Contribution ID: **141** Type: **Oral Presentation**

Thermodynamics and Morphology of Ganglia in 2D Heterogeneous Porous Media

Monday, 13 May 2024 17:45 (15 minutes)

Ganglia (bubbles, or droplets) are widespread in porous media of various industrial applications. Thermodynamic properties of a ganglion, including its volume (V), surface free energy (F), and capillary pressure (P_c), play pivotal roles in determining its transport and reactive performance. Although these properties in homogeneous porous media have been recently resolved [1, 2], quantitatively description of ganglia in heterogeneous media remains a challenge [3-5].

In this study, we develop a pore-scale algorithm for determining the morphologies and thermodynamic properties of hydrostatic ganglia in heterogeneous porous media (a 2D pillar array, as illustrated in Figure 1a). Notably, we reveal novel ganglion morphologies: the fluid-fluid interface can emerge between non-adjacent solid particles that do not share a pore unit (referred to as the "cross-pore interface"), although it has long been assumed that a pore is a basic unit of fluid and interface behaviors in porous media [2]. The presence of cross-pore interfaces is strongly associated with the pore-throat ratio: a smaller pore-throat ratio (wider throat) leads to a greater number of metastable morphologies. Interestingly, these novel cross-pore interfaces can also be found in homogeneous media.

We track cycles of quasi-static growth and shrinkage of a ganglion (Figure 1b) and resolve the corresponding thermodynamic properties'evolution (Figure 1c&d). During growth, the ganglion invades pore by pore, with only one major length scale (the throat) controlling P_c. In contrast, during shrinkage, the boundary of the ganglion in different pores contracts cooperatively, exhibiting multiple scales of P_c during different stages of ganglion shrinkage. In addition, although the $F - V$ correlations of both growing and shrinking ganglia are statistically linear, the surface free energy (F) of a shrinking ganglion is, in most cases, higher than that of a growing ganglion at the same V.

This work provides insights for investigating quasi-static degassing, ganglia dissolution, and ripening processes, as well as to analyze the thermodynamic stability of dispersed fluid clusters in heterogeneous porous media. In addition, we call for attention that the term "pore"may not always be a valid basic representative unit during the description of fluid and interface behaviors in porous media, as demonstrated by the presence of cross-pore interfaces.

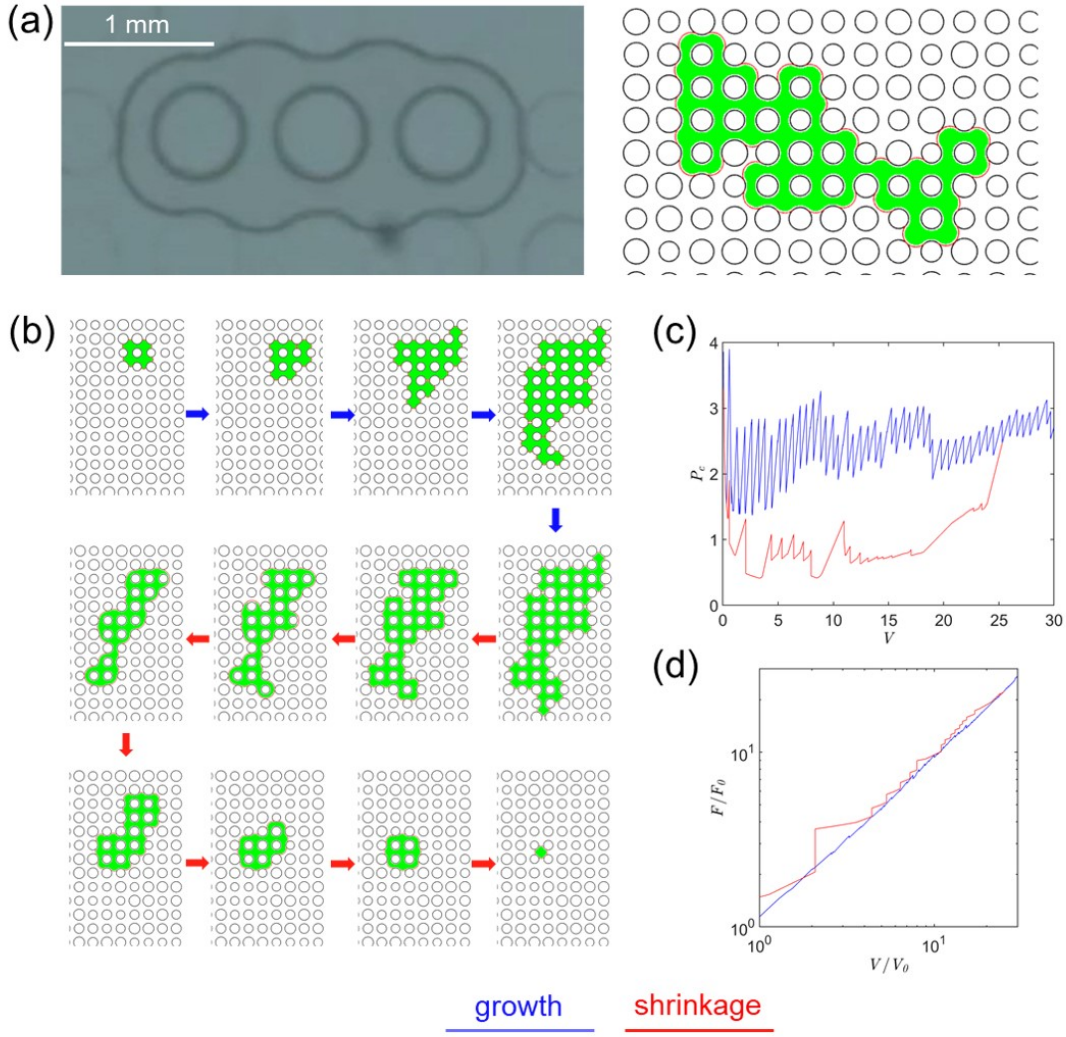

Figure 1: (a) Ganglion with cross-pore interfaces, in pore-scale experiments (left) and our model (right). (b) Snapshots of ganglion growth and shrinkage in heterogeneous porous media. (c&d) Evolution of capillary pressure (Pc) and surface free energy (F) with ganglion volume (V) during ganglion growth-shrinkage cycle in heterogeneous porous media.

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Session Classification: MS06-B

Track Classification: (MS06-B) Interfacial phenomena across scales