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From experiments to theory: 3D modeling of yield-stress fluid injection in confined pipes

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Abstract

The injection of a yield stress (viscoplastic) fluid into a domain containing a lighter Newtonian fluid arises in a variety of industrial processes including Plug and Abandonment of Oil and Gas wells. In this study we develop a three-dimensional numerical model of such flows, investigating parameter ranges relevant to the closure processes of oil and gas wells. We consider injecting the heavy fluid from an injector placed in a closed-end pipe. We illustrate the rheological properties of the injected fluid, in particular its yield stress, influence flow regimes, and overall displacement efficiency.

To validate our computational approach, a set of simulations is compared against experimental data involving two immiscible Newtonian fluids. The experiments showed that, the heavier fluid displaces the lighter fluid. Our numerical model predicts the same flow dynamics. The predicted advancing front velocity also closely matches the experimental data.

Building on this validated framework, the model is extended to predict the flow when the injected fluid has a yield stress. We explore a wide range of yield stress values, represented with Bn number ($0 < Bn < 50$). Two flow regimes are revealed: For low yield stress values, the flow of the injected fluid behaves similarly to a Newtonian fluid. it forms a downward-moving front below the injector, which gradually disperses and mixes radially. In contrast, at moderate to high yield stresses values, the flow rapidly develops a distinct unyielded region that slips along the bottom wall with minimal deformation. Once this unyielded region touches the bottom wall of the pipe or the lateral boundary, the downward progression stalls entirely, and subsequent injections are diverted into the annular region surrounding the inner pipe.

The results of our numerical simulations offer valuable guidance for applications where precise management of heavier-fluid injection is needed, whether to limit mixing in sensitive operations, improve displacement efficiency, or ensure robust fluid placement in geometrically constrained configurations.

Keywords-component

Yield Stress Fluid, Inclined Pipe Flow, Displacement Dynamics