

## Nanoflow Miscible Viscous Fingering in Real Porous Media: A Mesoscopic Approach

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### Extended Abstract

Viscous fingering has always been an inevitable challenge in porous media when a fluid displaces another fluid under unfavourable mobility ratio. In order to damp the finger growth and stabilize the system, several strategies such as adding viscous chemicals to the displacing fluid and controlling the injection rate, have been proposed. Recently, nanoparticles have been introduced as a promising technique to deal with this hydrodynamic instability. A number of studies, have been recently conducted to examine the effectiveness of the technique, however all of these studies were carried out at the macroscopic scale[1,2]. In order to address the uncertainties in nano-scale, a mesoscopic study has been conducted using the Lattice Boltzmann Method (LBM). In this study the effect of nanofluid Brownian and Thermophoretic forces are investigated. A new model for the deposition of the nanoparticles is also presented using a combination of DLVO (Derjaguin, Landau, Verveij, and Overbeek) and kinetic theories.

In order to analyze the effects of the nanoparticles on viscous fingering in mesoscopic scale, the conservation of mass, momentum, and energy equations are solved simultaneously using LBM [3]. For an incompressible flow displacement, the system of equations can be written as follows [4].

$$\nabla \cdot (u) = 0 \quad (1)$$

$$\rho \frac{Du}{Dt} = -\nabla P + \nabla \cdot (\mu[\nabla u + (\nabla u)^t]) \quad (2)$$

$$\frac{D\phi}{Dt} = \nabla \cdot \left[ D_{dis} \nabla \phi + D_T \frac{\nabla T}{T} \right] + \dot{C}_d \quad (3)$$

$$\rho c \frac{DT}{Dt} = \nabla \cdot (k \nabla T) + \rho_{np} c_{np} \left[ D_{dis} \nabla \phi \cdot \nabla T + \frac{D_T}{T} \nabla T \cdot \nabla T \right] \quad (4)$$

In which  $D_{dis}$  and  $D_T$  are dispersion in porous media and thermal diffusivity due to thermophoretic effect respectively. The term  $\dot{C}_d$  accounts for nanoparticle deposition in the porous medium, and it is proposed to determine it using two probabilities in the system,

$$\dot{C}_d = \zeta_s * \zeta_c \quad (5)$$

In the above expression,  $\zeta_s$  and  $\zeta_c$  represent the sticking probability of the collision and the collision frequency probability, respectively. The sticking probability can be estimated using fraction of particles having kinetic energy less than intermolecular potential. This probability can be estimated using Maxwell-Boltzmann kinetic energy distribution as follows [5].

$$\zeta_s = 1 - \frac{1 + \frac{\gamma}{k_B T}}{\exp\left(\frac{\gamma}{k_B T}\right)} \quad (6)$$

Where  $k_B$  is the Boltzmann constant,  $T$  is the temperature and  $\gamma$  is the average potential depth between particles. Based on DLVO theory, the potential depth is proportional to the particle diameter and can be expressed as below [6].

$$\gamma = k_1 d_{np} \quad (7)$$

$k_1$  is a constant and  $d_{np}$  is the diameter of nanoparticle. Based on the kinetic theory, the collision probability at a time span can also be estimated as below.

$$\zeta_c = k_2 \phi \quad (8)$$

In which  $k_2$  is a constant and  $\phi$  is the volume fraction of nanoparticles.

The expression of the dynamic viscosity in terms of the nanoparticle concentration and temperature is [7].

$$\mu = \bar{\mu} \exp\left(R_\phi \left(\frac{\phi}{\phi_0}\right) + R_T \left(\frac{T - T_c}{\Delta T}\right)\right) \quad , \quad R_\phi = \ln\left(\frac{\mu_\phi}{\bar{\mu}}\right) \quad , \quad R_T = \ln\left(\frac{\mu_T}{\bar{\mu}}\right) \quad (9)$$

$\bar{\mu}$  is the viscosity of the displaced fluid at the base state in which  $\phi = 0$  and  $T = T_c$ .  $\phi_0$  is a characteristic volume fraction of nanofluid and  $\Delta T = T_h - T_c$ .

The analysis shows that as the Reynolds number increases the propagation speed of fingers rises. Their morphology is also quite different in various Reynolds numbers. Moreover, the temperature profile is remarkably influenced by the Reynolds number. The inertial force dictates the temperature profile at high Reynolds numbers as opposed to thermal diffusivity in low Reynolds numbers and consequently the viscosity profile which is a function of temperature would have significant impact on the development and evolution of the fingers. Generally, the higher the Reynolds' number, the larger the cooler area, due to convection, and the higher the viscosity. Nanoparticles with various potential depths, different surface energies, and different sizes would also notably affect the fingering patterns in the porous media. In other words, a higher potential depth governs the sticking probability of the nanoparticles in a way that culminates in more stable system.

## References

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