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# Enhanced oil recovery by CO<sub>2</sub> injection in carbonate reservoirs.

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# Enhanced oil recovery by CO<sub>2</sub> 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<sub>2</sub> injection in experimental work. In addition, a high recovery factor has been recorded during miscible CO<sub>2</sub> 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<sub>2</sub> flooding. Miscible CO<sub>2</sub> 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<sub>2</sub> flooding has a relatively low recovery factor without any EOR techniques such as gravity stable displacement, WAG or mobility control. CO<sub>2</sub> injection below minimum miscibility pressure (MMP) reduces CO<sub>2</sub> emission, while it takes too long time to maintain reservoir pressure. On the other hand, CO<sub>2</sub> flooding above MMP improves pressure maintenance; causes oil swelling, and increases the oil density.

*Keywords: miscibility, MMP, CO<sub>2</sub> and WAG injections, carbonate reactivity.*

## 1 Introduction

Increasing the amount of greenhouse gases, especially CO<sub>2</sub>, 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<sub>2</sub> in the



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

It has been stated that CO<sub>2</sub> flooding has been started for some decades [4]. Worldwide CO<sub>2</sub> 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<sub>2</sub> flooding has been introduced as injecting a big volume of CO<sub>2</sub>, roughly 30% or more of the hydrocarbon pore volume (PV) as shown in Figure 1 [4].

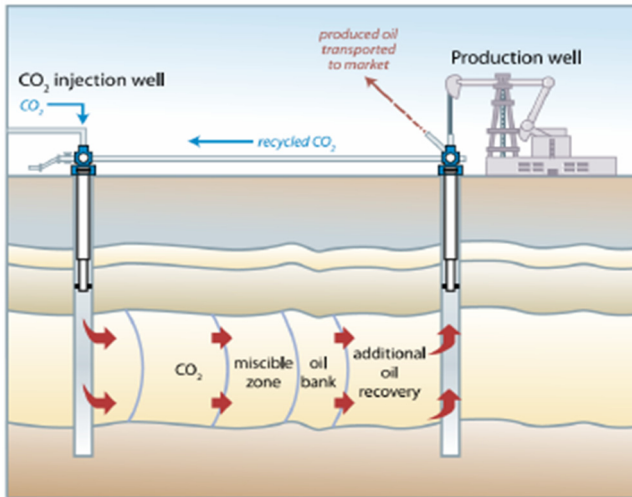


Figure 1: CO<sub>2</sub> flooding process.

Moreover, the main mechanisms of recovery oil by CO<sub>2</sub> injection are identified as; reducing viscosity of oil; swelling the crude oil; lowering the interfacial tension between the oil and the CO<sub>2</sub>/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<sub>2</sub> enhanced oil recovery, since CO<sub>2</sub> can obtain miscibility with the oil at low minimum miscibility pressure

300 bars [9]. Although, immiscible CO<sub>2</sub> 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<sub>2</sub> breakthrough and poor macroscopic sweep efficiency are resulted in due to viscous fingering and gravity override which are caused by unfavourable CO<sub>2</sub> 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<sub>2</sub>) and the stability of flood front can improve. The author also mentioned that at immiscible condition with CO<sub>2</sub>, 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<sub>2</sub> 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<sub>2</sub> injection, miscibility between the injected gas (CO<sub>2</sub>) 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].

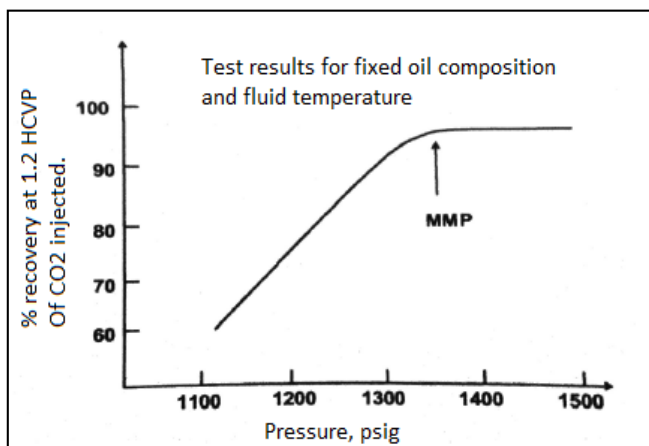


Figure 2: Schematic illustration showing minimum miscibility pressure for CO<sub>2</sub> for a fixed oil composition (Skarrestad and Skauge, 2011 [12]).

CO<sub>2</sub> is not miscible in the first contact with the reservoir oil, however, dynamic miscibility with the oil can be obtained when CO<sub>2</sub> 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<sub>2</sub>-rich gas, and extraction occurs at temperatures where the fluid at the displacement front is a CO<sub>2</sub>-rich liquid [13].

It has been argued that the main factors which impact on miscibility pressure are: 1) high density of CO<sub>2</sub> results in dynamic miscibility as it can dissolve the C<sub>5</sub>-through-C<sub>30</sub> 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<sub>5</sub>-through-C<sub>30</sub> fraction causes reducing miscibility pressure. 4) Light components in hydrocarbon crude oils, such as (methane and C<sub>2</sub> through C<sub>4</sub>) do not have impaction on the achieving MMP [14].

It has been evidenced that pressure is the principal criterion during CO<sub>2</sub> injection since CO<sub>2</sub> pressure need to be significant to impact on the hydrocarbon components [15]. In order to make distinguish between the two CO<sub>2</sub> 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<sub>2</sub> injection processes. Furthermore, dynamic miscibility of CO<sub>2</sub> 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<sub>2</sub> injection can be achievable, when the oil gravity and the injected pressure are lower than 25° API and 1450 psi, respectively. Otherwise, if the pressure greater than 3600 psi and oil gravity is higher than 40° API, then, miscible CO<sub>2</sub> displacement will be practicable [16].

Temperature is another important principle in the successfulness of CO<sub>2</sub> flooding and achieving miscibility since the solubility and density of CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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.

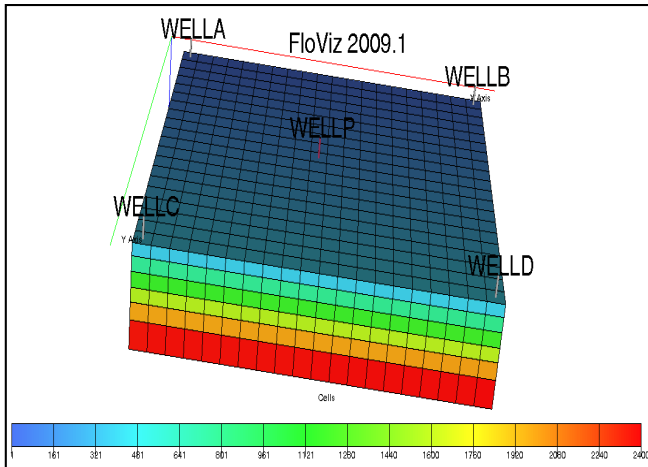


Figure 3: FloViz visualization shows well locations.

CO<sub>2</sub> 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<sub>2</sub> 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<sub>1</sub>, MC<sub>2</sub>, MC<sub>3</sub>, MC<sub>4</sub>, MC<sub>5</sub>, CO<sub>2</sub>, and N<sub>2</sub>). 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 <sub>2</sub> [MSCFD]	10
	Water [STBD]	200
Oil density [lb/ft <sup>3</sup> ]	49	
Water density [lb/ft <sup>3</sup> ]	63	
CO <sub>2</sub> density [lb/ft <sup>3</sup> ]	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.

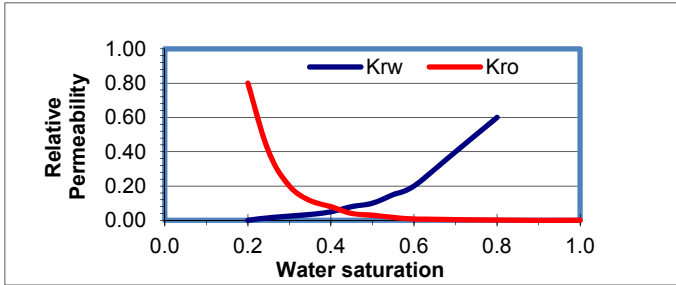


Figure 4: Relative permeability curve for oil-wet (carbonate reservoir).

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<sub>2</sub> gas. When CO<sub>2</sub> gas is injected into the reservoir, CO<sub>2</sub> becomes immiscible with oil at the first contact [7].

#### 4 Geochemical interactions between CO<sub>2</sub>, reservoir rocks and pore-waters

Various chemical reactions are another concern of injecting reactive gas (CO<sub>2</sub>) into the reservoirs. When, CO<sub>2</sub> is injected into the reservoirs, chemical reaction can occur as a result of interaction between CO<sub>2</sub>, cup rocks and reservoir rocks and CO<sub>2</sub> dissolution into pore-water. In addition, the interaction between CO<sub>2</sub>, water and the rocks might have positive or deleterious impact on the capacity of CO<sub>2</sub> storage and injectivity process. The carbonate reactivity and its interaction with the rock and pore-water are illustrated in Figure 5 [17, 18].

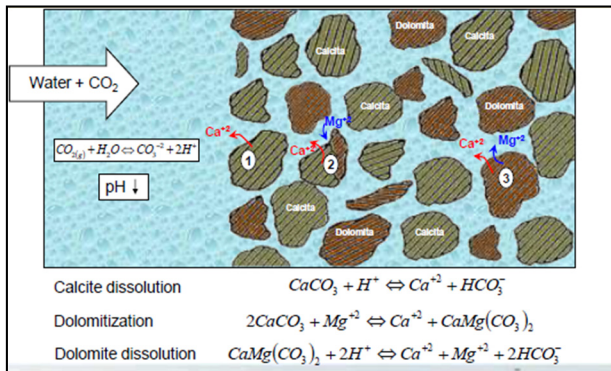



Figure 5: Shows rock fluid interaction (Sengul, M., 2007 [5]).

There have been discussed that several trapping are produced as a consequences of the chemical and mineralogical reactions of CO<sub>2</sub> storage in the deep underground with water and rocks. The mechanisms of the CO<sub>2</sub> 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<sub>2</sub>.

➤ Physical trapping	Increasing
CO <sub>2</sub> ‘bubble’: dense supercritical CO <sub>2</sub> phase	importance with
➤ Chemical trapping	time
• Solubility trapping: CO <sub>2</sub> (aq) or H <sub>2</sub> CO <sub>3</sub>	
• Ionic trapping: HCO <sub>3</sub> <sup>-</sup> , CaHCO <sub>3</sub> <sup>+</sup> , NaHCO <sub>3</sub>	
• Mineral trapping: CaCO <sub>3</sub> (calcite), CaMg (CO <sub>3</sub> ) <sub>2</sub> (dolomite)	
MgCO <sub>3</sub> (magnetite), FeCO <sub>3</sub> (siderite), NaAlCO <sub>3</sub> (OH) <sub>2</sub> (dawsonite)	

Physical trapping is produced by buoyant supercritical CO<sub>2</sub> ‘bubble’, however, reaction between formation water and CO<sub>2</sub> could create solubility trapping. Moreover, decreasing PH and enhancing solubility trapping associated with interaction of the dissolved CO<sub>2</sub> 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<sub>2</sub> and non-carbonate calcium-rich minerals [7].

It has mentioned that permeability and porosity modification is a big consequence of reaction between CO<sub>2</sub>, reservoir rocks and pore-water, the change can delay the process of CO<sub>2</sub> 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<sub>2</sub> injection. Whereas, there is a moderated increase during immiscible CO<sub>2</sub> injection, because miscible CO<sub>2</sub> 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<sub>2</sub> gas injected into the field. It can be clearly seen that as CO<sub>2</sub> miscible gas is injected into the reservoir, the efficiency of oil recovery increases significantly.



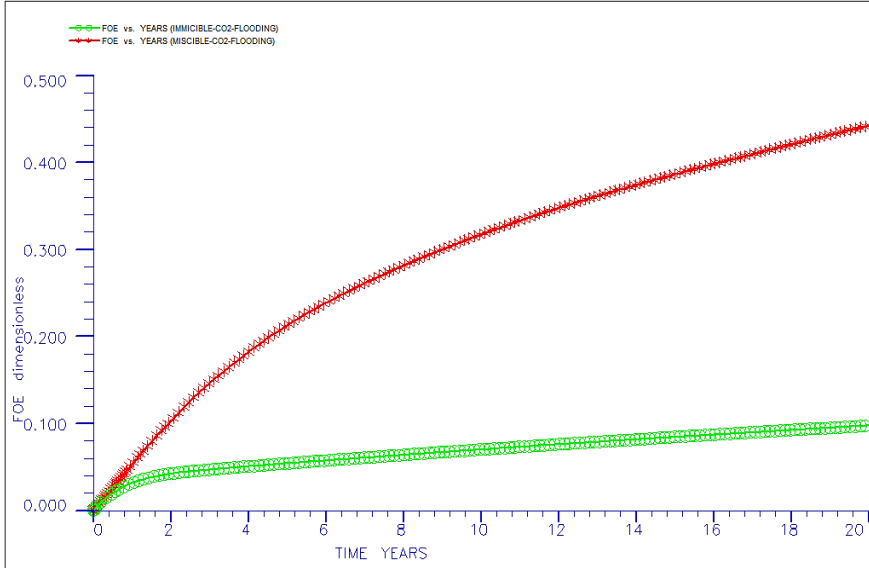


Figure 6: Field oil efficiency versus time (years).

Furthermore, CO<sub>2</sub> 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<sub>2</sub> only recovering the attic oil. The added effect of CO<sub>2</sub> 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<sub>2</sub> miscible injection, but results in the smaller overall efficiency as a lower advance during immiscible CO<sub>2</sub> injection.

In addition, there is also noticed some unsweep zones during CO<sub>2</sub> miscible injection as a result of the unfavourable mobility ratio. CO<sub>2</sub> 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<sub>2</sub> injection into carbonate reservoir because CO<sub>2</sub> dissolves and decreases the viscosity of oil that might cause fingering and gravity segregation. While no gas production was recorded during immiscible gas injection within 20 years as shown in Figure 8. Because immiscible CO<sub>2</sub> injection can cause push the oil horizontally that becomes pressure support and less sweep efficiency. On the other hand, Miscible CO<sub>2</sub> injection has better sweep efficiency and reduces the oil density in order to push the oil into the production well.

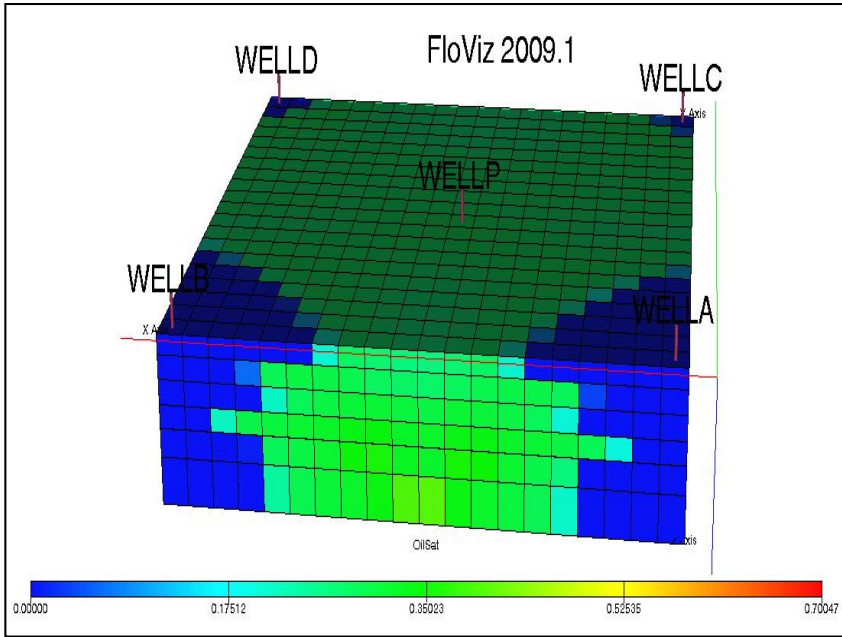


Figure 7: Floviz visualization during miscible CO<sub>2</sub> injection.

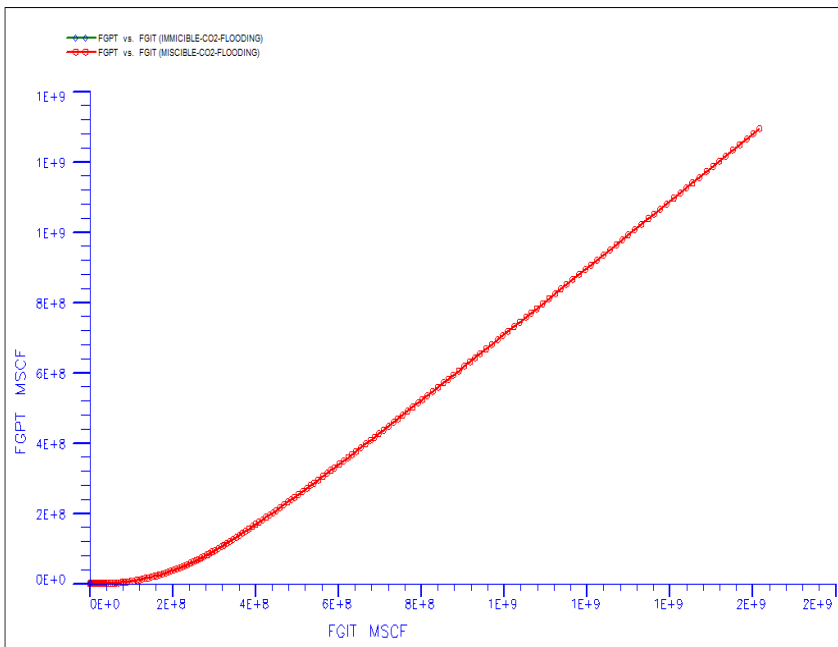


Figure 8: Field gas production total versus field gas injection total.



Furthermore, CO<sub>2</sub> makes some problems during reaction with reservoir fluid and rocks such as, fingering, gravity segregation and early breakthrough 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<sub>2</sub> injection has lower recovery efficiency compared to WAG injection that is related to increasing viscosity, controlling mobility ratio, increasing density as shown in Figure 9.

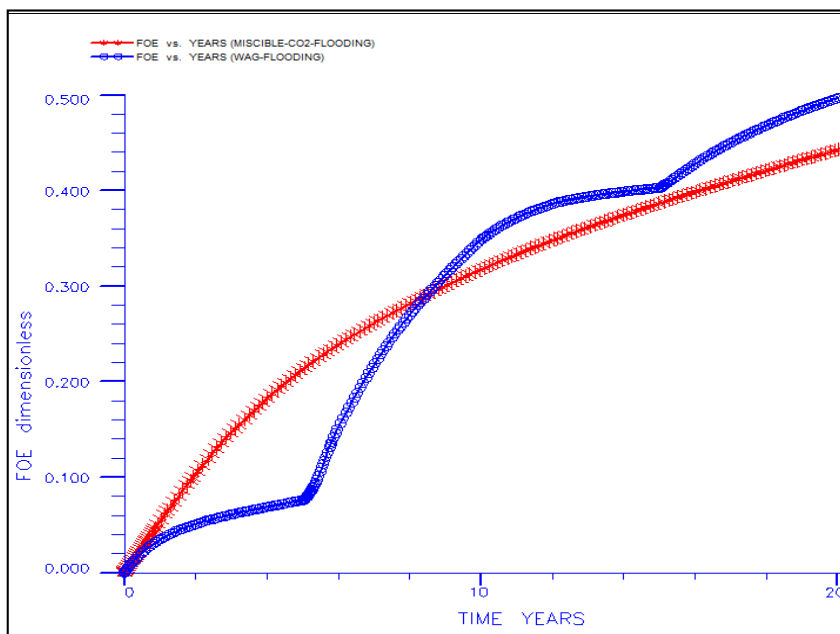


Figure 9: Field oil efficiency versus time (years).

## 6 Conclusion

1. CO<sub>2</sub> injection is a good candidate to recover oil in carbonate reservoirs.
2. Miscible CO<sub>2</sub> injection has better recovery factor than immiscible CO<sub>2</sub> injection into carbonate reservoirs.
3. Highest gas production total was recorded during miscible CO<sub>2</sub> injection.
4. CO<sub>2</sub> injection might cause physical and chemical trapping
5. Geochemical interactions between CO<sub>2</sub>, 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<sub>2</sub> 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<sub>2</sub> injection with the aid of water even using other chemical additives into the carbonate reservoirs.

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