Effects of heterogeneity of porous media and wettability on forced imbibition

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Abstract: Imbibition, the wetting fluid displacing a nonwetting one, occurs in many natural and industrial applications, such as enhanced oil recovery and CO₂ sequestration. The imbibition process is highly affected by wettability, viscosity ratio and injection flow rates, and the competition between these factors become more complicated when the heterogeneity of porous media is involved. In this work, forced imbibition in two-dimensional porous media is systematically investigated with different disorders over a broad range of wettability conditions and flow rates. Results show that the disorder and the wettability have different impacts on the imbibition process under different capillary numbers.

1. Introduction
Imbibition, which means the displacement of a non-wetting fluid by a wetting fluid driven by capillary forces, is a common process with a lot of practical applications, such as enhanced oil recovery, geological carbon storage, and remediation of non-aqueous phase (NAPL) and food industry[1-7]. For the enhanced oil recovery, the imbibition process is determined by the complex interplay between wettability, viscosity ratio and flow rates, which leads to different displacement patterns, interfacial features and displacement efficiency [8]. The competing effects become more complicated when the disorder of pore-size effect is involved.

The instability of the displacement front is an important aspect to understand and determine the displacement process. Lenormand et al. and Zhang et al. conducted a series experimental and numerical simulations of two-dimensional networks to monitor the displacement process and proposed a viscosity ratio-capillary number phase diagram. They grouped these displacements into three different patterns: capillary fingering (CF), stable displacement (SD) and viscous fingering (VF), according to the capillary number $Ca = \frac{u_i \mu_i}{\sigma}$ ($u_i$ is the characteristic fluid velocity, $\mu_i$ is the viscosity of the invading fluid and $\sigma$ is the interfacial tension) and the viscosity ratio $M = \frac{\mu_i}{\mu_d}$ ($\mu_d$ is the viscosity of the defending fluid). Slow displacement which usually means a relatively small capillary number leads to capillary fingering. Increasing the flow rate, the displacement leads to viscous fingering for an unfavorable viscosity ratio ($M<1$) or stable displacement for a favorable viscosity ($M>1$).

The disorder of porous media is common and inherent in natural media and has a significant influence on the pattern of displacement. At low capillary number, increasing the disorder can promote fingering and trapping which leads to a transition from stable displacement to capillary fingering. At high capillary number, increasing the disorder leads to more chaotic viscous fingering with more tortuous fingers.

In this paper, 2D porous media with different disorders are constructed. A series of numerical simulations are conducted over a broad range of wettability conditions and capillary numbers. It is...
observed that the coupling effects between the disorder and the wettability on the imbibition process under different capillary numbers are complex and have different influence on the displacement patterns.

2. Theory and numerical simulation set-up

2.1. Governing equations

In our cases where the gravity effects are neglected and fluids (oil and water) are incompressible, the fluid flow is characterized by the Navier-Stokes equation together with the volume of fluid (VOF) method.

The mass conservation equation and the momentum equation are as follows:

$$\nabla \cdot \mathbf{u} = 0,$$

$$\frac{\partial \left( \rho \mathbf{u} \right)}{\partial t} + \nabla \cdot \left( \rho \mathbf{u} \mathbf{u} \right) = -\nabla \cdot \left[ \mu \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right) \right] + \mathbf{F},$$

where $\mathbf{u}$ is the velocity field and $p$ is the pressure. $\mathbf{F}$ is the source term contributed by the interfacial tension and it can be expressed as $\mathbf{F} = \sigma \kappa \mathbf{n}$, where $\sigma$ is the interfacial tension, $\kappa$ is the curvature and $\mathbf{n}$ is the normal vector of the interface.

The VOF method is used to track the fluid-fluid interface. A phase indicator function is introduced to represent the volume fraction of fluid within cells, as mentioned:

$$\alpha = \begin{cases} 
0, & \text{in the defending fluid}, \\
1, & \text{in the invading fluid}, \\
0 < \alpha < 1, & \text{on the interface}. 
\end{cases}$$

Then the curvature can be expressed as $\kappa = -\nabla \cdot \left( \nabla \alpha / \| \nabla \alpha \| \right)$ and the normal vector can be expressed as $\mathbf{n} = \nabla \alpha$. The evolution of $\alpha$ is given by an advection equation as:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{u}) + \nabla \cdot (\alpha (1 - \alpha) \mathbf{u}_c) = 0,$$

where $\mathbf{u}_c$ is an artificial compression velocity to limit numerical diffusion and the density and the viscosity in the whole domain can be expressed as:

$$\rho = \rho_\alpha + (1 - \alpha) \rho_\omega, \quad \mu = \mu_\alpha + (1 - \alpha) \mu_\omega.$$

The wettability effect on the fluid flow is considered by imposing an additional constraint on $\alpha$ between the interface and the solid face as:

$$\frac{\nabla \alpha}{\| \nabla \alpha \|} = : \hat{n} = \hat{n}_s \cos \theta + \hat{n}_t \sin \theta,$$

where $\Gamma$ denotes the solid boundary, $\hat{n}_s$ is the unit normal pointing into the solid and $\hat{n}_t$ is the unit tangent on the solid pointing into the wetting phase.

All above governing equations are already implemented in an open-source library software OpenFOAM.

2.2. Model and Simulation Conditions

The 2D flow geometry with the length $L = 2840 \ \mu m$ and the width $W = 1420 \ \mu m$ is constructed by placing posts on a triangular lattice with a spacing $a = 84 \ \mu m$. The radius of the post is variable and follows a uniform distribution $r \in \left[1 - \frac{\lambda}{1 + \lambda}, \frac{\lambda}{1 + \lambda}\right]^*, \quad \text{where} \ \mathbf{r} = \text{the average radius}, \quad \mathbf{r} = 30 \ \mu m \quad \text{and} \ \lambda$ is the disorder [33]. In this paper, we construct four 2D flow geometries with $\lambda = 0, 0.1, 0.2$ and 0.3 (Figure 1b-e). The porosity and the pore area of four geometries are nearly the same, i.e., $\phi = 0.51$ and $A_p = 2.06 \times 10^{-6} \ m^2$. The pore area is discretized with relatively uniform meshes comprising of 164410 cells and 377324 nodes.

The pore network is initially saturated with the defending fluid ($\rho_d = 850 \ \text{kg/m}^3$ and $\mu_d = 0.03 \ \text{Pa} \cdot \text{s}$), and then the invading fluid ($\rho_i = 1000 \ \text{kg/m}^3$ and $\mu_i = 0.001 \ \text{Pa} \cdot \text{s}$) with the constant $Q$ is injected from
the inlet. The viscosity ratio is $M = \mu_i/\mu_d = 1/30$ and the interfacial tension $\sigma$ is 0.04 N/m. The wettability is characterized by the contact angle of the invading fluid $\theta$. The simulation is stopped once the invading fluid reaches the outlet.

Figure 1. (a) A 2D pore network model. The length and width are, respectively, 2840 μm and 1420 μm. (b-e) Four 2D pore network models and the radius range with four different disorders $\lambda = 0, 0.1, 0.2$ and 0.3.

3. Results and discussions
We conduct a series of numerical simulations over different 2D porous media. For each porous media, we conduct simulations over a broad range of wettability conditions ($\theta = 15^\circ, 45^\circ, 60^\circ$ and $89^\circ$) from strong imbibition to weak imbibition for each of four different capillary numbers ($\log_{10}Ca = -4.602, -4, -3.301$ and $-3$).

Figure 2. (a-d) Displacement patterns for four different porous media with the disorder $\lambda = 0, 0.1, 0.2$ and 0.3 when the invading fluid reaches the outlet. For each group, numerical simulations are conducted under different wettability conditions (from left to right: $\theta = 15^\circ, 45^\circ, 60^\circ$ and $89^\circ$) and capillary numbers (from bottom to top: $\log_{10}Ca = -4.602, -4, -3.301$ and $-3$). Black and white phases represent invading and defending fluid, respectively.

The displacement patterns for different disorders and contact angles under a range of capillary
numbers are shown in Figure 2. The fluid-fluid interface length \( A_{nw} \) and the normalized displacement front \( L_f \) as a function of saturation \( S_w \) are presented in Figure 3(a-b). The results indicate that \( A_{nw} \) and \( L_f \) for different disorders have a little difference which means that the morphology of displacement front has small sensitivity to disorder \( \lambda \). This is caused by two contradicting effects. Pore-size homogeneity can hinder cooperative pore filling events, which can reduce the compactness of the displacement. However it can also inhibit fingers which compacts the displacement.

The breakthrough saturation as a function of contact angle \( \theta \) presented in Figure 3(c) shows a monotonic behavior of saturation of invading fluid with wettability. The \( S_{wb} \) continuously decreases as the wettability condition changes from strong imbibition (\( \theta = 15^\circ \)) to neutral imbibition (\( \theta = 89^\circ \)) especially from strong imbibition (\( \theta = 15^\circ \)) to intermediate imbibition (\( \theta = 45^\circ \)), which manifests the displacement efficiency is strongly linked to the wettability.

As the capillary number increases to \( \log_{10} Ca = -4 \), the breakthrough saturation as a function of contact angle \( \theta \) is presented in Figure 4(a). It is observed that the breakthrough saturation continuously increases with the increase of the contact angle \( \theta \), which can also demonstrate the transition from capillary fingering to viscous fingering.

The normalized displacement front \( L_f \) as a function of saturation \( S_w \) are presented in Figure 4(b). The slope of \( L_f - S_w \) for \( \lambda = 0.3 \) is higher than the slope of three others which means lower displacement efficiency. This is due to the high entry pressure with the increase of the disorder. The entry pressure as a function of time is presented in Figure 4(c) where the pressure with \( \lambda = 0.3 \) is much higher than the three others. The higher entry pressure makes it harder to invade small pores which leads to a lower displacement efficiency.

With the further increase of capillary number (\( \log_{10} Ca = -3.301 \) and \(-3\)), the disorder of the porous media has a great influence on the front morphology and the displacement efficiency. With the increase of disorder, the fluid-fluid interfacial length \( A_{nw} \) and the displacement front \( L_f \) increase drastically under the same saturation, which means more unstable interface and lower displacement efficiency.
(Figure 5a-c).

The Figure 5(d-f) depict the variation of $A_{nw}$ and $Lf$ as a function of $Sw$ for different $θ$ and the $Swb$ as a function of $θ$ for different disorders. The results show that the front morphology and the breakthrough saturation under different $θ$ has a little difference which means the wettability in this regime has a relatively weak impact due to the dominance of the viscous force.

4. Conclusions
In summarize, we construct four porous media with different disorders and conduct a series of numerical simulations over a broad range of wettability conditions and capillary numbers. It is observed that the coupling effects between the disorder of the porous media and the wettability under different capillary numbers are complex and have different impacts on the displacement patterns. At low capillary number, the displacement process is not sensitive to disorder. At intermediate capillary number, only the largest disorder has obvious influence on the displacement process. At high capillary number, the disorder has a great influence on the front morphology and displacement efficiency.

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