Multi-Scale High-Performance Fluid Flow Simulations Through Porous Media

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1 Introduction

In petroleum production and engineering, the subsurface formation that surrounds the well screen gets, in many cases, deteriorated with time in relation to its hydraulic conductivity. As a consequence, well production declines with time and this limits to a large extent its efficiency. Since well installation is a major production operation that usually requires a large capital, it is always important to revive the use of the installed wells rather than abandoning them. One of the methods that have been proposed to alleviate this problem is to inject chemicals that dissolve, in a sense, the formation materials and open channels to ease the flow of the oil. Most of the research work that has been reported on this topic appeals to experimental correlations that are to a large extent specific to certain types of porous media (e.g., granular, consolidated porous media) and therefore not applicable to the wide range of soil material types. In this work, we provide an alternative route, thanks to the advancement in the CFD simulations of complex pore scale structures. The idea is to update the permeability based on pore scale simulations rather than based on experimental correlations. The main challenge beside coupling two different spatial scales is to handle the differences in time scales required to perform porous media simulations (which are relatively fast) versus the time required to update the permeability based on CFD simulations (which are relatively slow). This goal can be achieved through the generation of offline database data of permeability values with a direct access from a porous media simulator, which triggers the transmission whenever a new calculated value is available.

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In order to present our concept and some first findings, this extended abstract will shortly describe established and implemented governing laws and equations, the applied high-performance parallel computing techniques, and an application example enlightening the usability and efficiency of our implemented approach.

2 Groundwater Flow Through Porous Medium

2.1 Governing Equations

As stated before, two models are introduced in order to make such numerical simulations as efficient as possible – a macro model based on Darcy’s Law, described through the following equations:

\[
\frac{Q}{A} = -\frac{k}{\mu} \cdot \frac{\Delta H_p}{L}, \quad K = \frac{k\rho g}{\mu}, \quad \text{and} \quad U_{\text{darcy}} = -K \frac{\Delta P}{L},
\]

where the ratio \(\frac{Q}{A}\) is often referred to as Darcy flux, \(U\) the fluid velocity \([\text{m/s}]\), \(k\) denotes the permeability, \(\mu\) the dynamic viscosity of the fluid \([\text{kg/(m·s)}]\), \(K\) the hydraulic conductivity \([\text{m/s}]\), \(\Delta H_p\) \([\text{Pa}]\) the pressure drop.

A second micro model is based on the Navier-Stokes conservation of mass and momentum equations that can be written in their vector forms as follows:

\[
\nabla \cdot \mathbf{u} = 0,
\]

\[
\frac{\partial u_i}{\partial t} + \nabla \cdot (u_i \mathbf{u}) = \nabla \cdot (\nu \nabla u_i) - \frac{1}{\rho} \nabla \cdot (p \mathbf{e}_i) + b_i
\]

for \(i \in \{x, y, z\}\), where \(\mathbf{u} = (u_x, u_y, u_z)^T\) denotes the velocity field in \([\text{m/s}]\) in the three spatial dimensions, \(t\) the current time of the simulation in \([\text{s}]\), \(\nu\) the kinematic viscosity in \([\text{m}^2/\text{s}]\), \(\rho\) the density in \([\text{kg/m}^3]\) and \(p\) the pressure in \([\text{Pa}]\).

Since the description of the governing equations is kept quite brief here, the interested reader is referred to standard literature such as [2] or [6] for further information on the derivation of both laws.

2.2 High-Performance Computing Concept for CFD Simulations

In order to solve the Navier-Stokes equations described previously, a discretisation of the physical domain is performed, resulting in a complex data structure that consists of sets of non-overlapping block-structured orthogonal Cartesian grids as depicted in figure 1. While the logical grid structure contains topological and geometrical information such as parentage, the data grids themselves contain the actual variables such as velocity, pressure, permeability, temperature etc. necessary for performing any numerical calculations.
each cell is linked to one data grid of size $b_x \times b_y \times b_z$ surrounded by halo

Fig. 1: Logical data structure layout in tree form (on right-hand side) and in overlayed grid form (on left-hand side). Each logical grid holds a pointer to a data grid containing the actual data surrounded by a halo of ghost cells (mid of picture). (Source: [4])

Fig. 2: Generated geometry based on sieve curve input data

Having generated such complex data structures, a fractional step method proposed by Chorin [1] is applied while using numerical discretisation based on a finite volume scheme in space and a second order explicit Adams-Bashforth method in time [5]. An efficient multi-grid like solver is applied in order to solve the arising pressure Poisson equation. For detailed information on the realisation of the structure or the MPI exchange routines in order to ensure proper communication, the reader is referred to [4] or [3] for instance.

3 Application Example

For the purpose of a CFD simulation on the micro scale, the physical domain of a porous medium is generated as a set of spheres of different diameter randomly positioned in a predefined domain and depicted in figure 2.
Such domain represents just a small part of the domain (cf. figure 3) at which the macro-scale simulation is performed. In order to overcome the problem raised due to two different spatial and time scales, an offline database is generated and updated with values of permeability that are calculated on a micro level for several different scenarios. At this point, it is important to mention that coupling between these two models is exclusively done over the permeability value, as when the velocity and pressure values on the micro-scale are known, the permeability value can be calculated with almost no effort and upscaled for the macro-scale calculations. The later model is linked to the database, in such way to be able to take over calculated values of permeability for a specific case, whereas if the required value is not presented, to trigger a new micro-scale calculation.

Once the adequate coupling value is available, the fast macro-scale calculation of necessary amount of chemicals, inserted into the underground area in the vicinity of an existing well, can be performed. Within this calculation, the output parameters which describe the rate of soil degradation on a porous scale (also called, macro scale) are stored at some share memory medium. This medium can be a part of the database, but it might be also completely inde-
Having calculated this degradation value, a micro scale model is triggered once again to perform a completely new simulation, starting from discretisation of degraded geometry domain, setting all necessary boundary conditions, up to the calculation of new value of permeability, which will be then stored in the previously generated database.

Taking into account that Darcy equations are derived by means of volume averaging from the physical Navier-Stokes equations, the same principle is applied in order to achieve the permeability value at the micro scale that would fit into macro scale model. Having done that, additional analyses were performed, so to define a deviation of particular value of permeability at the micro scale comparing to the mean value calculated for the macro scale model. Such a deviation is a measure of how those two models can be coupled together and can be set to some specific value, depending on particular goals of research work.

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References