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On the influence of pore shape, contact angle and film flows on drying of capillary porous media

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Abstract

As pointed out in several previous works, thick liquid film flow can represent a major transport mechanism in drying. The effect of films is to greatly reduce the drying time compared to situations where they cannot develop. Using pore network simulations, we explore the influence of pore shape and contact angle on drying rates during the isothermal drying of porous materials in relation with the effect of liquid films when viscous effects are important in the films but not in the liquid saturated pores. It is shown that the overall drying time is greatly affected by the pore shape and contact angle when film flows are important and that incorporating the film effect in the pore network model leads to a much better agreement with experimental results. Film flows can significantly contribute to the occurrence and/or the duration of the constant rate period (CRP), which is a classical feature of convective drying. When film flows are important, the quantitative prediction of drying rate becomes very difficult for it depends on tiny details of the pore space geometry and is affected by possible changes in the local wettability conditions. This contributes to explain why the accurate prediction of drying rate still remains essentially an open question, at least when the effect of films cannot be neglected.

Keywords: Drying; Pore network; Film flow; Corner flow

1. Introduction

Drying of porous media has been the subject of many studies and is still a very active research topic. In addition to its practical importance in relation with the industrial drying of many products, drying can still be considered as an unsolved problem from a scientific standpoint. For example the quantitative prediction of drying rate without any parameter calibration is still essentially an open problem. In this paper, we try to shed some light into this problem with the analysis of the influence of film flows, pore shape and contact angle on drying rates. We begin with capillary tubes of polygonal cross-section and then consider a pore network model with pores of polygonal cross-section. Pore-network models for the study of drying have been used for more than 10 years, e.g. [1] and references therein. A pore network model for studying drying patterns and drying rates was first proposed in [2] for slow evaporation of a single component liquid when thermal effects can be ignored. This two-dimensional model takes into account capillary effects through an invasion percolation (IP) rule and the transport by diffusion in the gas phase of the evaporating species. Since this first attempt, increasingly sophisticated models have been developed so as to take into account gravity effects [3], viscous effects [4], thermal effects [5,6], film effects [7,8], binary liquids [9]. Three dimensional versions, though not including all effects, have also been developed [10–12]. Experiments with etched networks [13] have led to satisfactory comparisons in terms of drying patterns and have shown the strong influence of film flows on drying rates [14]. The analysis of drying patterns can be performed using invasion percolation concepts and this has been performed in some details in [15,16], notably in relation with the experimental results reported in [17] indicating that the viscous effects stabilize

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Nomenclature

A	cross-section area, m^2	S	overall liquid saturation
c	vapor mass fraction, kg/kg	t	time, s
c_e	equilibrium vapor mass fraction, kg/kg	t_c	time at which sub-regime 2 starts, s
c_i	vapor mass fraction at the interface, kg/kg	y	corner meniscus curvature radius, m
c_∞	vapor mass fraction in surrounding air, kg/kg	z	coordinates, m
$\bar{c}$	cross-section averaged mass fraction, kg/kg	z_c	bulk meniscus position at $t = t_c$, m
Ca	capillary number	z_f	film tip position, m
D	vapor diffusion coefficient, m^2/s	z_0	position of bulk meniscus, m
e	evaporation flux density, kg/m^2/s	Δc	$c_e - c_\infty$, kg/kg
E	evaporation flux, kg/s	α	half angle
E_{ref}	reference evaporation flux, kg/s	β	dimensionless resistance factor
f	dimensionless factor	δ	external transfer length scale, m
F	cluster mass flux, kg/s	ε	porosity
h	dimensionless mass transfer coefficient	γ	surface tension, N/m
g	gravity acceleration, m/s/s	κ	dimensionless parameter
ℓ	diffusion screening length, m	λ	dimensionless factor = 3.77
k	permeability, m^2	η	dimensionless factor
L	tube or porous medium length, m	ϕ	composite variable
N	number of tube sides	θ	equilibrium contact angle
p	pressure, Pa	θ_c	critical contact angle
p_g	gas pressure, Pa	μ	dynamic viscosity, Pl
p_{cth}	threshold capillary pressure, Pa	ψ_i, $i = 1,2,3,4$	numerical factors
P	wetted perimeter, m	ρ_g	gas phase density, kg/m^3
q_m	mass flow rate, kg/s	ρ_l	liquid phase density, kg/m^3
Q_{ev}	evaporation source term, kg/m/s	τ	reference time, s
R	curvature radius, m	χ	dimensionless curvature
R_0	tube size, m		

the invasion. More recently, pore network models have been used to study the influence of pore size distributions on saturation and transport parameters as well as on drying kinetics [11,18,19].

As mentioned before we concentrate in this paper on the influence of pore shape and contact angle on drying rates. More specifically, we consider three basic pore shapes, i.e. triangular, square and hexagonal and show that the pore shape and the contact angle can greatly affect the drying kinetics. This is first shown for a simple bundle of capillary tubes and then with pore networks. Note however that we restrict our attention to situations where the liquid is always the wetting fluid and the invasion percolation algorithm can be applied to determine which bond is to be invaded in each cluster present in the network. For example, the case of hydrophobic networks is not considered. The pore network model used in this study is an extension of the model proposed in [2] so as to include the transport in liquid phase by the pore corner films. For modelling the transport in the film region and dry region of network, the method is essentially the one proposed by Yiotis et al. [7]. In addition to the pore shape and the influence of contact angle the main difference lies in the boundary condition at the open edge of network with the introduction of an external boundary layer characteristic size (instead of a Dirichlet condition). The paper is organized as follows. In the next section we study the influence of shape and contact angle on evaporation kinetics for a bundle of non-interconnected capillary tubes. Section 3 deals with the case of pore networks. In Section 4 we discuss the results, notably in relation with the classical description of drying kinetics in several periods, e.g. [20].

2. Evaporation from capillary tubes of polygonal cross-section

Evaporation driven by mass transfer has been studied experimentally in microchannels of rectangular cross-section [21], as well as in capillary tubes of square cross-section [22]. These works indicate that evaporation in channels with corners is much faster than in a channel of circular cross-section. This is attributed to the effects of liquid films developing along the channel corners. Because of these films, the modelling of evaporation in a channel of polygonal cross-section is significantly more complex than for a circular tube. A model of liquid flow with evaporation in a channel of square cross-section in relation with the modelling of drying of porous media was presented in [7]. Various evaporation regimes can be distinguished in a tube of polygonal cross-section depending on the competition