THE EFFECT OF SUBGRID SCALES ON MOTION OF PARTICLES IN PARTICLE-LADEN CHANNEL FLOW (ENGLISH)

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Abstract

The effect of subgrid scales on motion of particles is studied in this work. The case of particle-laden channel flow was chosen as a test case. The method used for simulation of the transport (liquid) phase was Large Eddy Simulation using approximate deconvolution method [1] as a subgrid model. The dispersed phase (particles) was treated by Lagrangian approach. To Lagrangian equations of motion describing the motion of particles was added an additional stochastic term in order to include the effect of subgrid scales on particles. This term is proportional to the subgrid kinetic energy. The simulations were performed for various size of particles. The results are compared with the previous studies of LES particle-laden flows and DNS simulation done by Kuerten [2]. The stochastic model proposed in this work shows improvement in prediction of turbulent statistics of particles and concentration of particles close to the wall.

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 method of Large Eddy Simulation 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. In most Large Eddy Simulations of particle-laden flows is assumed that the effect of subgrid scales on particles is negligible, i. e. for calculation of the velocities seen by particle are used the filtered velocities. This assumption breaks down if the particle relaxation time is very small or the subgrid kinetic energy is significant.

Liquid phase

For simulation of the liquid phase is used Large Eddy Simulation method. The main idea of Large Eddy Simulation is to separate large scales (grid-scales) from small scales (subgrid-scales) to lower computational cost. The subgrid scales are modelled 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:

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

The main idea of approximate deconvolution model [1] is to approximate the unclosed term on rhs of equation (1) this way:

$$\frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} - \overline{\frac{\partial u_i u_j}{\partial x_j}} \approx \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} - \overline{\frac{\partial u_i^\star u_j^\star}{\partial x_j}}. \tag{2}$$

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

$$u_i^\star = Q_N * \bar{u}_i, \qquad \text{where} \qquad Q_N = \sum_{\nu=0}^{N} (I - G)^\nu \approx G^{-1} \tag{3}$$

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

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 to the fluid. The equation of motion for particle is:

$$\frac{\mathrm{d}\mathbf{v}_j}{\mathrm{d}t} = \frac{\mathbf{u}(\mathbf{x}_j, t) - \mathbf{v}_j}{\tau_p} \left(1 + 0.15\mathrm{Re}_p^{0,687}\right), \tag{4}$$

where $\mathbf{v}_j$ is velocity of j-th particle, $\mathbf{u}(\mathbf{x}_j, t)$ is velocity of fluid on particle position $\mathbf{x}_j$, $\tau_p = \rho_p d_p^2/(18\rho_f \nu)$ is particle relaxation time. The standard drag correlation is applied.

In order to include the effect of the subgrid scale, many models could be found in literature. Shotorban [4] used model based on adding additional equation to equations (4) in order to obtain velocity seen by particle with effect of subgrid scales. Similar approach is used in [5]. Sankaran [3] achieve the effect of subgrid scales by adding additional stochastic term in equations (4). This term is proportional to rms of subgrid kinetic energy multiplied by random variable with normal Gauss distribution (zero mean, unit variance). Slightly modified approach is used here. The velocity of fluid on particle position in (4) is computed as

$$u_i = \bar{u}_i + X\sqrt{\overline{u_i^2} - \bar{u}_i^2}, \qquad\qquad i = x, y, z, \tag{5}$$

where the rms on the rhs of (5) represents the subgrid kinetic energy of i-th velocity component and X is the normal Gaussian random variable.

Description of main results obtained

The effects of subgrid modeling in particle equations of motion proposed in this work were studied on case of particle-laden channel flow. This study is based on work of Kuerten [2]. It is used the same geometry and flow conditions as in [2]. More information can be found in this work. Simulation are performed for Reynolds number Re_τ=150. The channel has dimensions $4\Pi \times 2 \times 2\Pi$ (length×height×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 carried out for three different particles with different Stokes number, defined as $St = \tau_p^+ = \tau_p u_\tau^2/\nu$, of 1, 5 and 25. The results are compared with results of LES and

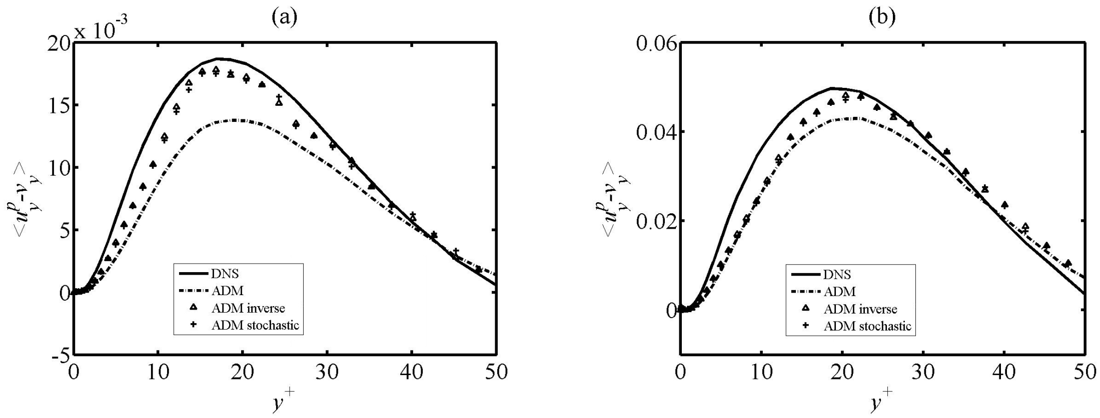

Figure 1: Mean relative velocity (a) St=1 and (b) St=5.

DNS simulations presented in [2]. Here proposed stochastic model is referred in the following paragraphs and graphs as ADM stochastic model.

In following paragrphs are graphs of chosen turbulent statistics and concentrations.

In figure 1 are y-components (wall-normal) of mean relative velocities of particles across the channel. The stochastic model shows good agreement with DNS results. The difference between stochastic and ADM inverse model is very small. The wall-normal velocity fluctuations of particles on figure 2 are also very close to the ADM inverse model. The results obtained using ADM stochastic model are slightly closer to the DNS data than ADM inverse model. In the field of turbulence statistics of particles were achieved little improvement.

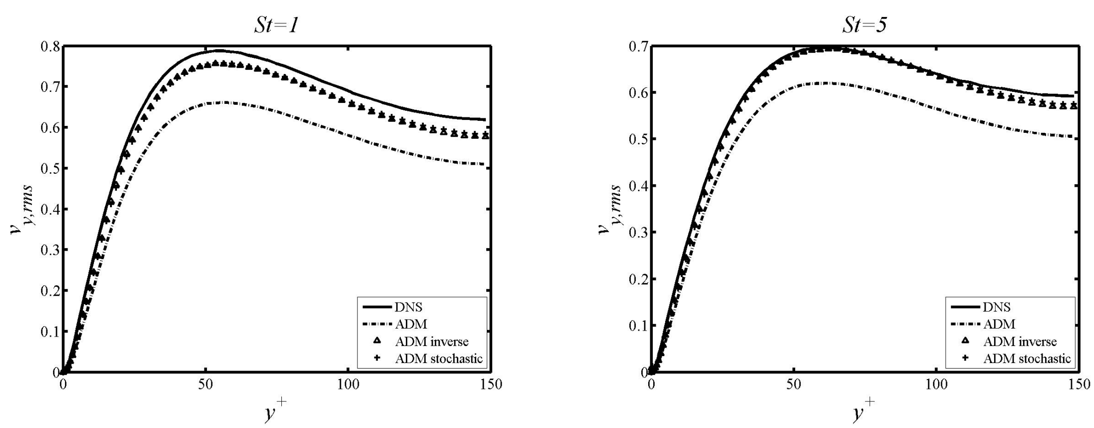

Figure 2: Wall-normal particle velocity fluctuations for St=1 and St=5.

Figure 3 shows the development in time of concentration of the particles near the wall. ADM stochastic models has similar behavior as ADM inverse model. For Stokes number 1 both model overpredict the concentration. For Stokes number 5 and time $t^+ < 1 \times 10^4$ the concentration predicted by ADM stochastic and ADM inverse model are almost identical but for time $t^+ > 1.2\times10^4$ there is good agreement of ADM stochastic model with DNS. For Stokes number 25 and time $t^+ > 1.3\times10^4$ the ADM stochastic model underestimate the concentration.

The concentration of particles in steady state across the channel is shown on figure 4. The results of ADM stochastic model are very similar to the results of ADM inverse model. For

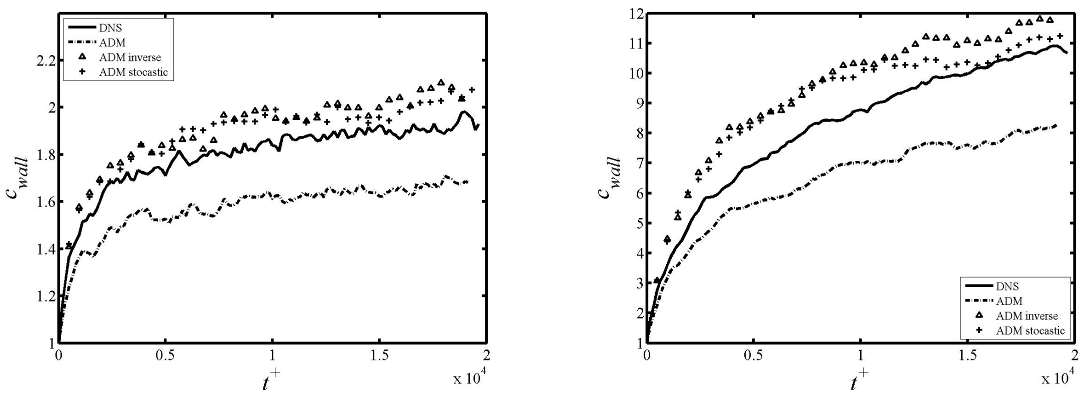

Figure 3: Concentration of particles close to the wall as a function of time for St=1, St=5.

Stokes number 5 the concentration predicted by ADM stochastic model is closer to the DNS than ADM inverse model.

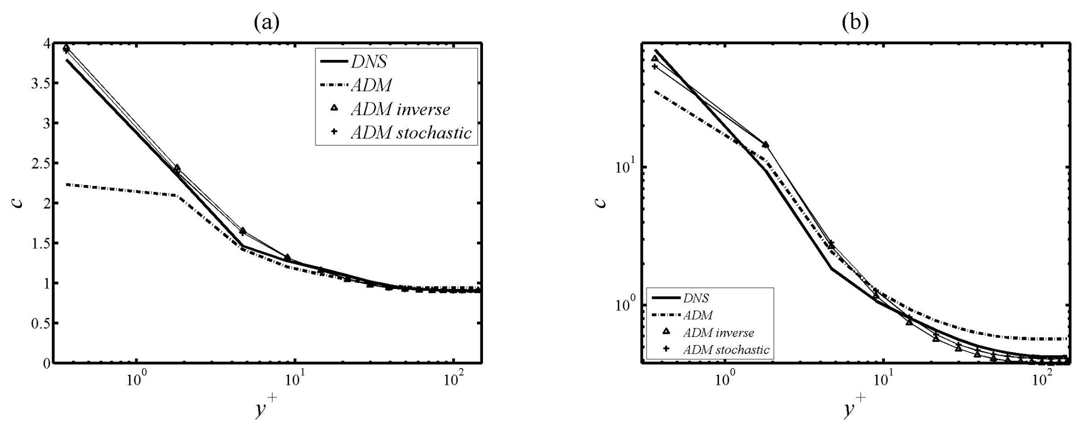

Figure 4: Concentration of particles close in the stationary state for (a) St=1 and (b) St=5

Summary

The stochastic model proposed in this work gives similar results as the ADM inverse model. The improvement in predicting concentration of particles were achieved especially for particles with Stokes number of 5.

Acknowledgments

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