Direct numerical simulations of flow through real porous media

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Keywords: pore-scale flow, diffuse interface approach, computed micro-tomography, transport properties

1 Introduction

Pore-scale single and two-phase flow in real 3D pore space geometry is addressed in our current work. The fundamental importance of pore-scale real media flow models and the range of their practical applications are difficult to overemphasize. From the other side, a typical study in this area encounters several challenges at different stages. This complexity is the main reason why only during last few years one may observe the significant increase in number of works of this type. Presentation and first analysis of most difficult steps of the model development is our general objective here.

Taking advantage of recent advances in X-ray computed micro-tomography (μCT), the reconstructed real porous medium samples (*Bentheimer* sandstone) were used for direct numerical simulations (DNS) of single and two-phase transport problems. The μCT improved software and measurements technique provided greater access to high resolution core sample images and to a larger set of useful information for porous media oriented modelling. The range of energies used in the X-ray tomography made possible to study very dense objects; moreover, the μCT technique gives a unique opportunity for non-destructive 3D core sample characterization (cf. Figure 1a).

It is well known that the Navier-Stokes (NS) equations may be used at certain limit to derive the Darcy law and to define at larger scale the single phase transport properties (cf. [1]). In a similar way, the modified NS model can be used to determine medium two-phase flow properties [5]. The description of a phase dynamic boundary (interface) is a problem of crucial importance for such a model. Available approaches to the interface separating fluids and possessing arbitrary configuration, are limited. Instead of using a regularization technique (cf. VOF [2] or level-set functions approach [3]), which may affect the results in a non-trivial way, the diffuse interface method (DIM) offers a rigorous thermodynamic description of phase "mixing" zone [4]. This is an excellent alternative for numerical applications, handling the morphological changes of the interface via solution of a PDE which implies a non-negligible advantage for modelling of such a kind.

Among interesting straightforward applications are the determination of real medium transport properties (for single and multiphase flow), the identification of oil recovery mechanisms and flow regimes in physically meaningful environment, *etc.* Other problems of interest which seem to be beyond the conventional theory framework, are so-called viscous fingering observed in porous medium at heavy oil displacement by a less viscous fluid (*e.g.* water), the emulsion and foamy oil flow still requiring an adequate general model. The contribution of DNS to understanding of transport phenomena in a real media becomes increasingly important factor of porous media research efforts.

2 Diffuse interface model: Cahn-Hilliard theory and modified Navier-Stokes equations

We present here only a brief description of the DIM, for more details see *e.g.* [5]. The second gradient theory assumes that free energy of a system is a functional of an order parameter φ, its gradient $\nabla\varphi$ and the temperature T [4]. For an isothermal binary fluid, a free energy can be defined for flow systems not in equilibrium as a certain functional $F(\varphi, \nabla\varphi)$ through which the chemical potential ν and then the convective Cahn-Hilliard equation describing the evolution of φ, can be introduced. The resulting Cahn-Hilliard-Navier-Stokes equations offer a basis for pore-scale DIM applications [5].

3 Main results

As stated above, in this work emphasis is made on presentation of different steps and features of the modeling methodology. This includes the μCT measurements, reconstruction and segmentation, characterization of pore surface and volume geometry, grid generation and computational models. Figure 1 illustrates some of them, (a) 3D image of the *Bentheimer* porous sample: raw reconstructed slice (upper face), sample texture (right face), segmentation (left face); side length L=2.45 mm; (b) pore surface and volume characterization: *numerized* pore volume ready for mesh generation, computed porosity value, ε=0.207±

This abstract was prepared for the InterPore2013 conference held in Prague on May 21 – 24, 2013.

0.006, is in good agreement with published data; (c) numerical grid example for 1/8 of the *Bentheimer* porous sample, $L_1 = L/2$; (d) the distribution of interstitial water velocity at stationary single phase flow conditions, $2\cdot10^{-7}\div6\cdot10^{-4}$ m/s; (e) the phase field variable, $\varphi(x,y,z)$, at equilibrium (v=0), neutral wetting case; (f) two-phase flow: injection of the black phase from left, viscosity ratio M=0.1.

The estimation of single phase flow properties of the *Bentheimer* sample, the study of boundary conditions impact on the flow magnitude, the modeling of equilibrium fluid distributions inside pore and influence of wettability conditions on the equilibrium phase configurations has been carried out and analyzed.

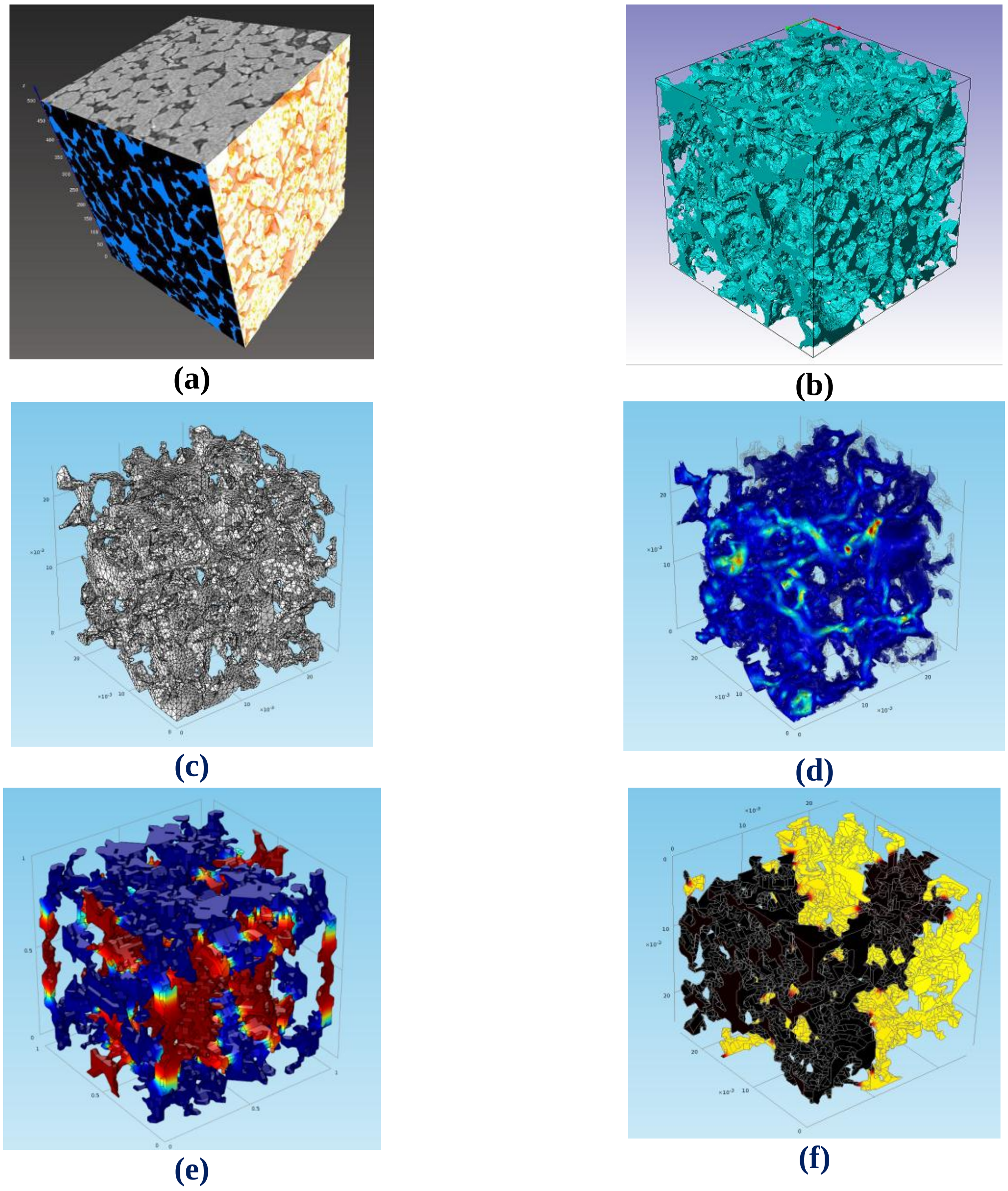
(a) **(b)** **(c)** **(d)** **(e)** **(f)**

Figure 1: Some illustrative results of the methodology developed and applied in current study.

4 References

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