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Modeling nanoparticle-stabilized foam flow in porous media accounting for particle retention and permeability reduction

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Nanotechnology has been rapidly growing in various industrial sectors, particularly in subsurface applications such as soil and aquifer remediation, greenhouse carbon storage, and enhanced oil recovery (EOR). An application of nanoparticles with great potential is the stabilization of emulsions and foams, which are used as mobility-control agents to optimize gas flooding. However, retention is a concern during the injection of suspended particles, as it can lead to reduced rock permeability and a decline in injectivity in injection wells. In the case of foam flow with nanoparticles, a high retention rate also reduces the number of particles available for foam stabilization, reducing foam flow efficiency. Consequently, conducting a quantitative analysis of nanoparticle loss is crucial for accurately evaluating foam stability. This work presents a model for nanoparticle-stabilized foam flow in porous media, accounting for particle retention and the resulting permeability reduction (Danelon et al., 2024c), based on the Stochastic Bubble Population model. We have included a transport equation incorporating suspended and retained nanoparticles based on the deep-bed filtration theory. We provide a semi-analytical solution under steady-state conditions, which allows for obtaining water saturation, foam apparent viscosity, and pressure drop profiles. We study different nanoparticle concentrations (in the presence and absence of salt) using retention parameters based on experimental data. When particle retention is neglected, the sweep efficiency of the porous medium improves compared to the case without nanoparticles, even at a low nanoparticle concentration (0.1 wt%). In contrast, when retention is accounted for, this enhancement is observed only at higher concentrations (0.5 wt% and 1.0 wt%). The loss of suspended nanoparticles reduces their positive impact on the foam's apparent viscosity, while retained nanoparticles decrease permeability. Both effects increase water saturation, generally leading to a lower pressure drop compared to models that ignore retention. Nevertheless, the reduction in permeability directly increases the pressure drop, so whether the pressure drop increases or decreases when retention is considered depends on which of these opposing effects is dominant. Based on our findings, models that neglect nanoparticle retention and those that account for retention but neglect permeability changes underestimate the pressure drop, particularly in scenarios with significant retention (e.g., in the presence of NaCl and high nanoparticle concentration). Furthermore, we compared the semi-analytical steady-state solution with the dynamic solution for foam flow with nanoparticles (neglecting particle retention) proposed by Danelon et al. (2024a) and obtained an excellent agreement.

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References

T. Danelon, P. Paz, G. Chapiro, The mathematical model and analysis of the nanoparticle-stabilized foam displacement, Appl. Math. Model. 125 (2024) 630–649. T. Danelon, R. Farajzadeh, P. Bedrikovetsky, G. Chapiro, Modeling nanoparticle-stabilized foam flow in porous media accounting for particle retention and permeability reduction, Under review (2024).

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