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Dynamics of a dense viscoplastic fluid placed on top of a Newtonian fluid

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Abstract

In this study, we investigate the dynamic behavior of a viscoplastic fluid placed above a Newtonian fluid in an inclined, long tube. The two fluids are miscible and have a density difference, with the viscoplastic fluid always being denser than the Newtonian fluid. The experimental setup is mounted on a structure that allows for varying inclination angles. Initially, the fluids are separated by a gate valve. Upon opening the valve, distinct flow behaviors are observed, which are captured using a high-speed camera. The flow regimes depend on the interplay between buoyancy (due to the density difference), the yield stress of the viscoplastic fluid, and the inclination angle. In a tilted tube, exchange flow with a slumping regime is observed, while in the vertical configuration, a relatively stable finger front forms at high values of the yield number (Y), which represents the ratio of yield stress to buoyancy stress. As Y decreases, helical, disconnected, and slug finger regimes emerge. We investigate these flow regimes and quantify their transition boundaries, focusing on key characteristics such as finger length and front velocity. To support the numerical analysis, we develop a three-dimensional computational model representing the viscoplastic fluid as a Herschel-Bulkley fluid. This model is implemented using the Papanastasiou regularization and the Volume of Fluid method within the finite volume framework of OpenFOAM. The simulations provide insights into the velocity profiles, finger thickness, and the distribution of yielded and unyielded regions in the flow. The results of this study are particularly relevant to the oil and gas industry, where the flow represents an idealization of the plug cementing process: important both in constructing and decommissioning/sealing wells. By developing our understanding of these flow regimes and using this knowledge for future process design, this work contributes to enhancing well integrity, protecting groundwater and the atmosphere.