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THE EFFECT OF TURBULENCE ANISOTROPY ON PARTICLE DEPOSITION IN PARTICLE-LADEN CHANNEL FLOW

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Abstract: *This work contains the study of turbulent particle-laden channel flow, in which the particles experience a drag force. The method used for simulation of the liquid phase was Large Eddy Simulation using approximate deconvolution method as a subgrid model. For tracking the dispersed phase were used Lagrangian equations of motion. The effect of turbulence anisotropy on motion of particles is obtained by adding the stochastic term into particle equation of motion. This term is proportional to the turbulent kinetic energy of each velocity component. The simulations were performed for various sizes of particles. The results are compared with the previous studies of LES particle-laden flows and DNS simulation. The anisotropic model proposed in this work shows improvement in prediction of turbulent statistics of particles and concentration of particles close to the wall.*

Keywords: ***Large Eddy Simulation, channel flow, particles, turbulence anisotropy.***

1. Introduction

In many technical applications we encounter with processes in which the dispersed phase (particles) is transported by the carrier phase (gas or liquid). In recent years the Large Eddy Simulation method has been improved so far that this method became fully applicable in most engineering applications concerning one-phase flow. So it is convenient to use this method for simulations of the carrier phase in two-phase flows.

Proper representation of turbulence in the near-wall region is very important in the Large Eddy Simulation of the two-phase flow. In this region, particle deposition occurs not only due to the impact of particles and gravity, but also due to turbulent diffusion. For this reason, it should be used an accurate subgrid model capable resolving near-wall region with sufficient accuracy. Another important issue is simulation of interaction of particles with fluid turbulence. The most used model for simulation of fluid-particle interaction is Eddy interaction Model (Gosman a Ioannides, 1981). However, this model shows overprediction of particles deposition in the near-wall region in combination with standard subgrid models, especially for particles with small relaxation time (Matida, 2000). This is caused by isotropic decomposition of turbulence kinetic energy. Wittig (1999) proposed three function for decomposition of turbulent kinetic energy to different direction in the near-wall region. Wang and Squires (1996) developed model, which solves additional transport equation in order to determine the velocity fluctuation close to the wall.

In this work is introduced new approach for including turbulence anisotropy and its impact on motion of particles. For the simulation of system fluid-particles was used Euler-Lagrange method. In the following sections are briefly described methods for solution of liquid and solid phase. Then is described test case used for validation of proposed model and introduced results obtained by this model.

2. Liquid phase

For the simulation of the liquid (carrier) phase was used Large Eddy Simulation method. The main idea of Large Eddy Simulation is to separate large scales (grid-scales) from small scales (subgrid-

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scales) in order to lower computational cost. The subgrid scales are modeled using subgrid model. The scale separation is done by applying filter operator on Navier-Stokes equation. If we apply the filter operator on Navier-Stokes equations we obtain filtered Navier-Stokes equations:

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_j \bar{u}_i}{\partial x_j} + \frac{\partial \bar{p}}{\partial x_i} - \frac{1}{Re} \frac{\partial^2 \bar{u}_i}{\partial x_k \partial x_k} = \frac{\partial \bar{u}_j \bar{u}_i}{\partial x_j} - \frac{\overline{\partial u_j u_i}}{\partial x_j}, \tag{1}$$

where $\bar{u}_i$ are filtered velocity components, $\bar{p}$ is filtered pressure and Re is Reynolds number of the flow. For the evaluation of the subgrid stress tensor (rand hand side of equation 1) is used here approximate deconvolution model proposed by Stolz (2001). The basis of approximate deconvolution model is replacement of the unfiltered velocity in subgrid stress tensor by an approximate defiltering of the filtered velocity:

$$\frac{\partial \bar{u}_j \bar{u}_i}{\partial x_j} - \frac{\overline{\partial u_j u_i}}{\partial x_j} \approx \frac{\partial \bar{u}_j \bar{u}_i}{\partial x_j} - \frac{\overline{\partial u_j^\star u_i^\star}}{\partial x_j}$$

The approximate doconvolution of $u_i^\star$ is given by applying the approximate deconvolution operator to $\bar{u}_i$:

$$u_i^\star = Q_N * \bar{u}_i,$$

where

$$Q_N = \sum_{\nu=0}^{N} (I - G)^\nu \approx G^{-1}$$

and G is the filter operator and I is identity operator. In our simulation we used $N = 5$.

3. Solid phase

The motion of particles is described by Lagrangian equations of motion for each particle. The only force considered here is drag force. Because of low concentration of particles we do not consider the influence of particles on the fluid. So it is used so called one-way coupling. The equation of motion for particle is:

$$\frac{\mathrm{d}\boldsymbol{v}_j}{\mathrm{d}t} = \frac{\boldsymbol{u}(\boldsymbol{x}_j, t) - \boldsymbol{v}_j}{\tau_p} \left(1 + 0.15 Re_p^{0.687}\right), \tag{2}$$

where $\boldsymbol{v}_j$ is velocity of j-th particle, $\boldsymbol{u}(\boldsymbol{x}_j, t)$ is velocity of fluid on particle position $\boldsymbol{x}_j$, $\tau_p = \rho_p d_p^2 / (18 \rho_f \nu)$ is particle relaxation time. The standard drag correlation for particles with particle Reynolds number $\mathrm{Re_p}$ is not small compared to 1 is applied.

In order to include the effect of turbulence anisotropy we proposed following model. The velocity on the particle position is evaluated as:

$$u_i = \bar{u}_i + X \sqrt{\overline{u_i^{\star 2}} - \bar{u}_i^2}, \qquad i = x, y, z \tag{3}$$

where the root square on the right hand side represents the estimation of subgrid kinetic energy of i-th velocity component and X is the normal Gaussian random variable.

4. Results and discussion

The effect turbulence anisotropy on particles proposed in this work was studied on case of particle-laden channel flow. This study is based on work (Kuerten, 2006). It was used the same geometry and flow conditions. More information can be found in this work. Simulation are performed for Reynolds number $\mathrm{Re}_\tau = 150$. The channel has dimensions 4π x 2 x 2π (length x height x width). The computational grid consists of 33 Chebyshev collocation modes in wall-normal direction, 32 Fourier modes in streamwise direction and 64 in the spanwise direction. The simulations were done in in-house developed code.

The simulations were carried out for three different particles with different Stokes number (defined as $St = \tau_p^+ = \tau_p u_\tau^2/\upsilon$) of 1, 5 and 25. The results are compared with results of LES and DNS simulations presented in (Kuerten, 2006). Full line represents DNS data, triangles refer to the LES simulation without anisotropic model. Here proposed anisotropic model is referred in the following paragraphs and graphs as LES anisotropic model.

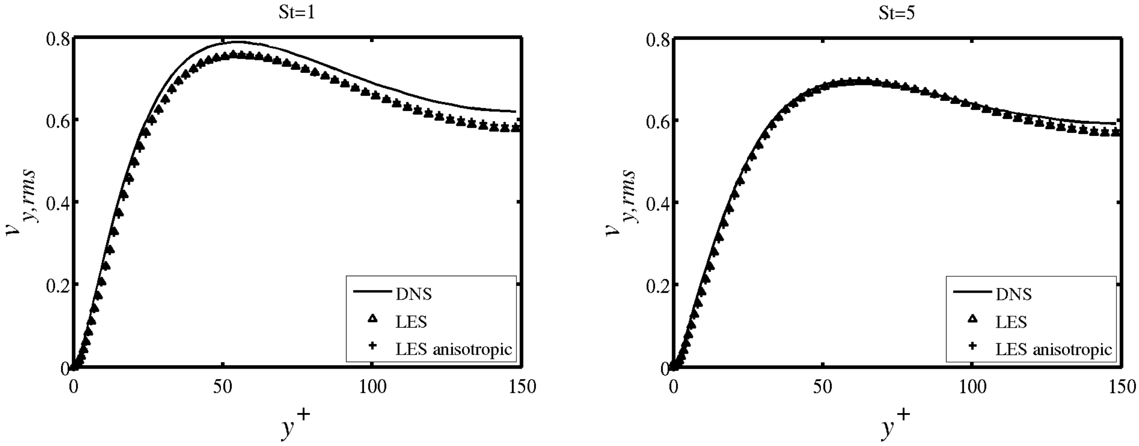

Fig. 1: Wall-normal component of particle velocity fluctuation of particles with Stokes number St = 1 and St = 5.

The wall-normal velocity fluctuations of particles are depicted on Fig. 1. The accurate prediction of this quantity is very important, because the particle deposition is directly influenced by this variable. The figure illustrates well-known fact, that the particle velocity fluctuation decrease with increasing Stokes number (the motion of heavier particles is more "smooth"). From the figure is evident, that the inclusion of the turbulence anisotropy has favorable effect. The error of prediction of this quantity is smaller with anisotropic model than with model neglecting the anisotropy of turbulence.

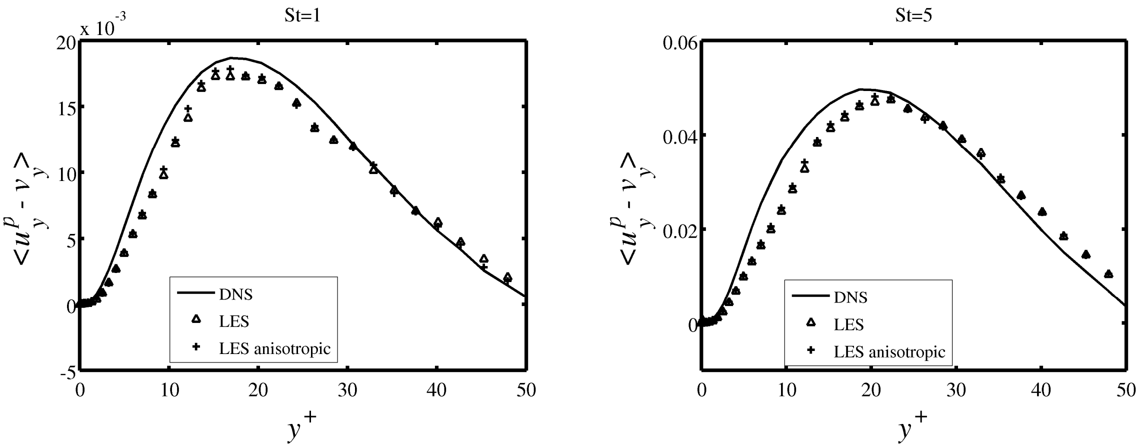

Fig. 2: Mean relative velocity of particles with Stokes number St = 1 and St = 5.

In Fig. 2 are y-components (wall-normal) of mean relative velocities of particles across the channel. The anisotropic model shows better agreement with DNS results than model without anisotropic decomposition. The difference between models is very small.

The nonzero mean wall-normal particle velocity fluctuation leads to accumulation of particles near to the walls of the channel. Fig. 3 shows the development of concentration of the particles near the wall in time. For this propose the computational domain was divided in 40 equidistant strips parallel to the wall and particles in the strips closest to the wall are counted. For Stokes number 1 both models overpredict the concentration. For Stokes number 5 and time $t^+ < 1 \cdot 10^4$ the concentration predicted by LES with and without including turbulence anisotropy model are almost identical, but for time $t^+ > 1.2 \cdot 10^4$ there is good agreement of LES anisotropic model with DNS.

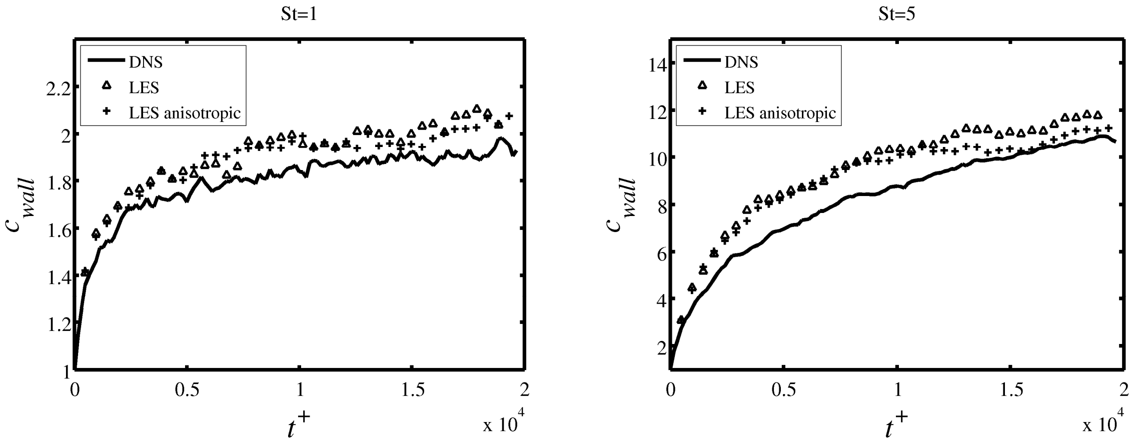

Fig. 3: Concentration of particles close to the wall

5. Conclusions

The modified model for particle motion in two phase flows (fluid + particles) was introduced in this work. This model includes the effect of turbulence anisotropy. Turbulence anisotropy becomes significant in the near-wall region. This effect was obtained by adding special term into particle equation of motion. This term is proportional to subgrid kinetic energy of corresponding velocity component. Here proposed model was tested on case of turbulent particle-laden channel flow. Model shows good results in combination with Large Eddy Simulation for solution of carrier phase and approximate deconvolution model for representation of subgrid scales. It was achieved improvement in prediction of turbulence statistics of particles, especially wall-normal component of velocity fluctuation. Better prediction of this quantity consequently leads to the more accurate estimation of particle concentration close to the walls. So the model is applicable for wall-bounded particle-laden flows.

Acknowledgement

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