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MODELLING THE FLOW ABOVE A POROUS AND ROUGH MEDIUM WITH AN LBM-AMR APPROACH

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Abstract. We simulate the turbulent flow over and in a porous and rough medium with an LBM-AMR method. The porous medium consists of two layers of spheres. LBM is used in combination with LES and provides accurate results outside of the spheres layers.

1 INTRODUCTION

Flows over porous and rough media can be found in nature (e.g., river beds or forest canopys) and in industrial devices (for instance, in heat exchangers). The combination of permeability and roughness effects leads to an outer flow that is significantly different than flows over impermeable flat or rough walls. Flows over porous and rough surfaces have raised some interest in the past few years and further investigations could result in industrial applications, such as flow control for drag or noise reduction. However, the combined action of porosity and roughness is still not fully understood. Developing a Computation Fluid Dynamics (CFD) tool for predicting such flows is thus of particular interest. The Lattice Boltzmann Method (LBM) is a CFD approach that has already been successfully used for such studies, for instance, by Kuwata and Suga [2].

In this paper, the LBM is used along with Large Eddy Simulation (LES) to capture the flow in and over a porous medium made of spheres. LBM-LES is interesting as it enables the computation of the outer flow at a lower cost than Direct Numerical Simulation (DNS). All calculations are made with our AMROC software. The use of Adaptive Mesh Refinement (AMR) enables accurate computation of turbulent structures generated by the porous medium by refining the mesh in areas of interest.

The next section briefly sketches the numerical method, followed by a description of the simulated case. Then, results of the LBM-AMR-LES simulation are presented. Finally, the conclusions highlight the outcomes of this study.

2 METHODS

The LBM is an unsteady CFD method that computes fluid behaviour by solving the Boltzmann equation

$$\frac{\partial f(\boldsymbol{x},\boldsymbol{\xi},t)}{\partial t}+\boldsymbol{\xi}.\nabla f(\boldsymbol{x},\boldsymbol{\xi},t)=\Omega(f(\boldsymbol{x},\boldsymbol{\xi},t),f(\boldsymbol{x},\boldsymbol{\xi},t)). \tag{1}$$

The distribution functions $f(\boldsymbol{x},\boldsymbol{\xi},t)$ represent groups of molecules at a given position $\boldsymbol{x}$ and time t, which have a certain velocity $\boldsymbol{\xi}$. In Eq. (1), $\Omega()$ is the collision operator representing collisions between molecules. Since distribution functions are continuous functions of the velocity space, the LBM approach uses a finite set of propagation directions for molecules. The velocity scheme used in this article has 27 directions and is commonly denominated as the D3Q27 scheme. The collision operator can take various forms. In the simulation presented afterwards, the regularized Bathnagar-Groos-Krook (BGK) collision operator described by Latt and Chopard [3] is used. It reads

$$\boldsymbol{f_i}(\boldsymbol{x},t+\Delta t)=\boldsymbol{f_i}^{(0)}(\boldsymbol{x},t)+(1-\omega)\boldsymbol{f_i}^{(1)}(\boldsymbol{x},t), \tag{2}$$

where $\omega=1/\widetilde{\tau}$ is the relaxation frequency and $\widetilde{\tau}=\tau/2$ is the effective relaxation time. To compute the equilibrium part $f^{(0)}$ and non-equilibrium part $f^{(1)}$, a recursive approach is applied. See [4] for details. The implemented model uses the recursive approach up to order 6 for both equilibrium and non-equilibrium parts. It has been shown that this RR-BGK scheme is stable and accurate at high Reynolds numbers, which makes it suitable for our application.

The LES model adopted is the constant coefficient Smagorinsky model. It is implemented in the LBM by altering the relaxation time of Eq. (1), cf. [1]. This approach leads to

$$\widetilde{\tau}=\frac{1}{c_s^2}(\nu+\nu_t)+0.5, \tag{3}$$

where $c_s=1/\sqrt{3}$ is the lattice speed of sound of the D3Q27 scheme, ν is the viscosity of the fluid and ν_t is the turbulent eddy viscosity computed from the stress tensor.

3 NUMERICAL SET-UP

The studied flow configuration is the same as in [5]. It consists of a channel of $5.3H\times 3.5H\times H$ extensions, where $H=0.041\,\mathrm{m}$ is the height of the channel above the two spheres layers. Each sphere has a diameter of $0.012\,\mathrm{m}$. The reference height $z=0\,\mathrm{m}$ is located at the top of the spheres layers. The Reynolds number based on channel height and average flow velocity is $\mathrm{Re}_H=17,630$. Periodicity is applied in the x- and y-directions. The bottom boundary is a no-slip condition and a free-slip condition is used at $z=H$. Zero velocity on the spheres is enforced with interpolated bounce-back, implemented in AMROC through a ghost cell approach. A force is used to maintain the flow velocity.

The mesh is composed of three levels and the mesh size at the finest level is $\Delta x_f=1.5\times10^{-4}\,\mathrm{m}$. The time step at the finest level is $\Delta t_f=2.9\times10^{-5}\,\mathrm{s}$. The maximum

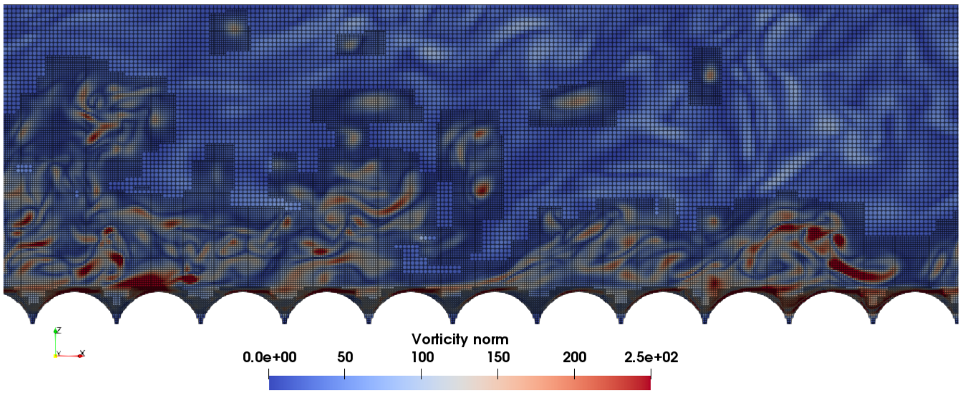

Figure 1: Instantaneous snapshot of the vorticity norm; xz-plane at $y = H/2$.

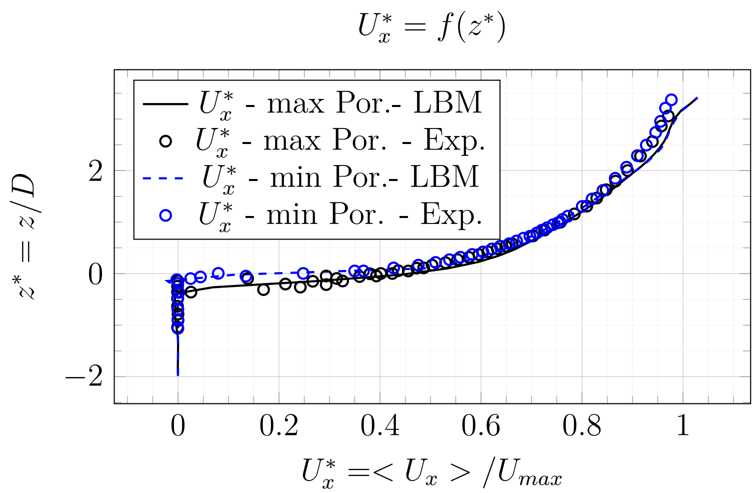

Figure 2: Average streamwise velocity in minimum and maximum porosity plane.

Mach number is approximately Ma $= 0.2$. The ratio between two levels is $\Delta x_c/\Delta x_f = \Delta t_c/\Delta t_f = 2$. Only the top of the spheres layers is refined at the finest level. The porous medium is refined at the intermediate level, as well as turbulent structures with high vorticity. The mesh has a total of $\sim 58 \times 10^6$ cells. The simulation has been run on 560 cores (2 GHz) and required 24,200 h CPU time to compute 1 s of simulated time.

4 RESULTS

Figure 1 shows the instantaneous vorticity norm in a plane of minimum porosity. The benefit of the AMR is clearly visible as turbulent structures with high vorticity are tracked and refined. Preliminary quantitative results are shown in Figs. 2 and 3. One can see that the outer flow close to the spheres layer is correctly computed. Some discrepancies are observed inside the spheres layers. It is probable that the mesh is still too coarse at the top of the spheres layer. Indeed, the dimensionless mesh size at the top of the spheres in the simulation is $\Delta z^+ \approx 4$, while it ideally should be equal to $\Delta z^+ = 1$. Moreover, the presently used constant coefficient Smagorinsky LES model does not return vanishing

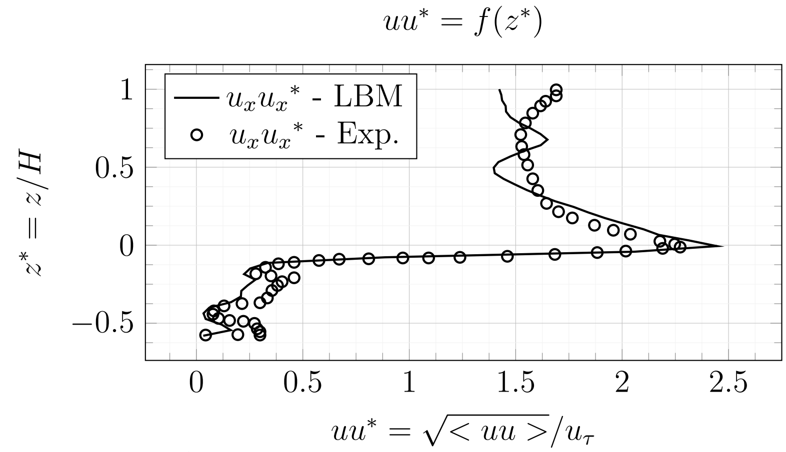

Figure 3: Average velocity fluctuations, x component.

turbulent eddy viscosity at the wall and would ideally be combined with a Van-Driest damping function close to the surfaces of the spheres, which might explain some of the differences.

5 CONCLUSIONS

Accurate modelling of a turbulent flow over a porous and rough medium has been achieved with an LBM-LES-AMR approach. Implementing a Van-Driest damping function should improve the results inside the spheres layers. Moroever, more advanced LES models are being developed for AMROC-LBM and could also be used, cf. [1].

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