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# Residual bubbles'local equilibrium after coarsening

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Residual bubbles in porous media, initially emerging at non-equilibrium state by direct injection, phase changes or imbibition, spontaneously coarsen towards a thermodynamic equilibrium state. During coarsening process, bubbles'morphology and pore occupancy change that affects hydraulic conductivity, mass & heat transfer coefficients, and chemical reaction kinetics. The kinetics from initial distribution to equilibrium is critical in determining physically-correct models for predicting $CO_2$ subsurface sequestration and gas condensate production.

Based on our earlier theoretical approaches on bubbles'coarsening [Xu et al., PRL, 2017; Xu&Mehmani et al., GRL, 2019] and on bubbles'stability analysis [Wang et al., PNAS, 2021], we apply recently-developed pore-network modeling (PNM) tool [Mehmani & Xu, JCP, 2022; Mehmani & Xu, AWR, 2022] to investigate the kinetics of bubble coarsening in porous media, and reveal the final state in both homogeneous and heterogenous media. The time scale of coarsening is also theoretically derived and numerically validated [Yu & Wang, et al., GRL, 2023].

We first study the local equilibrium state of a two-bubble system in two connected pores. Without external field, there are three different equilibrium states when increasing the initial bubble volume: (a)the smaller one is eaten by the larger one, (b)both bubbles survive but of different sizes, and (c)both bubbles survive and of the same size. When there is an external field, only (a) and (b) are found with the growth of initial bubble volume. Analytical solutions matches the simulation well.

We then simulate the bubble coarsening in a $200\times200$ homogeneous pore-network model. The results show that some bubbles survive and are all finally of the same volume while others disappear. Bubble coarsening kinetics in porous media deviates from Lifshitz-Slyozov-Wagner theory, showing a much slower radius –time scaling. We attribute this new scaling to that porous structure quantizes the space and decouple the mass transfer coefficient from the bubble size. We accordingly develop a new theory for bubble coarsening in porous media, that matches the theory well.

Finally, we investigate bubble coarsening in heterogeneous systems. Although slightly affected by initial condition, we note that survival bubbles at equilibrium statistically fill from the largest pore to smaller pores. We plot capillary pressure –saturation curve and pore-occupancy –saturation curve at equilibrium, that can well match our theory considering pore-size distribution. The time scale for reaching equilibrium can also be estimated by the homogenous media theory, with necessary modification of perfector.

## Participation

In-Person

## References

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