miscible gas is injected into the field, the efficiency of oil recovery increases significantly.

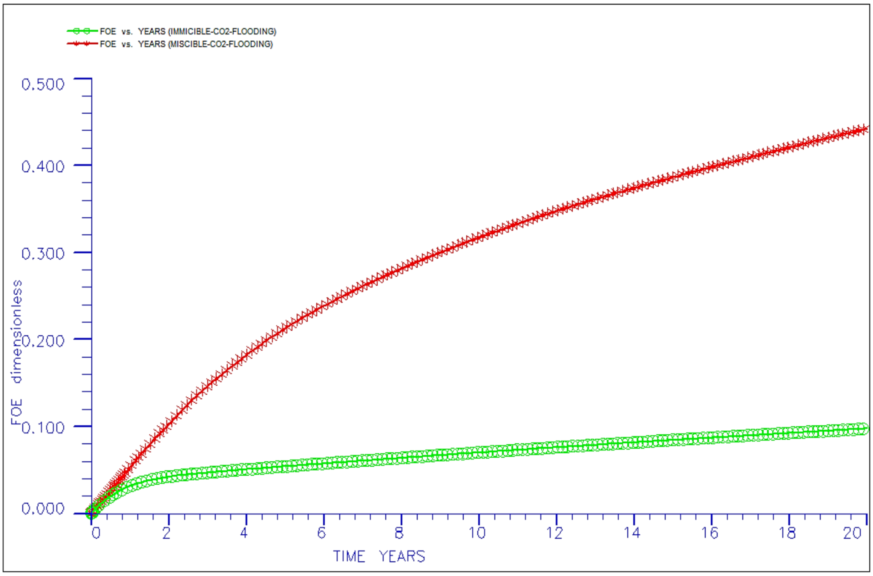

Figure 6: Field oil efficiency versus time (years).

Furthermore, CO_2 flows to the high permeable layers because of unfavourable mobility ratio as shown in Figure 7. Also, the low recovery records because of low density that can cause gravity override of the CO_2 only recovering the attic oil .The added effect of CO_2 gas dropping through the lower layers due to gravity and thus creating a better sweeping action can explain the improved efficiency achieved with high permeability in the top layer. Comparison on the speed of frontal advance showed that a faster advance will produce better oil recovery with amounts of CO_2 micsible injection, but results in the smaller overall efficiency as a lower advance during immicible CO_2 injection.

In addition, there is also noticed some unsweep zones during CO_2 miscible injection as a result of the unfavourable mobility ratio. CO_2 flows through high permeable zones and leaves low permeable zones (unsweep zones) because of unfavourable mobility ratio as shown in Figure 7. Moreover , the highest gas production was recorded during miscible CO_2 injection into carbonate reservoir because CO_2 disolves and decreases the viscoisity of oil that might cause fingering and gravity segregation. While no gas production was recorded during immicible gas injection within 20 years as shown in Figure 8. Because immiscible CO_2 injection can cause push the oil horizonally that becomes pressure support and less sweep effeciency. On the other hand, Miscible CO_2 injection has better sweep efficiency and reduces the oil density in order to push the oil into the production well.

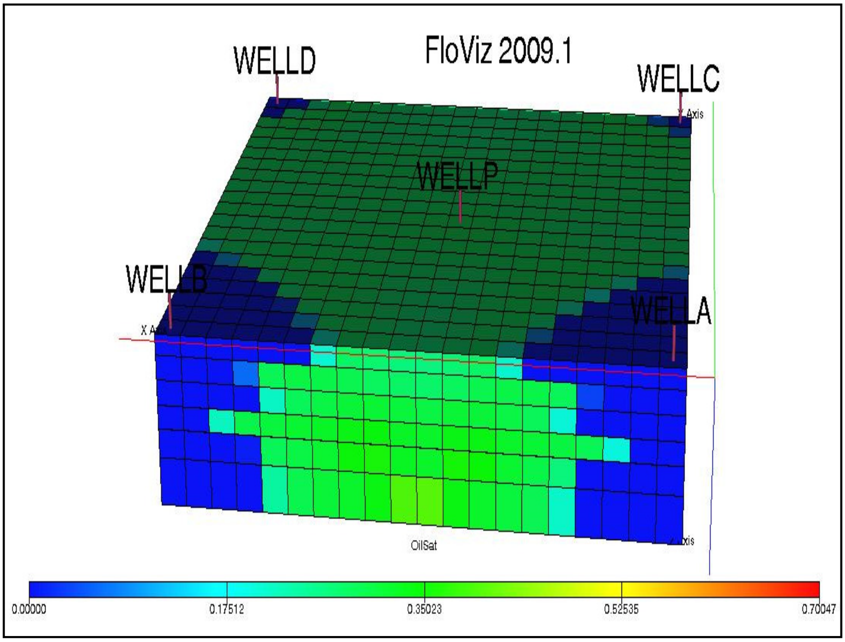

Figure 7: Floviz visualization during miscible CO_2 injection.

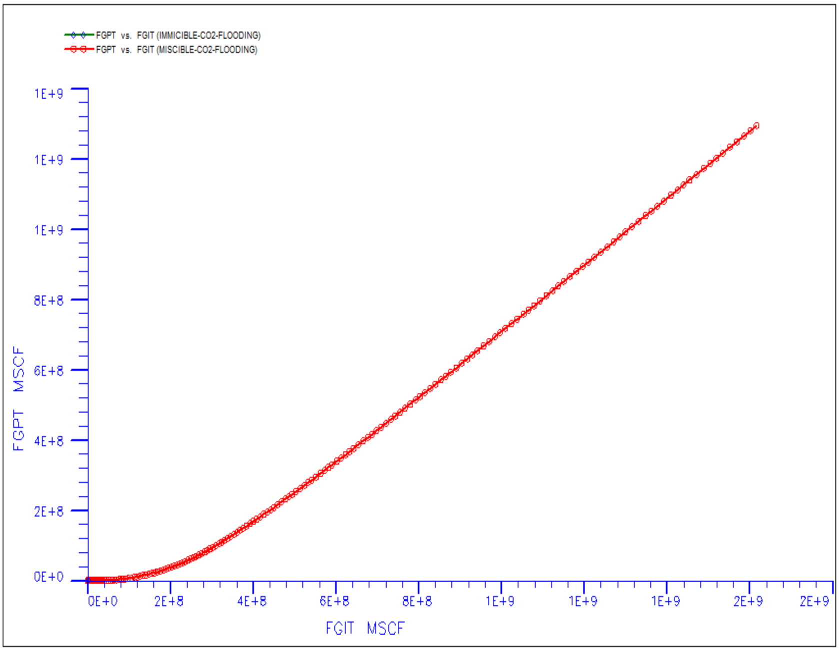

Figure 8: Field gas production total versus field gas injection total.

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Furthermore, CO_2 makes some problems during reaction with reservoir fluid and rocks such as, fingeing, gravity segregation and early breackthroygh as illustrated in Figure 7. Therefore, WAG injection is preferred to inject into carbonate reservoirs because it reduces fingering. WAG injection controls mobility ratio that makes later time breakthrough. CO_2 injection has lower recovery effeciency compared to WAG injection that is related to increasing visosity, controlling mobility ratio, increasing desnsity as shown in Figure 9.

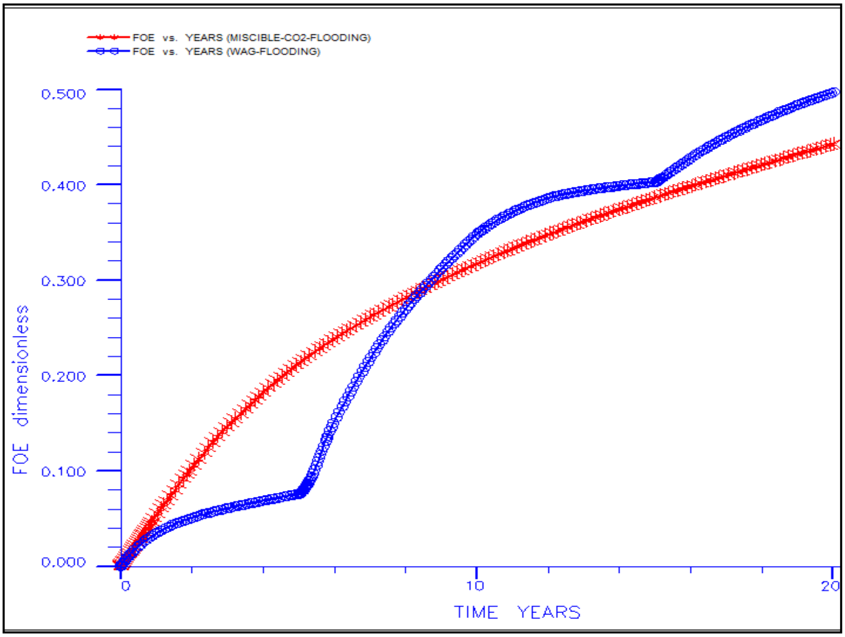

Figure 9: Field oil efficiency versus time (years).

6 Conclusion

1. CO_2 injection is a good candidate to recover oil in carbonate reservoirs.
2. Miscible CO_2 injection has better recovery factor than immiscible CO_2 injection into carbonate reservoirs.
3. Highest gas production total was recorded during miscible CO_2 injection.
4. CO_2 injection might cause physical and chemical trapping
5. Geochemical interactions between CO_2, pore-water and reservoir rocks can change the permeability and porosity of carbonate reservoir either reducing or improving them.
6. WAG process can control sweep efficiency during CO_2 injection, but it can also react with the carbonate components.

7 Recommendation for further work

More studies should be considered in order to investigate the combined mechanisms to maximize oil recovery factor. Further research should be done to examine the effect of CO_2 injection with the aid of water even using other chemical additives into the carbonate reservoirs.

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