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Investigations of Miscible Water Alternating Gas Injection Efficiency in Layered Sandstone Porous Media

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Abstract

Carbon dioxide (CO_2) flooding deliberated as one of the most common and feasible used gas to improve oil recovery. CO_2 utilization has grown significantly due to availability, greenhouse effect and easy achievement of miscibility relative to other gases. There have been limited experimental efforts conducted at core-scale focused on evaluating the influence of permeability heterogeneity on oil recovery. Thus, the results from this manuscript are essential to highlight the importance of geological uncertainties in the current and future enhanced oil recovery projects. This manuscript presents a coupled experimental and simulation study to assess the effect of cross bedded reservoir heterogeneity on WAG flooding performance. We performed core flooding experiments with a fluid system consisting of n-C_{10}, synthetic brine, and CO_2 at a temperature of 343 K and 17.2 MPa pore pressure. In addition to the experimental work, a 2D core scale CMG-GEM simulation associated with PVT module CMG WinProp has been built based on our experimental results. We found that oil recovery decreases dramatically with increasing permeability ratio of cross bedded core samples. Besides, our results revealed channeling of injected CO_2 in high permeability beds leaving a considerable amount of oil untouched in low permeability bed. Furthermore, we pronounced a water shielding effect which reduces further contact of the injected CO_2 with oil. We thus conclude that reservoir heterogeneity significantly impact WAG flooding performance and evaluation of these influences on oil recovery before any field application are essential.

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1. Introduction

Carbon dioxide (CO_2) flooding deliberated as one of the most common and feasible used gas to improve oil recovery. The investigation into the use of CO_2 flooding for enhanced oil recovery (CO_2-EOR) began in the early 1950's [1-3] and has since considered as one of the most promising technologies used to EOR. Besides, injecting CO_2 has captured more interest in the recent years in Carbon Capture and storage (CCS) as it can help to reduce CO_2 gas emissions [4-21]. The performance of CO_2-EOR greatly depends on CO_2 injection scheme.

1.1 CO_2 injection schemes

The injection scheme can be categorised on the basis of miscibility condition between CO_2 and oil as; immiscible, near miscible and miscible flooding, and the type of injection; continuous gas injection (CGI), water alternating gas (WAG), and simultaneous water and gas (SWAG). The mechanisms involved during miscible flooding usually include oil viscosity reduction, oil swelling, and dissolved gas driving [22, 23]. Another effective mechanism is the reduction in the interfacial tension (IFT) under miscible CO_2 flooding which enables the CO_2 to extract more oil from the reservoir pore space that may not be otherwise recoverable by traditional water flooding. Generally, CO_2 injection can prolong a reservoir's life by 15-20 years and may recover an additional 15-20 % of the original oil in place [24]; this is mainly due to the high microscopic displacement efficiency of the CO_2 flooding [25, 26]. However, CO_2 injection often suffers from poor macroscopic displacement efficiency resulting from its extremely low viscosity and relatively low density as well as the inevitable heterogeneity present in most reservoirs [27, 28]. The high viscosity contrast of the flood makes the mobility and consequently flood profile control a major concern for the successful application of CO_2-EOR. With the lack of control, early CO_2 breakthrough, unstable pressure distribution, viscous fingering, channelling and bypassing of the oil would work against the outstanding microscopic sweep efficiency of the flood resulting in reduced oil recoveries. The poor overall efficiency of a CO_2 displacement process can be increased by decreasing the mobility ratio [29]. One of the well-known methods for improving CO_2 sweep efficiency is by injecting water alternately with CO_2 (WAG). Injected water assists in reduction of the relative permeability of CO_2, which lowers the total mobility [14, 15, 17, 30].

1.2 Water Alternating Gas (WAG) Flooding

The literature indicates that WAG injection can improve the efficiency of both microscopic and macroscopic displacements [31-33] published some of the earliest literature on the application of WAG. Christensen et al., [34] who reviewed over 50 field projects, reported that WAG flooding generally results in 5-10% increase in the oil recovery. According to their review, about 79% of the reviewed WAG field applications were found to operate under miscible conditions, and about 57% have been applied in sandstone reservoirs. Field pilots and laboratory tests have shown that WAG flooding is an effective method to control the mobility ratio and reduce the viscous fingering [32, 35-37]. For instance, during CO_2 WAG process, the alternating injection of water reduces the relative permeability to CO_2 which then lowers the mobility of the flood enhancing the overall macroscopic displacement efficiency. In other words, the WAG flooding combines the improved microscopic displacement efficiency achievable with CO_2 injection with the reasonable macroscopic displacement efficiency that may be obtained with water flooding. In our earlier work [38, 39], we observed that the crossflow to negatively affect the RF of immiscible WAG in layered samples. Moreover, they revealed that changes in porosity are correlated reasonably with the clay minerals amount in the sample [40]. In general, available published literature of CO_2-EOR indicate that WAG flooding is a more effective injection technique than injecting either water or CO_2 continuously [41]. It is worth noting that being more effective does not necessarily equate to a higher ultimate recovery factor. For instance, Kulkarni and Rao [42] experimentally concluded that although continuous CO_2 injection resulted in higher recovery factors, WAG was found to be more effective when recovery factors were normalised by the volume of the CO_2 injected in each case. In other words, higher eventual recovery of the continuous CO_2 injection came at the cost of injecting larger CO_2 volumes (which is generally more costly to inject compared to water). There have also been many studies investigating factors that affect the WAG injection process efficiency such as fluid properties, trapped gas, wettability, reservoir heterogeneity, injection schemes and WAG related parameters such as WAG ratio, cycling frequency, slug size and injection rates [37, 43-59]. An extensive reviewing and analysis of WAG field applications, laboratory, and simulation works are available in the literature [34, 60-63].

1.3 Reservoir Heterogeneity

Reservoir heterogeneity is of key importance aspect of a hydrocarbon reservoir that impacts on its hydrocarbon yield. Reservoir heterogeneity presents in almost all hydrocarbon reservoirs discovered worldwide. In the petroleum industry, reservoir heterogeneity may refer to a variation of rock petrophysical properties (e.g. permeability, porosity, thickness, saturation, wettability and other rock characteristics). Reservoir permeability heterogeneity (Cross-bedding) has long been recognised as the critical aspects affecting reservoir performance and the oil recovery. Heterogeneity of a reservoir can seriously affect CO_2 flooding efficiency. Reservoir heterogeneity impacts on flood conformance and sweep patterns during an EOR process by intensifying fingering and channelling of the injected fluid resulting in early breakthrough and reduced sweep efficiency. In this manuscript, the authors would investigate the influence of core-scale cross-bedding on the performance of miscible CO_2 WAG flooding.

2. Experimental and simulation approach

2.1 Experimental work

Rock and fluids: initially, homogeneous sandstone core plugs with different permeabilities (100 mD, and 8 mD) and porosities (18%, and 23%), respectively, were sourced from quarried blocks in the U.S. The nominal length of the samples were 76.5 mm, and the diameter of 38.1 mm. These plugs were then used to manufacture heterogeneous core samples (for details see [64, 65]. The level of heterogeneity used in our experiment was 12.5; which represent the permeability ratio between the two adjacent layers. A synthetic brine consisting of 2% NaCl, 0.7% KCl, 0.5% $CaCl_2.2H_2O$, (all in weight%, ACS grade, Sigma- Aldrich) dissolved in distilled water, high purity CO_2 (99.9 wt%, BOC Gases), and *n*-Decane (99%, Sigma–Aldrich) were used in the experiments.

Core flooding apparatus: *Figure 1* depicts a high-pressure, high-temperature core flooding facility which built for performing CO_2 WAG flooding experiments. The system consists of three major components: the injection system, the core holder assembly and the production system. Core flooding system and procedure for preparing core sample used during experiments are detailed elsewhere [19, 64, 66]. We performed experiments under 17.23 MPa of pressure and 343 K of temperature.

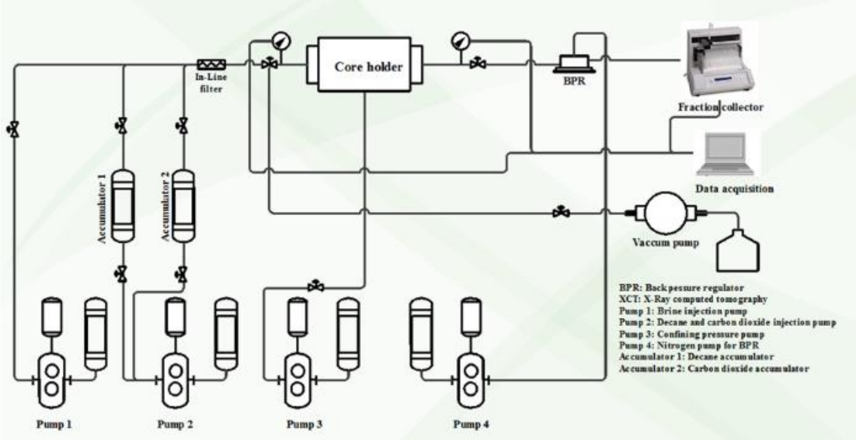


Figure 1. Experimental apparatus for core flooding experiments.

2.2 Experimental procedure

First of all, and before running the core-flooding experiment, core plugs were cleaned in a temperature controlled Dean-Stark apparatus using warm methanol and toluene (50% each) and then dried in a vented oven at 343 K for 24 hours or until there are no more changes detected in the weight. Then, we have used an automated helium porosi-permeameter to measure the porosity and absolute permeability of the initial homogeneous samples before undergoing any core cutting and then flooding. After wrapping the core sample with a multi-layered sleeve (see [19], the core placed in a Viton sleeve then inserted into the core-holder which is placed horizontally. In the next step, the core sample saturated with the synthetic brine and both confining pressure and system temperature was maintained under desired conditions. After this, nearly five pore volumes (PV) of *n*-Decane were injected into the sample at 5 mL/min to achieve residual water saturation (S_{wr}). In the next step, for conducting the WAG core flooding experiments as a secondary EOR method, WAG was injected at a ratio of 1:1, slug size of 0.15 PV, and a constant flow rate of 1 mL/min into the core sample until about 4 PVs of WAG were passed through the sample. Throughout this procedure, the volume of *n*-Decane collected at the production side of the setup was recorded as well as the pressures across the core sample.

2.3 Numerical model

We created core-scale numerical models with parameters identical to those used in the experiments to study the influence of heterogeneity on oil recovery factor, interpret the experimental results, and understand the displacement behaviour. A set of numerical simulations were conducted by using reservoir simulator of

Computer Modelling Group (CMG 2016). A compositional simulator, (CMG-GEM), is used for modelling $CO_2/n\text{-}C_{10}$ phase behaviour. Saturated Decane phase density and composition for binary mixture of CO_2 and Decane at 343 K is shown in (Figure 2). As it can be seen, the saturated Decane phase density at 17.23 MPa and specified temperature is representing a single phase (Miscible condition). A 2-D model (Figure 3) with 100 grid blocks in the x-direction, 1 grid block in the y-direction, and 10 grid blocks in the z-direction (1000 cell) was constructed and validated with the WAG displacement experimental results. Relative permeability curves and omegas-os (oil and CO_2 mixing parameter) were used to tune the simulation model to match gas and water breakthroughs and cumulative oil recovery. The simulation model was then extended to conduct sensitivity studies on permeability heterogeneity in layered core. The Peng-Robinson EOS is used to model the fluids system. Rock and fluid properties and initial conditions are kept the same as the experimental laboratory conditions. When a satisfactory history match was obtained, the experiments were modelled to study the behaviour of fluid flow in the layered core.

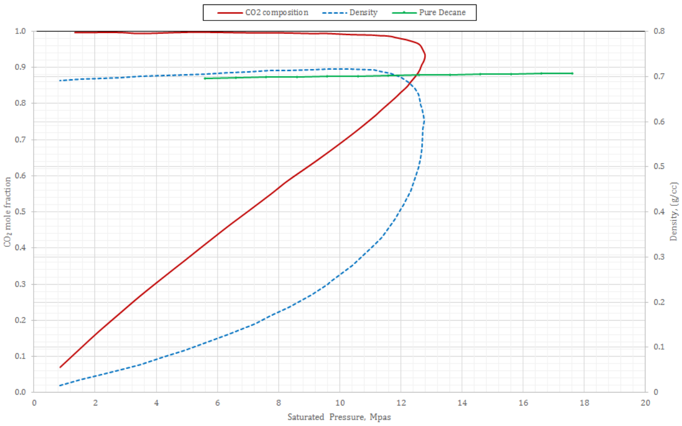


Figure 2. Winprop phase density data for CO_2 + Decane at 343 K.

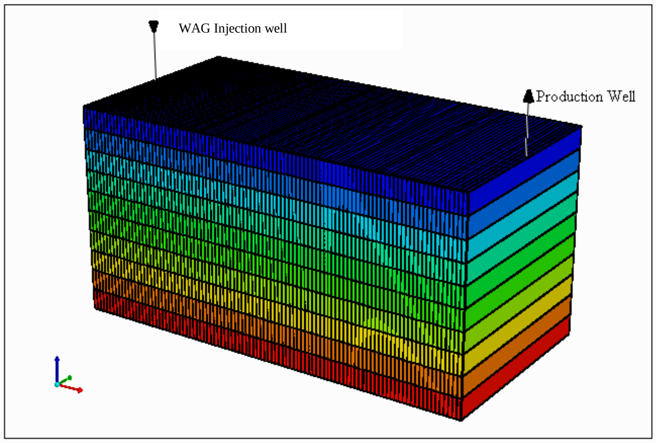


Figure 3. A schematic of simulation model Cartesian grids representing the experimental core sample (CMG-GEM).

3. **Results and discussions**

3.1 WAG Core flooding experiments

We performed two different CO_2 WAG injection tests using homogeneous and heterogeneous core samples under the experimental condition (i.e. temperature of 343 K and pressure of 17.23 MPa) to examine the influence of permeability heterogeneity on ultimate oil recovery (see our previous published experimental results [65]. *Figure 4* shows the dynamic *n*-Decane recovery of both experiments versus PV's of WAG injected. Decane recoveries of ~93.0% and ~73.0% were achieved for both homogeneous and heterogeneous sample, respectively. The results revealed the significant influence of permeability heterogeneity on oil recovery. This increase in heterogeneity lowered the recovery factor by ~20.0%. This lower recovery factor is due to channelling of the WAG through the high permeability layer leaving the low permeability zone untouched. Another observation is that the recovery during homogeneous sample displacement grows faster during the times leading to WAG breakthrough. This behaviour confirms the uniform flow of fluid through the homogeneous sample while in heterogeneous layered sample and because of flood channelling oil recovery comes mostly through the high permeability layer (flow through the preferential paths) [67].

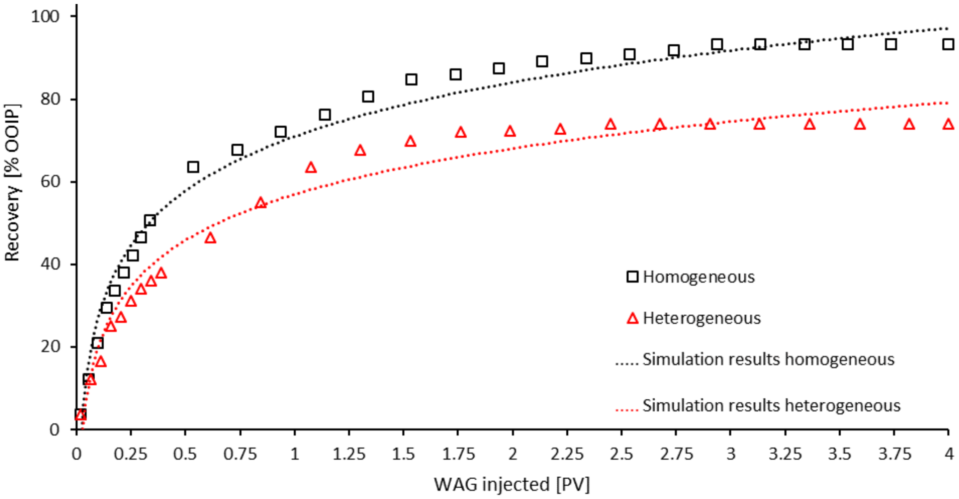
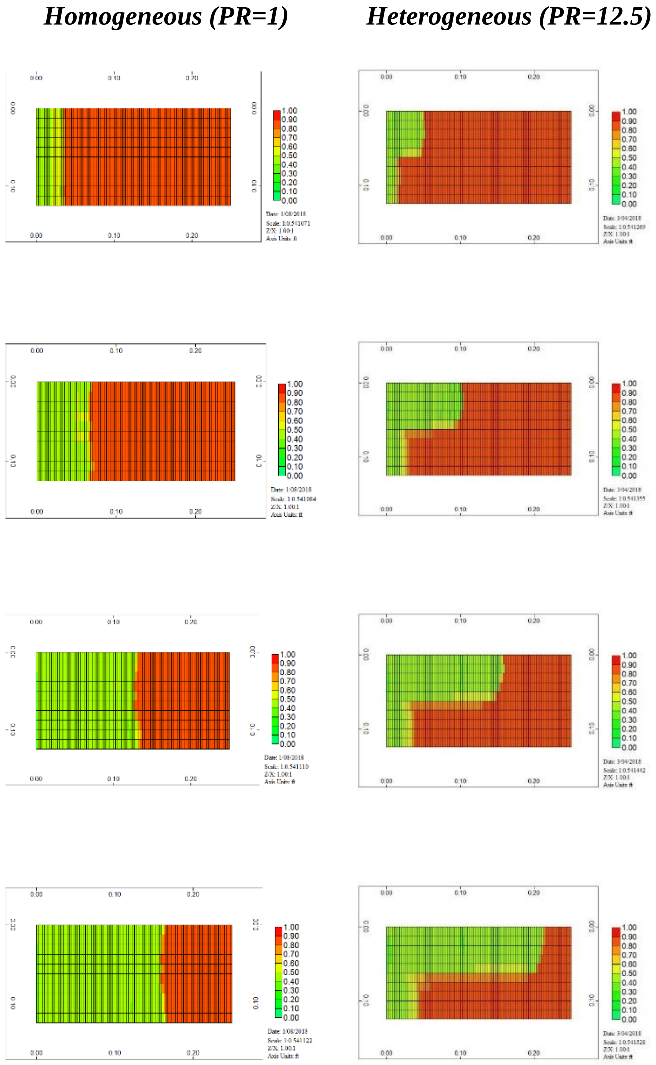


Figure 4. Oil recovery factor vs. pore volume of injected WAG

3.2 Numerical simulation of WAG displacements

To understand the behaviour of miscible CO_2 WAG flooding in heterogeneous porous media. We have built and run CMG-GEM model to quantify the influences of permeability ratio in cross-bedded reservoirs. To validate the model, the simulation results was history matched against oil recovery factor (Figure 4). Figure 5 depict different stages of CO_2 WAG flooding in both homogeneous (left) and heterogeneous (right) core sample in XZ direction. Results demonstrated the significant impact of heterogeneity on oil recovery factor and revealed the existence of water shielding effect during the WAG displacement reflected by the low recovery factor and blockage of some paths preventing oil to from mobilising. Increasing heterogeneity causes higher unstable flood front and an early breakthrough of injected WAG. On the other hand, WAG flooding in homogeneous core sample reveals the uniform frontal advance during the whole flooding stages. This results confirmed that the injected water reduces the relative permeability of CO_2, which lowers the total mobility [30]. Besides, channelling of WAG floods through high permeability layer is obvious thus production recovery is less than that of homogeneous case. On the other hand, Figure 6 shows the WAG flooding performance in heterogeneous core sample with and without crossflow. This figure confirms the positive effect of crossflow on oil recovery.

Moreover, the breakthrough time for non-communicating layer is faster than flood in communicating layer which is another reason for higher oil recovery. In addition to the simulation results discussed earlier, we have both history matched and evaluated the influence of heterogeneity levels on ultimate oil recoveries. These results revealed that with increasing heterogeneity level (PR's) oil recovery decreased significantly and breakthrough happened faster in both cases. It is also worth noting that increasing heterogeneity level diminishing the influence of crossflow on oil recovery, since the channelling with prevail. One could conclude that understanding heterogeneity level in layer reservoirs require more attention before any field application this could be done by understanding the behaviour of fluids in such porous media by running both experimental and simulation, also understanding the implication of different active driving forces is of key importance in such evaluation. Please refer to Appendix A for different simulation results evaluating the influence of heterogeneity and crossflow effects (Figure 7).



Homogeneous (PR=1) ***Heterogeneous (PR=12.5)***

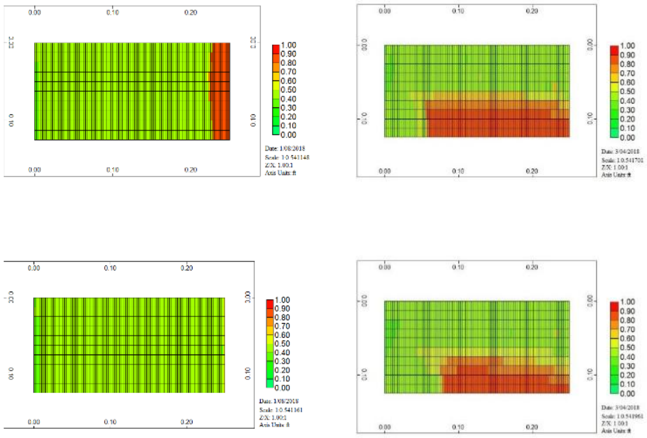
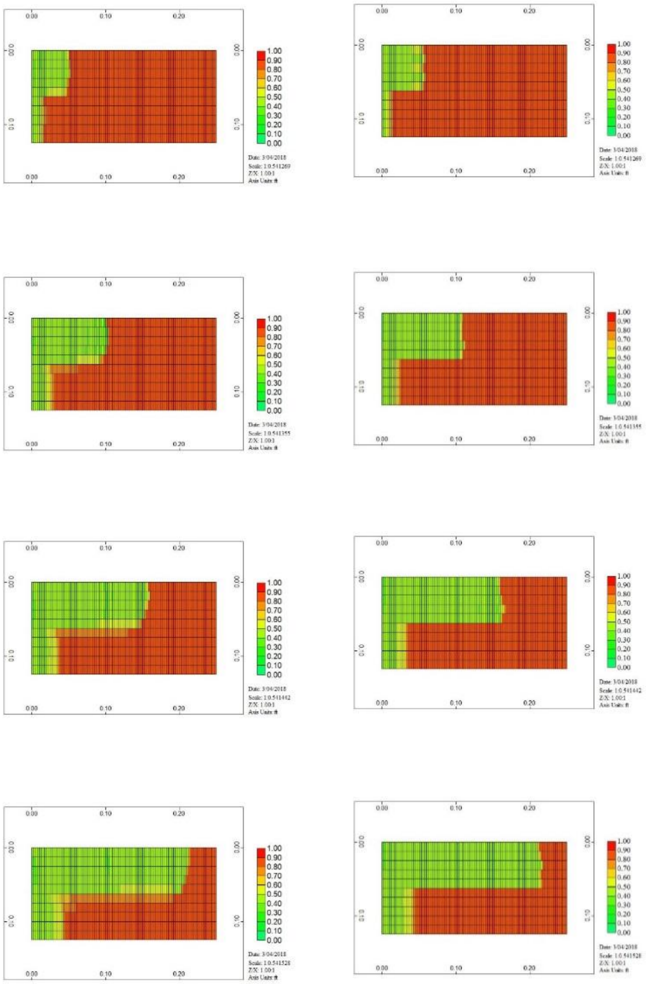


Figure 5. Oil saturation at different pore volumes of injected WAG in both homogeneous and heterogeneous core sample.



Heterogeneous with crossflow (PR=12.5)

Heterogeneous without crossflow (PR=12.5)

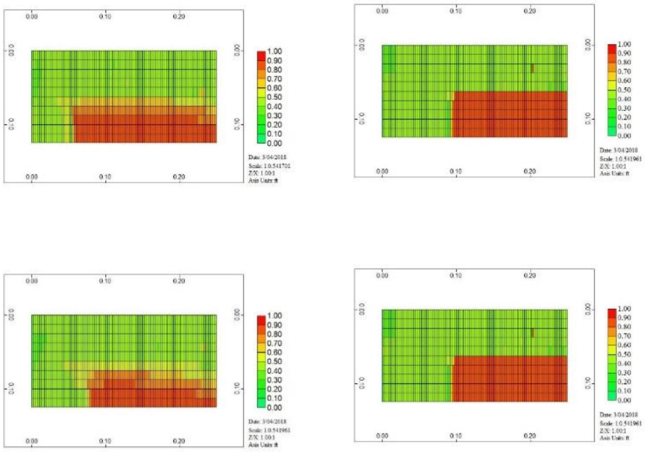


Figure 6. Oil saturation at different pore volumes of injected WAG in both heterogeneous core sample with and without crossflow (PR=12.5).

4. **Conclusions**

We performed two experiments to investigate and demonstrate the relative importance of core-scale heterogeneity during CO_2 WAG flooding, using both homogeneous and heterogeneous core sample. In addition, a core-scale CMG-GEM simulator was implemented to complement the results of the experiments. The following conclusions can be drawn upon combining the results of the experimental tasks and numerical investigations:

- WAG is displaced unevenly in the heterogeneous core sample, leaving plenty of oil in the area of relatively low permeability.
- As expected, a higher recovery was achieved from the homogeneous core flooding test. This higher recovery is attributed to the uniform distribution of displacing fluid inside the core sample.
- A higher production rate was achieved during WAG flooding in homogeneous core sample compared to heterogeneous core plug which attributed to floods channelling in the latter case.
- Recovery in both communicating and non-communicating layers revealed the negative influence of crossflow on ultimate oil recovery.
- Numerical simulation results revealed the occurrence of water shielding during WAG flooding preventing oil from mobilisation.
- Simulation results revealed a uniform frontal displacement during WAG flooding in homogeneous core sample, while channelling through high permeability layer is prevail with occurrence of heterogeneity.

Conflict of Interest: The authors declare that they have no conflict of interest.

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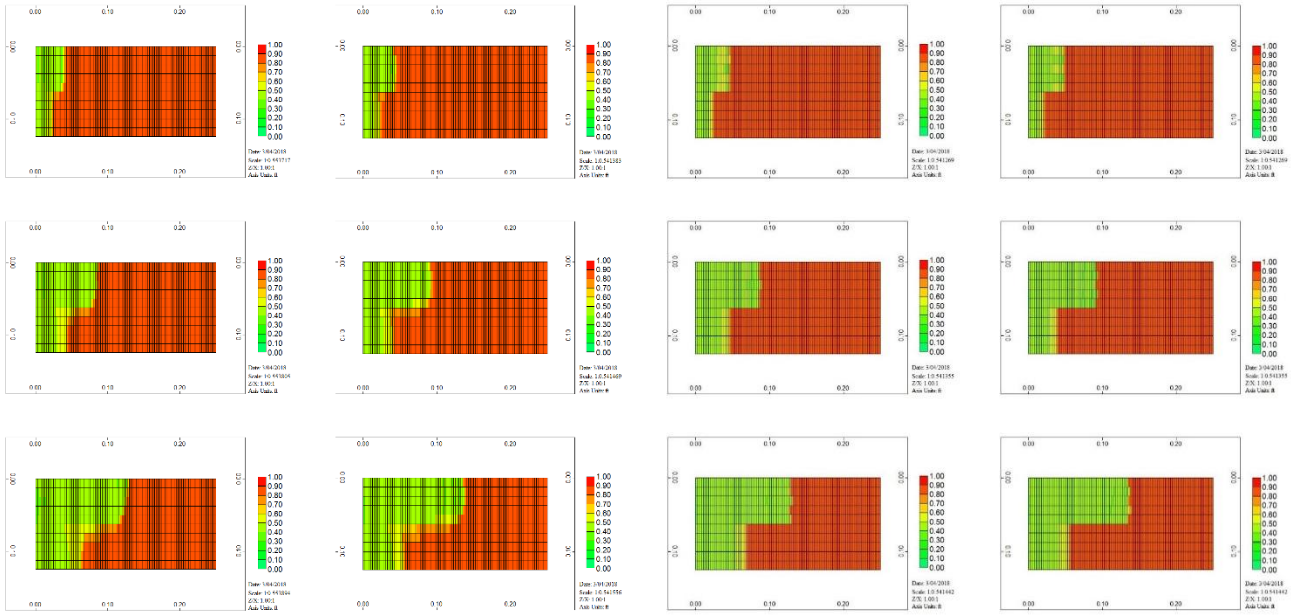
Appendix a

PR=2.5	***PR=5***	***PR=2.5***	***PR=5***
With Crossflow	***With Crossflow***	***Without Crossflow***	***Without Crossflow***



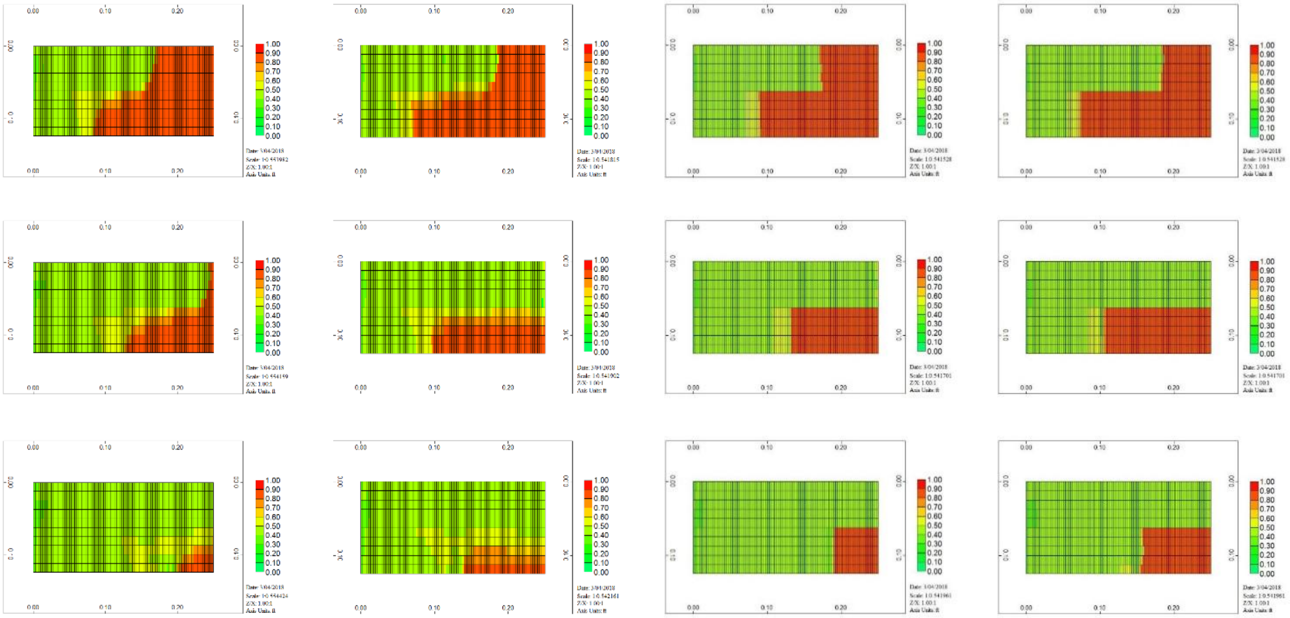


Figure 7. Oil saturation at different pore volumes of injected WAG in both heterogeneous core sample with and without crossflow (PR=2.5 and 5).