International Journal of Heat and Mass Transfer 94 (2016) 81–86

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Capillary valve effect during slow drying of porous media

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ARTICLE INFO

Article history:
Received 10 July 2015
Received in revised form 20 October 2015
Accepted 2 November 2015
Available online 1 December 2015

Keywords:
Drying of porous media
Pore network model
Capillary valve effect
PDMS microfluidic network
Image processing techniques

ABSTRACT

In this paper, a pore network model, which accounts for the capillary valve effect induced by the sudden geometrical expansion of the void space, is developed for slow drying of porous media. To validate the developed model, an optical drying experiment is conducted with a two-dimensional Polydimethylsiloxane microfluidic network composed of regular pores and throats. It is revealed that if the capillary valve effect is considered in the model, better agreement is obtained between numerical simulation and experimental data. If this effect is not incorporated into the model, however, more isolated filled throats and more liquid clusters are predicted as compared to the experimental results. Comparison between pore network simulation and experimental data clearly shows that the capillary valve effect must be taken into account in order to understand pore-scale processes during drying of porous media.

1. Introduction

Understanding drying processes in porous media is of great importance to many applications, such as, paper, pharmaceutical, food, and textile industries [1,2]. During drying of a porous material, the initially liquid filled pores are gradually invaded by gas. This gas invasion determines the liquid distribution in the porous medium and hence kinetics of drying. Nevertheless, it is a challenge to directly observe the gas occupying process during drying of porous media, since a real porous material not only is opaque but also has complex microstructures [3]. An alternative way to understand drying of porous media is to use the pore network modeling approach. In this method, the void space of a porous material is conceptualized as a network composed of regular ducts, e.g., pores and throats. Then, liquid and vapor transport as well as the gas invasion process in this network are simulated based on some prescribed physical rules, from which the drying process is uncovered.

Various pore network models have been developed to investigate physical and structural effects on drying of porous media such as the gravity, viscosity, wettability, liquid film flow, and heat transfer (see reviews in [4–6] and references therein). Nevertheless, in these pore network models, the capillary valve effect (CVE), induced by the sudden geometrical expansion between the small and large void space in porous media, has not been taken into account. It has been revealed that the CVE plays an important role in capillary forces dominated drainage and imbibition processes in porous media [7]. Drying induced gas invasion in a porous material resembles to the drainage or imbibition process. Therefore, it is desirable to also include the CVE in pore network models for drying of porous media.

In this contribution, a pore network model which considers the CVE is developed to simulate drying processes in porous media. To understand in detail this effect, we consider only the slow drying case and neglect the effects of gravity, viscosity, liquid film flow, and heat transfer. To validate the developed model, a drying experiment with a two-dimensional (2D) Polydimethylsiloxane (PDMS) microfluidic network is performed. We find that if the CVE is considered in the pore network model, better agreement is obtained between the numerical and experimental results, indicating that the CVE must be taken into account to better understand drying processes in porous media.

The paper is organized as follows. In Section 2, the optical experiment for drying of a PDMS microfluidic network is depicted. The pore network model with the CVE is introduced in Section 3. Comparison between the pore network simulation and the experiment is presented in Section 4. Finally, conclusions of this contribution are drawn in Section 5.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.11.004
0017-9310/

2. Microfluidic drying experiment

To validate the pore network model developed in this work, drying in a transparent 2D microfluidic network composed of ducts of different sizes is performed, as schematically shown in Fig. 1a. It should be noted that in the present pore network model for drying of porous media (see Section 3), the effects of gravity, viscosity, and liquid films in corners of network ducts (i.e., corner films) are not considered. That is to say, these effects need to be eliminated in the experiment. To suppress effects of corner films, a PDMS network supplied by CapitalBio Corporation (China) is employed. This is because PDMS has not only a transparent nature but also a hydrophobic surface characteristic. During drying of a PDMS network filled with water, the angle between the moving gas–liquid interface and the liquid–solid interface is about 69°. This means that corner films cannot exist in the network ducts, since the condition for formation of a film in a duct corner, as stated in [8], is $\alpha + \theta < 90°$; here, α is half of the corner angle (for cuboid network ducts, $\alpha = 45°$), and θ is contact angle between the gas–liquid interface and the liquid–solid interface.

It should be noted that PDMS is permeable to water. To reduce water loss due to permeation, the network is covered by a glass sheet of 1 mm thick, Fig. 1a. We find that if the network is not covered by the glass sheet, the total drying time will be about three times shorter. To eliminate the viscosity effect on the drying induced two-phase flow in the network, only one of the network ducts is open to the environment through a long tube, Fig. 1a. The purpose of this long tube is twofold. First, it controls the drying rate at a low level, which guarantees that the two-phase flow in the network is dominated by capillary forces, and the viscosity effect can be neglected. Second, this tube gives an explicit boundary condition for the mass transfer between the environment and the network, which can be easily incorporated in the pore network model. To relieve the gravity effect, the network is horizontally placed during the drying experiment.

The designed network consists of regular pores and throats (for convenience, throats and pores are also called ducts). In the plane shown in Fig. 1b, the pores are square, and the throat are rectangular. All the pores have the same side length of $l = 1$ mm, and the distance between the centers of two neighboring pores is $a = 2$ mm, which means that the throat length is $l_t = 1$ mm. The throat widths (w) are uniformly distributed in a range of 0.14–0.94 mm with an increment of 0.02 mm so as to eliminate effects of the fabrication uncertainty (0.01 mm). To guarantee that each throat has a different width, the network size is limited to 5×5 pores, as shown in Fig. 1b, where the numbers are the throat widths (the unit is mm). All the network sides are closed except that the middle pore at one side of the network is open to the environment through a

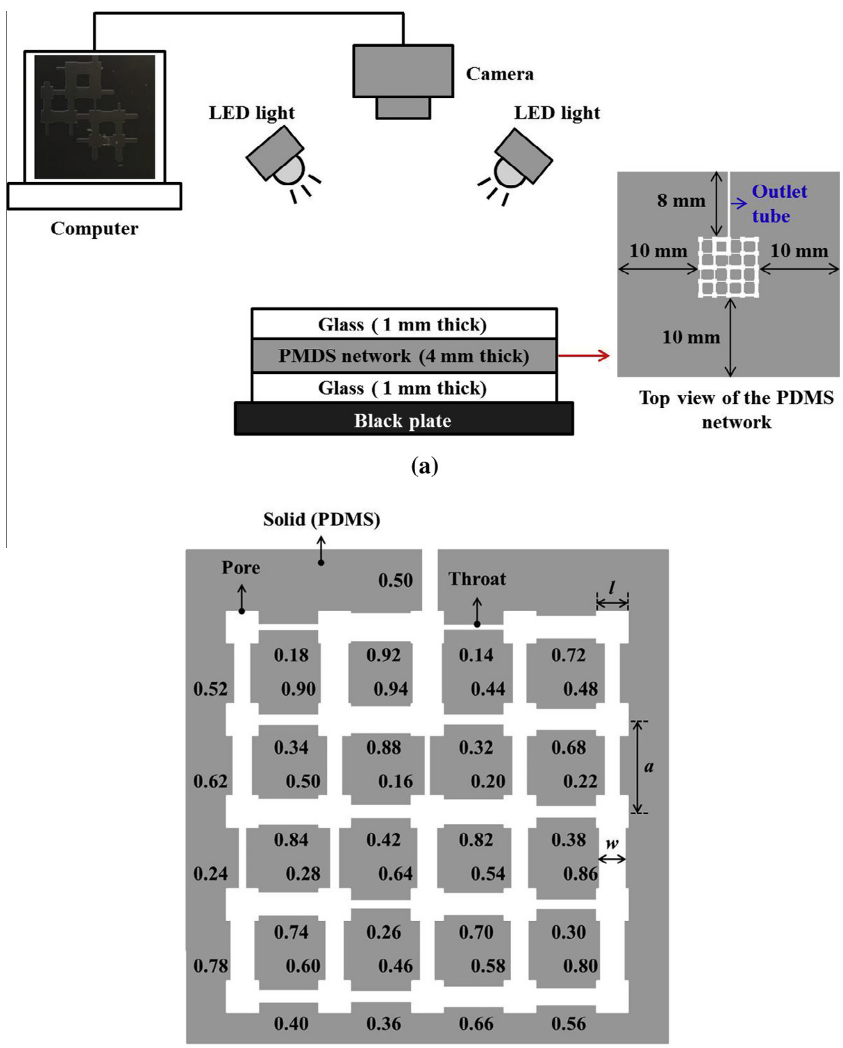

Fig. 1. (a) Schematic of the experimental setup used to record drying of a PDMS network; (b) structure of the network.