Capillary imbibition on a 3D-printed metallic rough surface with grooves

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INTRODUCTION

When a porous material is put in touch with a liquid that wets its surface capillary forces drive the liquid infiltration into the material. This process is called *capillary imbibition*. Capillary imbibition is still an active field of research nowadays due, in part, to the emergence of technological applications that rely on passive capillary-driven flow transport. One of them has motivated our work: heat pipes. In a heat pipe a liquid evaporates on the internal surface of a close tube at one of its ends, at the so-called *evaporator*. The fluid then travels inside of tube in vapor phase to eventually condense at the opposite end (*condenser*), thus transporting latent heat. The transport circuit is closed by a capillary-driven flow that takes the condensed liquid back to the evaporator along the porous inner surface of the pipe, dubbed *wick*. This wick is a porous material, usually with grooves or other topographies that enhance capillary transport.

What is not so well known is that a rough surface, like those of 3D-printed metallic materials, also exhibits imbibition phenomena very similar to those found in porous materials [1]. However, the modelling of capillary imbibition along the 3D-printed metallic surfaces is challenging, mainly because of the lack of control on the surface topography that current technologies allow. In this work, we explore experimentally and develop a quantitative model of the capillarity-driven imbibition taking place on 3D-printed metallic surfaces with grooves.

EXPERIMENTS

We have conducted experiments where 3D-printed metallic surfaces with vertical grooves (hereafter samples) were dipped a shallow depth into a liquid pool. We used samples with grooves of different sizes and cross-sections. Figure 1 shows images taken during one of the imbibition experiments.

Two liquids were used in the experiments: one that partially wets the surface (water dyed with sodium fluoresceine, figure 1(a)) and another one that exhibits total wetting (acetone, figure 1(b)). In the first case, the advance of the liquid along the grooves and surface was recorded using UV light and a commercial video camera (Nikon D850) whereas in the second a thermographic camera was employed (Optris PI640 with O15 telephoto lens).

In the two sets of experiments the liquid initially rises faster along the grooves than along the rough surface. However, a key difference is observed: while acetone climbs up the channels in a continuous fashion that follows Washburn's law with gravity effects [2, 3], water advances along the channel in a step-like manner, as can be seen in figure 2.

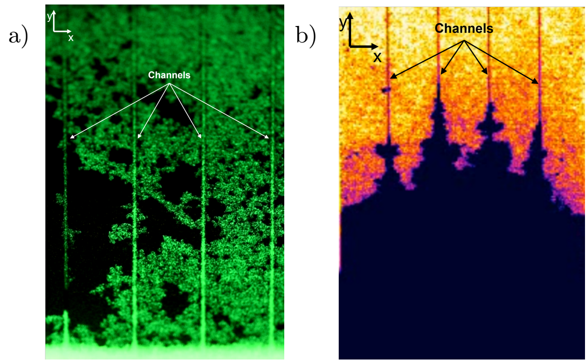

FIG. 1: Capillarity imbibition along a 3D-printed metallic surface with grooves for two different liquids. (a) Water with green fluorescent dye and (b) acetone. Image (b) has been acquired with a thermographic camera, thus the region wet with acetone appears dark.

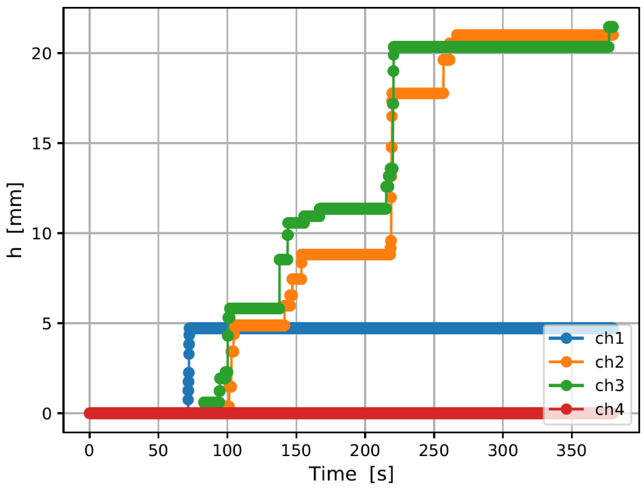

FIG. 2: Time evolution of the imbibited water height for four different grooves located on a same rough surface.

An interesting observation in the experiments carried out with water is the coupling between the liquid flow along the grooves and the surface. As the liquid imbibits a groove, water infuses from it into the surrounding surface. Then, when the flow in the same or a nearby groove stops temporarily before reaching its final stable height, the liquid can flow from the surface into the dry portion of the groove, which reactivates imbibition there. Effectively, the simultaneous groove/surface liquid flow acts as a redundant mechanism that allows the imbibition front to overcome localized arresting due to surface irregularities.

MODEL FORMULATION

To simulate the described behavior we formulate here a two-dimensional continuum model of liquid imbibition along a sample consisting of a rough porous surface with a periodic array of vertical grooves engraved on it. The model assumes that the liquid perfectly wets the material and ignores evaporation effects. Since we are not targeting the arresting of the imbibition front observed in partially-wetting liquids (e.g. water), the transport properties of both the surface and the grooves are assumed homogeneous. We will discuss below how this model can be extended to reproduce also the cooperative groove-surface imbititon observed in experiments with partially wetting liquids.

Our experiments reveal velocities low enough for inertia effects to be neglected. Thus, the liquid velocity $\vec{v}$ is given by Darcy's law [1]:

$$\vec{v} = -\frac{\bar{\bar{K}}}{\mu} \cdot \nabla(p + \rho g y), \qquad (1)$$

where μ and ρ are the dynamic viscosity and density of the liquid, g the gravity, p the pressure inside the liquid and $\bar{\bar{K}}$ a surface permeability tensor. This tensor characterizes the resistance that the channel walls and surface topography exert on the flow and will be a function of the position. This way, we can use equation (1) for both the channel and the surface. On the surface the permeability will be modelled as isotropic, with a value K_s related to the surface roughness. Conversely, on the channel it will have a different value when the flow is directed along the channel, K_c, or perpendicular to it K_s, in this case adopting the same value as for the surface. The value of K_c is such that the velocity along the channel computed with equation (1) coincides with that given by applying Washburn's law to the same open channel [4].

Neglecting evaporation, the surface flow must be incompressible. Consequently, if we define a surface flow rate $\vec{q} = \delta_e \vec{v}$, it must fulfill

$$\nabla \cdot \vec{q} = \nabla \cdot (\delta_e \vec{v}) = 0. \qquad (2)$$

The equivalent liquid depth δ_e measures how much liquid volume is accumulated per unit surface. On the channel, it will be taken as the depth of the channel δ_c, whereas on the surface $\delta_e = \varepsilon \delta_s$, i.e. the product of the thickness of the porous layer where flow takes place δ_s times its porosity ε. Combining equations (1) and (2) we find an equation for the pressure inside the liquid film:

$$\nabla \left(\delta_e \bar{\bar{K}} \cdot \nabla p \right) = -\rho g \nabla \cdot \left(\delta_e \bar{\bar{K}} \cdot \vec{e}_y \right). \qquad (3)$$

Notice that if we only let $\bar{\bar{K}}$ depend on the horizontal coordinate (as the permeability only depends on whether you are on the channel or on the surface, but otherwise is uniform inside each region), then the right hand side term is zero.

Equation (3) must be complemented with boundary conditions for the pressure. At the bottom of the domain ($y = 0$) we impose that the pressure is equal to zero, $p = 0$, as this surface is in touch with the free surface of the liquid pool. We place two vertical contours at $x = 0$ and $x = W/2$, where W is the distance between the center lines of two channels, which are symmetry places, $\partial_x p = 0$. Lastly, at the free surface –whose position must be computed as part of the solution– we impose that the pressure is given by the capillary pressure jump due to the local curvature that the topography imposes on the wetting film close to the front [1]. Mathematically,

$$p = -\sigma \kappa_e, \qquad (4)$$

where σ is the surface tension and κ_e a curvature field with value κ_s on the surface and κ_c on the channel. As we did with the permeability, we set κ_c such that the velocity along the channel corresponds to that given by Washburn's law, namely $\kappa_c = [\pi_{\mathrm{w}} \cos\theta - \pi_{\mathrm{f}}] / A_c$ [4]. Here, π_{w} is the wet perimeter of the channel, π_{f} the width of the channel free surface, A_c its cross-section and θ an effective contact angle which, in the case of total wetting, is $\theta = 0$.

To close the problem we need a kinematic boundary condition at the wetting front, $\vec{x}_{\mathrm{f}}$, stating that the front moves at the local fluid velocity,

$$\frac{\mathrm{d}\vec{x}_{\mathrm{f}}}{\mathrm{d}t} = \vec{v}(\vec{x}_{\mathrm{f}}, t). \qquad (5)$$

Our ongoing work is focused on comparing the imbibition rates on the channel and on the surface to determine experimentally the relevant wetting parameters of the system that will allow us to characterize imbibition on similar metallic 3D-printed surfaces, such as those found in heat pipe wicks.

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