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Two-phase flow with capillary valve effect in porous media

Rui Wu [a,b,*], Abdolreza Kharaghani [a], Evangelos Tsotsas [a]

[a] Chair of Thermal Process Engineering, Otto von Guericke University, P.O. 4120, 39106 Magdeburg, Germany
[b] School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai, 200093, China

HIGHLIGHTS

- Pore network model with the capillary valve effect (CVE) is developed.
- Two types of pore invasion are proposed.
- Simulation and experimental results agree well if CVE is considered.

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ABSTRACT

The capillary valve effect is studied on the capillary force dominated immiscible two-phase flows in the networks composed of regular pores and throats. Two types of pore invasion are revealed. One is bursting invasion, where the invading fluid enters a pore from one throat. The other is merging invasion, where a pore is invaded by the invading fluid from two throats. Drainage and imbibition are similar and show capillary fingering pattern in the cases where bursting invasion dominates over merging invasion. When merging invasion is dominant, a stable flow pattern can also be observed.

1. Introduction

Immiscible two-phase flow in porous media is of great interest to many industrial fields, such as oil recovery, CO_2 sequestration, and water management in fuel cells. Nevertheless, it is a challenge to fully understand the two-phase flow in a porous material, since it is affected not only by interactions between gravitational, capillary, and viscous forces but also by the structure of the pore space.

Porous materials contain pores of various sizes, such that small pores may be connected to large pores with a sudden geometrical expansion at their interfaces. This expansion can increase the resistance to the advancement of the invading fluid and has already been employed as a capillary valve to control the fluid flow in microfluidic devices (Duffy et al., 1999; Cho et al., 2007; Chen et al., 2008; Moore et al., 2011). When the invading fluid reaches an expansion interface, it will stop moving until its pressure increases to a critical value. We call this as the capillary valve effect.

Pore network models have been commonly used to understand the two-phase flows in porous media (Blunt, 2001; Sahimi, 2011; Joekar-Niasar and Hassanizadeh, 2012). In this method, the void space of a porous medium is conceptualized as a pore network composed of regular ducts of various sizes. The two-phase flow in a network is depicted by the prescribed rules. In the cases where the capillary forces dominate, the invasion percolation algorithm proposed by Wilkiinson and Willemsen (1983) has been widely used (Blunt et al., 1992; Knackstedt et al., 1998, 2001; Mani and Mohanty, 1999; Lopez and Vidales et al., 2003; Araujo et al., 2005; Bazylak et al., 2008; Chapuis et al., 2008; Rebai and Prat, 2009; Wu et al., 2010, 2012, 2013; Ceballos et al., 2011; Ceballos and Prat, 2013).

Only one network duct is invaded at each step in the invasion percolation algorithm. This duct is the largest available one in drainage, whereas in imbibition, it is the smallest available one. Bazylak et al. (2008) compared the pore network simulations against the experiments for slow drainage in networks of various structures. Differences between them were always observed and attributed to the uncertainty in the network fabrication. Although

* Corresponding author at: Chair of Thermal Process Engineering, Otto von Guericke University, P.O. 4120, 39106 Magdeburg, Germany. Tel.: +49 391 52280; fax: +49 391 11160.
E-mail address: ruiwu1986@gmail.com (R. Wu).

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this is an important reason, it will be shown later that neglecting the capillary valve effect in the pore network model can be another reason.

A pore network model with the capillary valve effect is developed in this paper for simulations of the capillary force dominated two-phase flows in porous media. Experiments for gas–liquid two-phase flows in microfluidic networks are performed. The numerical results agree well with the experimental data if the capillary valve effect is considered in the model. If this effect is not considered, the agreement is not so good.

The paper is organized as follows: In Section 2, the experiments for the gas–liquid two-phase flow in microfluidic networks are depicted. The pore network model with the capillary valve effect is developed in Section 3. In Section 4, the numerical results are compared with the experimental observations. The conclusions are drawn in Section 5.

2. Experiments with microfluidic networks

The gas–liquid two-phase flow experiments are conducted with the microfluidic networks supplied by CapitalBio Corporation (China). The transparent networks are fabricated using PDMS and have a semi-two-dimensional structure. The networks consist of square pores with the side length of $l=1$ mm and of rectangular throats with a randomly distributed width w. The ducts, i.e., pores and throats, have the same depth of $h=0.1$ mm. The distance between the centers of two neighboring pores is $a=2$ mm.

Two types of networks with different throat width distributions are used. In the network of type A, the throat widths are uniformly distributed in the range [0.14–0.94] mm. The minimal difference between two throat widths is 0.02 mm so as to relieve the effects of the fabrication uncertainty (± 0.01 mm). In the network of type B, the throat widths are 0.86, 0.88, 0.90, or 0.92 mm. Both networks have a size of 4×4 throats. Fig. 1 shows the structures of these two networks, where the numbers are the throat widths (the unit is mm). The middle pore at one side of the network is connected to an inlet tube of 0.5 mm wide and of 8 mm long, through which the invading fluid is injected. Opposite to this inlet side is the outlet open to the environment. The other two sides are impermeable.

The network is initially filled with the displaced fluid (air). The invading fluid is then injected into the network until the breakthrough moment. In the drainage experiment, the invading fluid is water with an advancing contact angle of about 67°. In the imbibition experiment, the invading fluid is the mixture of 20% v/v water and 80% v/v alcohol with an advancing contact angle of about 103°. The contact angle is measured in the displaced fluid. Dye agents are not used in the invading fluids to avoid wettability changes and duct blockages. The network is placed horizontally on a base to eliminate the effects due to gravitational forces.

The invading fluid is injected into the network by using a syringe pump (Harvard Apparatus, 11 Plus, USA). The flow rate is controlled to 0.1 μl/min so as to achieve a low capillary number ($Ca\sim10^{-8}$). The capillary number is defined as $Ca=\mu v/\sigma$, where σ is the surface tension, and μ and v are the viscosity and velocity of the invading fluid, respectively. The movement of the invading fluid is recorded by a camera equipped with a macro lens (Nikon D810, Japan).

3. Pore network model

During the immiscible two-phase flow in a network, the invading and displaced fluids are separated by menisci inside ducts, across which a pressure difference is established:

$$\Delta P = P_{invading\ \ fluid} - P_{displaced\ \ fluid} = \sigma\left(\frac{1}{r_w}+\frac{1}{r_h}\right) \tag{1}$$

where r_w and r_h are radii of curvatures of menisci in the width and height directions, respectively. These two curvature radii are vector quantities and have direction as well as magnitude. A curvature radius is taken as positive if the center is at the side of the invading fluid, otherwise negative. The network ducts have the same height but various widths. Hence, r_w varies from ducts to ducts; r_h remains constant and equals to $r_h=h/2\cos\theta_a$, where θ_a is the advancing contact angle. For this reason, only the variation of r_w is investigated in the following analysis.

For a meniscus in a duct of width w, its curvature radius is $r_w=w/2\cos\theta$, where θ is the contact angle taken in the displaced fluid. The pressure difference across the meniscus increases with decreasing θ, Eq. (1). The three-phase contact line, where the invading fluid, displaced fluid, and solid meet, cannot move forward if $\theta>\theta_a$. Hence, to advance the meniscus, the pressure difference across it must exceed that at $\theta=\theta_a$. This critical value is called the threshold pressure (Lenormand et al., 1983). The

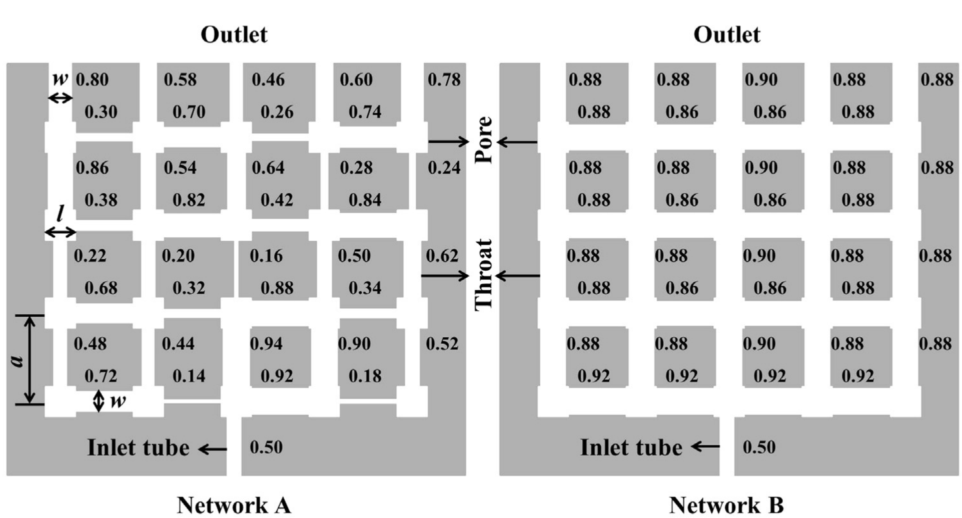

Fig. 1. Structures of the networks used in this work. The numbers are throat widths (the unit is mm).