Drop in Ferrofluids Subjected to an Azimuthal Field

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We perform direct numerical simulations of a non-magnetic drop immersed in immiscible ferrofluids in a confined Hele-Shaw cell under an azimuthal field by a diffuse-interface method. The interface is unstable in such a condition because of the inward attraction of the ferrofluids induced by the magnetic field gradient. We focus on the fingering onset and pattern influenced by the coupling viscous effect with different viscously stable conditions, which is achieved by varying the viscosity contrast of the ferrofluids and non-magnetic drop. In a viscously stable condition, in which the viscosity of the ferrofluids is greater than the immerse drop. The fingering pattern is simpler with numerous straightly developed fingers. On the other hand, a viscously unstable interface of less viscous ferrofluids results in ramified fingering pattern associated with the secondary phenomena, e.g., competitions and tip-splits of fingers. However, the fingering onset is delayed because the drop is less mobile. The interfacial instability of a circular non-magnetized drop (drop2) with radius \( R_0 \) surrounded by immiscible ferrofluids (fluid 1) in a Hele-Shaw cell, as the principle sketch shown in Fig. 1. The Hele-Shaw cell has gap spacing \( h \). An azimuthal field \( H \) is generated by wire with electric \( I \) placed at the center of the drop. The viscosity of ferrofluids and the drop are \( \eta_1 \) and \( \eta_2 \), respectively. We focus on the magneto-induced motion, but allow the inner drop (drop 2) to be either more or less viscous than other ferrofluids (fluids 1).

![Fig. 1: A non-magnetic drop inside ferrofluids subjected to an azimuthal field.](image)

In the following simulations, we present patterns induced by the destabilizing magnetic field. Influences of the magnetic effects, e.g., the magnetic strength \( Mg \) and magnetic susceptibility \( \chi \), coupled with viscosity contrast Atwood number (A) will be analyzed systematically. It is noted that a positive/negative \( A \) represent more/less viscous non-magnetic drop than the surrounding ferrofluids, respectively.

Shown in Fig. 2 are three representative cases for \( Mg = 2 \) and \( \chi = 1 \) for various viscosity \( A = -0.462, 0 \) and 0.462. The presence of magnetic field gradient to penetrate into the drop toward the origin, and squeeze partial mass of the drop to stretch outwardly. For easier identification, the penetrating ferrofluids fingers and stretching fingers of non-magnetic drop are denoted as inward fingers and outward fingers, respectively. For various Atwood number, the fingering pattern show
apparent distinctions. For a negative Atwood number of $A = -0.462$ as the fingering pattern shown in the top row of Fig. 2, in which the viscosity of non-magnetic drop is smaller than the ferrofluids the fingering pattern is very regular without strong finger competition i.e., most of the fingers emerging compatibly. Both the outward and inward finger develop in a nearly identical path to preserve circular inward and outward fingering fronts.

![Fig. 2: Fingering patterns for $A=-0.462$, 0 and 0.462. Remaining parameters are $Mg=2$ and $X=1$.](image1)

![Fig. 3: Fingering patterns for $A=-0.635$, 0 and 0.635. Remaining parameters are $Mg=2$ and $X=1$.](image2)

Direct numerical simulations of the interfacial instability of a non-magnetic drop surrounded by immiscible ferrofluids, confined in a Hele-Shaw cell and subjected to an azimuthal field, are performed by a diffuse-interface method incorporating with highly accurate numerical schemes. The interface is unstable because of the inward attraction of the ferrofluids included by the magnetic field gradient. The onset and pattern of interfacial fingering instability is analyzed to realize the coupling effects of the magnetic force and viscous contrast. If viscosity of the ferrofluids is greater than the immersed drop, in which the interface is viscously stable, the fingering onset takes place earlier because of the higher mobility of penetrated drop fluid. Nevertheless, the fingering pattern appears simpler with straightly emerging fingers. On the other hand, the viscous drop, results in more ramified pattern associated with the secondary fingering phenomena, e.g., competitions and tip-splits of fingers. However, the onset is delayed because less mobile drop fluid.

To quantify the prominence of fingering instability, development of the interfacial length is calculated as a global measure. In general, longer interfacial length indicate more unstable interface. We confirm the occurrences of earlier fingering onset and vigorous secondary phenomena both enhance growth of the interfacial length. Nevertheless, these two behaviors are favorable in opposite conditions, i.e., earlier onset and secondary phenomena in condition of more and less viscous ferrofluids, so that inconsistent evolutions of the interfacial length are observed. As a result, instead of the interfacial length, its growth rate is more appropriate for the consideration for the measure of instability. The earlier onset for cases of more viscous ferrofluids usually leads to greater rate in the early envelopment of fingering instability. On the contrary, the growth, rate is dramatically enhanced at the later period when the secondary fingering phenomena are active for conditions of less viscous ferrofluids.

**Keywords:** ferrofluids, azimuthal field, drop