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Critical Thresholds for CO2 Foam Generation in Homogeneous Porous Media

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Long-distance propagation of foam is one key to deep gas mobility control for CO2 sequestration (Rossen et al., 2022). It depends on two processes: convection of bubbles and foam generation at the displacement front. Prior studies with N2 foam show the existence of a critical threshold for foam generation in terms of a minimum pressure gradient (∇pmin) or minimum velocity (vt,min), beyond which strong-foam generation is triggered. Yu et al. (2020) show that the same mechanism controls foam propagation. There are few data for ∇pmin or vt,min for CO2 foam.

We conduct extensive experiments to quantify ∇pmin and vt,min for CO2 foam generation, and quantify the correlations of ∇pmin and vt,min with factors including injected foam quality (gas fraction)–fg, surfactant concentration–Cs, and permeability–K. In each experiment, steady-state pressure gradient is measured at fixed injection rate and quality, with velocity increasing in a series of steps. The abrupt jump in ∇p against vt marks the trigger of strong foam generation (see graphical abstract: N2 data on top, schematic in middle, data for ∇pmin on bottom).

In most cases, the experimental results for ∇p as a function of vt identify three regimes: coarse foam at low ∇p, an abrupt jump in ∇p (point B in graphical abstract) and strong foam at high ∇p. The abrupt jump in ∇p upon foam generation demonstrates the existence of ∇pmin and vt,min for CO2 foam. We further show how ∇pmin and vt,min scale with fg, Cs and K. The effect of K is dominant over the effects of fg and Cs. Specifically, both ∇pmin and vt,min increase with foam quality: e.g. for fg over a range 0.5 –0.9, ∇pmin rises by a factor ~ 2 –4 and vt,min by a factor ~ 4. Increasing Cs leads to decrease in both ∇pmin and vt,min by factors of less than three. ∇pmin changes considerably with permeability. Our results in consolidated sandpacks show that ∇pmin for CO2 foam scales with K as K-2, in comparison to N2 foam, where ∇pmin scales as K-1 in unconsolidated homogeneous sand or bead packs. However, the data of Gauglitz et al. (2002) for CO2 foam in Boise sandstone do not show a dependence of ∇pmin on K. The difference may be a result of the impact of heterogeneity of the Boise sandstone, since foam generation is easier in heterogeneous media.

∇pmin is about 0.17 bar/m (~ 0.75 psi/ft) for K ~ 270 mD, 2 to 3 orders of magnitude less than for N2 foam. This pressure gradient is easily attainable deep in formations. This suggests that generation is much less of a restriction for long-distance CO2 foam propagation than with N2. Foam propagation could still be challenging in low-permeability reservoirs (∇pmin ~ 10 bar/m for K = 27 mD). Nevertheless, realistic formations are heterogeneous and field application deploys alternating-slug injection. Both factors help foam generation and thus reduce the value of ∇pmin. More research is needed to determine conditions for CO2 foam propagation under those conditions.

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References

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Primary author: Dr TANG, Jinyu (United Arab Emirates University)

Co-authors: Prof. WEI, Bing (Southwest Petroleum University); Mr YANG, Mengke (Southwest Petroleum University); Prof. ROSSEN, William R. (Delft University of Technology)

Presenter: Dr TANG, Jinyu (United Arab Emirates University)

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