Can water advance against pressure?

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Abstract. We will show several simple and curious experimental results of pattern formation in a two-dimensional circular Hele-Shaw cell, in our experiments we inject a fluid from the center into a foam filled cell, allowing the presence of water at the outer (low pressure) region. Dendrites grow initially from the center, but when a branch is close to the outer boundary, the low pressure water begins to penetrate the foam apparently against the pressure field. In previous works, we predicted this counterintuitive behavior using a model based on energy minimization, the experiments were designed to find the effect in simple setups.

1. Introduction
In a normal viscous finger experiment using a radial Hele-Shaw[1] cell, a low viscosity fluid (water for example) is injected from the center towards a high viscosity fluid that fills the gap between the upper and lower plates. In this setup, if we put water at the outer boundary, the continuous outwards flux of the high viscosity fluid will prevent water to advance against this flux. It is well known[2] that in experiments where the high viscosity fluid is replaced by foams, produce dendritic patterns with structures persisting in the limit of zero velocity, we choose these experiments for testing the model, because it is possible to obtain a pressure gradient without the outwards flux. It was not clear that we could observe the appearance of a return branch in experiments using foams, because we expected the size for the return dendrites to be small compared to dendrites[3, 4, 5, 6, 7] coming from the center of the cell.

2. Experiments
We constructed our radial Hele-Shaw cell using a 44 x 44 cm plexiglass tray with raised edges of 5 cm to contain two circular plates and the low viscosity fluid, that will be present at the outer boundary of the plates. A circular glass plate 0.8 cm thick and 38 cm in diameter was glued to the bottom of the tray, a bigger circular glass plate with a small hole at its center was put on top of the lower plate and was fixed to the bottom of the tray using four guides, a small cylindrical container for the low viscosity fluid was attached to the central hole and connected to a constant pressure source. The main characteristics of this setup are: to allow the presence of the low viscosity fluid at the boundary, a clean circular boundary because the top glass plate is bigger than the lower plate, and that the surfaces in contact with the foam are flat and rigid. We used calibrated spacers in the guides to set the separation between the plates.

In figure 1, we show a sequence of images showing the main branch coming from the center and water invading the foam from the outer low pressure region. In this experiment, we injected kerosene from the central hole, into a two-dimensional region filled with a commercial shaving

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Figure 1. Sequence of images showing water from the outer perimeter invading the foam.

foam, the outer region was filled with water at atmospheric pressure, the gap between the plates was set to a separation of 0.2 mm, a constant pressure of 30 mm of Hg was used in this experiment. These images show clearly the low pressure water advancing from the outer region into the foam, but the attachment between a return branch and one of the branches coming from the center is not complete. We repeated this experiment using a higher central pressure of 48 mm Hg, in this experiment when the main branches get close to the outer boundary, water from the outer region begin to propagate into the foam forming small dendrites and attach to some of the main branches, then the kerosene coming from the center flows into the outer region using the formed channel.

To understand why some foams work better than others when one is trying to observe the return branch, we analyzed optical microscopic images for the foam reported in this work (foam
a) and another commercial foam (foam b) that shows only small return branches. Simple optical 
inspection, shows that bubbles in foam b are more spherical, this is a consequence of the poor
contact of this foam with the glass plates. The analysis for the distribution of diameter sizes D,
shows that the average diameters for the bubbles in the foam at the initial stage are: for foam a
$D_a = 0.03 \, (\text{mm})$, and for foam b, $D_b = 0.03 \, (\text{mm})$. We made the same analysis for the previous
samples after one hour, with the following results, for foam a, $D_a = 0.05 \, (\text{mm})$, and for foam b,
$D_b = 0.07 \, (\text{mm})$.

In our experiments we typically waited for about 40 minutes after the Hele-Shaw cell
preparation was completed, a shorter time was necessary to prevent any outwards flow in the
system, but we observed that the effect was strong after waiting for more than 30 minutes. The
previous analysis for bubble diameters, show that in our experiments, bubbles were approaching
a diameter of the same order of magnitude as the plate separation b. Bubble size and a good
contact between bubbles and plate surface, are the most important parameters for selecting a
working foam.

3. Conclusions

Adding water at the outer boundary of a well known experiment of pattern formation, produce
water dendrites advancing against the pressure field. Our explanation for this rare behavior
of water, is that there are non-local effects driven by the central pressure, and the system is
producing the optimal branches (that include the return branches) to release the energy stored
in the foam[8].

Because the effect is counter-intuitive, we have tried to discard other possible explanations.
We do not believe that capillarity could explain this effect, because we observed cause and effect
between central pressure and the return water dendrites, if there is no central pressure water
dendrites are not produced. To discard capillarity, new experiments with plate separations
bigger than a few millimeters should be designed. We are not sure if the concept of dilatancy,
that Osborne Reynolds used to explain why sand in the beach get dried when you press on it,
could help in explaining this behavior.

References

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