Contribution ID: **410**

Type: **Oral Presentation**

A Multiscale Approach to Simulate Multiphase Non-Isothermal Flow in Deformable Porous Materials

Tuesday 20 May 2025 12:35 (15 minutes)

Feedbacks between multiphase fluid flow and solid deformation are crucial for advancing many geotechnical applications. These feedbacks remain incompletely understood and challenging to represent, particularly in complex porous media with pores of varying sizes. Traditional hydraulic-mechanical coupled models often struggle to accurately represent hybrid systems that include both solid-free regions and porous media. The Darcy-Brinkman-Biot (DBB) framework has been demonstrated to effectively capture capillary, viscous, inertial, interfacial, and gravitational forces at both pore and Darcy scales. The solver converges to the solution of the two-phase Navier-Stokes equations at the pore scale, while it tends asymptotically toward the solution of the two-phase Darcy equations at the continuum scale.

In this study, we extend the DBB framework, originally based on isothermal conditions, to model non-isothermal problems. By incorporating a new energy conservation equation, we develop a solver called hybridBiotThermalInterFoam, implemented in the Computational Fluid Dynamics (CFD) software OpenFOAM. This model accounts for the temperature dependence of fluid viscosity, fluid density, surface tension, and permeability. We validate the new solver by comparing its results with analytical solutions for heat transfer in systems with two fluids and against other OpenFOAM heat transfer solvers, such as chtMultiRegionFoam. The new solver shows excellent agreement with both the simplified analytical solutions and numerical predictions.

To further demonstrate the versatility of the solver, we apply it to more complex cases, including an enhanced oil recovery (EOR) scenario where high-temperature water and supercritical CO2 are injected into an oil-saturated porous medium to study fingering phenomena under dynamic mobility conditions. Additionally, we simulate a hybrid-scale case where fluids such as water and glycerin are injected into a soft clay-like material in the presence of induced fractures. The results show that the new solver effectively predicts heat transfer in multiphase fluids and deformable solids exposed to strong thermal fluxes, with potential applications in a wide range of coupled thermal-hydraulic-mechanical-chemical problems. To our knowledge, this is the first model capable of representing multiphase, non-isothermal fluid flow in deformable porous media within a hybrid system.

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References

Author: ZHENG, Xiaojin (Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544, USA)

Co-author: BOURG, Ian (Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544, USA; High Meadows Environmental Institute, Princeton University, Princeton, NJ 08544, USA)

Presenter: ZHENG, Xiaojin (Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544, USA)

Session Classification: MS07

Track Classification: (MS07) Mathematical and numerical methods for multi-scale multi-physics, nonlinear coupled processes