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Multiscale Numerical Simulation of Flow in Porous Media using 3D Digital Twin Models from Computed Tomography

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ABSTRACT

Over the past decade, advancements in the numerical resolution of the Navier–Stokes equations for multiphase flow modeling have enabled the study of key transport processes in porous media while accounting for non-Darcian effects, including inertial, boundary, and variable porosity influences. Simultaneously, improvements in post-processing techniques for CT-scan images (such as reconstruction and segmentation) applied to porous material samples have made the process increasingly reliable. As a result, integrating real and complex geometries from CT scans into numerical simulations has become a cutting-edge topic in scientific research. This study explores different numerical approaches that utilize Computed Tomography (CT) data for porous media modeling, focusing on intricate couplings between flow dynamics and fluid–solid interactions. We present a workflow for generating a 3D numerical model from CT-scan images of porous media for Computational Fluid Dynamics (CFD) simulations. The uncertainties in porosity and permeability are assessed using CT-scan datasets of a reference material—assemblies of monodisperse glass beads—for which analytical and empirical solutions are available in the literature. Meshes are generated using the open-source platform Salome, and numerical simulations are conducted with Code_Saturne, a multiphysics CFD software based on a finite-volume approach, which supports arbitrary cell types and grid structures. The resolution of CT-scan data acquisition and the selection of image post-processing filters play a crucial role in the accuracy of numerical solutions. Notably, the reconstruction of pore space interfaces alters surface and volume representations, significantly affecting porosity and, consequently, permeability calculations. This study provides a detailed uncertainty analysis for an ideal porous medium, serving as a reference framework for the development of a multiscale and multiphysics methodology applicable to various particle assemblies, including geomaterials.