Introduction

The injection of carbon dioxide (CO₂) in deep geological formations such as saline aquifers has been identified as a promising solution for reducing anthropogenic CO₂ emission levels. Following injection into the subsurface, CO₂ invades the host rock and displaces the resident reservoir fluids by a process of immiscible two-phase fluid displacement. Successful implementation of the CO₂ storage technology strongly depends on understanding and being able to predict multiphase fluid displacement patterns and quantify the amount of CO₂ trapped at the pore scale. Reliable estimates of CO₂ storage capacity are critical to understanding the viability of geological storage in potential storage sites, allowing informed and sound business decisions to be made with regards to site selection and development (Solomon et al., 2014). Direct numerical simulations are a useful tool to improve our ability to predict the dynamics of immiscible two-phase flow in porous media.

The immobilization and trapping of a non-wetting fluid in a porous rock structure as isolated ganglia (known as capillary or residual trapping), is important to geological storage of CO₂. Entrapment of supercritical CO₂ in rock pore spaces, inhibits upward migration of the buoyant CO₂ plume and improves long-term CO₂ storage security. It is estimated that residual trapping contributes up to 40% of overall trapping in the first century following injection of CO₂ in the subsurface (Li et al., 2015). As such, achieving maximum trapping of the injected non-wetting CO₂ phase is one of the key objectives in CO₂ storage operations. The amount of capillary trapping that occurs is primarily determined by the, rock-fluid interactions, the flow rate and the structure of the porous medium (Tanino and Blunt, 2012).

Saline aquifers (water-wet, brine filled reservoirs) have been identified as having the greatest potential for CO₂ storage with an estimated cumulative storage capacity of 10⁴ Giga-tons of CO₂. As such, many studies have been devoted to studying residual trapping in water-wet systems. Not much attention has been given to intermediate-wet and oil-wet carbonate reservoirs. In the maturing stages of the CO₂ storage technology, projects are however, most likely to be conducted in depleted and oil producing carbonate reservoirs because of the monetary benefits associated with CO₂ enhanced oil recovery and the existence of installed infrastructure which can be reassigned for CO₂ injection purposes (Al-Menhal et al., 2016). More insight into fluid displacement under such conditions is required. It should be noted that CO₂-enhanced oil recovery processes can be miscible or immiscible, however in this study only immiscible two-phase fluid displacement is investigated. Pore scale simulations were conducted using the Finite Volume discretisation method (FVM) in OpenFOAM® in order to investigate the effects of structural heterogeneity of the reservoir rock on residual trapping under intermediate-wet conditions.

Method

OpenFOAM® is a Computational Fluid Dynamics (CFD) software package that is based on the object-oriented C++ programming language and uses the finite-volume method (FVM) for discretisation of the partial differential equations that describe the physics of a system being study. Fluid flow dynamics are governed by a set of coupled partial differential equations known as the Navier-Stokes equations. CFD is based on solving the Navier-Stokes equations using computers. The Navier-Stokes equations are based on the laws of conservation of, mass and momentum and energy. These laws are defined by the continuity, momentum and energy equations respectively. Depending on the system being studied, the relevant equations are chosen and solved. As there are no thermal (temperature) effects involved in this study, only the continuity and momentum equations are considered here.

The continuity equation (Equation 1 below) describes the conservation of mass, and states that the rate at which mass enters a cell volume is equal to the rate at which mass leaves the volume plus the accumulation term.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad \text{Equation 1}
\]

Where \( \rho \) is density (kg/m³), \( t \) is time (s) and \( \mathbf{u} \) is the fluid velocity (m/s).
The momentum equation (Equation 2 below) describes the conservation of momentum and states that for a closed system, when two bodies interact, their total momentum before the interaction is the same as after the interaction. For such a collision, the forces acting between the two bodies are equal in magnitude and opposite in direction (Newton's third law). The derivative form of this equation is as follows:

\[
\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} \tag{Equation 2}
\]

Where \( p \) is pressure (N/m\(^2\)) and \( \nu \) is kinematic fluid viscosity (m\(^2\)/s). Velocity and pressure fields are determined by solving the Navier-Stokes Equations. In two-phase flow, the system is considered as a medium with a discontinuity in fluid properties at the interface and an indicator function, \( \alpha \), is used to map the location of the two phases. The indicator \( \alpha \) denotes the concentration or volume fraction of a particular fluid in each cell on a computational grid block and the values of \( \alpha \) fall between 0 and 1. Taking an example of a two phase system comprising of a liquid phase and a gas phase, if a cell is entirely filled with fluid 1 (the liquid phase), then \( \alpha = 1 \). In cells filled with fluid 2 (the gas phase), \( \alpha = 0 \). Intermediate values of \( \alpha \) represent the interface between the two fluids.

Despite significant advances in pore scale simulation methods, there have been very few studies aimed at predicting capillary trapping curves through pore-scale numerical models and predicting capillary trapping for various displacement scenarios such as different flow directions and capillary numbers and different types of porous structures (Raeini, Bijeljic and Blunt, 2015).

In this study we contribute to filling this knowledge gap by investigating residual trapping in two types of porous media networks, a homogenous network and a heterogenous network. The pore network patterns (shown in Figure 1 below) are miniature representations of the internal porous structures of two naturally occurring reservoir rocks namely; Oolitic limestone a rock with a uniform and homogeneous structure and Berea sandstone a heterogenous rock.

![Figure 1 Pore Network Patterns used for direct numerical simulations in OpenFoam (Left) A homogeneous network: Oolitic limestone (Right) A heterogeneous network: Berea sandstone (Boek and Venturoli, 2010) (Wlodarczyk, Hand and Maroto-Valer, 2019)](image)

The uniform structure was designed in AutoCAD and converted to the stl format which is required for Volume of Fluid Simulations in the OpenFOAM® package. The patterned area of this model being 10mm by 7.5mm. The more complex pore network pattern for the Berea sandstone was generated by tiling an image of the pore network pattern from a thin section of Berea Sandstone acquired by Micro-Computed Tomography (micro-CT) X-ray imaging that was digitized from (Boek and Venturoli, 2010). The image was saved as a monochrome bitmap, which was then converted into a .dxf file as described in a paper recently published by our group describing a novel, rapid and mask-less method for fabrication of microfluidic devices using a pulsed picosecond laser which we recently developed (Wlodarczyk, Hand and Maroto-Valer, 2019). Once the .dxf file has been generated, it can be easily extruded and exported in the .stl file format. The patterned area used in the heterogeneous model simulation was 10mm by 5mm. Immiscible two-phase imbibition processes were then simulated in the porous structures with air as the non-wetting phase and water as the wetting phase. In both simulations, the models were initially fully saturated with air prior to water injection. A contact angle of 90° was used in the simulations.
Because of the high computational cost associated with direct numerical simulations, they are limited to small domain sizes and relatively high capillary numbers (magnitude of $10^{-5}$ and higher) (Raeini, Bijeljic and Blunt, 2015). As such, the original design dimensions of the model were scaled down by a factor of 10 in all planes to reduce the computational cost and simulations in both models were conducted at entry capillary pressures in the order of $10^{-4}$. In all images shown hereafter which are top views of the porous models, fluid displacement occurred in the horizontal plane (from left to right) and there were no gravity effects present in the simulations.

**Results and Discussion**

Immiscible two-phase fluid displacement under intermediate wettability in the above described models was analysed and residual fluid saturations were quantified for different porous structures. In the homogeneous model, simulation results showed the invading water-front propagating through a series of cooperative pore-filling events (shown in Figure 2 below) which included:

- merge mechanisms in which two menisci coalesce and form a single meniscus
- burst mechanisms in which a meniscus becomes unpinned from a pore throat and rapidly advances into a pore body
- touch mechanisms in which a meniscus advances and touches the nearest grain often splitting into two menisci soon after as shown in the image to the far right in Figure 2.

![Figure 2 Types of cooperative pore-filling mechanisms observed](image)

A stable and compact fluid displacement front was observed as a result of these cooperative pore-filling events as shown in Figure 3 (left) below.

![Figure 3 Image showing residual trapping of the non-wetting phase (red) in (Left) Homogeneous, Oolitic limestone rock structure (Right) Heterogeneous, Berea sandstone rock structure](image)

Residual trapping of the non-wetting phase in this model was observed only in small, dead-end pores found at the edges of the porous structure (circled in yellow in Figure 3 above). This occurred due to the occurrence of snap-off mechanisms in which continuous sections of the non-wetting phase are disconnected due to swelling of the advancing wetting layer. Cooperative pore-filling events were found to stabilize the invasion by promoting lateral fluid invasion (invasion in the vertical direction in the images) as opposed to forward invasion of the front thereby slowing down propagation of the front. The lateral fluid invasion resulted in high fluid displacement/sweep efficiency and was encouraged by pinning of the fluid-fluid interface in pore throats (capillary-valve effect). This occurs because there is
an abrupt geometrical expansion in throat-pore junctions and the invading fluid needs to acquire a certain threshold pressure value to advance from the throat into the pore. As such, the fluid-fluid interface remains pinned until this threshold pressure value is attained.

In the heterogeneous pore network, trapping of the non-wetting phase was more apparent and significant than in the homogenous pore network as shown in Figure 3 (right). This was attributed to the fact that dead-end pores were larger and more frequently occurring in the heterogeneous Berea sandstone porous model. Snap-off mechanisms which promote residual trapping were also more frequently occurring and more dominant than cooperative pore-filling mechanisms in this model than in the homogenous structure. This is because the pore to throat aspect size ratio was higher in the Berea sandstone model than in the Oolitic limestone model. Residual trapping of the non-wetting phase was also observed in non-dead-end type pores in the heterogeneous structure (as shown by the blue circles in Figure 3) unlike in the homogeneous structure where trapping was only observed in dead-end type pores.

Conclusions

This work has shown that fluid displacement during imbibition processes under intermediate-wet conditions occurs through a series of cooperative pore-filling events in homogeneous structures having relatively small pore-to-throat aspect size ratios. The type (isolated, throat, cross linked or dead end), size as well connectivity of pores present in the porous structure was found to have a strong impact on residual trapping under intermediate-wet conditions. The presence of large dead-end pores greatly enhanced residual trapping of the non-wetting fluid, whilst connecting and throat type pores primarily played the function of facilitating fluid transmission through the porous medium. Higher pore to throat size aspect ratios were found to promote snap-off which in-turn results in enhanced residual trapping.

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