The flow into a pore from a thin fluid layer

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During coating or printing on porous substrates, one key issue is the amount of penetration of the fluid into the pore space of the substrate. In some cases, pigments in the fluid may help stop penetration. In other situations, the pore dimension is much larger than the pigment. Therefore, it is important to understand the amount of fluid that is pulled into the pore space from the coating layer and how much is left on top of the substrate.

An experiment is developed, using a computer controlled syringe and a balance, to characterize the amount of fluid that is left behind on a flat region above a capillary opening. As fluid is forced through the capillary, a rim of fluid can be pinned on the surface around the top opening of the capillary. The amount left behind is a function of the viscosity, surface tension and rate of drainage. The amount that is pinned above the capillary is determined from the difference in weight in the pool of fluid on a balance accounting for evaporation if needed. Figure 1 depicts the experimental setup. Fluid is pulled into the syringe until the fluid covers the top cylinder as a drop. The syringe drives the fluid out, with some known speed, into the pool. The drop height shrinks during the flow until a point where a sudden dimple appears over the capillary inlet: air soon enters the capillary after the dimple is formed. When the first bubble is noticed in the pool, the weight of fluid is recorded.

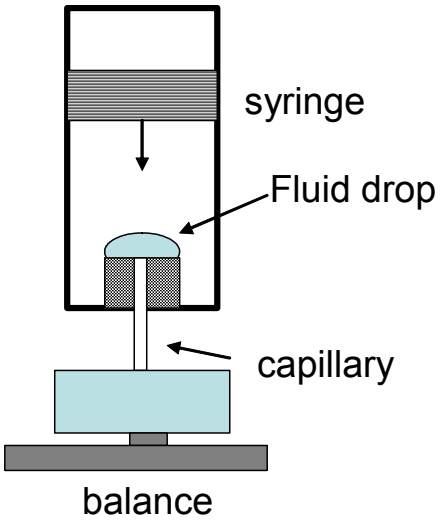

Figure 1. Experimental apparatus. The capillary opening is 1.09 mm and the base is 10 mm diameter.

A model is proposed that describes the flow from the planar region into a pore. Figure 2 illustrates the geometry and boundary conditions. The initial free surface is taken to be flat over the pore or a drop for the experiment. The problem is symmetrical around the z axis. The momentum and mass balance uses the lubrication or "long-wave" approximation as in Kheshgi and Scriven [1], but in an axi-symmetric form. Accounting for flow into the pore in the radial position over the pore, the expression is

$$\frac{\partial h}{\partial t} = \frac{-\sigma}{3\mu}\frac{1}{r}\frac{\partial}{\partial}\left(rh^3\frac{\partial^3 h}{\partial r^3}\right) + v_{z0} \qquad (1)$$

Where h is a function of radial position, σ is surface tension, μ is viscosity, and v_{zo} is the velocity into the pore if the position is over the pore, or zero if over the solid. The velocity profile into the pore is assumed to be parabolic and follow either a Lucas-Washburn expression that decreases with time or a constant velocity magnitude. A no slope condition is set far from the pore. A no-slip condition is used at the solid boundary. In general, as flow starts into the pore, the free surface dimples in the region above the pore. This dimple creates a low pressure region that pulls fluid from the sides of the

pore. If the fluid is able to easily flow towards the region over the pore, the free surface remains flat with a small dimple. This occurs for thick layers of fluid, low viscosities, or high surface tensions. If the flow towards the region is slower than the flow into the pore, the dimple grows and the free surface will contact the edge of the pore. What happens next depends on the contact angle of the fluid with the solid. If it is wetting, and the pore edge is not sharp, fluid could continue to flow into the pore from the surface. If the contact angle is large or the pore edge is sharp, the fluid will become pinned and stay at the surface. The Capillary number is found to be an important dimensionless parameter that helps predict the dimpling or not. Figure 3 shows two cases, a flat film profile, and a dimple that grows to touch the pore lip.

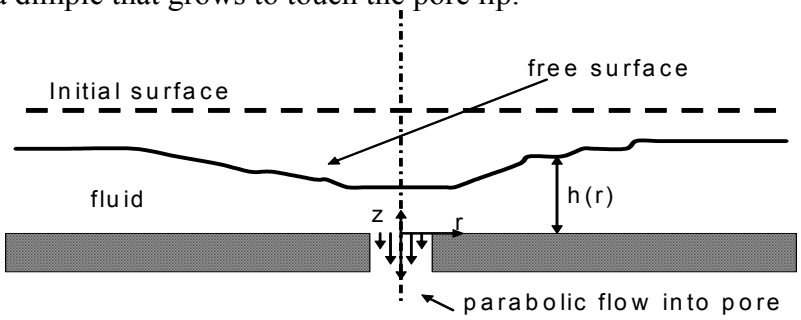

Figure 2. Model geometry. Right side of region shown below.

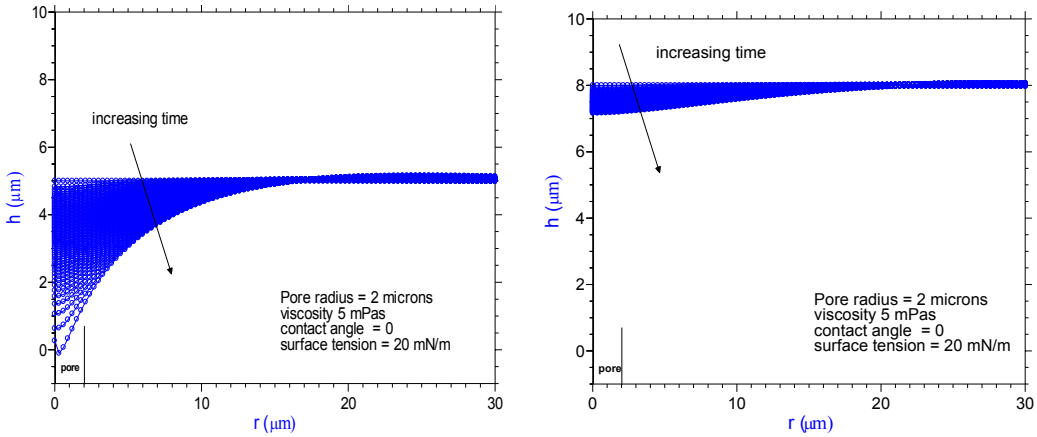

Figure 3. Results for a 5 mPa fluid. Left show the results with a thin film and 2 micron pore that dimples. Right shows a thick film that dimples but then drains into the pore.

Mixtures of water and ethylene glycol were prepared. Table 1 shows the properties of the solutions. Figure 4 shows the comparison of the model with the experiments. The model does predict the correct order of magnitude and trends, but the model is not as sensitive to the viscosity and the rate of flow. A number of experimental and theoretical issues can explain the differences.

Table 1. Fluid properties.

	actual wt fraction	surface tension, mN/m	viscosity, mPas
water	0.00	72	1.08
#1	0.20	64	1.73
#2	0.40	58	2.9
#3	0.60	54	5.3
#4	0.80	50	10
#5	0.90	49	15
ethylene glycol	1.00	48	22

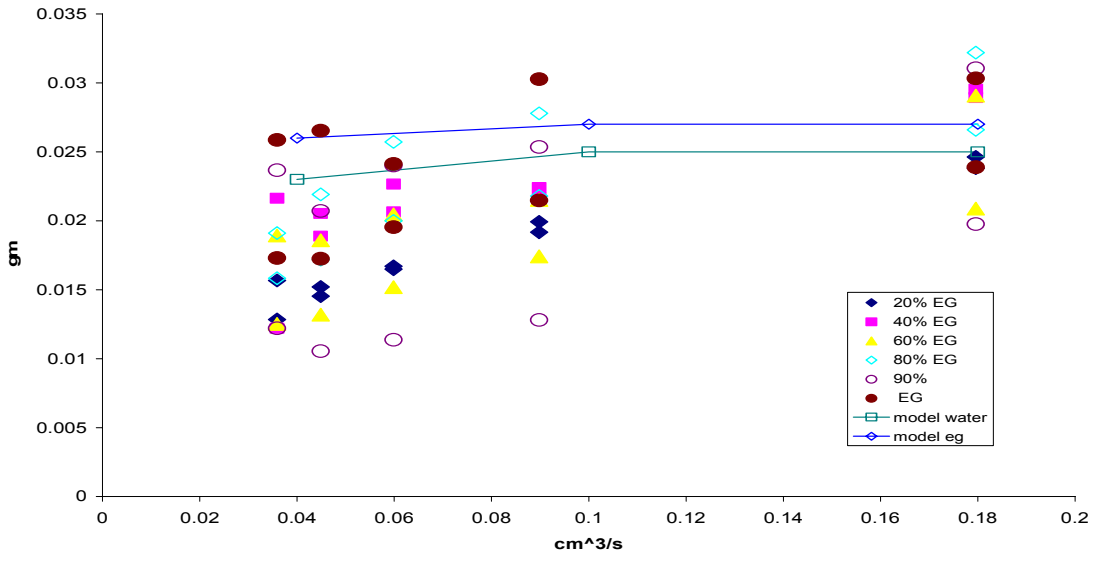

Figure 4. Amount of fluid left above capillary for the fluids in Table 1 and the model predictions (lines).

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1. Kheshgi, H.S. and Scriven L.E. "The evolution of disturbances in horizontal films", Chem. Engng Sci 43(4): 793-801 (1988).