EXPERIMENTAL AND NUMERICAL CROSS-VALIDATION OF FLOW IN REAL POROUS MEDIA. PART 2: NUMERICAL FRAMEWORK

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Summary: The main objective of this contribution is the cross-validation of a novel approach to fluid flow simulation inside porous media. The originality of the model stands both in the use of rather raw 3D volumes from X-ray tomography and the model's computational efficiency on standard calculation means. The performance of the model is assessed in different geometries and configurations, based on reference data obtained via a dedicated experimental setup.

1. INTRODUCTION

The investigation of fluid flow at the pore scale, based on X-ray scans of a porous medium of interest, is one of the most challenging problems in CFD. However, the predictive power of many existing simulators remains to be demonstrated. Model validation is crucial, as direct observation of the flow field inside real porous media is generally not possible, and since model and experiment generally exhibit differences in geometry, boundary conditions and/or physics.

In this study, we present the cross-validation of a next-generation flow simulator from a numerical point of view. The pore scale geometry used in the computation is obtained using X-ray tomography, as described in a companying paper. The dedicated experimental setup is designed to limit differences between the experimental and numerical setup (accurate control of the boundary conditions), rendering it an ideal tool to conduct systematic validation studies.

2. A NEXT-GENERATION HYBRID GRID-PARTICLE SOLVER FOR PORE-SCALE MODELING

Flow simulation at pore scale is difficult because of the inherent complexity of the geometry, which includes a fluid-solid interface with possible roughness. The high resolution needed to capture relevant geometrical details has to be handled without using tremendous memory resources, excluding traditional assembling methods like finite elements or finite volumes. In our study, we use a robust hybrid grid-particle method [2, 3, 4] to solve the advection-diffusion problem: the fluid velocity field is first computed on a Cartesian grid, then particles manage transport. Interpolation between grid and (moving) particles needs to conserve mass and positivity for the sake of physical coherence. Velocity field computation, i.e. the solution of the 3D Stokes equation coupled to the diffusion-transport of the fluid medium [1], is carried out using an adapted velocity-vorticity formulation based on the method described in [5] for external flows. This allows to efficiently satisfy adherence and slipping conditions at fluid-solid interface. Roughness is then taken into account through the setting of slipping coefficients.

3. SIMULATION SETUP

An important point is the validation of the model by assessing its performances via direct measurements. Hereby the performance is understood as the capability to numerically predict the permeability of a porous medium. To conduct these tests, a dedicated experimental setup has been built (see companying paper). For each studied configuration, a 3D tomographic scan is made from the dry state. The reconstructed geometry is extracted and the resulting 3D geometrical virtual volume is used as input for computing the permeability. On the same configuration, the permeability is measured experimentally. Numerically calculated and experimentally measured permeabilities are then compared. By systematically increasing the level of complexity of the medium, we can attribute the eventual differences between models and experiments to specific features. Two different configurations are tested: first, a network of smooth micro-spheres, packed in the cylindrical cavity of a Hassler-like cell, is used for preliminary

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test. This sample permits the validation of an accurate 3D model, as it presents a complex topology. This first case uses a synthetic medium, whereas the second test relies on a natural geometry. A rock sample, precisely a Bentheimer stone (a well-documented sandstone), is chosen to conduct this real case test. A rendering of the fluid-solid splitting for this geometry is shown in figure 3.

4. RESULTS AND OUTLOOK

The first configuration of interest consists of a pack of smooth micro-spheres (dry soda lime glass, Duke Standards) whose nominal diameter of 553 ± 11 µm is certified. This diameter was selected to have around 10 spheres across the diameter of the test cell. When using binning 4, the region of interest will be around 500^3 voxels, which can be handled by a typical numerical solver, and each sphere is described by around 50 voxels across its diameter, which is sufficient to have an accurate geometrical representation. A voxel size of 15µm has been selected to ensure that the entire sphere pack is within the field of view. Spheres at the top and bottom part of the sample are truncated as both metal inlet/outlet grates induce an image artefact. Replacing them by synthetic filters will enable imaging the entire sample, and therefore remove a key uncertainty when comparing to simulations on the same geometry. Figure 2 depicts a rendering of the resulting velocity field computing over the domain, while figure 1 shows particle advection according to the computed field.

Measurements using different fluids, using multi-modal sphere-packs and at higher spatial resolutions are foreseen as well, and it is anticipated to make the reference data available to the scientific community.

Figure 1: Rendering of advected particles from computed velocity field

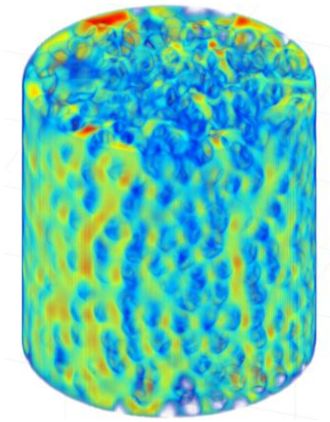

Figure 2: Norm of velocity field inside beads network (257^3 grid)

Figure 3: Rendering of fluid and solid phase inside a 299^3 Bentheimer sandstone

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