中國石油大學 (华东)
China University Of Petroleum

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Flow behavior in a rough channel with pore scale simulation

Chao Xu, Lei Zhang, Guangpu Zhu, Hai Sun, Yongfei Yang, Jun Yao
China University of Petroleum (East China)

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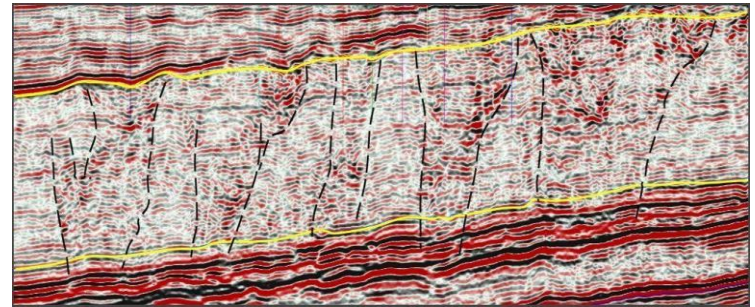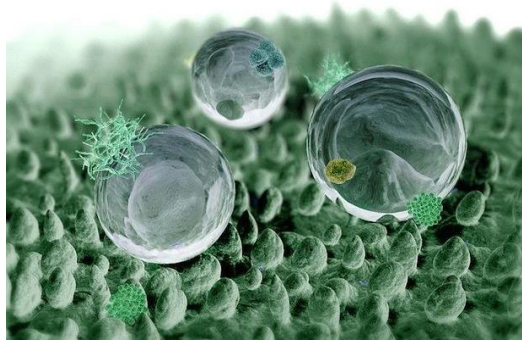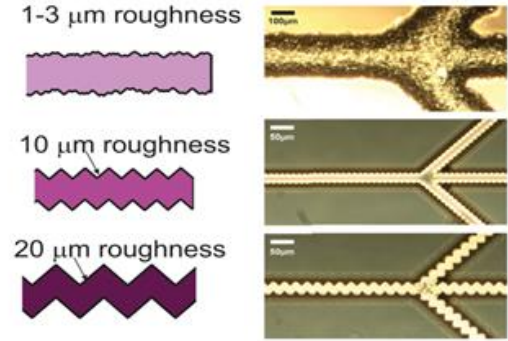
- **Roughness exists in every aspect of life. Rock surfaces, lotus leaf surfaces, rough throats in the reservoir**

- **The simulation of immiscible displacement and the description of two phase interface are essential in many industries.**

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2.1 N-S equation coupled with Cahn-Hilliard equation

(1) The mixing free energy of the interface region is defined based on the phase field variable：

$$F = \int_V \left[f(\phi) + \frac{1}{2}\lambda |\nabla \phi|^2 \right] dV$$
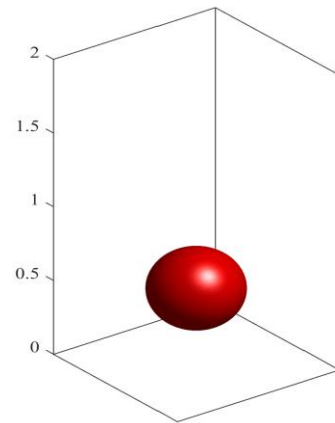
(2) Through the variational derivative of the free energy functional F with respect to the phase-field variable ϕ, we can obtain the chemical potential G：

$$G = \frac{\delta F}{\delta \phi} = f'(\phi) - \lambda \nabla^2 \phi$$
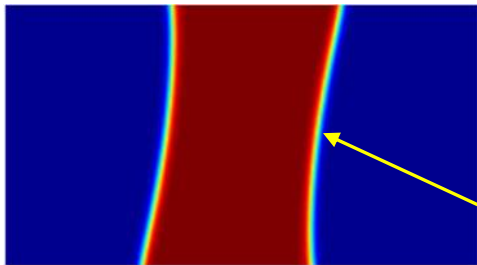
An interface with a certain thickness

ϕ=-1   water phase

ϕ= 1   oil phase

-1< ϕ <1   interface

2.1 N-S equation coupled with Cahn-Hilliard equation

(3) The formation, development and deformation of the phase interface are described by the

Cahn-Hilliard equation：

$$\begin{cases} \dfrac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \nabla \cdot \left(\dfrac{\gamma \lambda}{\varepsilon^2} \nabla \psi \right) \\ \psi = -\nabla \cdot \varepsilon^2 \nabla \phi + \left(\phi^2 - 1 \right) \phi \end{cases}$$

(4) $G\nabla\phi$ as the interfacial tension term was added into the N-S equation：

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \rho \mathbf{g} + \mu \nabla^2 \mathbf{u} + \boxed{G\nabla\phi} \longrightarrow \text{interfacial tension term}$$

(5) The Cahn-Hilliard and N-S coupling equations were solved to

obtain the values of phase field variables

boundary condition：

$$\begin{cases} \mathbf{u} = u_w = 0 \\ \mathbf{n} \cdot \dfrac{\gamma \lambda}{\varepsilon^2} \nabla \psi = 0 \\ \mathbf{n} \cdot \varepsilon^2 \nabla \psi = \varepsilon^2 \cos(\theta_w) \left| \nabla \psi \right| \end{cases}$$

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3.1 Influence of rough wall surface on oil-w

(a)

The interface length

t=0.0004s

t=0.0008s

(b)
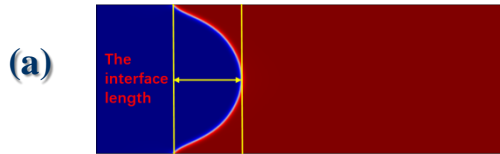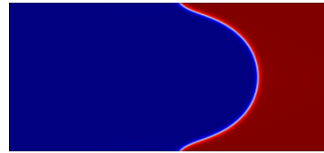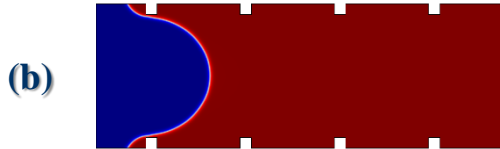
t=0.0004s

t=0.0008s

t=0.00011s

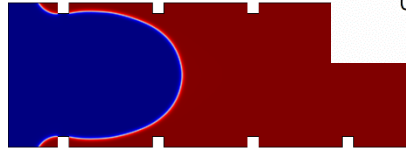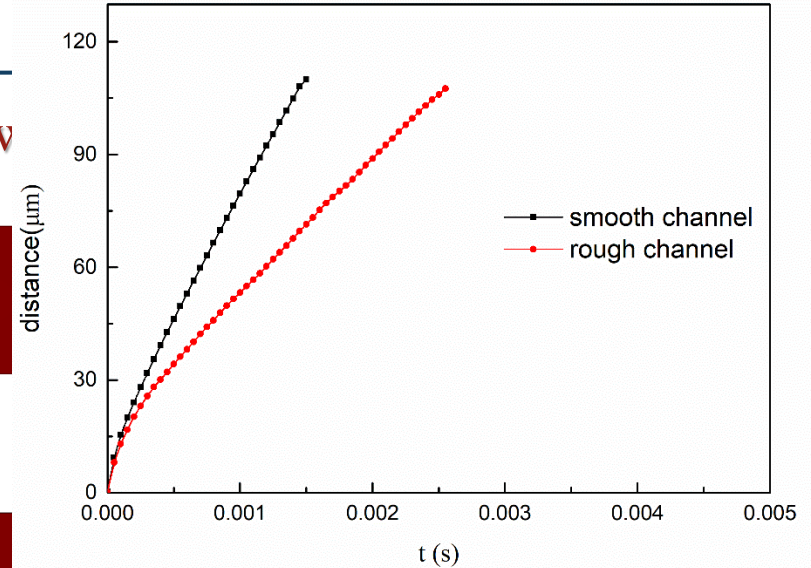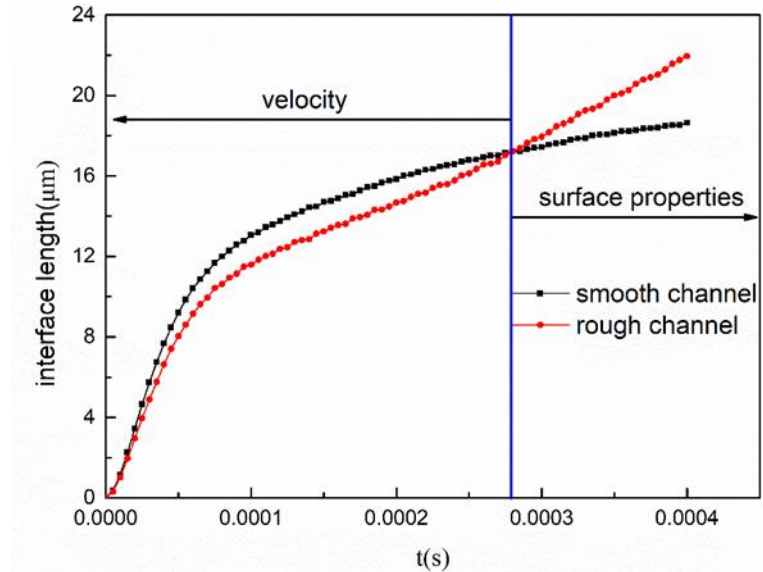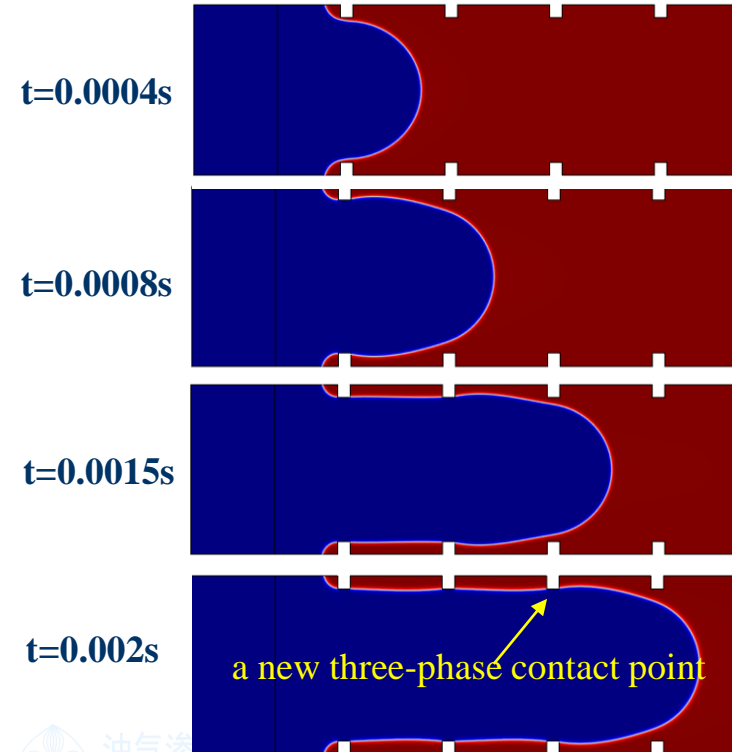**Immiscible displacement in a smooth channel and a rough channel: (a) smooth channel; (b) rough channel**

3.1 Influence of rough wall surface on oil-water flow
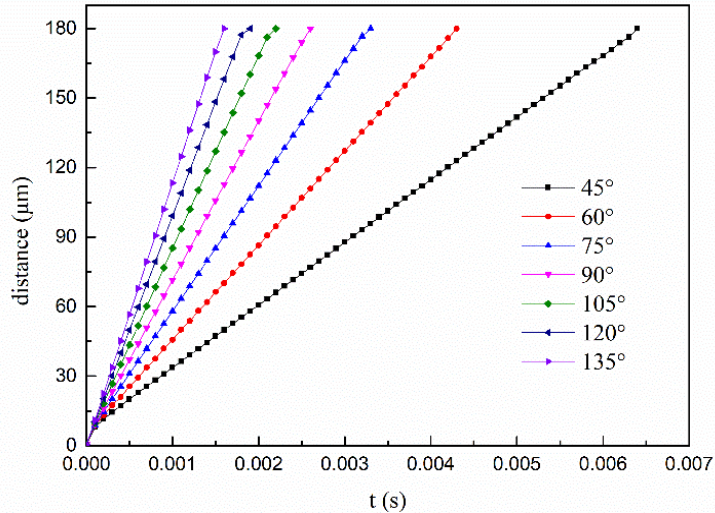
t=0.0004s

t=0.0008s

t=0.0015s

t=0.002s

a new three-phase contact point

Variation of interface length in a smooth channel and a rough channel
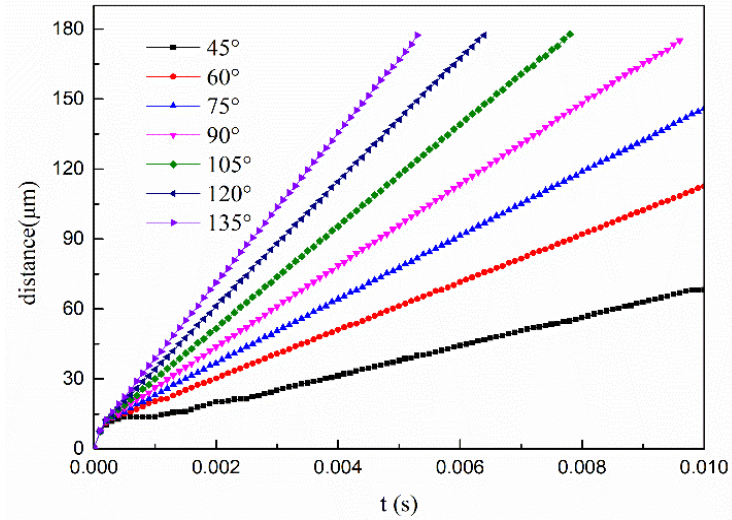
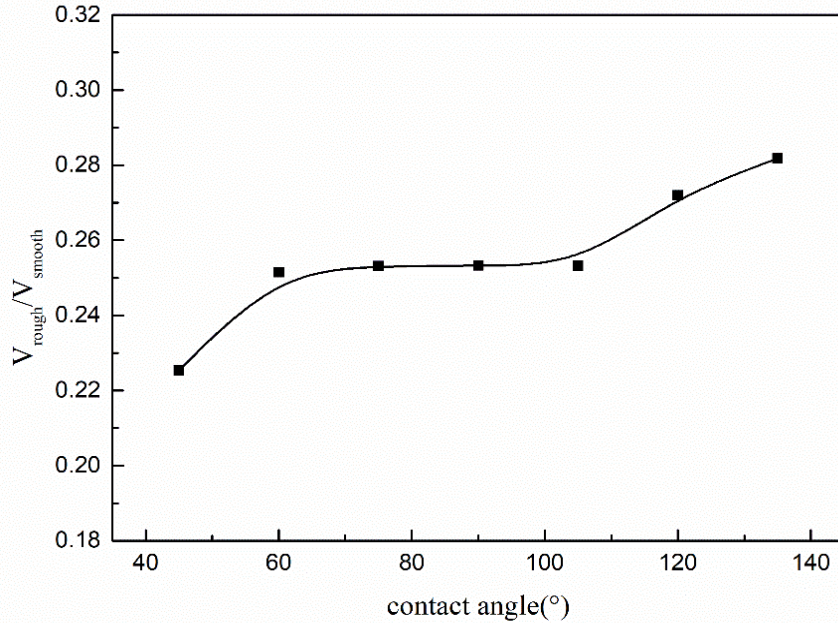## 3.2 Influence of wettability on oil and water flow in rough channel

Immiscible displacement of smooth channel and rough channel with different contact angles(oil contact angles): (a) smooth channel (b) rough channel

3.2 Influence of wettability on oil and water flow in rough channel

The rate of interface moving velocity in a rough channel to that in a smooth channel under different wetting conditions
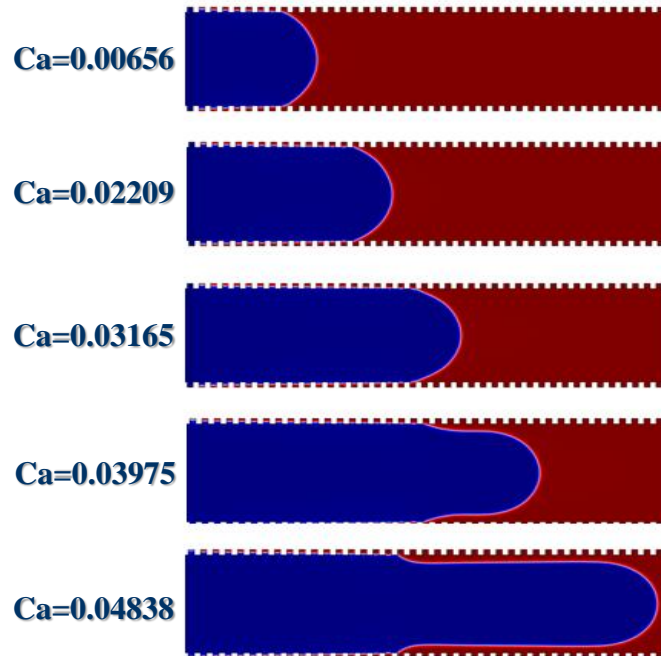
- **As the wettability of wall surface changes from oil-wet to water-wet, the influence of rough wall surface on the moving velocity of two-phase interface falls down**

3.3 Influence of capillary number on oil and water flow in rough channel

Ca=0.00656

Ca=0.02209

Ca=0.03165

Ca=0.03975

Ca=0.04838

The distribution of oil and water under different capillary numbers at t=0.002s.
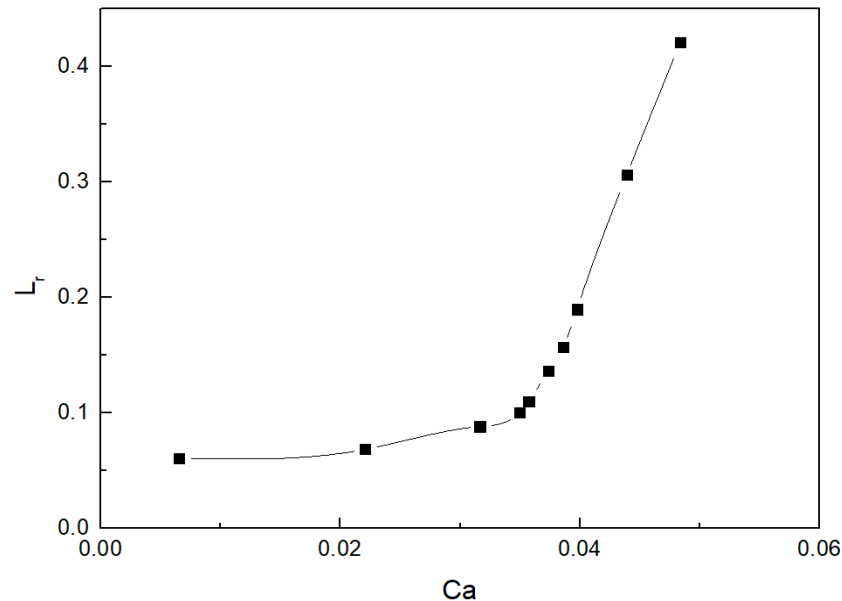
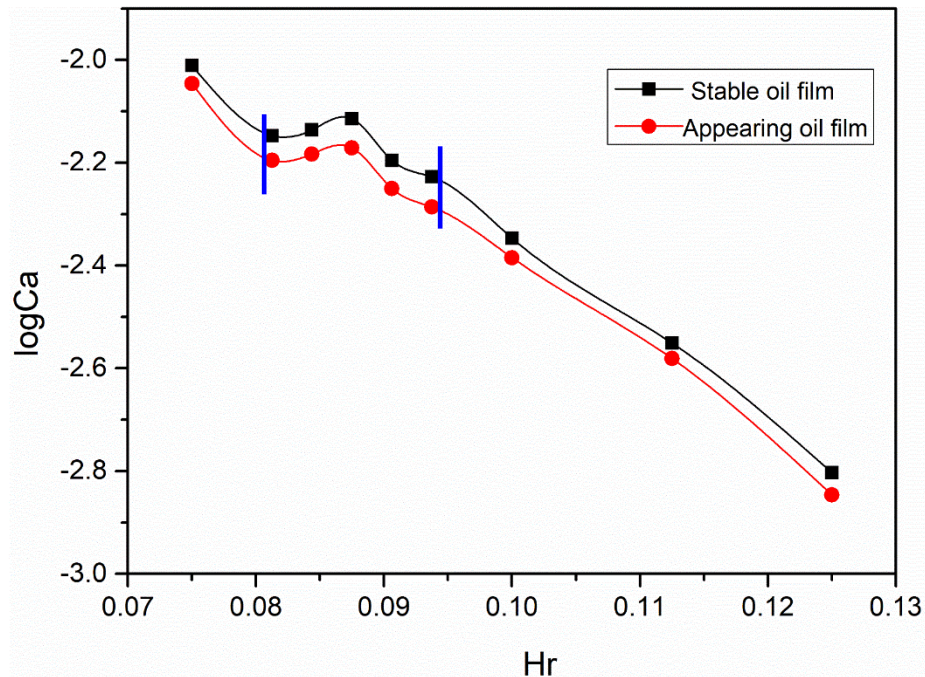
Relationship between the ratio of interface length to channel length and capillary number

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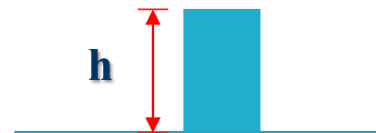## 3.4 Influence of roughness size :Hr （ongoing work）

Appearing oil film

Stable oil film

3.4 Influence of roughness size :Sr （ongoing work）
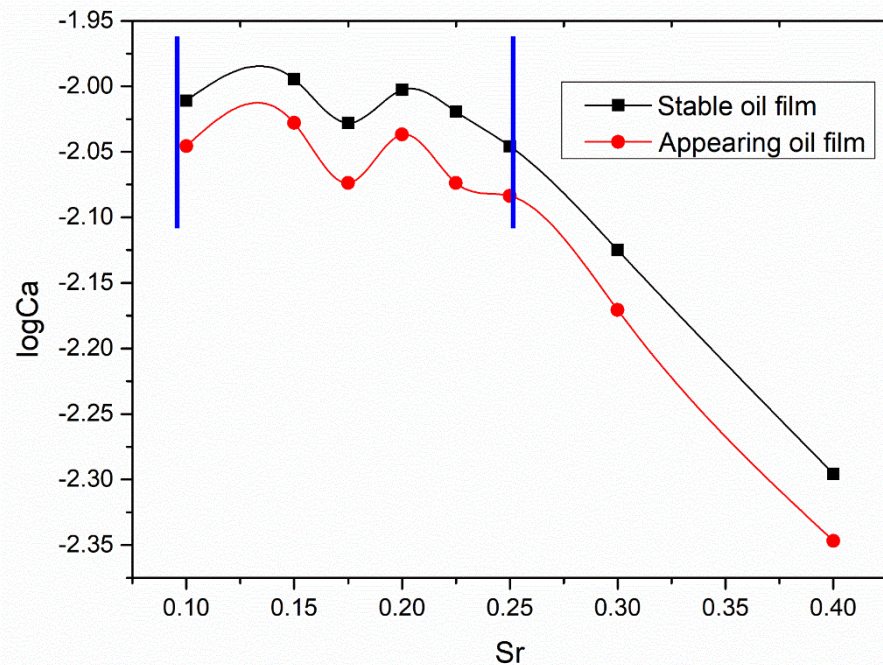
$$F = \mu A \frac{\mathrm{d}u}{\mathrm{d}y}$$

According to Newton's law of internal friction, the increase of Sr increases the rough contact area, which strengthens the shear force between the fluid and the wall, and makes it easier to cause the phenomenon of viscous fingering

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- **The roughness of the wall will increase the resistance of two-phase flow and the velocity of the phase interface will decrease significantly in rough ones.**

- **Increase the deformation of the oil-water interface, promoting the formation of viscous fingering**

- **In the process of water flooding, the influence of wall roughness on two-phase interface movement in oil-wet channels is greater than that in the water-wet channels**

- **Capillary number has a great influence on the instability of the interface in rough wall surface, the influence of capillary number is amplified by roughness**

- **The existence of wall roughness will lead to the change of wettability of the channel wall**

The Effect of Surface Roughness on Immiscible Displacement Using Pore Scale Simulation.

Transport in Porous Media, 2021:1-13.

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