A Pore-Scale Investigation of Fluid Displacement and Residual Trapping Under Water-Wet and Intermediate-Wet Conditions

LEADERS IN IDEAS AND SOLUTIONS

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Study Aim and Description

- Trapping of fluids in the interstitial spaces of porous rocks by capillary forces (residual trapping) is dependent on the wettability and intrinsic heterogeneity of the porous medium in geological applications such as CO_2 storage and oil recovery operations.

- Heterogeneity in pore structure is common in many geological formations and is known to have a strong impact on flow in porous media. As such;

  The Aim of this study was: To investigate and isolate the effects of pore structure heterogeneity and wettability on residual trapping by comparing fluid displacement mechanisms and quantifying residual saturations for water-wet and intermediate-wet conditions for homogeneous and heterogeneous porous media.

- Pore-Scale simulations were conducted using the two-phase solver InterFoam in OpenFoam using the finite volume discretization method

- Two pore network patterns were used:

i. Heterogeneous Berea Sandstone model

ii. Homogeneous Pillars model

Pore Network Patterns Studied

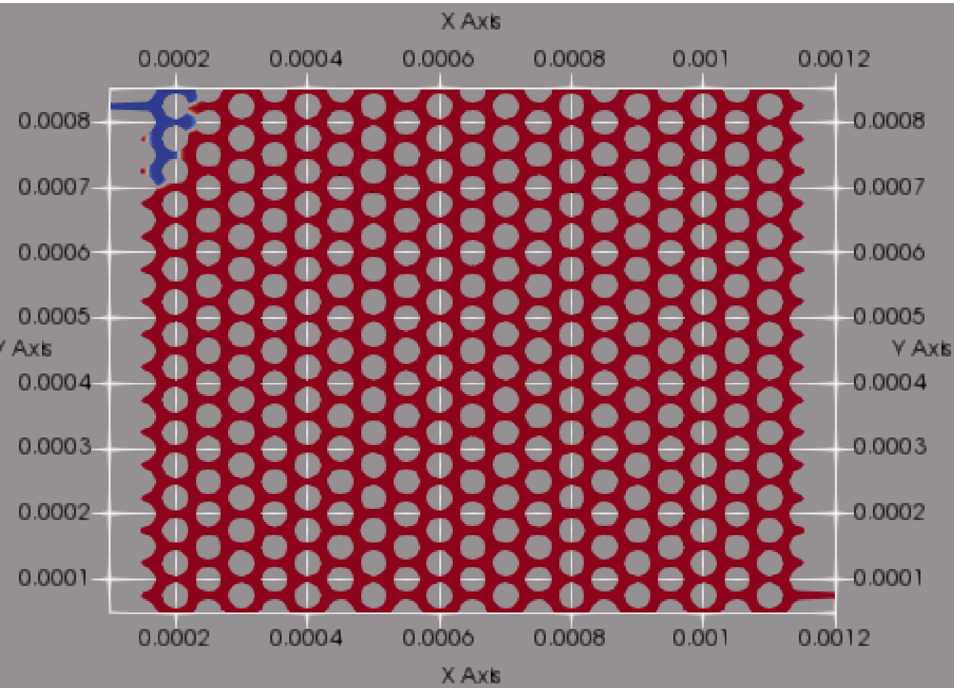


Figure.1

Homogeneous Pillars Model

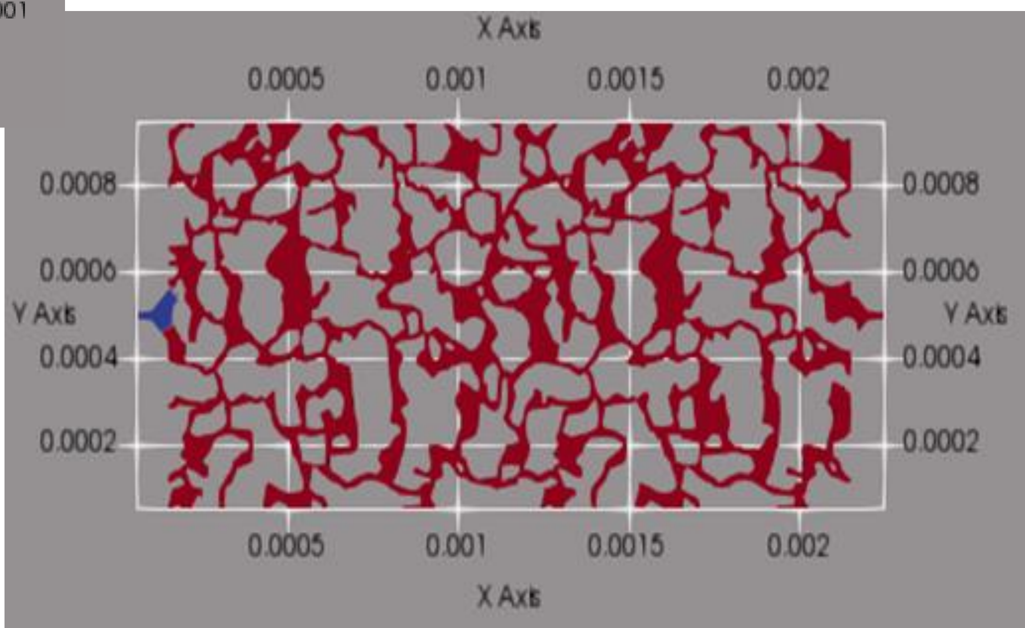
Pore Matrix: rhombohedra sphere packing (Oolitic limestone)

- Length =1mm
- Width= 0.8mm
- Depth 0.005 mm
- Inlet/outlet width= 0.012mm

Heterogeneous Berea Model

Pore Matrix: Berea Sandstone

- Length =2mm
- Width= 1mm
- Depth 0.005 mm
- Inlet/outlet width= 0.012mm



Simulation Parameters

Homogeneous and Heterogeneous Networks

Fluid Properties:

- Displacing fluid (Water)- kinematic viscosity 1E-06 m^2/s
- Displaced fluid (Decane)- kinematic viscosity 1.25E-06 m^2/s

* The water phase is shown in blue in whilst the decane phase is shown in red in all simulation images shown - The direction of fluid flow is from left to right*

- Mobility ratio; Log M= 0.037
- Fluid Velocity= 0.3m/s
- Log_{10} Ca= -3
- Reynold's number; Re = 2.117 (Laminar flow)

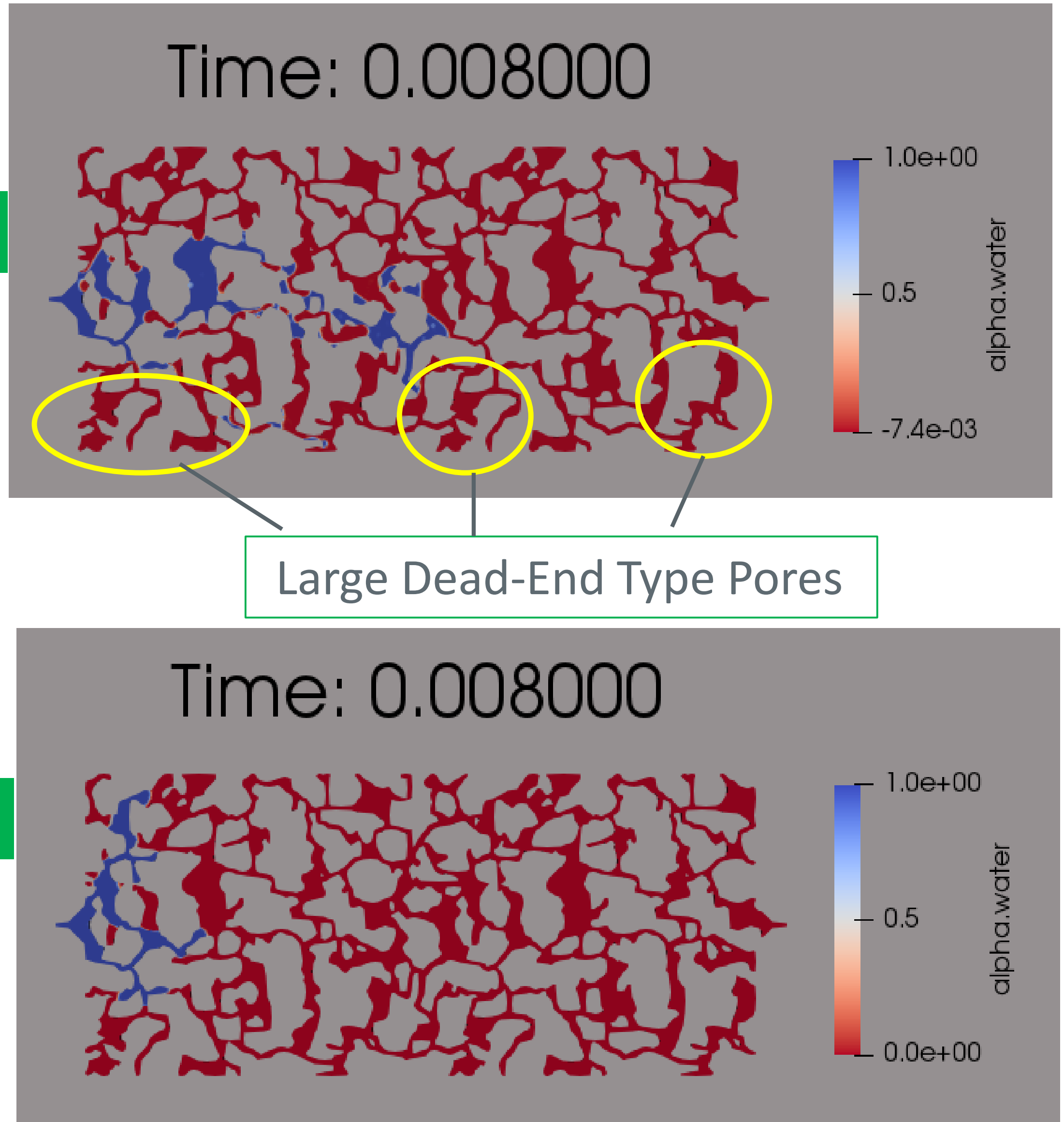
- For both pore networks, simulations were conducted for water-wet conditions (Contact Angle (CA)=45°) and intermediate-wet conditions (CA= 90°)

Wettability Impact on Residual Trapping

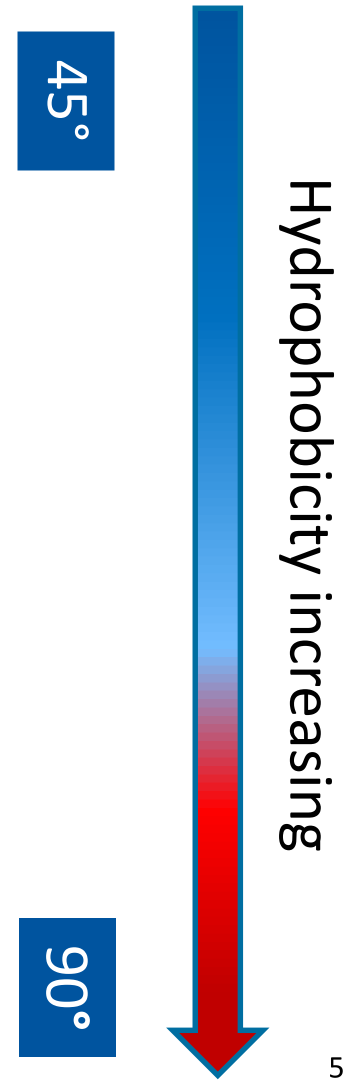
(Heterogeneous Berea Model)

Water-wet

Figure.2



Intermediate-wet



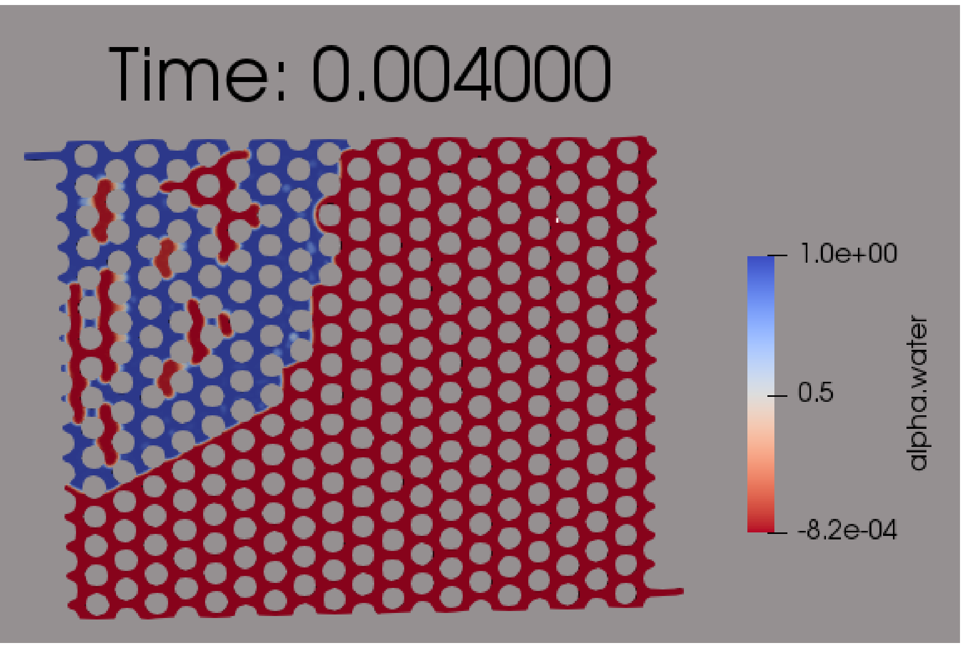
Analysis of Pore-Scale Fluid Displacement Sequence
(Heterogeneous Berea Model)

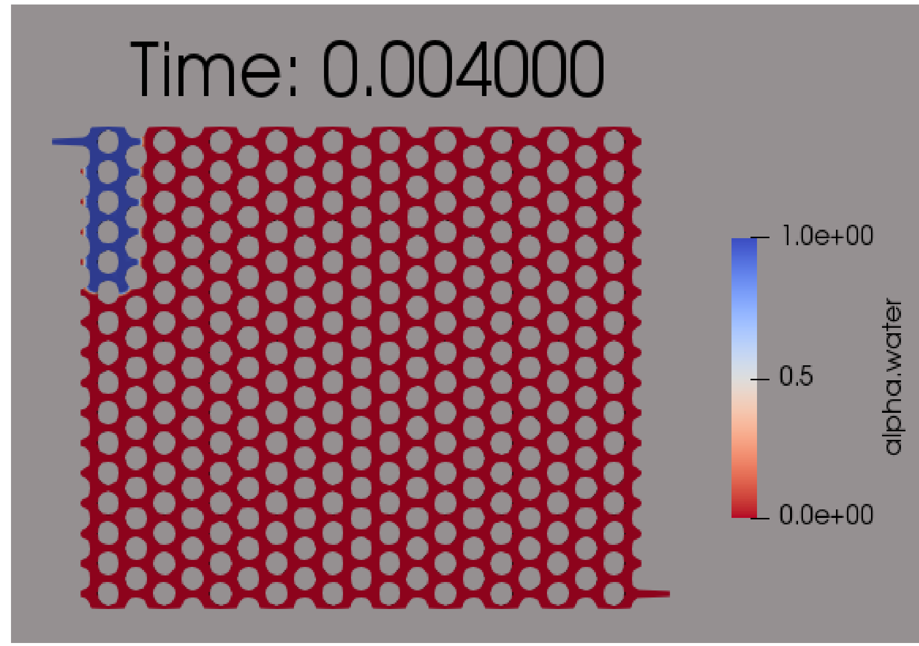
- Under strongly water wet conditions, water invasion is parallel to the direction of injection
- Parallel invasion results in large clusters of non-wetting phase (NWP) being by-passed, thereby enhancing residual saturation
- When the porous medium is neutrally wetting (intermediate-wet), lateral spreading of invading fluid is observed. Lateral invasion significantly slows down invading front as seen in. The invading water front in the water-wet scenario was approx. 6 times faster than that under water wet conditions (see Figure 2). As a result, breakthrough was achieved earlier under water-wet conditions
- A significant amount of trapping observed in large dead-end pores (shown in Figure 2). at the edges of the porous medium regardless of wetting properties
- Residual saturations Water-wet- 47% ; Intermediate-wet-33%

Effect of Wettability on Residual Trapping

Homogeneous Pillars Model

Well connected uniform porous matrix; No Large Dead-End Type Pores





Water-wet

Figure.3

Intermediate-wet

45°

Hydrophobicity increasing

90°

Analysis of Pore-Scale Fluid Displacement Sequence
(Homogeneous Pillars Model)

- In this model, the effects of wettability are isolated as the porous matrix is uniform hence there are no structural heterogeneity effects.
- In the homogeneous pillars model, the NWP is mostly trapped as large clusters spanning over multiple pores (see Figure 3) unlike in the heterogenous Berea sandstone model where trapping is mostly in single pores (see Figure 2). Few small, isolated ganglia are however seen trapped in individual pores and this is due to the occurrence of snap-off in pore throats.
- Trapping was significant under water wet conditions whilst little to no trapping was observed under intermediate wet conditions indicating higher sweep efficiency under intermediate wet conditions as displacement occurred through a series of co-operative filling events
- The delay in breakthrough between water wet and intermediate-wet conditions for the homogeneous model was more than twice that observed in the heterogenous sandstone model.
- Residual saturations Water-wet- 35% Intermediate-wet-14%

Summary of Findings

- Residual trapping is more pronounced and sweep efficiency decreases when the porous medium is more wetting to the invading phase.
- Narrow throat constrictions in the pore matrix promote trapping and fluid break up. Water-wet conditions were also observed to promote fluid break up
- Under both water-wet and intermediate-wet conditions, residual saturations were higher in the heterogenous model. This highlights the dominance of structural effects on residual trapping.
- Dead-end pores significantly enhance the irreducible trapped saturation, as ganglia are trapped permanently in dead end pores (immovable saturation)

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