NUMERICAL INVESTIGATION OF PARTICLES TURBULENT DISPERSION IN CHANNEL FLOW

by

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This paper investigates the performance of Reynolds-averaged Navier-Stokes model on dispersion of particles in wall turbulence. A direct numerical simulation of wall-bounded channel flow with particles suspensions was set as a benchmark. The standard k–ω model coupled with two different eddy interaction models was used in Reynolds-averaged Navier-Stokes model and compared to the direct numerical simulation. Detailed comparisons between direct numerical simulation and Reynolds-averaged Navier-Stokes model on particle distribution evolving over time were carried out.

Key words: *turbulent dispersion, eddy interaction model, particle distribution, direct numerical simulation*

Introduction

Turbulent particle-laden flow is a significant feature in many industry applications. One of the most widely used methods is Eulerian-Lagrangian approach. Taking the advantage of complete fluid velocity information from direct numerical simulation (DNS), treatment of the particle tracking becomes straightforward. Turbulent dispersion of particles is explicitly obtained by drag through the fluid velocity fluctuations. Eaton *et al.* [1] performed the DNS and experiments on the particle preferential concentration in turbulence. Marchioli *et al.* [2] found that sweeps and ejections are efficient transfer mechanisms for particles. Lin *et al.* [3] explored the effect of Stokes number, density ratio and aspect ratio on the particle spatial and orientation distributions. Yamamoto *et al.* [4] performed a four-way coupled large eddy simulations (LES) in a vertical channel and obtained a good agreement with experimental data. Yu *et al.* [5, 6] performed a LES on nanoparticle coagulation in the planar jet flow and on nucleated vehicle exhaust particulate. However, both DNS and LES are time consuming. More commonly, empirical equations or Reynolds-averaged Navier-Stokes (RANS) models are chosen. Unfortunately, due to lack of turbulent velocity fluctuations information, turbulent dispersion of particles has to be modeled. Lin *et al.* [7] adopted a Fourier series and studied orientation distribution of fibers immersed in turbulent pipe flows. Zhang *et al.* [8] and Lin *et*

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al. [9] assumed the fluctuating velocities of the fluid as a random variable with Gaussian distribution and investigated the orientation of cylindrical particles in a turbulent T-shaped branching channel flow and a turbulent contraction flow. Smith *et al.* [10] studied particle motion using diffusion force. However, in the model a diffusion coefficient is obscure and usually difficult to be determined. To overcome this, a novel approach called stochastic particle dispersion model was presented. Eddy interaction models (EIM) has been widely applied and also plenty of modified EIM models were proposed. Graham [11] developed an improved EIM model with random length and time scales. Chen [12] studied particle dispersion in inhomogeneous, anisotropic turbulent flows by using Reynolds-stress transport model. Agnihotri *et al.* [13] presented an anisotropic EIM and studied mono-disperse aerosols in a simplified human upper airway and a 90° bend pipe. Among the literatures mentioned above, detailed comparison between DNS and RANS model results on particle distribution is rarely reported. The present study aims to evaluate the performance of RANS model with EIM by comparing the results of particle distribution obtained by DNS.

Modeling approach

The standard k–ω model with low Reynolds number corrections is used to simulate the fluid phase. The trajectories of particle are solved in a Lagrangian frame. The only force taken into account is the Stokes drag $\boldsymbol{F}$. The dispersion of particles is caused by the fluid fluctuation velocity $\boldsymbol{u}'_f$. By using Reynolds decomposition of the fluid velocity, the force acting on the particle is decomposed as $\boldsymbol{F} = 3\pi\mu d(\boldsymbol{u}_f - \boldsymbol{u}_p) = 3\pi\mu d(\boldsymbol{U}_f - \boldsymbol{u}_p) + 3\pi\mu d\boldsymbol{u}'_f$ (μ is the viscosity of the fluid, d – the particle diameter, $\boldsymbol{u}_f$ – the fluid velocity, $\boldsymbol{U}_f$ – the fluid mean velocity, and $\boldsymbol{u}_p$ – the particle velocity). EIM simulates the turbulent dispersion of particles as a succession of interactions between fluid eddies and particles, in which the interaction time t_{int} and velocity fluctuations $\boldsymbol{u}'_f$ both need to be modeled. For t_{int}, the eddy lifetime t_{e} and the particle crossing time t_{c} should be calculated firstly: $t_{\mathrm{e}} = -C_l \ln(r)(k/\varepsilon)$ and $t_c = -\tau_{\mathrm{p}} \ln[1 - (l_e/u_{\mathrm{rel}}\, \tau_{\mathrm{p}})]$ (C_l is a coefficient, r – a random number between 0 and 1, τ_{p} – the particle relaxation time, l_e – the eddy length scale, and u_{rel} – the relative velocity between local fluid and particle). By using t_{c} and t_{e}, the t_{int} can then be determined as $t_{\mathrm{int}} = t_e$, if $u_{\mathrm{rel}} < l_e/\tau_{\mathrm{p}}$, otherwise, $t_{int} = \min(t_{\mathrm{e}}, t_{\mathrm{c}})$. The fluid velocity fluctuations $\boldsymbol{u}'_f$ in terms of Cartesian components are modeled as $u' = v' = w' = \xi\,(2k/3)^{1/2}$, where ξ is a Gaussian random number with zero mean and unit standard deviation. After an interaction time t_{int}, a new value of the velocity fluctuations is obtained by applying a new random number.

Anisotropic eddy interaction model

The original EIM model is based on an isotropic assumption. However, the flow field is indeed not isotropic in wall turbulence. By using damping functions, Wang *et al.* [14] provided a modified EIM which can account for the effects of anisotropy. The damping functions are given by Kim *et al.* [15] and Mansour *et al.* [16]. The fluid velocity fluctuations with the damping functions are [15]: $u' = f_u\xi(2k/3)^{1/2}$, $v' = f_v\xi(2k/3)^{1/2}$, $w' = f_w\xi(2k/3)^{1/2}$, $f_u = 1 + 0.285(y^+ + 6)\exp[-0.455(y^+ + 6)^{0.53}]$, $f_v = 1 - \exp(-0.02\, y^+)$, $f_u = (3 - f_u^2 - f_v^2)^{1/2}$, and y^+ is the dimensionless wall distance). The interaction time as discussed above is modeled in the same manner, including the definitions of the eddy life time and particle crossing time.

Numerical set-up

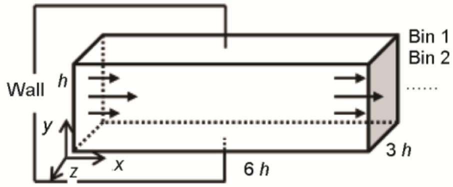

Figure 1. Sketch of the channel model

Figure 1 shows the calculation domain. Apart from non-slip boundaries of the upper and lower walls, all the other boundaries are imposed with periodic boundary conditions. The turbulent channel flow was driven by a constant pressure gradient with $\mathrm{Re}_\tau = 360$ [17]. The Re_τ is defined as $\mathrm{Re}_\tau = U_\tau h/\nu$ (U_τ is the friction velocity, h – the channel height and ν – the kinematic viscosity of the fluid). The pseudo-spectral DNS code consists of 192^3 grid nodes. The mesh contains 31 × 41 × 31 grid points. The particle initial velocity equals to local fluid velocity. The dimensionless relaxation time τ^+ is 30, particle dimensionless diameter d^+ – 0.72, density ratio ρ_p/ρ_f – 1041.7 (ρ_p – the particle density, ρ_f – the fluid density), and the total number of particles N_p is 10^5.

Results and discussions

To enable an in-depth exploration of turbulent dispersion of particles, the channel was evenly divided into 20 bins in wall-normal direction as shown in fig. 1. The number of particles in each bin was counted and results from bin 1, 4, 7, and 10 are shown in fig. 2. Because of the symmetrical channel, a clear picture of particle distribution evolution can be constructed by the information from those four bins.

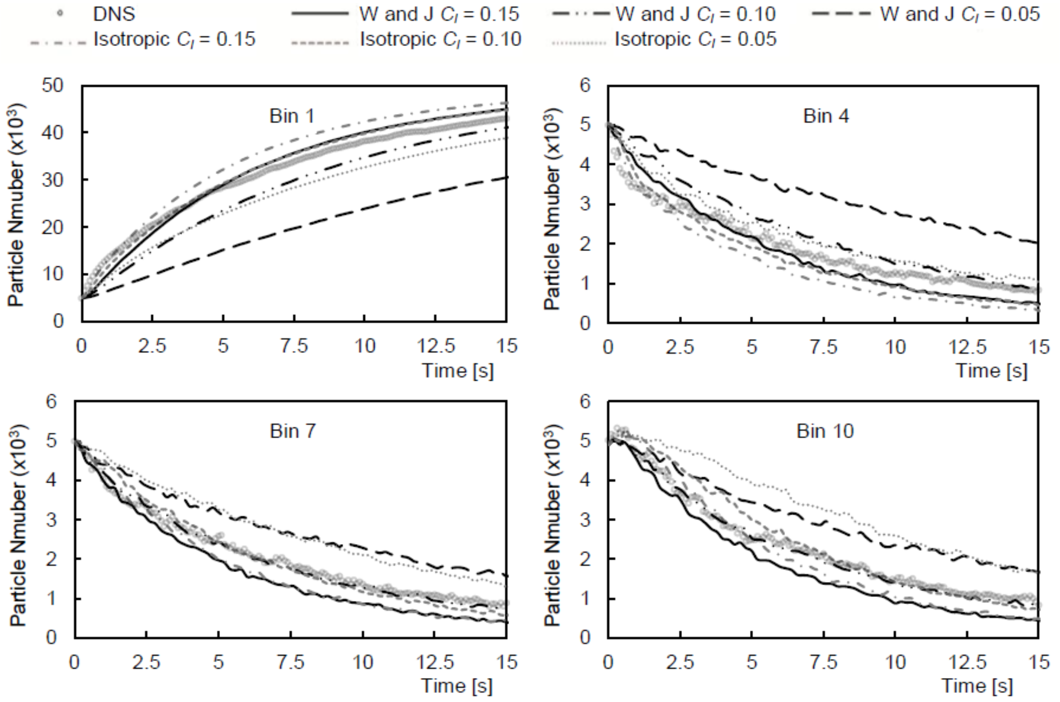

Figure 2. Particle distribution evolution (W and J stands for EIM [14] and isotropic is original EIM)

As shown in fig. 2, a steady increase of the particle number in Bin 1, which is closest to the wall, can be observed. The particle numbers in other bins decreased, *i. e.*, particles in the channel center tend to migrate to the wall. According to the data in fig. 2, the particle numbers in selected bins predicted in EIM [14] is in better agreement with the DNS results than the results given by the original isotropic EIM. The velocity fluctuations in the original EIM cause great deviations of v'. It is the overproduction of v' which accelerates the particle dispersion rate by providing particles with a stronger drag force in wall-normal direction. Consequently, the particle numbers in Bin 4, 7, and 10 reduced faster than DNS result, while correspondingly particle number in Bin 1 increased much faster. With Fluent default setting ($C_l = 0.15$), neither the original EIM nor the EIM [14] can give satisfactory results of particle dispersion. A larger C_l could extend the interaction time between particle and fluid, which also indicates stronger turbulent dispersion effect. By adjusting C_l, the overall optimum is found around 0.10 for EIM [14].

Conclusions

It has been shown that the original isotropic EIM cannot fully reproduce the particle distribution development calculated by DNS. However, with EIM [14], RANS model can give more reasonable particle distribution prediction. By adjusting C_l, the optimal overall distribution trend was obtained when C_l equals to around 0.10 with EIM [14].

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