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Thermodynamic Stability of Bubble Population in Porous Media

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Bubbles (or droplets, ganglia) emerge in porous media aftermath of flow, phase change, or chemical reactions and significantly impact the hydraulic, transport, and reactive properties of the system. However, compared to continuously connected phases, the behavior of dispersed bubbles, or ganglia, are far less understood. In particular, the thermodynamic stability of bubbles, despite their large specific surface area, remains a puzzle.

Our earlier works (Xu et al., PRL, 2017; Xu et al., GRL, 2019; Mehmani et al., in preparation) have shown that bubble population in porous media can keep stable, rather than coarsen like bubbles in open space, by "anti-coarsening". This anti-coarsening is shown to be driven by Ostwald ripening as that in open space, but the driving force –capillary pressure difference –is reversed by porous structure. Further pore-network modelling (PNM) approach show distinct ripening kinetics of bubbles in porous media from Classic L-S-W theory.

However, these above approaches only demonstrate one kinetic mechanism that stabilizes the bubble population, without answering the very fundamental question: is the bubble population in a porous medium thermodynamically stale? The answer would be very important to interpret the origin and long-term evolution of dispersed fluids in subsurface porous media, which is highly relevant to geologic CO2 sequestration, hydrocarbon recovery, fuel-cell water management, and vadose zone oxygen supply.

To identify bubble population's thermodynamic stability in porous media, we propose a simple conceptual model in 2-dimensional (2D) to describe the equilibrium states of a bubble with arbitrary size inside a homogeneous porous medium. The model accounts for the bubble's morphology, the geometry of the solid matrix, and the wettability between the two, and enable an analytical expression of a bubble'capillary pressure (Pc) and surface free energy (F) as functions of bubble volume (V), bubble Euler characteristic (X), and pore occupancy (n). This model can be easily incorporated into PNM approaches.

This conceptual model shows that, when a bubble is larger than the maximum inscribed sphere of a pore, it starts to be deformed by porous structure, and both Pc and F's scaling against V deviate from that for spherical bubbles. Specifically, the specific area of a large bubble (spanning over more than one pore) fluctuates in a very narrow interval regardless of V, which results in an approximately linear correlation between F and V regardless of the (X,n) value. As a result, merging of bubbles does not necessarily reduce total free energy, so bubble coalescence and coarsening become thermodynamically unfavorable.

Therefore, we demonstrate that bubble populations in porous media can be thermodynamic stable, without continuously coarsening towards the formation of one single big bubble. We further calculate the total free energy of a bubble population and identify all possible final equilibrium status of bubble population. Future study will focus on extend this conclusion to more complex scenario, like non-uniform pore size and 3D scenario.

Time Block Preference

Time Block A (09:00-12:00 CET)

References

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