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Two dimensional pore network modelling and simulation of non-isothermal drying by the inclusion of viscous effects

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ABSTRACT

Drying as an immiscible displacement process has a great importance in chemical industries. The efficiency of the process is highly affected by the pore space structure of the solids. In this study non-isothermal drying behaviour of capillary porous media is studied in two dimensional (2D) mono-modal and bi-modal pore network models. Non-isothermal drying in the absence of viscous force has been studied previously. The presented model includes viscous flow in liquid phase while capillary pumping in liquid phase and diffusion in gas phase are the other mass transfer mechanisms at the pore scale. Conduction is considered as the heat transfer mechanism. The effect of viscous flow and temperature of drying air are studied. The simulation results are compared with a non-viscous model. The results indicate that the effect of viscous force is more significant in low temperatures. During the first falling drying rate period viscous forces dominate capillary pumping and decrease drying rate. The first drying rate period is not affected by viscous forces; however, the morphology of the pore space is an important parameter in forming this period. In bi-modal pore network, drying rate is higher due to the suitable arrangement of macro and microthroats in its structure.

1. Introduction

Drying is a common method to take liquid away from a porous material by evaporation. It is a remarkable process in many industrial applications such as food, paper, washing powder, wood and the like. In this process, liquid phase in the pore space is replaced by gas phase as a result of evaporation. Drying kinetics depends on material properties, pore structure and drying conditions. Continuum models are the traditional concept to model drying process. These models have been reviewed by Whitaker (1999). Pore space connectivity does not influence these models. Thus, they are not suitable where the connection of the pore space has an essential role in fluids displacement. Pore network models are used to predict the effect of pore space morphology and the contribution of different displacement mechanisms. Discrete models on the basis of statistical physics, i.e. percolation theory, can describe transport phenomena in pore scale and can be applied instead of continuum models (Laurindo and Prat, 1998). Pore network models in drying a capillary porous media were first used by Daian and Saliba (1991) and Nowicki et al. (1992) in order to compute the effective transport parameters as a function of liquid saturation. Yiotis et al. (2001) investigated the effect of viscous flow in gas and liquid phases in isothermal drying of a porous media. Metzger et al. (2007a) studied the effect of liquid viscosity on isothermal drying process. He showed the stabilizing effect of viscosity on the drying front is similar to the gravity effect in Prat's studies (1993). Most of previous efforts on pore network drying models are accomplished under isothermal condition. However, drying is a simultaneous process of mass and heat transfer and ignoring temperature changes in isothermal drying may not always be an adequate assumption. The effect of temperature gradients on drying process was investigated by Huinink et al. (2002) and Plourde and Prat (2003). In addition, Surasani and his co-workers (2008, 2009) studied non-isothermal drying in pore network models. The presented study is pursuing Surasani's studies moreover that viscous effects are included. Here, a pore network model is developed for non-isothermal drying of porous media while viscous forces in liquid phase are also included.

In this paper first the modelling method including pore network and boundary layer models and transport mechanisms are identified. Then simulation method is described. Afterwards the results are presented and explained. The paper is summarized in the final section.

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2. Modelling

2.1. Pore network and boundary layer model

A 2D square pore network model having the coordination number of four is assumed to represent a porous medium, where nodes represent the junctions at which the throats are connected to each other. Throats contain all the void space and act as the channels for heat and mass flow in the network. It is assumed that there is no accumulation in the nodes and they are connected by cylindrical pore throats. The radii of the throats are distributed randomly according to a normal distribution for density function:

$$f(r) = \frac{1}{\sqrt{2\pi}\sigma_0} e^{\frac{-(r-r_0)^2}{2\sigma_0^2}} \quad (1)$$

where r_0 and σ_0 represent mean radius and standard deviation, respectively.

To study non-isothermal drying process, it is assumed that the pore network is initially saturated with water. Other assumptions for the modelling are that the Kelvin and Knudsen effects are negligible. Viscous effect in the gas phase is ignored. Film effects are not included in the chosen cylindrical geometry of throats either. Gravity effect is also neglected. Heat transfer in the network is due to conduction mechanism and heat transfer of solid phase is also included in the energy equations. The solid phase is assumed to be nonhygroscopic and is chosen as glass. It is assumed that only the top edge of the network is exposed to evaporation and other faces are impermeable to mass and heat transfer. The initial temperature of the network is assumed 20 °C and the total gas pressure is constant and equal to 1 atm.

To indicate the first drying period in simulation results, it is necessary to model the boundary layer separately (Yiotis et al., 2006; Metzger et al., 2007b). Therefore, additional nodes are extended along the open edge of the network in the gas phase (Fig. 1).

2.2. Transport mechanisms

As mentioned, throats are the places where different transport mechanisms occur. They are divided into gas throats, liquid throats and partially filled throats according to their inner liquid saturation, S_{ij}, where the subscript ij denotes the throat connecting nodes i and j as shown in Fig. 1. Transport mechanisms in a throat are affected by liquid saturation in that throat. If the saturation is equal to one, liquid flow is due to the competition between viscous and capillary forces. If it is equal to zero, mass transfer is caused by vapour diffusion. If liquid saturation in a throat is between zero and one, liquid flow, evaporation at the meniscus and vapour diffusion are the simultaneous transfer mechanisms in that throat. Partially filled throats can be counted as a single liquid throat when both adjacent nodes are gas nodes. These throats lose their connectivity with liquid phase in other throats.

Liquid saturation at each node, S_i, depends on the saturation of its neighbouring throats. A node is considered as a liquid node if all of its neighbouring throats are partially or totally filled with liquid ($S_i = 1$). A node is assumed a gas node if (a) it is at equilibrium that means at least one of its neighbouring throats is empty of liquid ($0 < S_i < 1$) and (b) all its neighbouring throats are empty of liquid ($S_i = 0$).

In drying process, gas is the invading phase and stays continuous while liquid typically splits up into numerous clusters. Mass transfer is controlled by vapour diffusion in the gas-filled parts of porous space. Liquid displacement is due to the competition between viscous force and capillary pumping in the liquid-filled regions.

If viscous forces are not taken into account in modelling procedure, capillary flow is the dominant displacement mechanism in each cluster. Thus, liquid is pumped from the throat with the highest liquid pressure to all other meniscus throats. It leads to one throat with moving meniscus (MM) while other throats menisci remain stationary. However, by considering viscous effects the

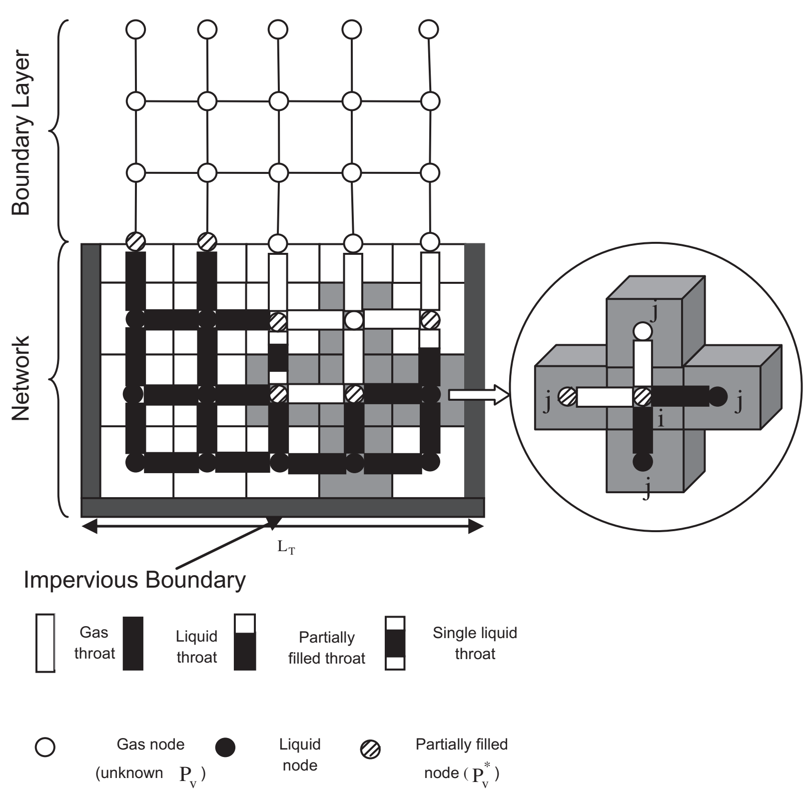

Fig. 1. Representation of a pore network model with corresponding boundary layer, a zoomed control volume and the state of nodes and throats during the drying process.