



## A new numerical approach for investigation of the effects of dynamic capillary pressure in imbibition process

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### ABSTRACT

Capillary pressure is important in simulation of fluid flow in porous media at different scales. In ongoing simulation methods, capillary pressure is considered as a static process. However, recent researches have shown that capillary pressure is dynamic parameter. That is, its value directly depends on the rate of saturation changes. Including the effects of dynamic capillary pressure is especially important in prediction of imbibition process, which is an important mechanism in oil production from naturally fractured reservoirs. In this study, to investigate the effects of dynamic capillary pressure in two-phase flow process, an implicit and iterative method is proposed, and it is implemented in an open-source simulator named Matlab Reservoir Simulation Toolbox (MRST). The convergence results show that the proposed algorithm works well and the obtained results are acceptable. Furthermore, the analysis is made on the effects of dynamic capillary pressure functions in vertical imbibition process cases. The results confirm that considering dynamic capillary effects is critical in the simulation of two-phase flow in porous media. This is more important in imbibition process, where the capillary force is the dominant driving force. It is also found that at high permeability cases, considering dynamic capillary pressure effects is more crucial. Also, it is concluded that in high mobility ratios, due to low imbibition rates, effect of considering dynamic capillary pressure curves is not significant.

### 1. Introduction

Capillary imbibition is an important flowing process in different physical and engineering areas. In this process, the wetting phase replaces non-wetting phase (Schmid et al., 2016). Imbibition process occurs because of surface effects including wettability of porous media and interfacial tensions between the fluids (Mason and Morrow, 2013). This process is important in water movement in soils, the behavior of non-aqueous phase liquids (NAPLs) in water aquifers (Lenhard et al., 1993), carbon dioxide sequestration (Juanes et al., 2010), gas storage and oil production from carbonate fractured reservoirs (Ghaedi and Riazi, 2016). Also, in processes like the design of waterproof clothes imbibition needs to be considered (Mason and Morrow, 2013). If the flow is only affected by capillary forces, it is called spontaneous imbibition. But, at larger scale systems, like oil reservoirs, imbibition usually is controlled by gravity, capillary, and viscous forces. Where gravity effects are considerable in comparison with capillary forces, some oil production is because of gravity drainage and flow rate analysis is more complex (Abbasi et al., 2016b).

Capillary pressure, which is defined as the pressure difference between the wetting and non-wetting fluids, is important in simulation of fluid flow in porous media. Although, the distribution of fluid phases in porous media is controlled by highly complicated processes, the capillary pressure usually is assumed to be dependent only on the relative saturation of the wetting phase. The main theoretical and practical tool currently used to quantify the capillary pressure is defined as a function of saturation (Bear and Verruijt, 1987):

$$p_n - p_w = P_c = f(S_w) \quad (1)$$

where  $p_n$  and  $p_w$  are average pressures of non-wetting and wetting phases, respectively.  $P_c$  is capillary pressure, and  $S_w$  is the wetting phase saturation. All equilibrium processes and influences, such as surface tension, presence of fluid–fluid interfaces, grain size distribution, viscosity and density ratios, the wettability of solid surfaces, and microscale heterogeneities are assumed to be accounted implicitly using this simple model. Determination of static capillary pressures is a highly time-consuming process, and the flow necessarily does not occur under

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equilibrium conditions, especially at initial times of flow at which saturation changes fast. In general, the capillary assisted flow needs days to weeks to reach equilibrium at laboratory scale domains (i.e. 10-cm to 12-cm long) (Mirzaei and Das, 2007). Different researchers concluded that capillary pressure is depended on the rate of saturation change of wetting phase more than the saturation itself. This is called dynamic capillary pressure and can be mathematically defined as follows:

$$p_n - p_w = P_c = f(S_w, \partial S_w / \partial t) \quad (2)$$

where  $dS/dt$  is the rate of wetting phase saturation change. Hassanizadeh and Gray (1993) presented the following formulation, which considers dynamic effects in the conventional  $P_c$ - $S_w$  relationship:

$$P_c^{dyn} - P_c^{sta} = \tau \frac{\partial S_w}{\partial t} \quad (3)$$

where,  $P_c^{dyn}$  is the dynamic capillary pressure defined as  $P_c^{dyn} = p_n - p_w$  and  $P_c^{sta}$  is the capillary pressure at equilibrium conditions ( $\partial S_w / \partial t = 0$ ). The coefficient  $\tau$  is called the dynamic coefficient, which is a measure of the rate of change in saturation and hence the speed to reach to an equilibrium condition. In the last decades, there have been many debates on the value of  $\tau$  during dynamic flow in porous media, and there is not an acceptable agreement on the quantity of  $\tau$  at different situations.

O'Carroll et al. (2010) have measured  $\tau$  in the range of  $1 \times 10^6$  to  $5.7 \times 10^7 \text{ Kg.m}^{-1}.\text{s}^{-1}$ . Moreover, there is a wide variety of the reported values of  $\tau$  ( $0$  to  $10^9 \text{ kg m}^{-1}.\text{s}^{-1}$ ) with respect to factors such as the domain size, and geometry of system, fluid and rock properties, types of experiments, and heterogeneities (Mirzaei and Das, 2007). Most researches show that  $\tau$  inversely depends on the wetting phase saturation (Abidoeye and Das, 2014; Bottero et al., 2011). There is not a good agreement between the values of the dynamic coefficient obtained for different scales. Dahle et al. (2005) suggested that the dynamic coefficient may become arbitrarily large as the averaging volume increases in size. Bottero et al. (2009) studied  $\tau$  experimentally and observed an order of magnitude increase in  $\tau$  value, by changing the window of observation from 11 to 18 cm and 18–21 cm. Also, Abidoeye and Das (2014) reported an order increase in the magnitude of  $\tau$  as the domain increases from 4 to 8 cm. Stauffer (1978), using laboratory experiments, presented a scaling equation in which  $\tau$  depends on the fluid and rock properties. Also, Abidoeye and Das (2014) utilized experimental datasets from Das and Mirzaei (2012) and Buckingham's theorem, presented the following scaling equation:

$$\frac{\tau \sqrt{g}}{K^{1/4} P^d} = 9 \times 10^{-14} \left[ \frac{VK - \sum \gamma_{ij} \mu_{ij}}{\phi \partial S_w} \right]^{1.31} \quad (4)$$

Where, in this equation,  $V$  is rock bulk volume,  $\lambda$  and  $P^d$  are pore size distribution index and rock entry pressure, respectively. It could be simulated using Brooks-Corey correlations (Brooks and Corey, 1964). Eq. (4) is the only available equation that relates dynamic coefficient value to the dimensions of flow. The datasets have been used for calibration of this scaling equation were in the range of 4 cm–16 cm. This range is too far from the usual field scale domains. However, there is not any documented method of measuring of the dynamic coefficient at large scale systems. That leads to some uncertainties on the impact of non-equilibrium effects at large-scale flow in porous media.

However, there is not any agreement in the literature on the influence of dynamic effects in imbibition process. The assumption of instantaneous capillary equilibrium allows for the two-phase flow equations to similar to a self-similar, diffusion-like problem (Mirzaei-Paiaman et al., 2011). Le Guen and Kavscek (2006) stated that capillary imbibition is inherently a capillary dominated flow and the traditional formulation of multiphase flow in porous media cannot properly represent the physics of capillary imbibition. They showed that imbibition process may not be self-similar and concluded that dynamic effects might be the reason for

this deviation from idealities. Mirzaei-Paiaman et al. (2011) investigated the self-similarity of some imbibition tests and stated that imbibition flow is affected by non-equilibrium effects, but, classical local equilibrium approach can be sufficient to model spontaneous imbibition process at small scale cases. Schembre and Kavscek (2006) also reported that non-equilibrium impacts, detected at laboratory scale, influence the estimation of relative permeability and capillary pressure values and it must be considered during simulation of multiphase flow in porous media. Moreover, the non-equilibrium influences in capillary imbibition are not yet clear at large scale systems.

In this paper, by extending an open-source simulation software (MRST), a tool which is useful for simulation of fluid flow in porous media in presence of the dynamic capillary pressure effects is developed. In the following sections, the modeling algorithm will be thoroughly discussed. After that, in an interesting scenario, the impact of considering dynamic capillary pressure effects on imbibition process in a one-dimensional vertical model will be investigated. Then, to investigate the effect of dynamic behavior of capillary pressure on imbibition process, different scenarios including the effect of changing dynamic coefficient, Bond number, matrix permeability, and mobility ratio values on imbibition recovery curve will be investigated. The paper ends with conclusions.

## 2. Modeling approach

Two-phase flow in porous media can be characterized by pressure and saturation of each phase in different places. Mass conservation equation, for wetting and non-wetting phase, is represented as the following equations:

$$\frac{\partial}{\partial t} (\phi S_w \rho_w) + \nabla \cdot (\rho_w \vec{v}_w) = \rho_w q_w \quad (5)$$

$$\frac{\partial}{\partial t} (\phi S_n \rho_n) + \nabla \cdot (\rho_n \vec{v}_n) = \rho_n q_n \quad (6)$$

where  $\phi$  is the porosity,  $\rho$ ,  $v$  and  $q$  are density, volumetric velocity, and source of each phase, respectively. For the two-phase system, it can be written that:

$$S_w + S_n = 1 \quad (7)$$

where  $S_w$  and  $S_n$  are the saturations of the wetting and non-wetting phase. Assuming that the gravity acts in the vertical direction and by accepting Darcy assumptions, volumetric velocity for each phase could be defined as:

$$v_w = -\frac{k_{rw} K}{\mu_w} (p_w - \rho_w g \nabla z) \quad (8)$$

$$v_n = -\frac{k_{rn} K}{\mu_n} (p_n - \rho_n g \nabla z) \quad (9)$$

where  $K$  is the permeability of the porous medium and  $g$  is the gravitational acceleration constant. Also,  $k_r$ ,  $\mu$ , and  $p$  are the relative permeability, viscosity, and pressure of each phase, respectively. Then, one can reformulate Eqs. (5) and (6) as:

$$\frac{\partial}{\partial t} (\phi S_w \rho_w) + \nabla \cdot \left( \frac{\rho_w k_{rw} K}{\mu_w} (\nabla p_w - \rho_w g \nabla z) \right) = \rho_w q_w \quad (10)$$

$$\frac{\partial}{\partial t} (\phi S_n \rho_n) + \nabla \cdot \left( \frac{\rho_n k_{rn} K}{\mu_n} (\nabla p_n - \rho_n g \nabla z) \right) = \rho_n q_n \quad (11)$$

This system is highly coupled and strongly non-linear. The strong coupling comes from the fact that the difference in unknowns ( $p_n - p_w$ ) enters the computation of saturations (Lie et al., 2012). This complexity

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