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Regular Article

Saturated imbibition under the influence of gravity and geometry

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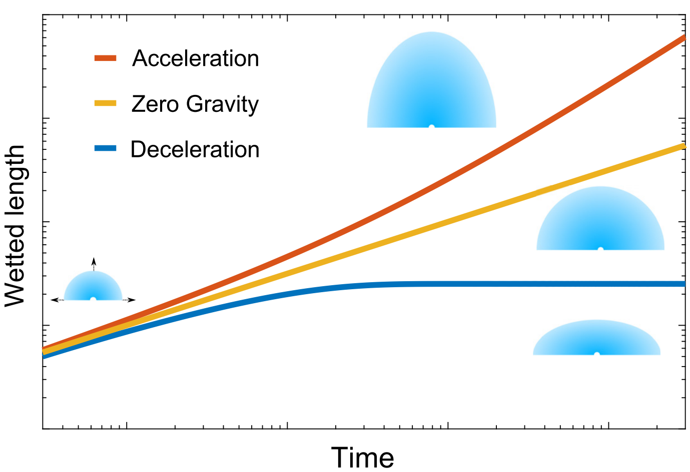
GRAPHICAL ABSTRACT



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ABSTRACT

Hypothesis: The effect of gravity was generally neglected in the classical imbibition law for one dimensional geometries. Following researches complemented the classical "Lucas-Washburn law" with consideration of gravity, but no examination of geometries under influence of gravity has been done, while geometry was shown to yield different scaling law for the imbibition process. Hence, it is possible to discover new time exponents for imbibition length in two dimensional and three dimensional imbibition process under gravity.

Methods: Through theoretical analysis and numerical simulations, the size of wetted region under three gravitational scenarios (zero gravity, acceleration and deceleration) in three geometries (one dimensional, two dimensional radial and three dimensional radial) are determined quantitatively.

Findings: New time exponents other than classic 1/2 are identified under different directions of gravity in two dimensional radial and three dimensional radial imbibition, and symmetry of time exponents due to different directions of gravity is discovered. A new time exponent of 1 for the acceleration case in one dimensional imbibition is found. The flow field in the wetted region is also determined from simulations. Discoveries in this paper show that new physical laws for imbibition length exist at the intersection of gravity and geometry.

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1. Introduction

The classical "Lucas-Washburn law" [1,2] indicates that imbibition length l in one dimensional geometry (illustrated in Fig. 1) evolves according to time exponent of 1/2, *i.e.* $l \sim t^{1/2}$, which is also known as "spontaneous imbibition" or "diffusion imbibition" [3]. Lucas-Washburn law applies to unidirection imbibition process in capillary tube or porous media, in which capillary pressure at the wetting front provides necessary pressure gradient as the driving force. As shown in Eqs. (3) and (4), gravity is neglected in the derivation of Lucas-Washburn law, which only applies to straight geometries. Recently, Cai and Yu introduced fractal theory to characterize the effect of tortuosity on imbibition [4], and they found the time exponent is not a constant 1/2, but related to the tortuosity fractal dimension. The gravity is also not included in their model. Neglection of gravity is appropriate under a lot of scenarios at microscale or at early stage when gravity is minute compared to the driving force. Researchers have been employing this quantitative law in the analysis of bloodstain pattern [5] and design of paper-based microfluidic devices [6,7].

However, gravity becomes a vital factor as the imbibition length proceeds, and the length-time relation in one dimensional imbibition deviates from the $l \sim t^{1/2}$ law with larger hydrostatic force. On the application side, gravity is an important factor at large imbibition scale during the analysis for water/oil movement in geological process [8]. Fries and Dreyer utilized Lambert W function to solve analytically the imbibition process with gravity in one dimensional geometry [9,10], and their results serve as a reference in following research [11,12]. With various importance of inertia and viscosity, dynamic oscillations of one dimensional imbibition length under gravity are studied theoretically and numerically, and a dimensionless coefficient Bo/Oh determining the appearance of oscillation has been identified [13–16], where Bo indicates Bond number and Oh Ohnesorge number.

On the other hand, new aspects are introduced to the imbibition process when geometry is expanded from one dimension to two dimension and three dimension. Even in the absence of gravity, imbibition goes beyond $l \sim t^{1/2}$ law for higher dimensional geometries. Reyssat et al. discovered $l \sim t^{1/4}$ law in capillary tube with small opening angle [3]; $l \sim t^{1/3}$ law was identified in three dimensional radial imbibition [17,18]; Mendez et al. also found deviation from classic Lucas-Washburn law in two dimensional radial imbibition [19]. Researchers then started to design geometry to achieve desirable imbibition process [20,21]. Given the importance of geometry, it is needed to study the imbibition process under the combined influence of gravity of geometry, which is not discussed previously in the literatures. This paper elucidates the effect of gravity on the imbibition process, especially on the time exponents of imbibition length, in one dimension, two dimension radial and three dimensional radial imbibition through theoretical analysis and numerical simulations.

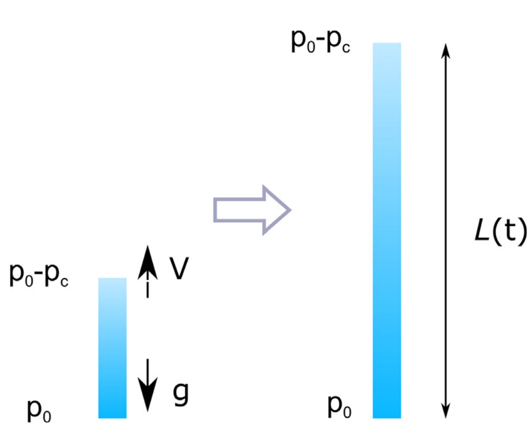

Fig. 1. One dimensional imbibition under the influence of gravity. Intensity of color indicates the magnitude of pressure in the wetted region.

2. Theoretic analysis and numerical simulations

2.1. 1D imbibition with gravity

Before the derivations, several assumptions are made:

- Saturated imbibition is considered.
- No dynamic and entry effects are considered.
- There is no liquid loss due to evaporation from the wetted region.
- The influence of gas can be neglected when liquid replaces gas in the advancing of wetted region.

The classic one dimensional imbibition process is described by Darcy's law, which applies to imbibition in capillary tube or slender porous media:

$$\mathbf{v} = -\frac{\kappa}{\mu}\nabla p \tag{1}$$

where $\mathbf{v}$ indicates velocity in the porous media, κ the permeability for porous media, μ the dynamic viscous of the fluid and p the pressure in fluid field. Together with the continuity equation for incompressible fluid, Darcy's law can be converted into a Laplace equation for pressure:

$$\nabla \cdot \mathbf{v} = 0, \text{so that } \nabla^2 p = 0 \tag{2}$$

The driving force for the imbibition process stems from the pressure difference between the source (p_0) and the wetting front (p_0-p_c), which is illustrated in Fig. 1. In the absence of gravity, wetting length l can be correlated with pressure in the wetted region according to Darcy's law,

$$l\frac{dl}{dt} = \frac{\kappa}{\mu}p_c \tag{3}$$

where p_c is the capillary pressure at the wetting front, which is essentially the driving force for the imbibition process. As shown in previous study [17], capillary pressure can be calculated from average pore size in porous media using geometrical reasoning, while permeability can be determined from pore size and porosity in porous media. In this paper, capillary pressure is treated as a constant parameter across the geometry, which remains unchanged during the imbibition process. In essential, a constant capillary pressure is a time independent mean pressure, so the variation of capillary pressure in the porous material is neglected. This assumption is consistent with literatures [15,17,22]. Eq. (3) can be integrated on both sides to yield classic Lucas-Washburn law:

$$l = \left(\frac{2\kappa p_c}{\mu}\right)^{1/2} t^{1/2} \tag{4}$$

With gravity coming to the derivation, there are two scenarios: imbibition is accelerated by gravity and imbibition is decelerated by gravity. For the deceleration case, gravity acts in the opposite direction of imbibition, which leads to additional term in Eq. (3) with negative sign:

$$l\frac{dl}{dt} = \frac{\kappa}{\mu}(p_c - \rho g l) \tag{5}$$

With gravity slowing down the imbibition process, the wetted length should finally reach a steady value (also well known as capillary rise or Jurin height), which can be determined by terms in the parenthesis of Eq. (5):

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