HPC Fluid Flow Simulations in Porous Media Geometries

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Abstract: The simulation of flows in porous media on the microscale level requires a high number of unknowns to resolve the geometry of the fissures in-between the sand grains. For the geometric representation of the sand grains we use sphere packings, generated with an in-house scenario generator based on a modified and extended version of the Lubachevsky-Stillinger algorithm. The fluid solver is implemented in the in-house PDE framework Peano using adaptive Cartesian grids for the explicit geometric resolution of spheres and the fluid domain. As underlying equations we use incompressible Navier-Stokes. The verification of the solver is based on 2D and 3D scenarios. Representative scenarios require thousands of spheres and hundreds of millions of grid elements. This makes high parallel efficiency of the simulation environment essential and a major task in our project work.

Keywords: Computational Fluid Dynamics, Adaptive Cartesian Grids, HPC, Porous Media, Geometry Generation.

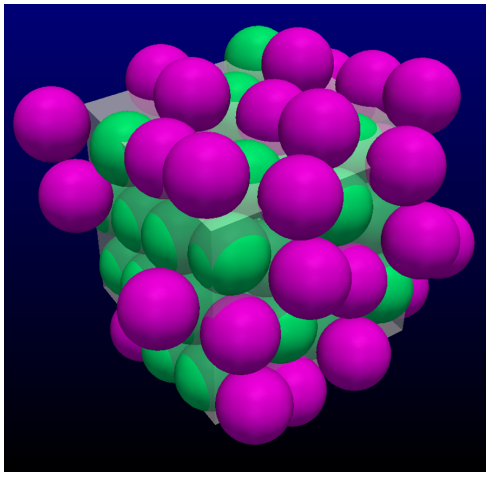
1 Introduction

One way to simulate the fluid flow in complex geologic formations such as oilfields or saline aquifers is to do an upscaling from a fine scale solution on representative volumes to a homogenized solver for the full domain. Within this paper we focus on the explicit computation of fluid flows in representative elementary volumes (REV). The sand grains are approximated by different sphere packings representing subdomain patches and different sediment layers. For the generation of sphere packings extended the Lubachevsky-Stillinger algorithm [3] such that we can implement radii variations in the packings while reducing the time needed for the generation of a dense packing (e. g. Figure 1a). The CFD solver is implemented in the PDE framework Peano [1, 2].

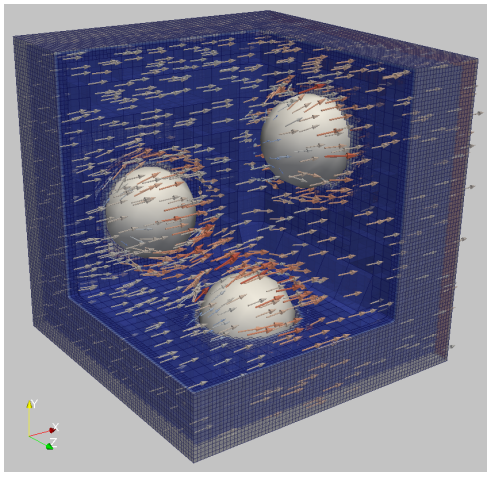
2 Problem Statement

In order to compute the permeability tensor for the further use in a Darcy solver we have to perform a number of flow simulations for each REV. The minimum number of simulations which has to be executed per REV is one simulation per dimension. In two and three dimensional scenarios the domain setup is as follows: Dirichlet pressure boundary conditions imposing a constant pressure difference on two opposing sides and Neumann boundary conditions ($u\vec{n} = 0$) at the remaining sides. After a steady state solution is achieved we extract the permeability

and continue with another flow direction. Due to the high number of degrees of freedom, a full and efficient parallelization of the complete simulation is necessary.



(a) Artificially generated sphere packing with periodic domain boundaries. The packing has been generated using a molecular-dynamics-like algorithm resulting in an average maximum density of 63.4%.



(b) Streamlines of a fluid simulation in a simple example geometry.

Figure 1: Validation and simulation scenarios solved with the Peano fluid solver.

3 Conclusion and Future Work

For the simulation of a flow in a porous medium on the microscopic level we have explicitly discretized the domain using a parallel adaptive Cartesian grid and computed the permeability tensor for a number of representative elementary volumes. The simulations were executed in parallel on different HPC systems (IBM Blue Gene System Shaheen[1] and Intel processor based petaflop System SuperMUC[2], e.g.). The next step will be to use these tensors as input data for a Darcy solver on a coarser spatial scale. Furthermore, we plan to use 3D rock scans as input data for the flow simulation.

References

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