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Numerical Investigation of Multiphase LNAPL Displacement by Complex Fluids in Porous Media

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Industrial development has led to extensive contamination of soils and aquifers, particularly by light non-aqueous phase liquids (LNAPLs), exposing to danger ecosystems and public health. Conventional remediation methods, such as pump-and-treat systems, often show limited efficiency because a substantial fraction of LNAPLs remain immobilized within porous media due to capillary forces and geological heterogeneity. Therefore, alternative strategies capable of improving LNAPL displacement are required.

This study investigates the use of viscous, shear-thinning fluids for in situ remediation, focusing on colloidal gas aphrons (CGA) and emulsions as unconventional flushing agents. Their non-Newtonian behaviour enhances mobility control, improves sweep uniformity and hydrocarbon mobilization.

The formulations were prepared using a polymer–surfactant system as the base solution. Biopolymer xanthan gum (XG) was introduced as a viscosifying agent and sodium dodecyl sulphate (SDS) as a surfactant. For emulsion preparation, an alcohol was added as a cosolvent. The resulting formulations exhibited pronounced shear-thinning behaviour, characterized by high apparent viscosity at low shear rates, enabling controlled injection and stable transport in porous media.

Performance was assessed through laboratory-scale one-dimensional (1D) sand-packed column experiments, complemented by numerical modelling. Conventional water flushing resulted in only 64% diesel recovery, while polymer solution alone improved recovery to 90%. In contrast, significantly higher recoveries were achieved with CGA and emulsion injection, reaching approximately 98% and 99%, respectively. Both CGA and emulsion systems demonstrated stable, piston-like displacement fronts during flushing, highlighting their superior displacement efficiency compared to water and polymer solution alone.

A numerical model was developed in CMG-STARS and calibrated using experimental parameters, including porosity, permeability, fluid properties, and injection conditions, with explicit implementation of shear-thinning rheology. The model reproduced displacement stability and recovery efficiency with deviations below 1%, with minor discrepancies attributed to simplified representations of pore-scale heterogeneity.

The validated model was subsequently extended to two-dimensional (2D) simulations to assess the impact of flow geometry on apparent viscosity distribution. Results revealed spatial viscosity variations and flow patterns not captured in 1D models. The combined experimental-numerical framework provides a solid basis for optimizing complex-fluid flushing strategies. Future work will address three-dimensional heterogeneous systems and injection optimization for sustainable LNAPL remediation.