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DISTRIBUTION OF CO_2 IN FRACTURED CARBONATE RESERVOIRS

N.C.I. FURUVIK & B.M.E. MOLDESTAD
Faculty of Technology, University College of Southeast Norway, Porsgrunn, Norway.

ABSTRACT

Deep geologic injection of supercritical carbon dioxide (CO_2) for enhanced oil recovery (EOR) has been widely used for improved oil recovery from depleted oilfields since early 1970s. The CO_2 injection maintains the pressure, mobilize the oil and release the petroleum resources that would otherwise be inaccessible. In addition to improving the oil recovery, the CO_2-EOR contributes to minimize the impact of CO_2-emissions to the atmosphere. The injected CO_2 will be remained trapped in the underground geological formations, as the CO_2 replace the oil and water in the pores. Carbonate reservoirs are characterized by low permeability and high heterogeneity, resulting in early breakthrough of gas and water and hence low oil recovery. The presence of naturally fractures in carbonate reservoirs is a major problem for the oil industry using CO_2-EOR, because significant amount of CO_2 are recycled to the well, and thereby not distributes in the reservoir. This study focuses on CO_2 injection into a naturally fractured carbonate reservoir, including near-well simulations of CO_2-distribution in the rock matrix. The simulations are carried out using the reservoir simulation software Rocx in combination with OLGA. The simulations show that CO_2-injection into a naturally fractured carbonate reservoir in combination with closing of the fractured zones result in good distribution of CO_2 in the reservoir.

Keywords: CO_2-EOR, fractured carbonate reservoir, inflow control, near-well simulations.

1 INTRODUCTION

Sequestration of carbon dioxide (CO_2) in subsurface geological formations and deep saline aquifers assures long-term containment of CO_2 for atmospheric purposes. Besides the geochemical reactions that occur between the reservoir fluids and the rock matrix, the CO_2 sequestration process induces complex phase behaviors of CO_2 with oil [1, 2]. Injection of CO_2 for enhanced oil recovery (CO_2-EOR) refers to the oil recovery technique where supercritical CO_2 is injected into the reservoirs to stimulate oil production from depleted oilfields. The CO_2 mixes with the stranded oil, changing the oil property and making the immobile oil mobile and producible. CO_2-EOR has been widely studied for the last 40 years and is already in use in several countries [3].

Combining CO_2-EOR and CO_2 sequestration is an environmental win-win situation, where both oil recovery is increased and the emission of greenhouse gases is reduced. Advanced carbon capture technology used in the petroleum industry has the ability to separate CO_2 from the oil and the water at the production facility. The oil is sold, the water is recycled and the CO_2 is compressed and readied for underground reinjection. The injected CO_2 ends up trapped by physical and capillary mechanisms and will remain sequestered at the depth [1, 3].

The reservoir properties (porosity, permeability) affect the field response to the CO2-storage process and determine the effectiveness of the CO2 injection for the EOR [3]. In carbonate reservoirs, the petrophysical properties generally are controlled by the presence and the distribution of naturally fractures. Fractures are high permeability pathways for fluid migration in a low permeability rock matrix [4, 5]. Most carbonate reservoirs are naturally fractured, causing significant amounts of water and CO_2 to be produced together with the main stream

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from the production well during the CO_2-EOR process [3, 4]. For the oil companies, this is economically, operationally and environmentally challenging. High demands and rising oil prices have increased the focus on new inflow technology to improve oil recovery from low recovery oilfields [6]. By installing Autonomous Inflow Control Valves (AICV) in the inflow zones in the well, the breakthrough of water and CO_2 can be limited. The AICV will automatically shut off the production of water and CO_2 from one specific zone in the well, but at the same time continue the production of oil from other zones. The AICV can replace the conventional Inflow Control Devices (ICD) installed in a well [7].

This study focuses on CO_2 injection in naturally fractured carbonate reservoirs including simulations of CO_2 distribution in the porous rock. Both ICD and AICV completion were simulated in order to study the problem with fractures in reservoirs. The simulations were carried out using commercial reservoir simulation software Rocx in combination with OLGA.

2 CO_2-EOR AND CO_2-STORAGE

CO_2-EOR is an oil recovery technique that involves injection of supercritical CO_2 into underground geological formations, or deep saline aquifers. The goal is to revitalize matured oilfields, allowing them to produce additional oil. CO_2 is highly soluble in oil and to a lesser extent in water. As CO_2 migrates through the reservoir rock, it mixes with the residual oil trapped in the reservoir pores, enabling the oil to slip through the pores and sweep up in the flow from the CO_2-injection well toward the recovery well [1]. The principle of CO_2-EOR is shown in Fig. 1.

When CO_2 and oil mix, a complicated series of interactions occur wherein the mobility of the crude oil is increased. Injection of CO_2 into the oil formation changes the oil physical properties in two ways, leading to EOR. The first thing is reduction in oil viscosity so that the oil flows more freely within the reservoir. Then a process of dissolution occurs thereby causing swelling of the oil, and resulting in expansion in oil volume which means that some fluid have to migrate. The amount of swelling depends on the reservoir pressure and temperature, the hydrocarbon composition and the physical properties of the oil [1, 8–10]. Complete miscibility between the oil and the CO_2 reduces interfacial tension and capillary forces between the oil and the water phase, and could help recover in theory all of the residual oil [8].

CO_2-EOR improves the oil production, simultaneously it contributes to minimizing the atmospheric emissions of CO_2 by storing the gas permanently underground [9]. CO_2 can be stored as a supercritical phase in the rock matrix, or in deep saline aquifers, most likely as a dissolved phase in the formation water [8]. The preferred depth to inject CO_2 is greater

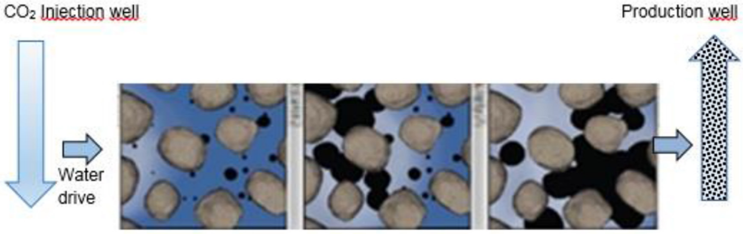

Figure 1: Principle of CO_2-EOR.

than 800 m, as it provide the required conditions above the critical point of CO_2. At these conditions, the CO_2 is kept in a supercritical phase, which increases the CO_2-storage capacity and more CO_2 can be stored within a specific volume [9]. In a supercritical phase, the CO_2 is denser than the gaseous CO_2, but less dense and viscous than the reservoir fluids. Supercritical CO_2 fills less than 1% volume compared to gaseous CO_2. The volume available for storage depends on the reservoir structure, the heterogeneity of the rock formation, the porosity and the permeability. At well-selected storage sites, the rock matrices are likely to preserve more than 99% of the injected CO_2 for over 100 years [11].

3 CARBONATE RESERVOIRS

More than 60% of the world's oil resources occur in carbonated rocks [4]. Although carbonate reservoirs contain a majority of the oil reserves, only small amounts of the production worldwide come from these reservoirs [4]. Generally, carbonate reservoirs have complicated pore structures and strong heterogeneity [4, 5]. Most carbonate reservoirs have a dual character of rock matrix and natural fractures. Fractures are discontinuities in the rock appearing as breaks in the natural sequence. The orientation of the fracture can be anywhere from horizontal to vertical, as illustrated in Fig. 2. The fractured corridors exist in all scales, ranging from microscopic cracks to fractures of ten to hundreds of meters in width and height [4, 5]. This results in greatly variable permeability in carbonate reservoirs, from values less than 0.1 mD in cemented carbonates to over 10 000 mD in fractures.

Some of the world's largest remaining oil reserves are found in oil-wet, fractured carbonate reservoirs. CO_2-EOR in these reservoirs poses great challenges to the oil industry, as the CO_2 preferably will flow through the high permeable fractures and thereby not contribute to EOR. The result is poor sweep efficiency and potentially low oil recovery, due to very early breakthrough of water and CO_2 [12]. The oil production performance from fractured carbonate reservoirs is nearly half the production from other reservoirs, whereas the CO_2 utilization is about 60% less [3, 4]. Presumed petrophysical properties of carbonate reservoirs are presented in Table 1.

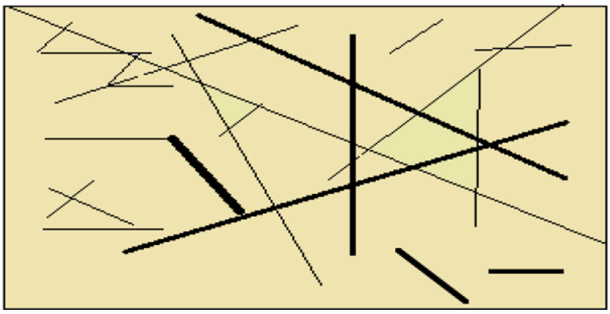

Figure 2: Fractures in a reservoir.

Table 1: Petro physical properties of carbonate reservoirs [4, 5].

	Porosity	Permeability	Permeability in fracture	Wettability
Range	0.01–0.3	0.7–130 mD	Large	Intermediate-wet to strongly oil-wet

4 WELL TECHNOLOGY

On world basis, it has been more and more common to use horizontal well technology in the production of oil and gas. A horizontal well is drilled parallel to the reservoir-bedding plane, which provide large contact area between the well and the reservoir. Horizontal well technology has many benefits, but is still prone to the problem with reduced oil production due to early water breakthrough [7].

Different types of passive Inflow Control Devises (ICD) are developed to limit the unwanted production of water [13]. The ICD restricts the flow, and the diameter of each nozzle is chosen to obtain the desired pressure drop over the ICD at a specific flow rate. The pressure drop highly depends on the nozzle diameter and the density of the fluid and less on the viscosity. Passive ICDs are capable of delaying the water breakthrough significantly [13] and the technology has opened up for production from reservoirs with thin oil columns. The total oil recovery increases significantly with use of ICDs. However, ICDs neither choke nor close for fluids like CO_2 and water, and after breakthrough, the whole well has to be choked to reduce the production of CO_2 and water. The principle behind the nozzle ICD is based on the following equations [13]:

$$\Delta P = \frac{\rho v^3}{2C^2} = \frac{\rho Q^2}{2A_{valve}^2 C^2} = \frac{8\rho Q^2}{\pi^2 D_{valve}^4 C^2} \tag{1}$$

$$C = \frac{C_D}{\sqrt{\left(1-\beta^4\right)}} = \frac{1}{\sqrt{K}} \tag{2}$$

$$\beta = \frac{D_2}{D_1} \tag{3}$$

where ΔP is pressure drop across orifice, ρ is average fluid density, v is fluid velocity through an orifice, Q is fluid flow rate through orifice, A is area of orifice, D is diameter of orifice, C is flow coefficient, C_D is discharge coefficient and K is pressure drop coefficient.

New inflow control technologies are continuously developed. One of the latest invention is the Autonomous Inflow Control Valve (AICV), which is completely self-regulating and does not require any electronics or connection to the surface. AICV gives low flow restriction for oil production and has the ability to close almost completely for water and CO_2. The valves will locally close in the zones with gas and/or water breakthrough, and simultaneously produce oil from the other zones along the well. The AICV technology consists of two different flow restrictors placed in series. The first one is a laminar flow restrictor and the second is a turbulent flow restrictor. Figure 3 presents a sketch of the combination of flow restrictors, where 1 is the laminar flow element and 2 is the turbulent flow element. The pressure in

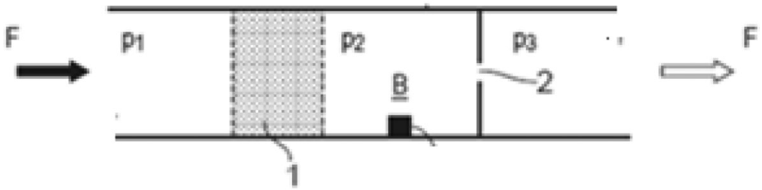

Figure 3: Combination of laminar and turbulent flow restrictors in series.

chamber B activates the piston in the valve to close or open. If oil is flowing through the AICV, the pressure drop through the laminar flow element is high, resulting in low pressure in chamber B and the valve is open. Water and gas give a lower pressure drop through the laminar restrictor, resulting in high pressure in B, and the valve closes. [13, 14].

The pressure drops through laminar and turbulent flow elements are expressed by eqns (4) and (5), respectively. [13, 14] The laminar flow element is considered as a pipe segment, and the pressure drop through the element is expressed as:

$$\Delta P = f \, . \frac{L.\rho.v^2}{2D} = \frac{64}{Re} . \frac{L.\rho.v^2}{2D} = \frac{32.\mu.\rho.v.L}{D^2} \tag{4}$$

where ΔP is the pressure drop, f is the laminar friction coefficient, ρ is the fluid density, μ is fluid viscosity, L is length of the laminar flow element, D is the diameter of the laminar flow element, Re is Reynolds number.

The pressure drop through the turbulent flow element is proportional to the density and the velocity squared, and is given as:

$$\Delta P = k.\frac{1}{2}.\rho \, .v^2 \tag{5}$$

where k is a geometrical constant, ρ and v is the fluid density and velocity.

AICV has the same performance as ICD in open position, and when closed, the flow rate through the valve is reduced to less than 1%. This relationship between open and closed valve is used to simulate the AICV functionality.

5 SIMULATIONS

The near-well simulations of CO_2 distribution in the carbonate reservoir were carried out using the commercial reservoir simulation software Rocx, in combination with OLGA. The OLGA software is the main program, but several additional modules are developed to solve specific cases. Criterion for the performed simulations was a naturally fractured oil-wet carbonate reservoir. The geometry for the simulated reservoir is 105 m in length, 96 m in width and 50 m in height. Three grid blocks are defined in x-direction, 25 in y-direction and 10 in z-direction. Figure 4 shows the grid and geometry of the simulated reservoir section at initial

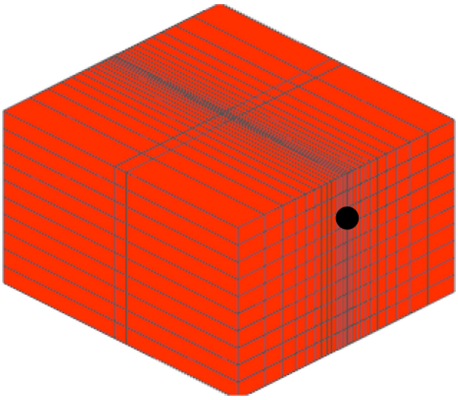

Figure 4: Grid and geometry of the simulated reservoir.

Table 2: Reservoir fluid properties.

Properties	Value
Oil viscosity	10 cP
Reservoir pressure	176 bar
Reservoir temperature	76°C
Oil specific gravity	0.8
Porosity	0.15
Permeability first zone (x- y-z- direction)	40–40–20 mD
Permeability second zone (in x-y-z-direction)	4,000–4,000–2,000 mD
Permeability third zone (in x-y-z-direction)	40–40–20 mD
Wellbore pressure	130 bar

conditions. The well is located 35 m from the bottom, and indicated as a black dot in the figure. The radius of the wellbore is 0.15 m.

The reservoir is divided into three zones in *x*-direction. A constant porosity of 0.15 is used in the entire reservoir. A permeability of 4,000 mD is set in the second zone, and a permeability of 40 mD is set in the first and the third zone. The second zone represents the fractured part, thus the permeability is set much higher in this zone compared to the two other zones. The temperature is maintained constant at 76°C and the waterdrive pressure from the bottom of the reservoir is 176 bar, the wellbore pressure is set to 130 bar. The reservoir and fluid properties for the simulations carried out are presented in Table 2.

The simulation software Rocx generates the relative permeability curves, using the parameters listed in Table 3. The calculations are based on the Corey correlation, a power law relationship with respect to water saturation. S_{wc} defines the maximum water saturation that a reservoir can retain without producing water, and S_{or} refers to the minimum oil saturation at which oil can be recovered by primary and secondary oil recovery. K_{rwoc} is the relative permeability of the water at the residual oil saturation, and K_{rowc} is the relative permeability of oil at the irreducible water saturation. n_w and n_{ow} are the Corey coefficients for water and oil, respectively. Figure 5 shows the implemented relative permeability curves for the simulations. The green lines represent the relative permeability of oil (K_{ro}) and the blue lines represent the relative permeability of water (K_{rw}).

The module Rocx is connected to OLGA by the near-well source component in OLGA, which allows importing the file created by Rocx. In order to get a simulation of the complex system including valves and packers, OLGA requires both a ‘Flowpath’ and a ‘Pipeline’ as shown in Fig. 6. In the simulations, the ‘Flowpath’ represents the pipe and the ‘Pipeline’ represents the annulus. The annulus is the space between the pipe and the rock, see Fig. 7 [15].

Figure 8 shows how the ‘Flowpath’ is divided into six equal sections. The sources implemented in the ‘Pipeline’ are connected to the boundaries in Rocx, and indicate the inflow from the reservoir into the annulus. The leaks indicate the inflow from the annulus into the

Table 3: Relative permeability data for the specific simulations.

Swc	Sor	Krowc	Krwoc	nw	now
0.1	0.1	1	0.75	3	3.4

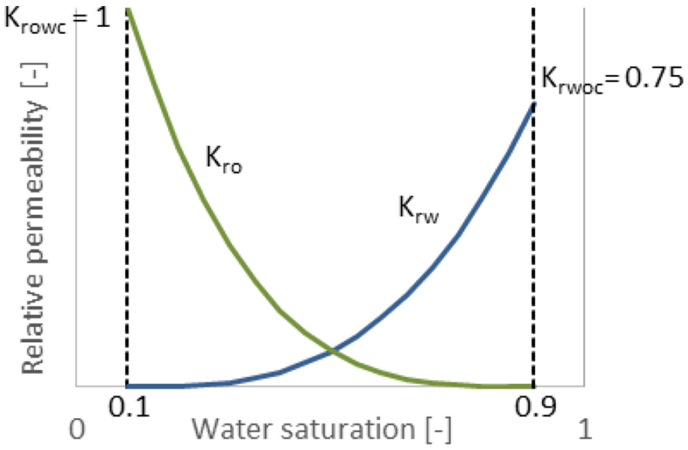

Figure 5: Relative permeability curves.

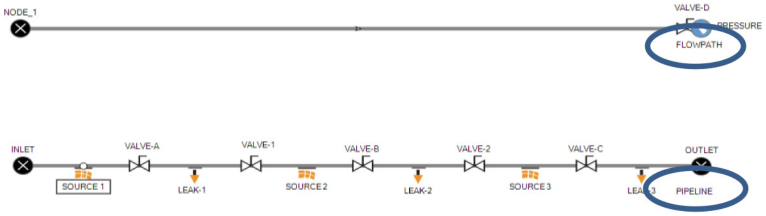

Figure 6: OLGA Study case for the performed simulations.

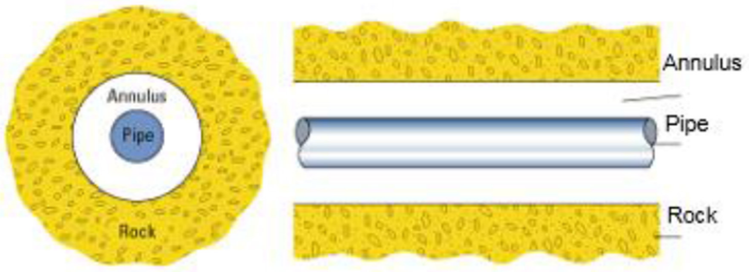

Figure 7: A schematic of the pipe and the annulus. [15].

pipe, through the control valves A, B and C. The packers are simulated as closed valves and are installed to isolate the different production zones in the well. In the simulations the packers divide the 'Pipeline' into three zones. The inflow from Source-1 goes from section one in the annulus and enters the pipe in section two. Similarly, for the flow in production zone two and three.

6 INPUT TO OLGA AND ROCX

The simulations were carried out for an oil-wet carbonate reservoir with fracture. Two different cases were simulated. Both cases include the relative permeability curves seen in Fig. 5,

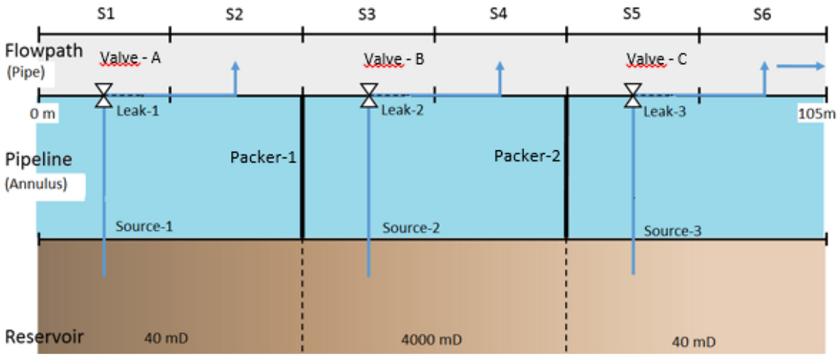

Figure 8: The near-well simulation in OLGA.

and the reservoir and the fluid properties listed in Table 2. Case 1 represents oil production with ICD completion, where the control valves A, B and C are specified as fully open. In Case 2, the well is completed with AICV. Thus, the control valves A and C are specified as open, while control valve B is kept closed. This is to illustrate how chocking the fractured zone will affect the CO_2-distribution in the reservoir. The simulations were run for 400 days. Detailed specifications for the simulations are listed in Table 4.

7 RESULTS

Figure 9 shows the oil saturation scale used in the results generated from TechPlot RS. The color goes from red to dark blue, where red color indicates oil saturation of 1.0 and dark blue color indicates an oil saturation 0.2.

Figure 10 shows the oil saturation in the reservoir, initially and after water breakthrough for the simulations of the two cases. For the simulations, it is assumed that CO_2 is injected into the water phase, and therefore, this water phase represents carbonated water and CO_2. Carbonated water goes upward, from the bottom of the reservoir toward the production well. Water breakthrough happens at different time for the two cases. The water breakthrough takes place in the second production zone due to the high permeability specified for this zone.

Table 4: Input for the performed simulations.

Case	Inflow controller	Data input to Rocx	Relative permeability curve	CO_2-injection	Position Valve A and Valve C	Position Valve B
1	ICD	See Table 2	See Fig. 5	Yes	Open	Open
2	AICV	See Table 2	See Fig. 5	Yes	Open	Closed

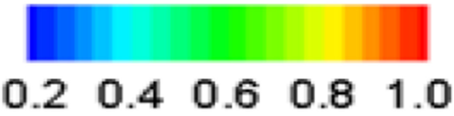

Figure 9: Oil fraction scale used in the results generated by Techplot RS.

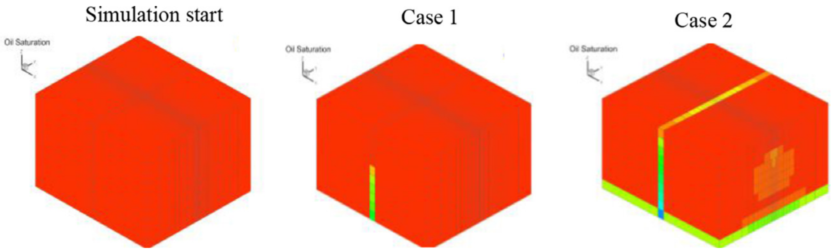

Figure 10: Saturation of oil initially and at water breakthrough.

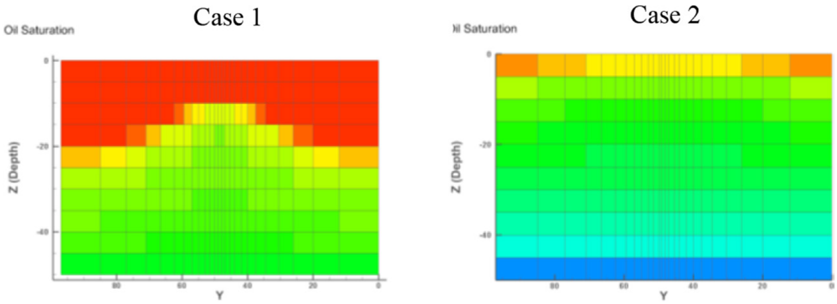

Figure 11: 2D view at water breakthrough in the second production zone.

After only 2.9 days, the water breakthrough occurs in Case 1. As seen from Fig. 10, the carbonated water flows straight through the fracture and into the production well, without distribute in the reservoir. In Case 2, the water breakthrough occurs after 64 days. Due to the chocking of the fractured zone in Case 2, the carbonated water distributes within the reservoir. This is more easily seen in the 2D-plot displayed in Fig. 11.

From the 2D-plots of the oil saturation in the second production zone, it is seen that the carbonated water in Case 1 flows straight through this zone without dispersing into the other zones. The well is located in the third grid block in z-direction, and the oil saturation decreases from this position and downwards in the production zone. Subsequently, the oil saturation is high in the area above and around the production well. This is due to the pressure difference between the reservoir and the wellbore. In Case 2, the oil saturation in the second production zone is more evenly distributed due to the closed valve.

Figure 12 shows the distribution of CO_2 and water in the reservoir for Case 1 and Case 2 after 400 days of production. From Fig. 12, it is seen that Case 2 shows good distribution of carbonated water in the reservoir compared to Case 1. This is due to closing of the fractured zone in Case 2, causing the carbonated water to disperse from the high-permeable zone to the low-permeable neighbor zones. For Case 1, the carbonated water flows directly into the production well, causing low production from the other zones in the reservoir and large amounts of the injected CO_2 to be recycled. This is also seen in the 2D-plots of the second production zone in Fig. 13. The plots represent the saturation of oil after 400 days of production. The closed valve in Case 2 allows the CO_2 to be in contact with the oil within the reservoir. CO_2 acts as a solvent that reduces the oil viscosity and enables the oil to flow into the production well. As seen, closing the fractured zone of the reservoir results in good distribution.

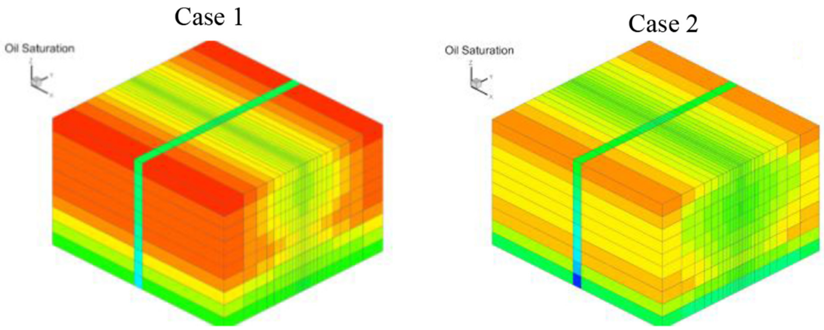

Figure 12: Saturation of oil after 400 days.

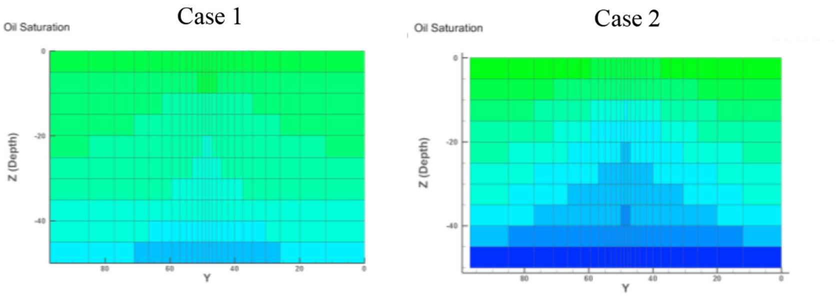

Figure 13: 2D view in the second production zone after 400 days of production.

8 CONCLUSION

The objective of this work was to study the distribution of CO_2 in a fractured carbonate reservoir. The study included near-well simulations of CO_2-injetion and CO_2-distribution, using the reservoir software Rocx in combination with OLGA. Both ICD and AICV completions were simulated in order to study the benefits of the AICV technology.

The reservoir was characterized by low permeability and high heterogeneity. Fractures in the reservoir are a major problem for the oil industry using CO_2-EOR. Due to the very early breakthrough of water, significant amounts of the injected CO_2 will be recycled with the produced water. To investigate the distribution of CO_2 in the reservoir, it was necessary to choke the production from the fractured zone in one of the performed cases. This was done by closing the control valve in the specified production zone. The simulations indicate that CO_2-injection into a carbonate reservoir in combination with closing the fractured zone causes delayed water breakthrough and good distribution of CO_2 in the reservoir.

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