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Magnetic field effects on viscous fingering of a ferrofluid in a radial Hele–Shaw cell

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Abstract

We have studied the effects of a magnetic field on viscous fingering when a ferrofluid is pushed in a more viscous liquid in a circular Hele–Shaw cell. The main effect of the magnetic field, as already known, is to stabilize interfaces parallel to the field and to destabilize interfaces normal to the field. Depending on the growth regime (quasi static, fingering, dendritic growth), which depends on parameters like the cell thickness and oil viscosity, the combination of field effect and anisotropy is analyzed through the various observed patterns.
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1. Introduction

When a viscous fluid is pushed into a more viscous one in a Hele–Shaw cell, the interface between the two fluids may become unstable, leading to fingering and ramified patterns. Magnetic field effects on viscous fingering of ferrofluids have already been studied: in a rectangular Hele–Shaw cell, a magnetic field applied in the cell plane is stabilizing when parallel to the interface between the two fluids and destabilizing when normal to the interface [1]. A magnetic field perpendicular to the plane of a radial Hele–Shaw cell has the same destabilizing effect as the pressure [2]. Here we study the effect of a magnetic field, parallel or normal to a radial Hele–Shaw cell, combined with the anisotropy introduced by engraving a grid in one plate of the cell [3], allowing one to obtain dendritic patterns.

2. Experimental setup

The Hele–Shaw cells we used are made of two plexiglas plates 5 mm thick, of diameter 50 mm, with an inter-plates spacing from 0.15 to 0.50 mm. Hexagonal or square anisotropy is introduced by engraving circular-shaped lattice elements in the bottom plate, of diameter, depth and distance edge to edge of 0.50 mm. We also used different grids not presented here (0.20 mm depth or "linear", engraved with parallel channels). The ratio between the depth of the engraved elements b', and the cell thickness b, defines the effective anisotropy. The magnetic field was produced by a device built with permanent magnets called "magnetic mangle" [4]. It allows us to apply fields up to 0.23 T, horizontally or vertically, approximately homogeneous in a volume of

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about $2 \times 2 \times 2\,\mathrm{cm}^3$. Some experiments were performed in more homogeneous fields up to 1.2 T generated by an electromagnet. Both apparatuses show the same field effects. The ferrofluid was injected at the center of the cell, through a hole in the top plate, using a syringe pushed by hand, controlling qualitatively the pressure in a reproducible way. The magnetic fluid we used is based on cobalt ferrite dispersed in a 50/50 mixture of glycerol and water, of dynamical viscosity $\eta = 10\,\mathrm{mPa\,s}$, immiscible with the silicone oils of dynamical viscosity ranging from 200 to 29100 mPa s. The parameters of each experiment are given with the following notation: [cell thickness (mm), anisotropy type (–, sq, hex or sq*), dynamical viscosity η (mPa.s)]. sq* means a square lattice with larger depth of holes of 1.00 mm.

3. Results and discussion

We performed experiments with and without a magnetic field, with magnetic field normal and parallel to the plane of the cell, and in cells with and without anisotropy. We considered slow, intermediate and fast growth regimes, by changing the cell thickness or the oil viscosity.

3.1. Growth without field

When no magnetic field is applied, the ferrofluid behaves like an ordinary fluid and the experiments show the usually observed patterns: equilibrium shapes when the growth is very slow, circular or facetted in case of anisotropy (Fig. 1a); oriented fingers related to tip-splitting processes (Fig. 1b); dendrites on hexagonal grids (Fig. 1c).

When the anisotropy strength becomes very large, dendritic patterns change to disordered ones on a square grid (Fig. 2a), but remain dendritic on a hexagonal one (Fig. 2c). We are trying to understand this transition better.

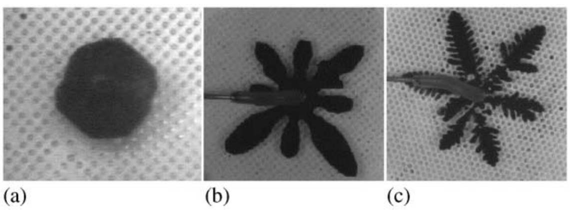

Fig. 1. Patterns corresponding to different growth regimes in anisotropic cells: (a) facetted [0.30, sq*, 200]; (b) oriented fingers [0.20, sq, 1000]; (c) dendritic [0.20, hex, 29100].

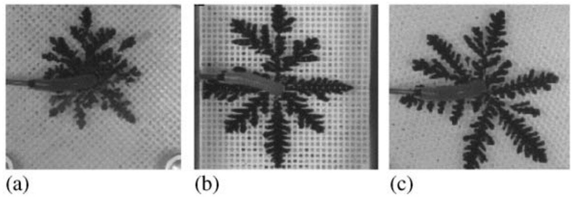

Fig. 2. (a) Disordered pattern in an anisotropic cell [0.15, sq, 29100]; (b) in the same conditions, under an in-plane magnetic field of 0.23 T, the dendritic pattern is restored; (c) dendrites on a hexagonal grid [0.15, hex, 29100].

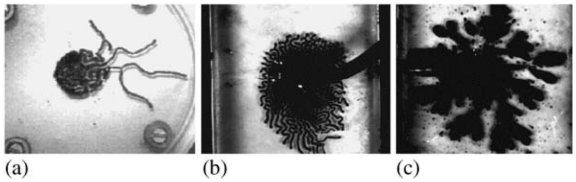

Fig. 3. (a) Drop of ferrofluid in normal field (0.078 T) [0.50, —, 200]; (b) injecting a labyrinth [0.30, —, 200] (0.23 T); (c) small-scale ramifications on a finger in normal field [15, —, 1000] (0.23 T).

3.2. Growth in a perpendicular field

In a perpendicular field, a drop of ferrofluid tends to form a labyrinth, which can be seen as an equilibrium pattern, the width of the stripes corresponding to a balance between dipolar energy within the magnetized fluid and interface energy. Labyrinth patterns may be obtained without injection (Fig. 3a): several stripes grow from the edge of the drop which itself becomes a labyrinth. When the ferrofluid is injected under magnetic field, a homogeneous labyrinth is built, with a circular envelope, certainly very close to equilibrium (Fig. 3b). It would be interesting to study in detail this labyrinth formation, the branching process, etc.

Injecting faster or decreasing the mobility leads to a fingering regime, similar at a macroscopic scale to the pattern without field (Fig. 1b). Oscillations are present on the edges of the fingers with a smaller length scale comparable to the width of the labyrinth stripes obtained with the same value of the normal field (Fig. 3c).

When the same set of experiments is done in anisotropic cells, the normal field instability leads to fill the engraved holes of the bottom plate of the cell. When the field is applied on an already grown drop (Fig. 1a), the envelope is preserved and the obtained pattern is compact but "discrete" (Fig. 4a). When a slow injection is performed under normal field, the holes are filled uniformly, but the shape of the envelope reveals the underlying anisotropy (Fig. 4b). When the injection is faster, the probability of filling the holes is not uniform

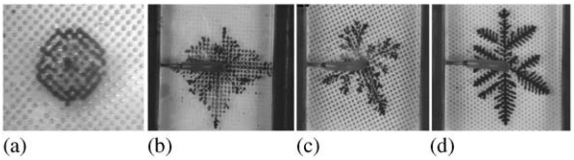

Fig. 4. Filling of the holes of anisotropic cells in normal field. (a) [0,30, sq*, 200]; (b) [0.20, sq, 1000]; (c) [0,15, sq, 29100]; (d) [0,15, hex, 29100].

and keeps a random character leading to a pattern reminiscent of DLA fractal aggregates (Fig. 4c). Finally during a fast growth regime, the injected fluid follows only directions defined by the anisotropy and the filled holes sharply reveal the dendritic morphology (Fig. 4d).

The filling of the grid has a large effect only if there is enough space to store the ferrofluid, which means an effective anisotropy larger than 1. For lattices with small engraving depth ($b' = 0.20$ mm), only labyrinths are observed in normal fields. Patterns obtained by filling the engraved holes are interesting, since they are different from the usual viscous fingering and quite similar to an "experimental" DLA.

3.3. Growth in an in-plane field

The equilibrium shape of a drop of ferrofluid subjected to an in-plane magnetic field in a 2D cell appears to be an "eye-shape". This will be checked by numerical simulation.

Starting from a drop of ferrofluid with an irregular but smooth shape, applying an in-plane magnetic field leads to a stack of such "eyes" (Fig. 5a). When injecting the ferrofluid slowly under an in-plane field, one or several "eyes" may be obtained (Fig. 5b, c). Figs. 5b and c correspond to a square anisotropic cell, but the anisotropy does not seem to be very important during the growth of these patterns, affecting only eventually the orientation of the spikes.

Concerning moderate growth rate, viscosities of 200 and 1000 mPa s gave nice fingers in no field experiments, but we were not able to capture clear images of a fingering (tip-splitting) regime in magnetic fields of 0.23 or 0.11 T. Perhaps the rapid relaxation and a maximum capture rate of 25 frames/s is the reason.

In a faster growth regime, using high viscosity oil, $\eta = 29100$ mPa.s, field effects are stronger. In a tip-splitting growth pattern (with no anisotropy), the in-plane magnetic field changes the pattern envelope from circular to elliptical (Fig. 6a,b). At a more local scale, the velocity of the fingers depends on their orientation with respect to the field direction: fast and thin fingers propagating along the field direction, slower and wider fingers propagating normal to the field direction.

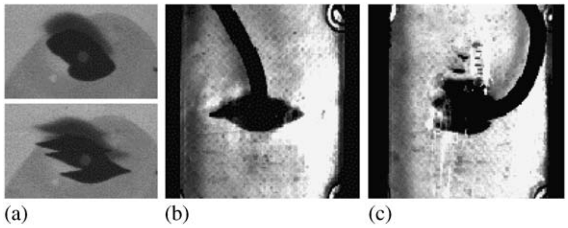

Fig. 5. (a) Changes of shape when an in-plane field of 1.2 T is applied. [0.15, —, 1000]; (b) an "eye-shaped" growth under 0.23 T in an anisotropic cell [0.15, sq, 200]; (c) stack of eyes in the same cell under a field of 0.11 T.

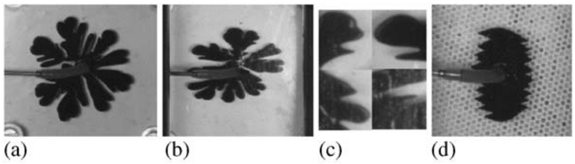

Fig. 6. (a) Fingering resulting from tip-splitting processes in zero field; (b) effect of an in-plane magnetic field (0.23 T); (c) details. (a, b, c) correspond to the same parameters [0.30, —, 29100]; (d) stack of "eyes" in an anisotropic cell under in-plane field [0.15, hex, 200].

This can be understood by taking into account the instabilities leading to the tip-splitting process and the expected effect of the field: interfaces normal to the field will split more quickly, interfaces parallel to the field will split more slowly. Figs. 6b and c show that a finger normal to the field has ramifications on both the sides, a finger at an angle close to 45° has ramifications on one side only. At the end of the growth, the ramifications become spikes and if the system has time to relax the pattern becomes a set of "eyes". Fig. 6d shows an example of such a pattern, where the competition between the anisotropy and the magnetic field affects the orientation of the spikes.

In anisotropic cells, the pattern consists of oriented fingers (Fig. 7a) or dendrites (Fig. 7b). In both the cases the field can affect the envelope, but for high flow rates the dendrite can grow without being influenced by the field. The fingers can have local ramifications, again on one or two sides. They also evolve into spikes that, like for the "eye" shapes, may be oriented along the "easy" lattice directions of lower energy. Dendrites start growing as usual (parabolic tip, sides branches at 60° for the hexagonal grid, 45° for the square grid) but the ramifications are deformed during the growth. When an in-plane field is applied in the same conditions as the ones giving a disordered pattern (Fig. 2a), the magnetic field is able to restore the dendritic morphology (Fig. 2b). An in-plane field then seems to reduce the effect of the anisotropy.

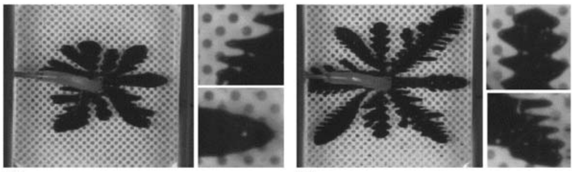

Fig. 7. In-plane magnetic field effects in anisotropic cells (0.23 T). (a) on fingers and details [0.30, sq, 29100]; (b) on dendritic growth and details [0.20, sq, 29100].

4. Conclusion

The main effect of a magnetic field on a drop of ferrofluid, stabilized by surface tension in a Hele–Shaw cell, is to change the equilibrium pattern, to labyrinth in normal field and to eye-shaped under an in-plane field. When the magnetic field is superimposed to the hydrodynamic instabilities provoked by the injection, it can be stabilizing or destabilizing depending on the orientation of the interfaces with respect to the magnetic field. This leads to morphological modifications: slowing down and widening of fingers, acceleration of others, dissymmetry of dendrites, etc. Secondary branches have a shape of spikes reminiscent of the ''eyed-shaped'' equilibrium pattern. The field may also affect the envelope, by selecting fast growing directions. Anisotropy effects, induced by engraving one plate of the cell, are increased by a normal field and decreased by an in-plane field.

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