Investigations of microstructure and hydraulic permeability of rocks samples by means of X-ray computed microtomography and Lattice Boltzmann Method

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Introduction

Microfocus X-ray computed tomography (µCT) is a non-destructive method widely applied in various geological disciplines. It reveals the internal structure of investigated objects, determined by variations in density and atomic composition. Microfocus X-ray computed tomography has recently emerged as an important and powerful tool because it is relatively easy to apply providing at the same time fine spatial resolution (about 10 µm). In this work, the study of microstructure and porosity, applied to investigations in the field of petroleum geology has been presented. Moreover, simulations of fluid dynamics in void pore space have been performed in order to obtain the hydraulic permeability of investigated media. The measurements of the microstructure, porosity and specific surface area of sandrock samples, extracted from a drill hole have been carried out using the X-ray microprobe at IFJ PAN, Krakow. Basing on tomographic data obtained with the high spatial resolution, simulations of the fluid dynamic in void space of porous media have been carried out. Lattice Boltzmann Method (LBM) in D3Q19 geometrical model has been used in order to predict the hydraulic permeability of the media. In order to avoid viscosity-permeability dependency the multiple-relaxation-time model with half-way bounce back boundary conditions has been used. Computing power-consuming calculations have been performed with the use of modern grid infrastructure [1].

Experimental Setup

The µCT measurements of the porous sandstone rock samples extracted from a drill hole at 2680 and 2743 m depth have been carried out with the use of an experimental line of the multipurpose X-ray microprobe at IFJ PAN, Kraków. The line consists of an open type Hamamatsu L9191 X-ray tube with microfocusing to about 2 µm, a high resolution X-ray sensitive CCD camera, and a high precision rotary stage. Depending on the required X-ray energy, the Hamamatsu tube is used with Ti, Mo, Ag, or W targets. A small focus size and short focus-to-object distance enable to obtain images of samples with high magnification and resolution of the order of few µm. The µCT measurements are carried out using home developed code combined with commercial software.

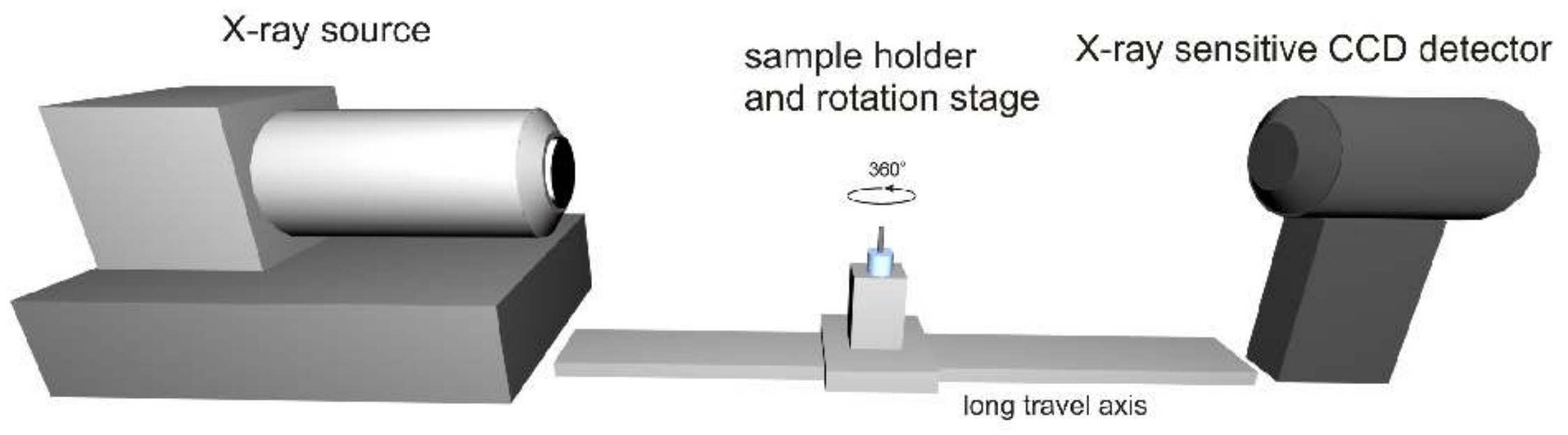


Fig. 1. Schematic view of the µCT experimental line.

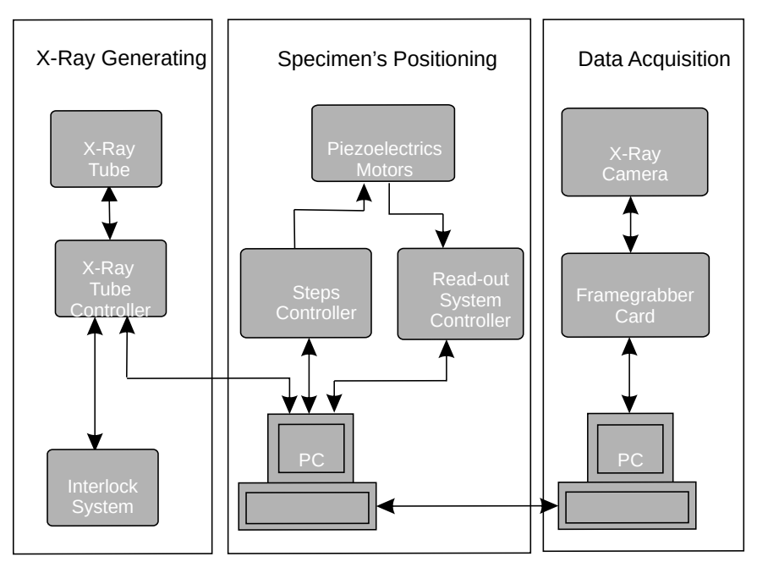


Fig. 5. Electonics associated with µCT experiments.

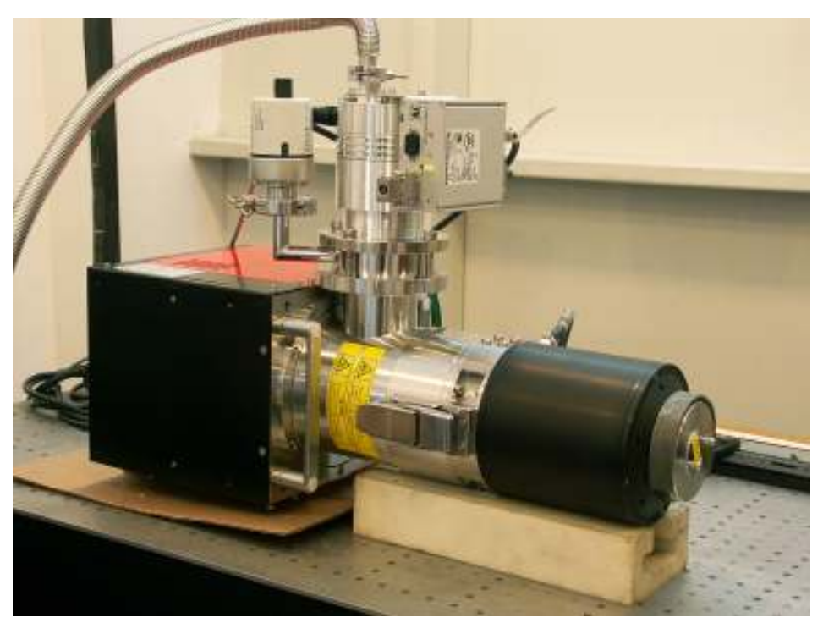


Fig. 2. X-ray source - Hamamatsu L9191 microfocusing X-ray tube.

Fig. 3. Precise rotary stage.

Fig. 4. X-ray sensitive, high resolution CCD camera.

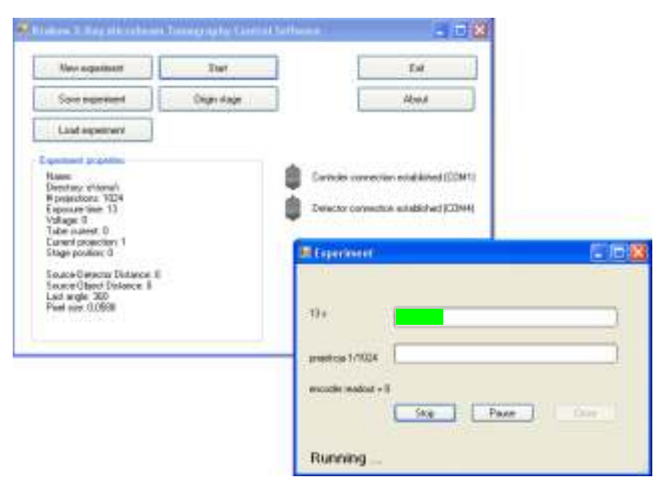


Fig. 6. Experiment control software.

Lattice Boltzmann Method

Lattice Boltzmann Method (LBM) is a class of computational fluid dynamics (CFD) methods for simulation of fluid dynamic. It is a relatively new simulation technique for complex fluid systems which has attracted interest of computational physics researchers. In the LBM, instead of solving the Navier–Stokes equations, the discrete Boltzmann equation is solved in order to simulate the flow of a Newtonian fluid with collision models such as Bhatnagar-Gross-Krook (BGK). Unlike the traditional CFD methods, which solve the conservation equations of macroscopic properties i.e. mass, momentum, and energy numerically, LBM models the fluid consisting of fictive particles, and such particles perform consecutive propagation and collision processes over a discrete lattice mesh. In this computations D3Q19 model (3 dimensions, 19 discrete velocity vectors) has been used (Fig. 7). Due to its particulate nature and local dynamics, LBM has several advantages over other conventional CFD methods, especially in dealing with complex boundaries which occur in porous media, as well as in parallelization of the algorithm [2]. In order to avoid viscosity-permeability dependency the multiple-relaxation-time (MRT) model with half-way bounce back boundary conditions has been used.

CODE BENCHMARK

In order to check the correctness and speed of the used code a test run simulating Poiseuille flow between two parallel plates (Fig. 8) has been carried out. The vertical velocity profile has been obtained and compared with analytical solution (Fig.9, Fig. 10). A good agreement of simulation with analytical prediction was observed.

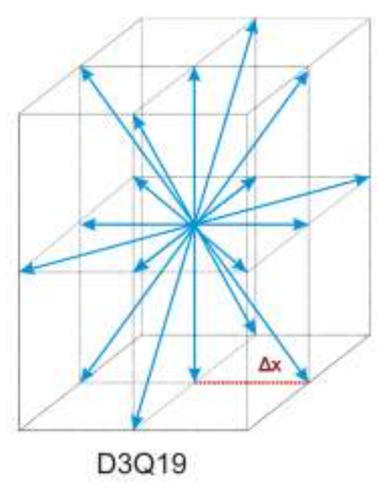


Fig. 7. Velocity vectors available in D3Q19 model.

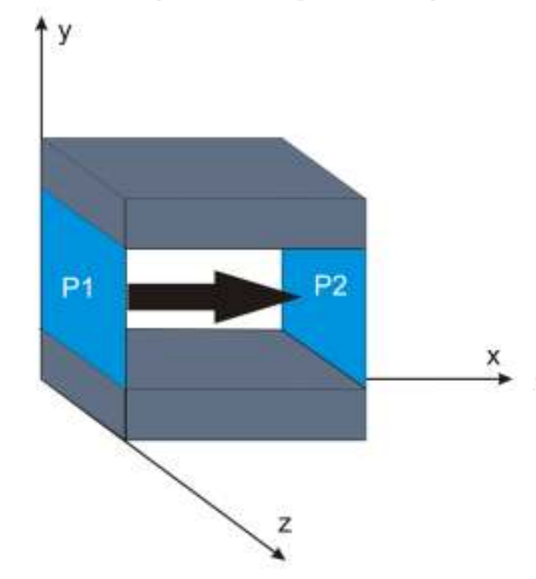


Fig. 8. Geometry of the Poiseuille flow - flow between two parallel plate. Velocity profile in the y direction is parabolic.

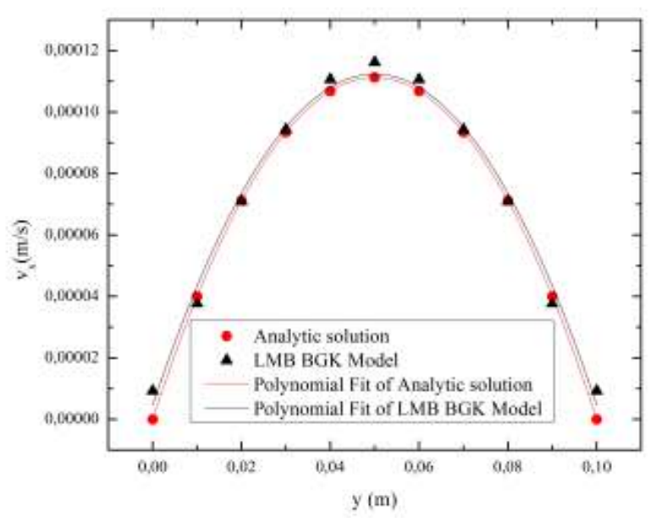


Fig. 9. Fluid x velocity component as a function of y coordinate. Simulation resualts vs analitic solution.

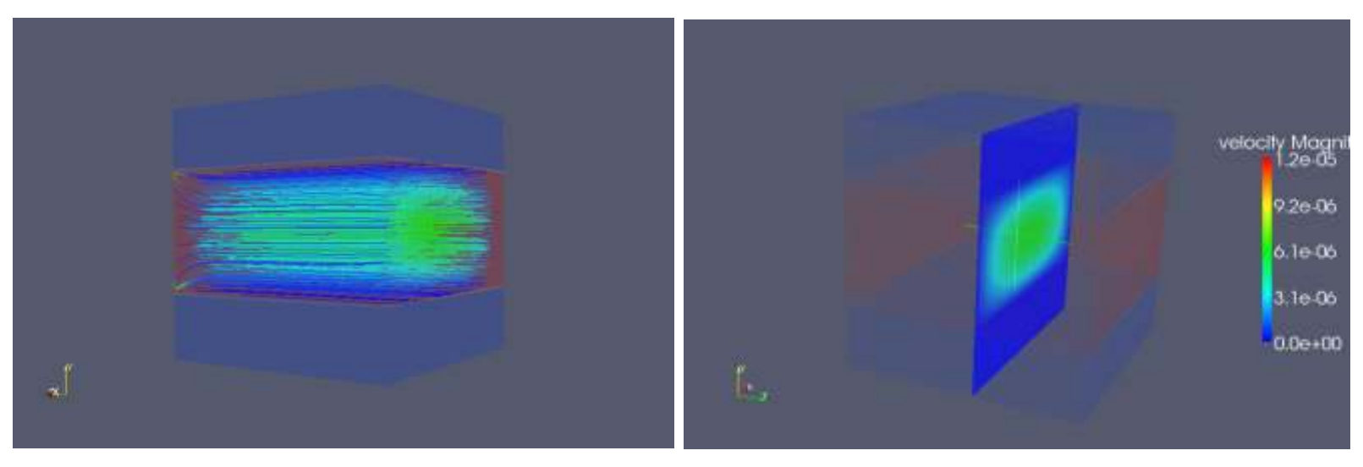


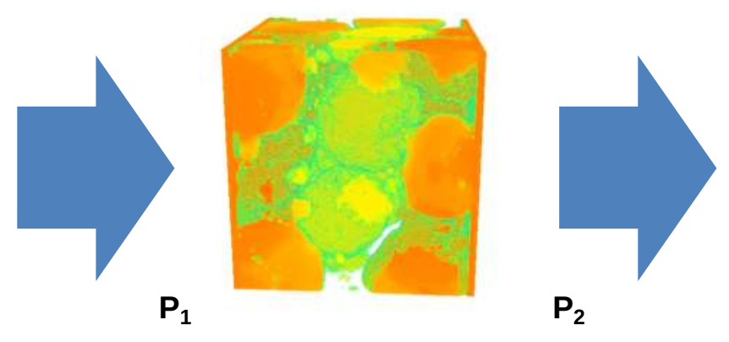
Fig. 10. Visualization of fluid velocity field. Streamlines a) and b) x velocity component. Arbitary simulation units used.

PERMEABILITY DETERMINATION

The simulations were performed on 255x255x255 lattice (voxel physical dimention = 20µm) with geometry of the medium obtained from the µCT measurements and binary sampled into two regions – fluid and void space. The permeability *K* of the medium was determined using the Darcy law:

$$< q_x > = \frac{k}{\mu} \frac{dP}{dx}$$

where:
P - pressure, $<q_x>$ - volumetric average of fluid flux, µ - dynamic viscosity.



Results

The porosity (Fig. 11), specific surface area (a property of solids which measures the total surface area of porous media per unit of volume) (Tab. 1) and pore size distribution (Fig. 12) have been determined with the use of home-made code. Results of the porosity measurement are in good agreement with results obtained with the use of the mercury porosimetry technique (15.28 % for the sample from 2680 m depth).

An open source LBM solver „Palabos” [3] has been used in order to calculate total permeability of the media. The average permeability of the sample extracted from drill hole at 2680 m depth has been estimated to 20.01 ± .4.2 mD (1D = 9.869233×10^{-13} m^2).

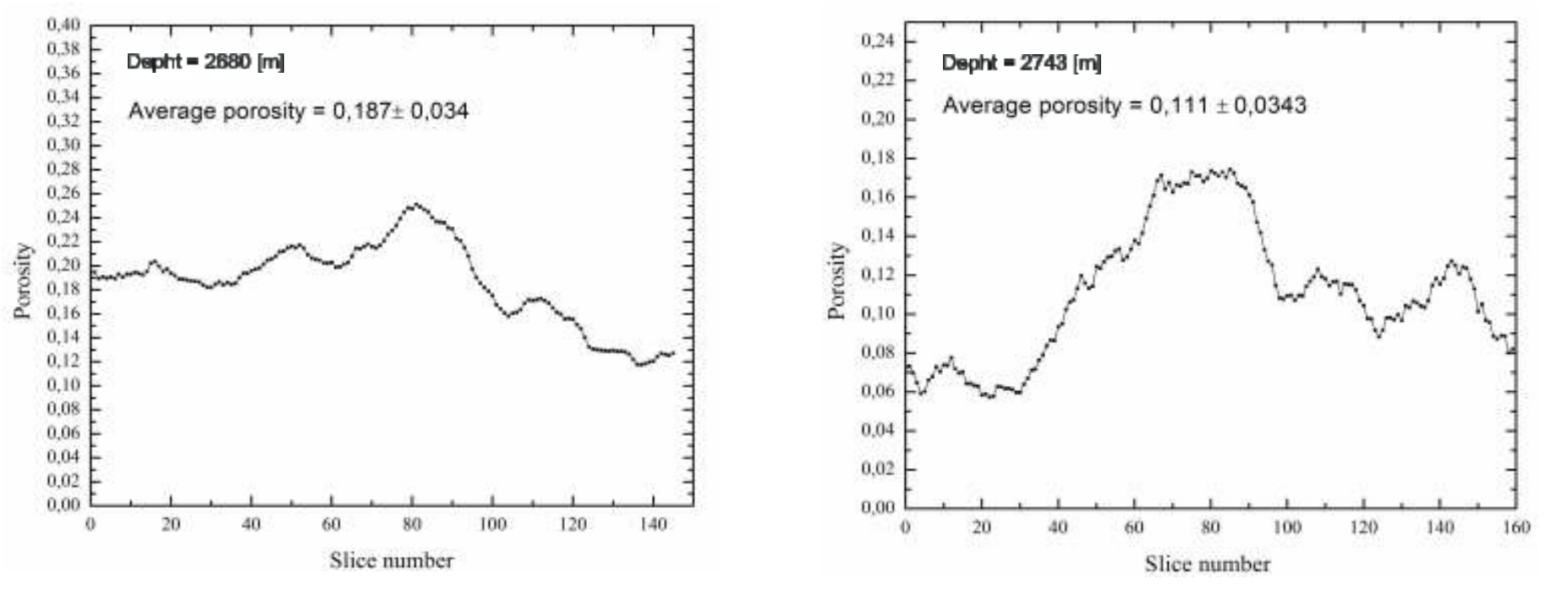


Fig. 11. Results of the porosity measurement.

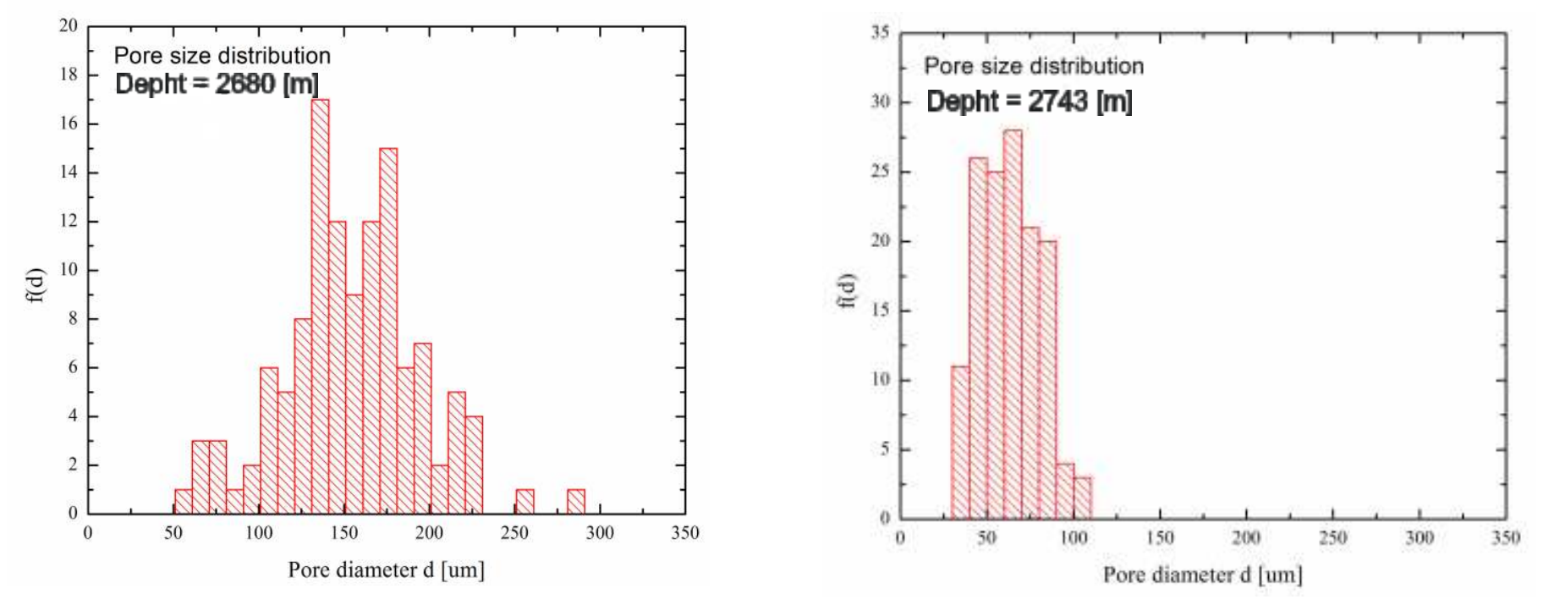


Fig. 12. Pore size distributions.

Sample from depth [m]	Specific surface area [um^{-1}]
2680	0,248 ± 0,007
2743	0,187 ± 0,004

Table 1. Results of the specific surface area measurement.

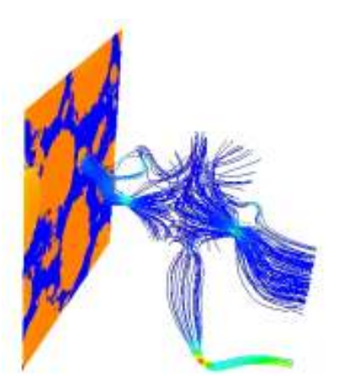


Fig. 13. An example of simulated fluid flow trough porous media. One of the reconstructed slice and streamlines are shown. Speed of fluid particles is presented in colour scale.

Bibliography:
[1] www.plgrid.pl
[2] S. Succi „The Lattice Boltzmann Equation for Fluid Dynamics and Beyond”, Oxford Press, 2001
[3] http://www.lbmethod.org/palabos/

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