

## Research Article

# Effects of Gravity and Inlet Location on a Two-Phase Countercurrent Imbibition in Porous Media

M. F. El-Amin,<sup>1,2</sup> Amgad Salama,<sup>1</sup> and Shuyu Sun<sup>1</sup>

<sup>1</sup> Computational Transport Phenomena Laboratory (CTPL), Division of Physical Sciences and Engineering (PSE), King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia

<sup>2</sup> Department of Mathematics, Aswan Faculty of Science, South Valley University, Aswan 81528, Egypt

Correspondence should be addressed to M. F. El-Amin, mohamed.elamin@kaust.edu.sa

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We introduce a numerical investigation of the effect of gravity on the problem of two-phase countercurrent imbibition in porous media. We consider three cases of inlet location, namely, from, side, top, and bottom. A 2D rectangular domain is considered for numerical simulation. The results indicate that gravity has a significant effect depending on open-boundary location.

## 1. Introduction

Oil recovery by imbibition mechanism, from fractured reservoirs, is a significant research area in multiphase flow in porous media especially for water-flooding process in fractured oil reservoirs. Fractured reservoirs are composed of the fracture network and matrix. Fractures have a higher permeability and relatively low volume compared to the matrix, whose permeability is very low but it contains the majority of the oil. Water flooding is used to increase oil recovery by increasing water pressure in fractures since water quickly surrounds oil-saturated matrices of lower permeability. The process of water flooding works well when the matrix is water-wet, and imbibition can lead to significant recoveries, while poor recoveries and early water breakthrough occur with oil-wet matrix conditions. Imbibition is defined as the displacement of the nonwetting phase (oil) by the wetting phase (water) with dominant effect of capillary forces. Imbibition can occur in both countercurrent and cocurrent flow modes, depending on the fracture network and the water injection rates. In cocurrent imbibition, water displaces oil out of the matrix; thus both water and oil flows are in the same direction. Countercurrent imbibition, on the other hand, is whereby a wetting phase imbibes into the porous matrix (rock), displacing the nonwetting phase out from one open boundary. In spite of the fact that cocurrent imbibition is faster and more efficient

than countercurrent imbibitions, the latter is often the only possible displacement mechanism for cases where a region of the matrix is exposed from one side to water filling the fracture [1–4]. Imbibition has also been investigated by several other authors either for cocurrent or countercurrent flows or both of them together (e.g., [5–8]). Reis and Cil [9] introduced one-dimensional model for oil expulsion by countercurrent water imbibition in rocks. An examination of countercurrent capillary imbibition recovery from single matrix blocks and recovery predictions by analytical matrix/fracture transfer functions was introduced by Cil et al. [10]. Lee and Kang [11] have introduced an experimental analysis of oil recovery in a fracture of variable aperture with countercurrent imbibition. Scaling of countercurrent imbibition was estimated by many authors in terms of fluid and rock properties (e.g., [12, 13]). Morrow and Mason [14] introduced a comprehensive review on recovery of oil by spontaneous imbibition. Kashchiev and Firoozabadi [15] gave analytical solutions for 1D countercurrent imbibition in water-wet media. Analytical analysis of oil recovery during countercurrent imbibition in strongly water-wet system was given by Tavassoli et al. [16]. The Barenblatt model of spontaneous countercurrent imbibition was investigated by Silin and Patzek [17]. Behbahani et al. [18] have performed a simulation of countercurrent imbibition in water-wet fractured reservoirs.

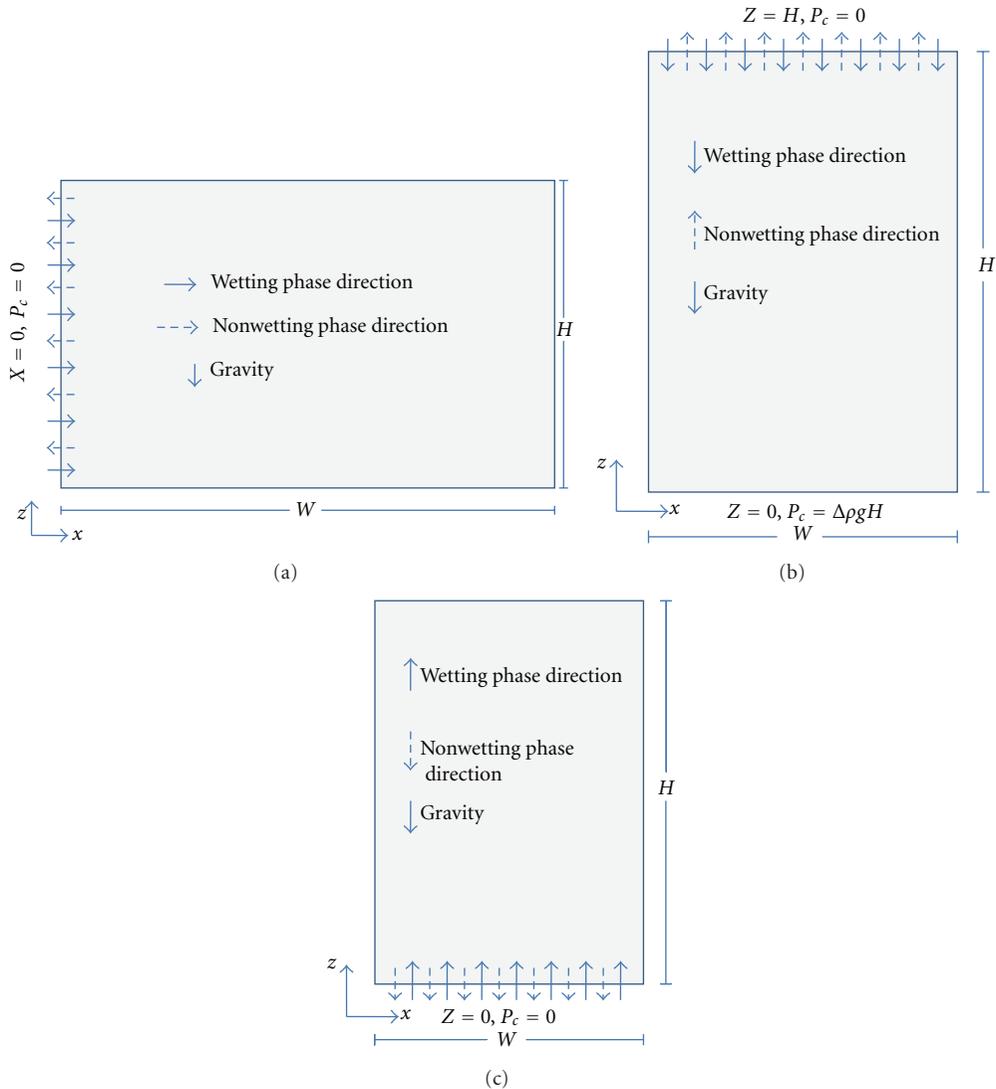


FIGURE 1: Schematic diagram of countercurrent imbibition with gravity effect for different locations of the open boundary: (a) side, (b) top, and (c) bottom.

In most of the previously mentioned imbibition studies, researchers have neglected the gravity force effect by dropping the gravity force term from the flow equations especially for the oil-water modeling. Wilkinson [19] studied the percolation model of immiscible displacement in the presence of buoyancy forces. Analytical and numerical solutions of gravity-imbibition and gravity-drainage processes were given by Bech et al. [20]. Tavassoli et al. [21] have introduced analysis of countercurrent imbibition with gravity in weakly water-wet system. A pore-scale study of gravity, capillary and viscous forces during drainage in a two-dimensional porous medium, was introduced by Løvoll et al. [22]. Effect of injection rate, initial water saturation, and gravity on water injection in slightly water-wet fractured porous media was examined experimentally by Karimaie and Torsæter [23]. Ruth et al. [24] provided an approximate analytical solution for countercurrent spontaneous imbibition. The problems of buoyancy-driven vertical migration of fluids have been

treated analytically or numerically by some researchers. For example, Silin et al. [25] have introduced simple analytical solutions in a model of gas flow driven by a combination of buoyancy, viscous and capillary forces for the problem of two-phase countercurrent fluid flow.

This study is devoted to numerically investigate the influences of gravity and open-boundary location on the countercurrent imbibition of two immiscible phases in a 2D porous medium domain.

## 2. Formulations, Results, and Discussion

The purpose of this study is to investigate the influence of gravity for different locations of the open boundary of an incompressible, two-phase, immiscible, countercurrent imbibition in a 2D homogenous porous medium domain. In this work both buoyancy and capillarity are considered. Figures 1(a), 1(b), and 1(c) show schematic diagrams of

the problem domain for different locations of the open boundary (side, top, and bottom). Wetting phase imbibes inwards in the porous medium domain of height  $H$  and width  $W$  with zero capillary pressure at the open boundary and no-flow boundary at the other boundaries.

Consider a rectangular core saturated with oil with irreducible water saturation, closed all around except at one face that is open to flow (countercurrent imbibition). The flow is governed by the combined Darcy law and the equations of mass conservation for each phase in 2D as follows:

$$\begin{aligned} \varphi \frac{dS_w}{dP_c} \left( \frac{\partial P_o}{\partial t} - \frac{\partial P_w}{\partial t} \right) &= \nabla \cdot \left( \frac{Kk_{rw}}{\mu_w} (\nabla P_w - \rho_w g \nabla z) \right), \\ \varphi \frac{dS_w}{dP_c} \left( \frac{\partial P_o}{\partial t} - \frac{\partial P_w}{\partial t} \right) &= -\nabla \cdot \left( \frac{Kk_{ro}}{\mu_o} (\nabla P_o - \rho_o g \nabla z) \right), \end{aligned} \quad (1)$$

where  $\nabla \equiv (\partial/\partial x, \partial/\partial z)$ , subscripts  $w$  and  $o$  designate wetting phase (water) and nonwetting phase (oil), respectively.  $P$  is the phase pressure,  $S_w$  is the water saturation,  $k_r$  is relative permeability,  $\mu$  is phase viscosity,  $\rho$  is phase density, and  $g$  is gravity acceleration.  $K$  is permeability and  $\varphi$  is porosity of the porous medium.

The capillary pressure functions are dependent on the pore geometry, fluid physical properties, and phase saturations. The two-phase capillary pressure can be expressed by the Leverett dimensionless function  $J(S)$ ; see, for example, Chen [26], which is a function of the normalized saturation  $S$ :

$$P_c = P_o - P_w = \gamma \left( \frac{\varphi}{K} \right)^{1/2} J(S), \quad (2)$$

where  $\gamma$  is the interfacial tension.

In order to consider a certain case of study, we may use a specified empirical formula of the capillary pressure in terms of normalized saturation function. The  $J(S)$  function typically lies between two limiting (drainage and imbibition) curves which can be obtained experimentally. Correlation of the imbibition capillary pressure data depends on the type of application. Since our current research is concerned with the water-oil system, we use the correlation by Firoozabadi and coworkers [3, 15], in which the capillary pressure and the normalized wetting phase saturation are correlated as follows:

$$P_c = -B \ln S, \quad (3)$$

where  $B$  is the capillary pressure parameter, which is equivalent to  $\gamma(\varphi/K)^{1/2}$  in (2); thus,  $B \equiv -\gamma(\varphi/K)^{1/2}$  and  $J(S) \equiv \ln S$ . Note that  $J(S)$  is a scalar nonnegative function.

Also,

$$S = \frac{S_w - S_{iw}}{1 - S_{or} - S_{iw}}, \quad 0 \leq S \leq 1, \quad (4)$$

where  $S_{iw}$  is the irreducible water saturation and  $S_{or}$  is the residual oil saturation.

For the countercurrent imbibition in which the only open end is initially in contact with oil, the ambient pressure

is considered zero. The water pressure in the core is given by the capillary pressure relationship, (2) and (3), which at  $t = 0$  leads to

$$\begin{aligned} P_o &= 0, \quad t = 0, \quad 0 \leq x \leq W, \quad 0 \leq z \leq H, \\ P_w &= P_o - P_c(S_{wi}) = -P_c(S_{wi}), \\ t &= 0, \quad 0 \leq x \leq W, \quad 0 \leq z \leq H. \end{aligned} \quad (5)$$

In this study we consider three different locations of the open boundary, at side, top, or bottom, namely, Case A, Case B, and Case C, as follows.

*Case A. Side open-boundary*

$$\begin{aligned} P_w &= P_o = 0, \quad t > 0, \quad x = 0, \quad 0 \leq z \leq H, \\ q_w &= q_o = 0, \quad t > 0, \quad 0 \leq x \leq W, \quad z = 0, \\ q_w &= q_o = 0, \quad t > 0, \quad 0 \leq x \leq W, \quad z = H, \\ q_w &= q_o = 0, \quad t > 0, \quad x = W, \quad 0 \leq z \leq H, \end{aligned} \quad (6)$$

where  $q_w$  and  $q_o$  are the water and oil flow rate, respectively.

*Case B. Top open-boundary:*

$$\begin{aligned} q_w &= q_o = 0, \quad t > 0, \quad x = 0, \quad 0 \leq z \leq H, \\ q_w &= q_o = 0, \quad t > 0, \quad 0 \leq x \leq W, \quad z = 0, \\ P_w &= P_o = 0, \quad t > 0, \quad 0 \leq x \leq W, \quad z = H, \\ q_w &= q_o = 0, \quad t > 0, \quad x = W, \quad 0 \leq z \leq H. \end{aligned} \quad (7)$$

*Case C. Bottom open-boundary*

$$\begin{aligned} q_w &= q_o = 0, \quad t > 0, \quad x = 0, \quad 0 \leq z \leq H, \\ P_w &= P_o = 0, \quad t > 0, \quad 0 \leq x \leq W, \quad z = 0, \\ q_w &= q_o = 0, \quad t > 0, \quad 0 \leq x \leq W, \quad z = H, \\ q_w &= q_o = 0, \quad t > 0, \quad x = W, \quad 0 \leq z \leq H. \end{aligned} \quad (8)$$

Case A represents a domain of size (0.2, 0.2) m which is meshed by 10439 nodes and 19968 triangle elements, corresponding to more than 81690 DOF (quadratic Lagrange elements), while Cases B and C are meshed by 10591 nodes and 20272 triangle elements, corresponding to more than 82906 DOF (quadratic Lagrange elements). All computations have been performed using the commercial software COMSOL version 3.5a with the direct solver UMFPACK and were running on multi(7)-core workstation using SMP mode of parallel computation. Figures 2(a) and 2(b) show mesh distributions for Case A and Cases B and C, respectively, with fine mesh on the inlet side and the opposite side.

The simulation was running for imbibition time of 40 days so that it may be compared with the study of Pooladi-Darvish and Firoozabadi [3]. We use the same values of physical properties used by Pooladi-Darvish and Firoozabadi [3] as given in Table 1. Figure 3 shows distributions of water saturation and velocity vectors of the case of incorporating

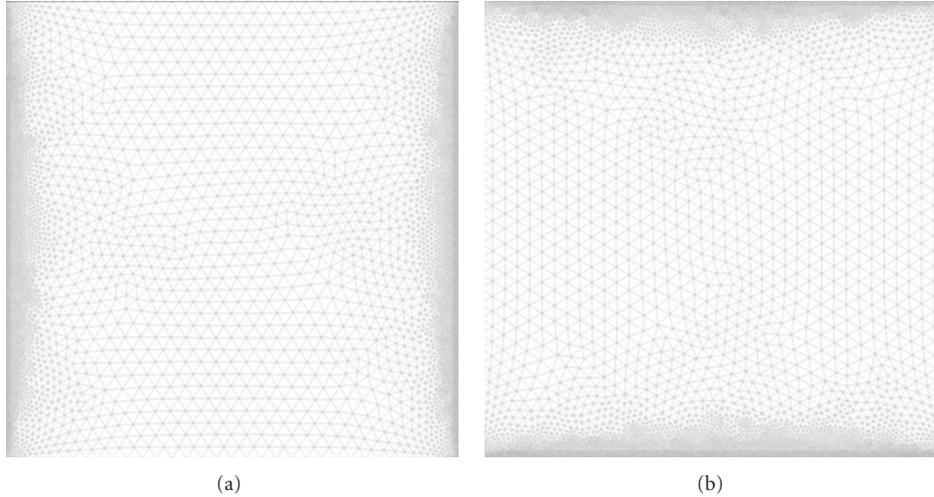


FIGURE 2: (a) Mesh distributions for the 2D dimensional Cases A. (b) Mesh distributions for the 2D dimensional Cases B and C

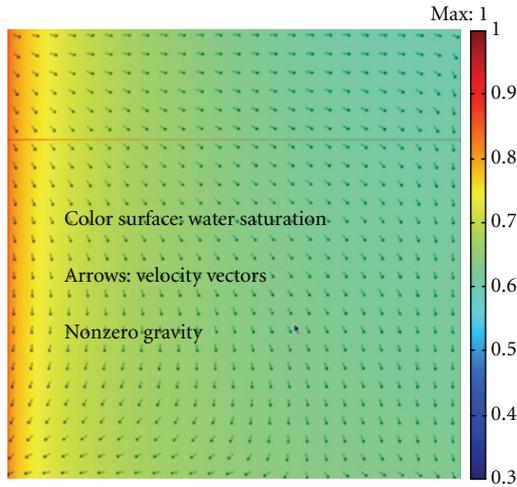


FIGURE 3: Distributions of water saturation and velocity vectors of nonzero gravity of Case A, at time imbibition of 40 days.

gravity in the flow equations. The zero-gravity case may be matched well by 1D simulation, while the opposite is true for the case of nonzero gravity which shows a nonuniform distribution of water velocity as shown in Figure 3. Additionally, a comparison between considering and neglecting gravity effect on water saturation against  $x$ -axis of Case A is plotted in Figure 4. It can be seen from this figure that considering the gravity term in the flow equations results in a slight increase in water saturation. Also, from the same figure we may note that the saturation profiles are comparable to the 1D case as shown by Pooladi-Darvish and Firoozabadi [3]. Comparison between considering and neglecting gravity effect on water and oil pressure against distance with considering gravity effect of Case A is plotted in Figure 5. From this figure, one may note that water and oil pressure vary downstream of the saturation front with time and location. Also, it can be seen that oil pressure reaches the

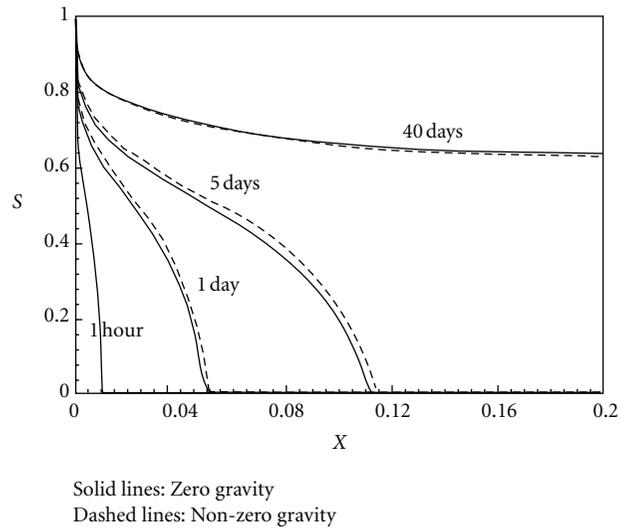


FIGURE 4: Comparison between considering and neglecting gravity effect on water saturation against  $x$ -axis of Case A, at  $z = 0.15$  m.

TABLE 1: Primary parameters from Pooladi-Darvish and Firoozabadi [3].

$a$	$b$	$B$	$K$	$k_{ro}^0$	$k_{rw}^0$	$L$	$S_{wi}$	$\varphi$	$\mu_{w,o}$
4	4	10 kPa	$0.02 \mu\text{m}$	0.75	0.2	0.2 m	0.001	0.3	1 mPa

maximum in the two-phase region. It is interesting to note that gravity has a slight effect on water and oil pressures.

Figure 6 shows a comparison between considering and neglecting gravity effect on water  $x$ -velocity profiles against the horizontal distance for Case A. This figure indicates that at the beginning of the imbibition time the velocity is higher while after longer time of imbibition the velocity slows down as water imbibes inside the matrix. This may be interpreted based on the fact that the flow in this system is dominated by capillarity which reduces with the increase in saturation.

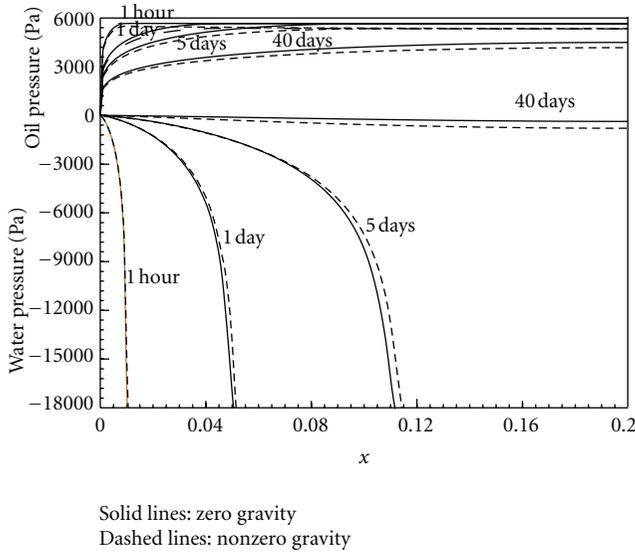


FIGURE 5: Comparison between considering and neglecting gravity effect on water and oil pressure against  $x$ -axis of Case A, at  $z = 0.15$  m.

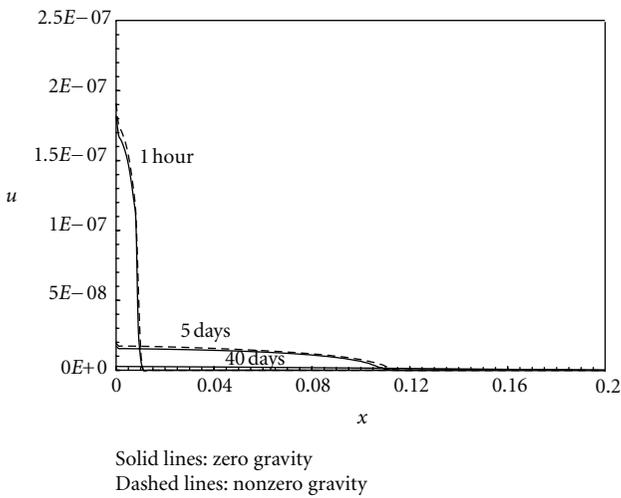


FIGURE 6: Comparison between considering and neglecting gravity effect on water  $x$ -velocity against  $x$ -axis of Case A, at  $z = 0.15$  m.

In this figure, it is apparent that gravity has, generally, slight effect at early time of imbibition. However, this effect is seen to be more pronounced at later time of imbibition (e.g., after 40 days).

A comparison between considering and neglecting gravity effect on water saturation against  $z$ -axis for Case B is plotted in Figure 7. It is obvious that in the case of considering gravity the water saturation is slightly higher than that without gravity particularly after longer period of time (e.g., after 40 days of imbibition). A comparison between considering and neglecting gravity effect on water and oil pressure against  $z$ -axis of Case B is plotted in Figure 8. It is interesting to note that, for this case, both water and oil pressures are assisted by the gravity force.

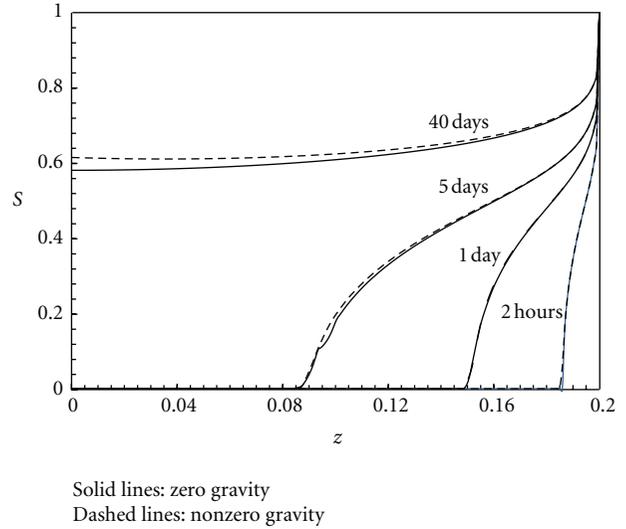


FIGURE 7: Comparison between considering and neglecting gravity effect on water saturation against  $z$ -axis of Case B, at  $x = 0.15$  m.

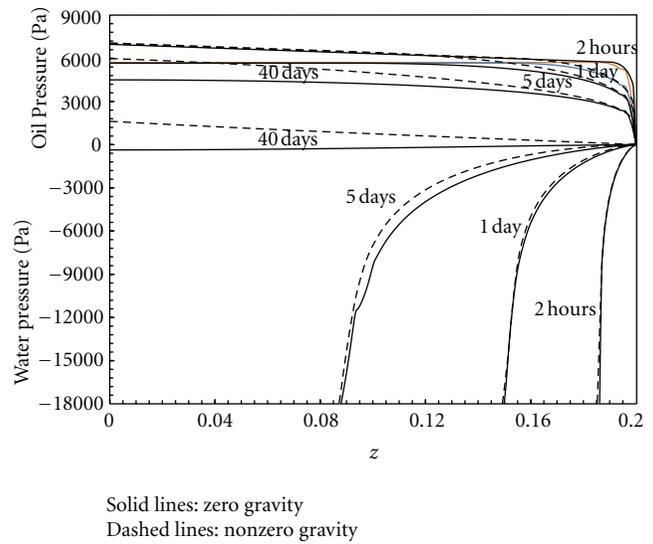


FIGURE 8: Comparison between considering and neglecting gravity effect on water and oil pressure against  $z$ -axis of Case B, at  $x = 0.15$  m.

Figure 9 shows a comparison between considering and neglecting gravity effect on water saturation against  $z$ -axis of Case C. It can be seen from Figure 9 that considering the gravity force in the flow equations reduces water saturation. In this case the gravity works in the opposite direction of the water flow so it resists water imbibition. Also, considering the gravity force reduces both water and oil pressures as illustrated in Figure 10.

### 3. Conclusions

The aim of this work is to examine the influence of gravity on countercurrent imbibition of two-phase flow in porous

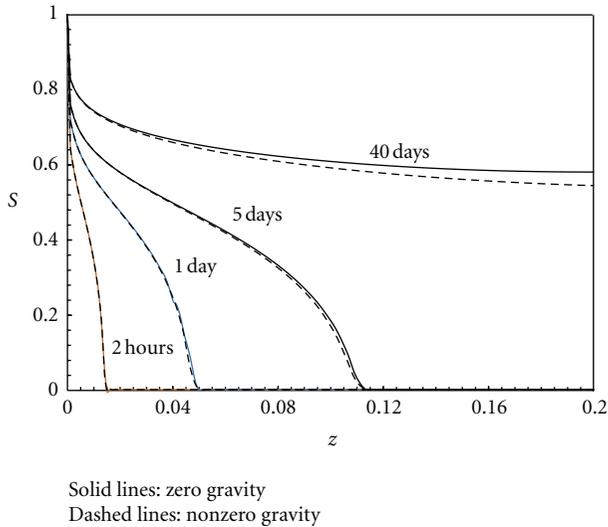


FIGURE 9: Comparison between considering and neglecting gravity effect on water saturation against  $z$ -axis of Case C, at  $x = 0.15$  m.

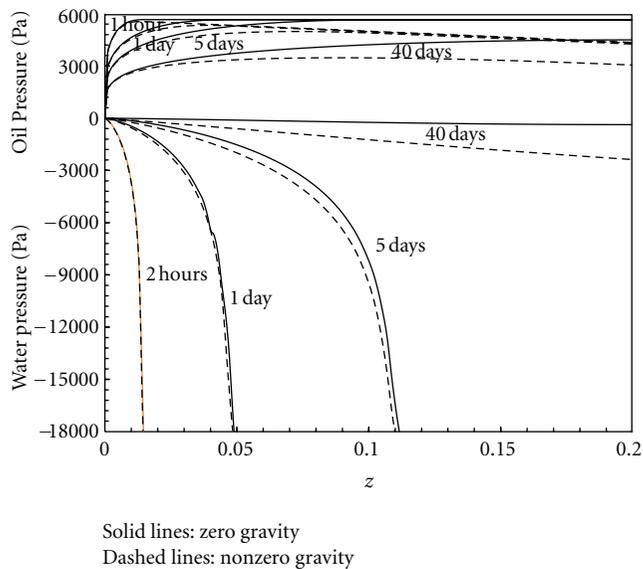


FIGURE 10: Comparison between considering and neglecting gravity effect on water and oil pressure against  $z$ -axis of Case C, at  $x = 0.15$  m.

media for different locations of the open boundary. A 2D simulation for three different locations of the open boundary (side, top, and bottom) is considered. A comparable study of considering and neglecting gravity in the model is done for the three different open-boundary locations. From this work one may conclude that the bottom open-boundary reduces the water imbibition in the rock matrix and therefore decreases the oil recovery, while the opposite is true for both top and side open-boundary. The results indicate that the buoyancy effects due to gravity force take place depending on the location of the open boundary.

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