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# Numerical and dimensional analysis of nanoparticles transport with two-phase flow in porous media

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## ABSTRACT

In this paper, a mathematical model and numerical simulation are developed to describe the imbibition of nanoparticles–water suspension into two-phase flow in a porous medium. The flow system may be changed from oil-wet to water-wet due to nanoparticles (which are also water-wet) deposition on surface of the pores. So, the model is extended to include the negative capillary pressure and mixed-wet relative permeability correlations to fit with the mixed-wet system. Moreover, buoyancy and capillary forces as well as Brownian diffusion and mechanical dispersion are considered in the mathematical model. An example of countercurrent imbibition in a core of small scale is considered. A dimensional analysis of the governing equations is introduced to examine contributions of each term of the model. Several important dimensionless numbers appear in the dimensionless equations, such as Darcy number **Da**, capillary number **Ca**, and Bond number **Bo**. Throughout this investigation, we monitor the changing of the fluids and solid properties due to addition of the nanoparticles using numerical experiments.

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## 1. Introduction

The applications of nanoparticles in oil/gas exploration/production become a promising field of research. The nanoparticles injection in an oil reservoir may modify the rheology, mobility, wettability, and other properties of the fluids and therefore need comprehensive investigations. For example, certain types of nanoparticles can be used as tracers for oil and gas exploration and others may be used in oilfields. Nanoparticles have been used in the oilfields to enhance water injection by virtue of changing the wettability of reservoir rock through their adsorption on porous walls. Two types of polysilicon nanoparticles have been considered to improve oil recovery and enhance water injection, respectively (Ju and Fan, 2009). The polysilicon nanoparticles are classified based on wettability of their surfaces. The first type is called lipophobic and hydrophilic polysilicon nanoparticles and they exist in water phase only, while the second type is called hydrophobic and lipophilic polysilicon nanoparticles and they exist in the oil phase only. Nanopowders are agglomerates of ultrafine particles, nanoparticles, or nanoclusters. One kind of polysilicon nanopowder having the range between 10 and 500 nm was used in oilfields to enhance water injection by changing wettability of the porous media. If the particles are larger enough they may block pore throats during particles transport with flow. Experimental results

(Ju and Fan, 2009) illustrated that the sizes of polysilicon particles are in the range of 10–500 nm, while pore radii of a porous medium (sandstone) are from 6 to  $6.3 \times 10^4$  nm. A few numbers of nanoparticles that have sizes slightly less than a pore throat may bridge at the pore throat. However, the nanoparticles can adhere to the pore walls if the nanoparticles sizes are much less than the pore sizes. Ju et al. (2002) reported that when the suspension of the polysilicon nanoparticles of one nanosize is injected into an oil reservoir, it could change the wettability of porous surfaces of sandstone and consequently have effects on water and oil flows. Ju et al. (2002) and Ju and Fan (2009) have established a mathematical model of nanoparticles transport in two-phase flow in porous media based on the formulation of fine particles transport in two-phase flow in porous media provided in Liu and Civian (1993, 1994, 1996). Improvements in the recovered volumes by injecting hydrophobic nanoparticles which enhance or reverse the initial reservoir wettability favoring an increase in the relative permeability of the oil phase and the capillary pressure drop between phase pressures have been reported in Onyekonwu and Ogolo (2010). El-Amin et al. (2012a,b, 2013c) presented modeling and simulations of nanoparticles transport associated with two-phase flow in porous media. Suleimanov et al. (2011) and Hendraningrat et al. (2013) performed experimental studies of nanofluids intended for enhanced oil recovery. Ryoo et al. (2012) have introduced theoretical and experimental investigation of the motion of multiphase fluids containing paramagnetic nanoparticles in porous media.

In the current work, we introduce a mathematical model to describe the nanoparticles–water suspension that imbibes into a

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water–oil two-phase flow in porous media. The model includes general formulae for both positive/negative capillary pressure and mixed relative permeability correlations to fit with the mixed-wet system. Also, both buoyancy and capillary effects are considered. Countercurrent imbibition problem is taken as an example. Moreover, we introduce a dimensional analysis to examine contributions of each term of the model.

## 2. Modeling and mathematical formulation

### 2.1. Model assumptions

The model of coupled two-phase flow and nanoparticles transport is based on the following assumptions:

- (1) No mass transfer between the two phases.
- (2) The flow and transport is under isothermal conditions.
- (3) The rock and fluids are considered incompressible.
- (4) The fluids are Newtonian and their viscosities are constants.
- (5) The porous media is heterogeneous.
- (6) The two-phase flow in porous media is governed by extended Darcy's law.
- (7) The nanoparticles exist only in the water-phase and are divided into a number of size intervals.
- (8) Brownian diffusion is considered for the nanoparticles.

### 2.2. Flow model

The governing equations of the two-phase water–oil flow in porous media are mass conservation equation and constitutive equation. The vertical (i.e.,  $z$ -direction) one-dimensional two-phase immiscible and incompressible flow in porous media is considered. The governing equations may be written as (El-Amin et al., 2013a)

$$\phi \frac{\partial S_\alpha}{\partial t} + \frac{\partial u_\alpha}{\partial z} = 0, \quad \alpha = w, o \quad (1)$$

$$u_\alpha = -\frac{k_{r\alpha}}{\mu_\alpha} K \left( \frac{\partial p_\alpha}{\partial z} - \rho_\alpha g \right), \quad \alpha = w, o \quad (2)$$

where  $\phi$  (-) is the porosity of the medium,  $\rho_\alpha$  ( $\text{kg m}^{-3}$ ) is the phase  $\alpha$  density,  $S_\alpha$  (-) is the phase  $\alpha$  saturation and  $u_\alpha$  ( $\text{m s}^{-1}$ ) is the phase  $\alpha$  velocity.  $w$  stands for the water (wetting) phase, and  $o$  stands for the oil (nonwetting) phase.  $K$  ( $\text{m}^2$ ) is the absolute permeability,  $k_{r\alpha}$  (-) is the phase- $\alpha$  relative permeability,  $p_\alpha$  (Pa) is the phase- $\alpha$  pressure,  $g$  ( $\text{m}^{-2}$ ) is the gravitational acceleration, and  $\mu_\alpha$  (Pa) is the phase- $\alpha$  viscosity. The fluid saturations for the two-phase flow of water and oil are interrelated by

$$S_w + S_o = 1. \quad (3)$$

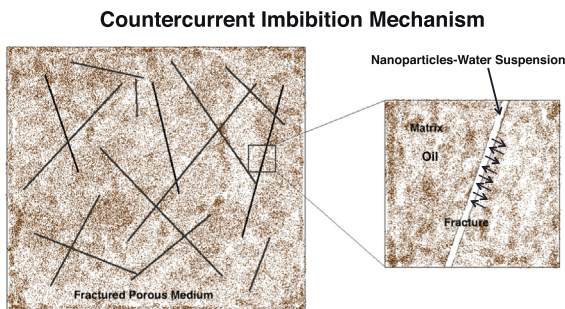


Fig. 1. Schematic diagram of the flow in fracture porous medium.

As an example let us consider a flow of type countercurrent imbibition. The imbibition is an important mechanism in oil recovery from water-wet fractured-matrix reservoirs subjected to water drive. Imbibition is defined as the displacement of the oil phase by the water phase with capillary force dominating other forces. Imbibition may be classified as countercurrent or cocurrent. In cocurrent imbibition, water displaces oil out of the matrix, with both water and oil flows in the same direction. During imbibition process the capillary force is the dominated force to recover oil from naturally fractured reservoirs. The oil that reaches the fracture is displaced by the injected water towards the production end of the fracture, as shown in Figs. 1 and 2. In the case of countercurrent imbibition, both the wetting phase and non-wetting phase flow through one boundary in opposite directions. So, the sum of the velocities of the wetting and non-wetting phases is zero, thus,

$$u_t = u_w + u_o = 0 \quad (4)$$

On the other hand, the capillary pressure is the difference in pressure across the interface between two immiscible fluids, water and oil, therefore,

$$p_c = p_o - p_w \quad (5)$$

Substituting from Eq. (2) into Eq. (4), and eliminating  $\partial p_o / \partial z$ , we have

$$\frac{\partial p_w}{\partial z} = -f_w \frac{\partial p_c}{\partial z} - \chi g, \quad (6)$$

and the water velocity becomes

$$u_w = K \lambda_w f_o \left( \frac{\partial p_c}{\partial z} - \Delta \rho g \right) \quad (7)$$

Therefore, the saturation equation for the water phase becomes

$$\phi \frac{\partial S_w}{\partial t} + \frac{\partial}{\partial z} \left[ K \lambda_w f_o \left( \frac{\partial p_c}{\partial z} - \Delta \rho g \right) \right] = 0 \quad (8)$$

where  $\lambda_w = k_{rw} / \mu_w$  and  $\lambda_o = k_{ro} / \mu_o$  are mobility ratios of water and oil phases, respectively.  $\lambda_t = \lambda_w + \lambda_o$  is the total mobility.  $f_w = \lambda_w / \lambda_t$  and  $f_o = \lambda_o / \lambda_t$  are the flow fraction of water and oil phases, respectively.  $\chi = (\rho_w \lambda_w + \rho_o \lambda_o) / \lambda_t$  and  $\Delta \rho = \rho_w - \rho_o$ . Moreover, the expressions of the relation between the relative permeabilities and the normalized water phase saturation:

$$S = \frac{S_w - S_{iw}}{1 - S_{ro} - S_{iw}}, \quad 0 < S < 1, \quad (9)$$

is given as

$$k_{rw} = k_{rw}^0 S^a, \quad k_{ro} = k_{ro}^0 (1 - S)^b \quad (10)$$

where  $S_{iw}$  is the irreducible water saturation and  $S_{ro}$  is the residual oil saturation.  $a$  and  $b$  are positive numbers.  $k_{rw}^0 = k_{rw}(S=1)$  is

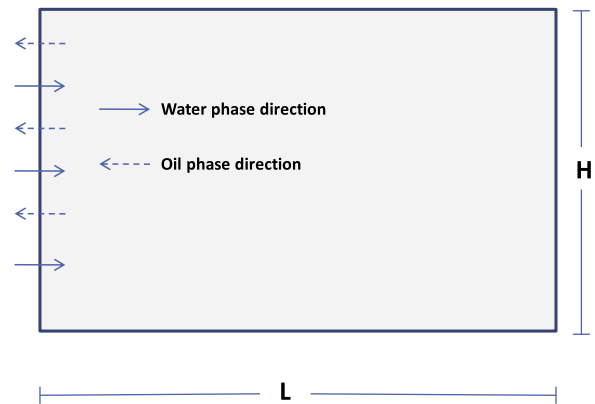


Fig. 2. Schematic diagram of the countercurrent imbibition.

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