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Spontaneous Symmetry Breaking during Dispersed Fluid Flow through Porous Media

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Dispersed fluid systems (foam, emulsion, bubbly liquid, etc.) involves in many key geophysical/geochemical, environmental, and engineering processes[1-3]. However, regardless of many pore-scale and channel-scale approaches[4, 5], predicting dispersed fluid flow behavior in porous media is still a major challenge. Here we conduct experimental and theoretical investigation, trying to rationalize the long-puzzling gap between single-channel scale and porous media scale models for dispersed fluid flow.

We first conduct experiments in doublet microfluidic model (Fig. 1a). We fix Ca_d (dispersed fluid capillary number) and observe the flow state at varying Ca (total capillary number). At low *Ca*, very significant difference for blob fluxes between two parallel channels are identified even when the two channels are highly symmetric (Fig. 1b). After careful quantitative analysis, we realize that minor fabrication error cannot rationalize this symmetry breaking.

We thus hypothesize that this asymmetric flow of dispersed fluid is originated from a new symmetry breaking mechanism. We thus conduct stability analysis in a doublet system, that introduce an infinitesimal perturbation to assess its potential for self-amplification. Analysis shows that such symmetry breaking can emerge, if there is a negative correlation between pressure drop and total flow rate at a constant dispersed fluid flux ($\frac{\partial F}{\partial Ca}\big|_{Ca_d} < 0$) within a specific channel. The existence of $\frac{\partial F}{\partial Ca}\big|_{Ca_d} < 0$ correlation is successfully validated: theoretically, by classic Bretherton's correlation for non-viscous gas slug flow in a uniform cylindrical tube [6] (Fig. 1c); and experimentally, by microfluidic experiment along a single channel of sequential pore-throat structure (Fig. 1d).

This breaking of flow path symmetry, if emerges in porous media, may result in preferential flow even in homogeneous media. We conduct a demonstrative experiment in a homogeneous porous medium to validate the above inference. Surprisingly, we do observe significant non-uniform flow at steady state, as shown in Fig. 1e and Fig. 1f. Preferential paths carry almost all dispersed fluid flux, while blobs in other paths flow only occasionally and slowly. Noticeably, the dispersed fluid saturation is negatively correlated with its flux, which is contradictory against classic relative permeability idea, but can be well explained by the abovementioned spontaneous symmetry breaking.

This discovery of spontaneous symmetry breaking of dispersed fluid in porous media may bring new insight into the understanding and modeling of complex fluid behaviors in disordered geometry.

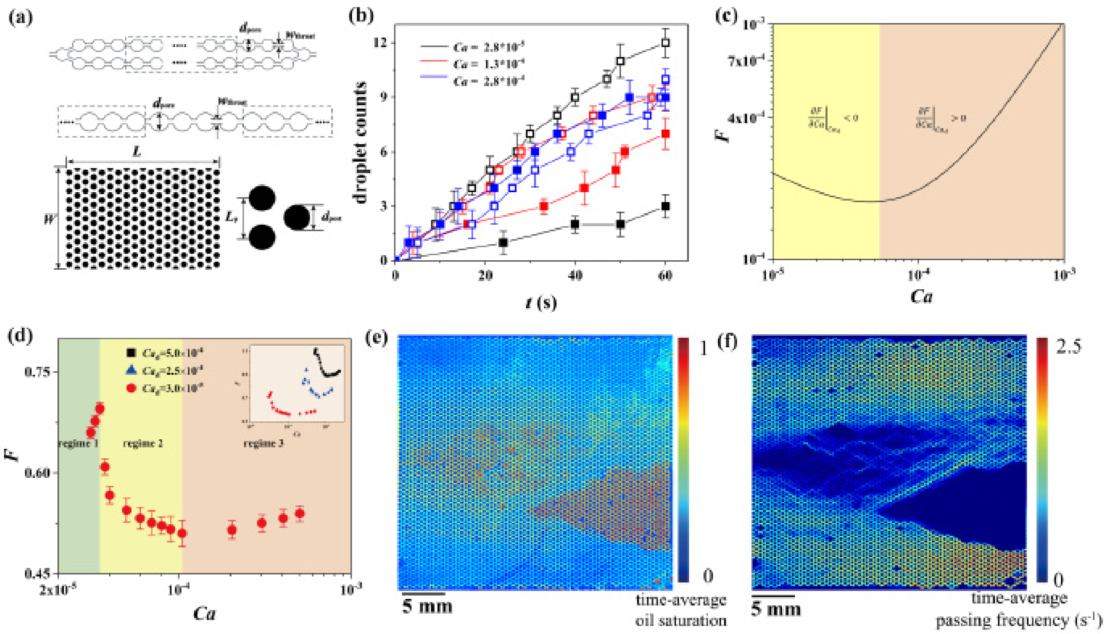

Figure 1: (a) The design of the doublet-channel model, single-channel model and homogeneous porous media model. (b) The experimental results of the cumulative number of droplets in doublet system for Cad = 1.5×10-5. Hollow symbols denote channel 1 results, while solid symbols represent channel 2 results. (c) Schematic diagram of F-Ca curve in a single channel for Bretherton model. (d) The experimental results of F-Ca curve along a single channel with Cad = 3.0×10-5 (in the main plot, and colors mark different regimes), and with Cad = 2.5×10-4 and 5.0×10-4 (in the inserted plotting). (e) Time-average dispersed fluid saturation map of the whole micromodel. (f) Time-average blob-passing frequency field map of the whole micromodel.

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