ON THE INFLUENCE OF TEMPERATURE GRADIENTS ON DRYING OF PORE NETWORKS

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Abstract: The influence of imposed temperature gradients on the structure of the front during drying has been studied in non-isothermal drying experiments on pore network models. In experiments, a smooth (stabilized) drying front could be established for temperature gradients with hot open network side. Contrarily, a ramified (destabilized) drying front was obtained for the reverse temperature field. For this latter case, condensation of significant amounts of vapour in empty network pores could be observed, with growth and merging of small liquid clusters. The experimental phase distributions are compared to simulation results of a non-isothermal pore network model.

Keywords: non-isothermal, experimental pore networks, stabilized and destabilized drying fronts

INTRODUCTION

In drying of porous media, the history of liquid distributions can strongly influence the final material properties: e.g., the distribution of disperse catalyst particles after impregnation of a solid matrix with a slurry, or local pore structure, which is determined by shrinkage and pore blocking. During the drying process, the interface between gas and liquid phase can either recede as a rather sharp front or the gas phase can penetrate into the network in individual branches resulting in a ramified (fractal) liquid phase. In pore network simulations of non-isothermal drying, it was recently shown that the distribution of liquid and gas phase during drying is depending on the orientation of temperature gradient (perpendicular to the open side of the pore network). Huinink et al. (2002), Plourde and Prat (2003) and Surasani et al. (2008) have reported numerical results for positive and negative temperature gradients. In the following, z denotes the distance from the network surface. This means that a positive temperature gradient ($dT/dz > 0$) corresponds to a cold open network side and a negative gradient ($dT/dz < 0$) to a hot open side. Phase distributions for $dT/dz > 0$ are comparable to those of a drying process with contact heating; liquid patterns for $dT/dz < 0$ are similar to those developing in convective drying of porous media. The mentioned authors have shown that in the case of negative temperature gradients, a smooth front is receding uniformly into the network and drying rates decrease rapidly as the liquid level detaches from the network surface; this is the case of a stabilized drying front. In contrast, for a positive temperature gradient, the gas is fingering into the network, so that the liquid phase splits up into many small clusters and emptying of pores occurs simultaneously all over the network (destabilized drying front); later on, a second liquid front is initiated from the opposite network side.

The same observations have been made in drying experiments, which are reported in the following. Linear temperature profiles have been imposed on the experimental pore network. For $dT/dz > 0$, the condensation of water vapour in colder network regions is clearly demonstrated. Simulation results with an adapted network model are compared to the experimental findings.

NON-ISOTHERMAL DRYING EXPERIMENTS

The experiments have been run with a 2D square 50×50 pore network. Pore throats of width 100 µm to 205 µm (normally distributed with mean 150 µm and standard deviation 15 µm), length 1000 µm and depth 50 µm have been etched into a plate of silicon dioxide by isotropic wet-etching; the pore network was closed by chemically bonding a silicon wafer (fabrication by Institute of Micro and Sensor Systems of Otto von Guericke University and TEPROSA). Due to the etching process, pore throats have cross sections as illustrated in Fig. 1. The network is only open to one side.

In the experimental setup, the network is mounted on a metal plate with the transparent (silicon dioxide) side on top to enable recording of liquid distributions by a digital camera. Furthermore, the open side of the network is exposed to a convective flow of dry air at
room temperature. The metal plate can be heated and cooled on either side by temperature controlled water circuits. In this way, the two temperature gradients \((d\text{T}/dz > 0)\) and \((d\text{T}/dz < 0)\) can be imposed.

![Fig. 1. Cross section of pore throats.](image)

Liquid distribution in the network evolves as a result of evaporation and capillary pumping. Liquid flow may be considered as non-viscous (for given network geometry and drying rates) and is determined by pressure differences due to different capillary pressures \(P_c\):

\[
P_w = P - P_c = P - \frac{2\sigma(T)}{r_m}
\]

\(P_w\) is liquid pressure and \(P\) gas pressure, \(\sigma\) denotes surface tension and \(T\) temperature; the mean radius of meniscus curvature \(r_m \approx 2r_1r_2/(r_1 + r_2)\) is computed from throat depth \((2r_1 = 50 \mu m)\) and throat width \((2r_2 = 100...205 \mu m)\). If temperature effects are negligible, capillary pumping is pronounced; large throats can supply liquid for smaller throats (even over large distances) and throat emptying is in the order of decreasing radius. A rise in temperature leads to a decrease of capillary pressure, because surface tension is temperature dependent. As a result, capillary pumping is influenced by temperature gradients, and the order of emptying can be reversed if temperature variations are large enough.

Experimental results for \(d\text{T}/dz < 0\) and \(d\text{T}/dz > 0\) are shown in Fig. 2. Full pores appear as black and empty pores as white. Initially, the network is saturated with water; in both experiments, some pores (< 0.3 %) could not be filled with liquid, even when applying vacuum conditions.

If high temperatures are imposed at the open network side \((d\text{T}/dz < 0)\), the drying front (i.e. the interfacial area between wet and dry pores) is rather flat and homogeneously (left column in Fig. 2). Hot pores near the surface have higher liquid pressures, and temperature effects can dominate over variations in pore radii leading to a stabilization of the front (Fig. 2a-b). In the experiments, the front seems to widen as it recedes into the network and reaches colder regions (Fig. 2c); whether this effect is significant and what might be the reason still needs to be investigated. Additionally, liquid films in gas throats can be observed at the left and right network sides (as grey pores, instead of white); their role shall be studied in future work.

Concerning drying kinetics, the initial drying rates are very high due to high saturation pressure \(P_v^*\) near the hot surface and small saturation pressure \(P_v\) in the cold regions. As drying proceeds, the rate drops drastically due to the increase of mass transfer resistance and the decrease of saturation vapour pressure in the colder regions.

![Fig. 2. Phase patterns at different drying times for](image)

For \(d\text{T}/dz > 0\) (right column in Fig. 2), hot pores towards the closed side of the network can develop a liquid pressure that is higher than in the cold (and even large) pores near the open network side. This leads to an early break-through of the gas phase (see Fig. 2a). As long as the liquid is connected in large clusters over long distances, preferential emptying of pores is observed in the cold network region, near the closed side. Drying rates are high, since capillary flow keeps the network surface (partially) wet. When the liquid has split up into many small clusters, capillary pumping loses its importance and the drying front slightly recedes into the network (see Fig. 2b) causing a decrease in drying rate. At the same time, a second effect becomes important: the temperature gradient is accompanied by a gradient of (saturation) vapour pressure. As a result, liquid can evaporate in the hot regions near at the closed side of the network – initiating a second drying front – and vapour may diffuse through the partially saturated region towards the open network side. However, on
its way, it may condense in the colder regions, leading to the formation of a large liquid cluster (see Fig. 2c) by growth and merging of small clusters. A similar condensation effect has been reported by Surasani et al. (2008) for a freely evolving temperature during contact drying; the effect it is enhanced by imposing a linear temperature gradient (due to the non-linear temperature dependence of vapour pressure.) The position of the condensing cluster depends on the temperature field and other experiments suggest that it is closer to the open network side for higher temperature gradients.

SIMULATION OF NON-ISOTHERMAL DRYING

Simulations have been conducted with the pore network model as described in Metzger et al. (2007), extended by the temperature dependency of the parameters surface tension, saturation vapour pressure at the liquid-gas interface and vapour diffusion coefficient (see Fig. 3). Viscous effects in the liquid phase are disregarded and pores empty in the order of decreasing liquid pressure as computed by Eq. (1). Hence, mass balances only have to be set up and solved for vapour diffusion. The mass flow rate through a gas throat between nodes i and j is

$$M_{ij} = A_{ij} \delta(T_{ij}) \frac{PM_{ij}}{RT_{ij}} \ln \left( \frac{P - P_{j}}{P - P_{i}} \right)$$  \hspace{1cm} (2)

where $A_{ij}$ is cross sectional area, $\delta$ vapour diffusion coefficient, $M_{ij}$ molar mass of vapour, $L_{ij}$ throat length, $R$ ideal gas constant and $P_{v,i}$ vapour pressure. Heat transfer is not modelled, but a linear temperature profile is imposed. Network geometry is adopted from the experimental set up.

Simulations are reported as phase distributions in Fig. 4 for $dT/dz > 0$ with temperature settings as in the experiments (right column of Fig. 2). As above, liquid throats are shown in black and gas throats in white; additionally, evaporating throats are plotted in red and condensing throats in blue. Condensation mainly occurs at the cold (bottom) side of the clusters, whereas evaporation is dominant on their hot (top) side. Refilling of pore throats by condensation is not yet modelled, instead net cluster condensation rates are discarded (corresponding to a numerical sink). In the example of Fig. 4, the total amount of neglected condensation is 12% of the initial pore liquid. Nevertheless, overall behaviour is in reasonable agreement with experimental results. Neglecting condensation (and liquid films) might be the reason for the lower position of the wet region.

CONCLUSION

High-quality images of the liquid distributions during drying have been obtained by optical experiments with a silicon-silicon dioxide network model. Linear temperature profiles have been imposed on the network to mimic air drying with convective and contact heating, respectively. Distinct evolutions of the phase distributions were found for different directions of the thermal gradient, both by experiment and simulation. Condensation effects significantly influenced the experimental liquid patterns.

REFERENCES


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