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Drying of a porous medium with multiple open sides using a pore-network model simulation☆

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ABSTRACT

Pore-network models are employed frequently to study drying in porous media as they, unlike continuum approaches, provide insight into the pore-scale phenomena prevalent during the drying process. Drying characteristics of a 2D rectangular pore network with two opposite sides exposed to the air are investigated numerically, while ignoring gravitational and viscous forces as well as the liquid film effects. The invasion percolation (IP) algorithm is applied to simulate the slow capillary-dominated drying process under isothermal conditions. The drying characteristics of such a network are compared with those of the same network with only one side exposed to the air (the case typically studied in the literature). The results obtained from this novel configuration show that the exposed surface of the network with two open sides dries faster in terms of actual time but requires a larger number of time-steps. Also, the number of thus formed liquid clusters and consequently the number of meniscus pores inside the two-sides-open network is higher than that of the one-side-open network. Therefore, the evaporative mass-loss rate for the network with two open sides is much higher than that of the network with one open side. The study yields some new insights into the evaporation dynamics of networks with multiple open sides.

1. Introduction

To overcome some of the shortcomings of continuum approach such as inaccuracy in prediction of the surface heat and mass transfer coefficients, and inaccuracy in prediction of small-scale heterogeneities in the liquid phase distribution, a discrete method has been used to simulate drying from a porous medium [1]. Pore-network models as powerful tools in the discrete approach have been used and modified by several investigations. As the first ones, Prat [2] studied numerically and experimentally drying from a porous medium using a two-dimensional pore-network to investigate the capillary and gravitational effects and drying stabilization. Later on, gravitational [3], viscous [4], liquid film [5,6], pore structure [5,7] and heat transfer effects [8–11] were investigated as well. Metzger et al. [12] conducted a thorough review of drying simulations using pore-network models and presented a novel algorithm.

Although many attempts have been made to improve the pore-network models for simulating drying of porous media, most of these investigations relate to drying of pore-networks with only one side exposed to the air, while the remaining sides are impervious. Since in many real situations, evaporation occurs from more than one side of a porous medium, it is necessary to have an estimate of drying behavior of a pore-network with multiple sides open to the air.

The aim of the present study is to predict isothermal drying characteristics of a pore-network when drying occurs from two opposite sides of the pore-network. Therefore, a two-dimensional rectangular pore-network with two exposed sides is considered, and its drying characteristics are compared with those of the same pore-network with only one exposed surface. Note that to simulate drying from the pore-networks, the drying algorithm proposed by Metzger et al. [12] has been used.

2. Problem description and drying algorithm

A 30×30 rectangular pore-network model including 1800 throats with circular cross sections (to avoid liquid film effect) is considered. Throats with a nominal diameter of 90 μm are distributed randomly inside the network based on a normal distribution function with a standard deviation of 5% of the nominal diameter. Also, all throats have the same length equal to 500 μm. Due to isothermal drying, pores of the network can be considered as nodes without volume [7]. Due to the horizontal orientation of the network and the relatively large diameter of the network throats, the gravitational and viscous forces are neglected [7,12]. Therefore, capillary force is the major mechanism for the transport of liquid water inside the network. Using the drying algorithm proposed by Metzger et al. [12], drying characteristics of the above mentioned pore-network are investigated, and compared when

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Nomenclature

A	Cross sectional area (m^2)
D	Vapor diffusivity ($m^2\ s^{-1}$)
L	Throat length (m)
L_N	Length of pore-network along the airflow (m)
$\dot{M}$	Mass flow rate ($kg\ s^{-1}$)
$\dot{M}_N$	Mass flow rate from the pore-network at each time step ($kg\ s^{-1}$)
$\dot{M}_t$	Total mass flow rate from a cluster ($kg\ s^{-1}$)
$\overline{M}$	Vapor molecular-mass ($kg\ kmol^{-1}$)
m	Liquid mass inside the largest meniscus throat of a cluster (kg)
n	Number of clusters at a particular time step
P	Total air pressure (kPa)
p	Vapor pressure (kPa)
R	Universal gas constant ($kJ\ kmol^{-1}\ K^{-1}$)
Re_L	Reynolds number based on the network length
Sc	Schmidt number
$\overline{Sh}$	Average Sherwood number
T	Temperature (K)
t	Minimum time scale at each time-step (s)
t_s	Time scale of a cluster (s)
u_∞	Free stream velocity ($m\ s^{-1}$)

Greek symbols

β	Mass transfer coefficient ($m\ s^{-1}$)
δ	Mass transfer boundary layer thickness (m)
ν	Kinematic viscosity of air ($m^2\ s^{-1}$)

one and two sides of the network are open to the air. Fig. 1 illustrates the pore-networks for the two different situations.

To simulate mass transfer outside a pore-network, Surasani et al. [8] and Metzger et al. [12] considered a constant mass transfer boundary layer thickness, δ, over the exposed surface of the network (see Fig. 2) and placed additional nodes within the outside boundary layer by using the following relations:

$$\text{Average Sherwood number}: \quad \overline{Sh} = \frac{\beta L_N}{D} = 0.664 Re_L^{1/2} Sc^{1/3} \tag{1}$$

where the Reynolds (Re_L) and Schmidt (Sc) numbers are defined as

$$Re_L = \frac{u_\infty L_N}{\nu} \tag{2}$$

$$Sc = \frac{\nu}{D} \tag{3}$$

and finally the boundary layer thickness, δ, is determined using the mass transfer coefficient β [12] from Eq. (1):

$$\delta = \frac{D}{\beta} = NL \tag{4}$$

where N and L in Eq. (4) are the number of rows of additional nodes to be placed in the boundary layer, and the length of the throats, respectively [8,12]. The distance between any two rows or columns inside the boundary layer is equal to L.

The black and white portions of throats in Fig. 2 signify the filled and empty parts of the throats, respectively. Throats connected to a black pore in Fig. 2 are non-empty, whereas those connected to a white pore are completely empty. A meniscus pore (shown in gray) is located at the interface of the vapor and liquid phases, and all the non-empty throats connected to this pore are called meniscus throats [12].

All non-empty throats that are connected to each other via black pores form a *cluster* [8,12]. The largest meniscus throat in a cluster has the lowest capillary pressure. As a result, during the evaporation process, and in the absence of the viscous and gravitational forces, liquid will be transported from the largest meniscus throat[2] in a cluster to other meniscus throats within the same cluster [12]. This is to compensate for the liquid evaporated from other meniscus throats of the cluster. This process is described as the invasion percolation algorithm proposed by Prat [2]. Then at each cluster, vapor will be transported from any meniscus pore with index i to all its neighboring gas (dry) pores inside the network and/or the nodes in the boundary layer, based on the Stefan's law [8,12]:

$$\dot{M}_{ij} = -A_{ij} \frac{D}{L_{ij}} \frac{P\overline{M}}{RT} \ln\left(\frac{P-p_i}{P-p_j}\right). \tag{5}$$

Note that the cross sectional area in Eq. (5), A_{ij}, varies based on the location of gray and white pores inside the network as well as nodes inside the boundary layer [8,12]. When the total mass flow rate out of each cluster is determined, the *time scale* of the cluster i is calculated [12] as:

$$t_{s,i} = \frac{m_i}{\dot{M}_{t,i}} \tag{6}$$

where m_i and $\dot{M}_{t,i}$ are mass of water inside the largest meniscus throat of the cluster i, and total mass flow rate from the cluster i, respectively. It is evident that the number of time scales is equal to that of clusters formed inside the pore-network. Therefore, among all of the existent time scales of the network, the smallest one will be selected, and the mass of liquid evaporated from the largest throat of each cluster during this time period will be determined.

Metzger et al. [12] divide the total network drying time into several time-steps in such a manner that at each time-step, at least one meniscus throat becomes completely empty. It is necessary to identify the new clusters as well as the locations of new meniscus pores at the end of each time-step during the cluster labeling process [8,12]. When one time-step finishes, a new one starts and the drying process continues until the total mass of water inside the network is completely evaporated.

In the present study, air with a free-stream velocity, pressure and temperature equal to 0.11 $m\,s^{-1}$, 1 atm and 25 °C, respectively, flows over the two exposed surfaces of the pore-network. Also, the number of additional rows considered within the boundary layer is equal to 4.

3. Validation of the developed code

Although the trend in the drying of network has been modeled suitably in several studies such as [1,13], the drying times have not been simulated accurately. In fact, the liquid-film effect that occurs in throats with corners in their cross sections is the major reason for the discrepancy in drying rates between simulation and experimental data [13,14]. Although the liquid-film effect does not occur in throats with circular cross sections such as those used in the present study, the manufacturing of completely smooth interior surfaces is difficult. Therefore, some roughness is most likely to exist even in throats with circular cross-sections, and consequently the liquid-film effect is inevitable. Therefore, drying

[2] In this study, largest meniscus throat, refers to the throat with the largest cross-section area. In the presence of gravitational and viscous effects, the term 'largest meniscus throat' has to be replaced with 'meniscus throat with the highest *potential*' [12].