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Large Eddy Simulation of Particle Wake Effect and RANS Simulation of Turbulence Modulation in Gas-Particle Flows*

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Abstract The turbulence enhancement by particle wake effect is studied by large eddy simulation (LES) of turbulent gas flows passing a single particle. The predicted time-averaged and root-mean-square fluctuation velocities behind the particle are in agreement with the Reynolds-averaged Navier-Stokes modeling results and experimental results. A semi-empirical turbulence enhancement model is proposed by the present authors based on the LES results. This model is incorporated into the second-order moment two-phase turbulence model for simulating vertical gas-particle pipe flows and horizontal gas-particle channel flows. The simulation results show that compared with the model not accounting for the particle wake effect, the present model gives simulation results for the gas turbulence modulation in much better agreement with the experimental results
Keywords large eddy simulation, gas-particle flow, turbulence modulation

1 INTRODUCTION

Turbulence enhancement by the particle wake effect is an important aspect of gas-particle interaction. It is well known that the wake formation and shedding of vortices behind particles will induce gas turbulence. Significant advances toward the understanding of the mechanism of turbulence enhancement have been achieved. Yuan and Michaelides[1] proposed a semi-empirical mechanistic model, in which the velocity defect in the wake is responsible for the augmentation of gas turbulence and the work associated with the motion of a particle is responsible for the attenuation of gas turbulence. This model has not been used to predict practical gas-particle flows. Yarin and Hetsroni[2] utilized a similar idea, with more detailed description of the wake, but such an analysis has not been incorporated into conventional turbulence models for gas-particle flows. Kenning and Crowe[3] proposed a turbulence modulation model in gas-particle flows based on the work done by the particle drag and the dissipation based on a length scale corresponding to the inter-particle spacing. Yu and Zhou[4] proposed a turbulence enhancement model taking the particle diameter as the mixing-length, but the predicted results for gas-particle pipe flows gave only qualitative agreement with the experimental results.

Fundamental studies on particle-wake induced turbulence are conducted by many investigators. Most numerical predictions of separated flows passing over a sphere are obtained from Reynolds-averaged Navier-Stokes (RANS) modeling[5]. There is an increasing interest in the use of large eddy simulation (LES) to predict flows past a sphere[6], however, no statistical data of turbulence enhancement are given.

In this paper, the gas turbulent flows passing over a single particle is simulated using LES, and the prediction results of turbulence enhancement are compared with the experimental data and RANS modeling results, in order to validate a turbulence enhancement model by the particle wake effect. The proposed turbulence enhancement model is then incorporated into a second-order moment two-phase turbulence model to simulate vertical gas-particle pipe flows and horizontal gas-particle channel flows. The prediction results by the two-phase turbulence models taking and not taking into account the particle wake effect are compared with each other and with the experimental data.

2 LES OF TURBULENT GAS FLOWS PASSING A SINGLE PARTICLE

The gas turbulent flows passing over a single particle are simulated using LES. The filtered large-eddy continuity and momentum equations are

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_k}\left(\rho U_k\right)=0 \quad (1)$$

$$\frac{\partial}{\partial t}\left(\rho U_i\right)+\frac{\partial}{\partial x_k}\left(\rho U_i U_k\right)=\frac{\partial}{\partial x_k}\left(\mu \frac{\partial U_i}{\partial x_k}\right)-\frac{\partial \overline{p}}{\partial x_i}-\frac{\partial \tau_{ik}}{\partial x_k} \quad (2)$$

The Smagorinsky-Lilly model[7] is adopted for the sub-grid scale stress τ_{ik}, and LES is performed using a commercial Computational fluid dynamics (CFD) software—Fluent 6.1.

For the 3-dimensional computational domain, the

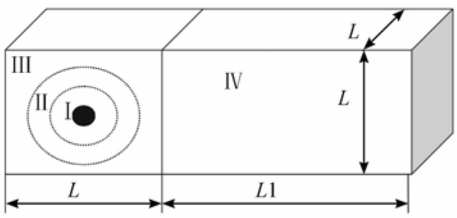

Figure 1 The computational domain

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size in the streamwise direction is about 30 times of the particle diameter D, and the width in transverse and spanwise directions are about 12 times of the particle diameter. In order to control the mesh distribution, the domain surrounding a particle is divided into four zones that have different mesh distribution, so that the grid points are clustered near the surface and in the wake region. A sphere is located at the origin of the three-dimensional Cartesian coordinate system, and the uniform inflow enters the domain in the direction parallel to the x-axis. Zone Ⅰ is a spherical volume of constant diameter $4D$ surrounding the sphere, and it is designed to have very fine grids, the size of mesh is set to about $D/14$, which is the smallest in the entire domain. Zone Ⅱ is a buffer region, which is also spherical with the diameter of $9D$, the size of mesh in this zone is about $D/8$. The size of the mesh in Zone Ⅲ and Zone Ⅳ is set to about $D/4$ throughout the computation. In LES, the time step is taken as 0.0012s. For each time step the convergence can be reached after about 20 iterations. For the numerical procedure, the PISO algorithm[8] is used for p-v corrections, the second order implicit difference scheme for the time-dependent term, the QUICK (second order) difference scheme for the convection term and the central difference scheme for the diffusion term are adopted. Running a case in a PC computer with a 2G EMS memory and double 2.8G CPU needs about two months to make the flow field reaching a statistical steady state.

3 LES RESULTS AND DISCUSSION

For gas flow passing over a particle[9], the inlet air velocity is 1.82m·s^{-1}, the turbulence intensity is 0.039, the air kinematic viscosity is 1.67×10^{-5}m^2·s^{-1}, the particle diameter is D=5.6×10^{-3}m, the particle Reynolds number is 610. Figs.2 to 4 show the LES predicted gas time-averaged, root-mean-square (RMS) fluctuation velocities and turbulence kinetic energy in the region behind the particle on the axis and their comparison with the RANS modeling (using Reynolds stress model) results. For RANS modeling, the air density is 1.2kg·m^{-1} and the dynamic viscosity is 1.8×10^{-5}kg·m^{-1}·s^{-1}. The particle diameter is 1.0mm, the inlet air streamwise velocities is in the range 6—13m·s^{-1}, and the particle diameter is in the range of 0.7—1.2mm. The 3-D computational domain and the setting of mesh are similar to those in LES. It can be seen that the two models give almost the same time-averaged velocity (Fig.2). Qualitatively, the predicted gas RMS fluctuation velocity and turbulent kinetic energy by LES and RANS modeling has similar distribution (Figs.3 and 4).

Figure 5 gives instantaneous vorticity maps at different time instants, showing the asymmetrical vortex structures behind the particle.

4 TURBULENCE ENHANCEMENT MODEL

Figures 6 and 7 show the relationship of the turbulence enhancement due to particle wake effect based on RANS modeling results for a single particle.

In Fig.6, when the particle size keeps constant,

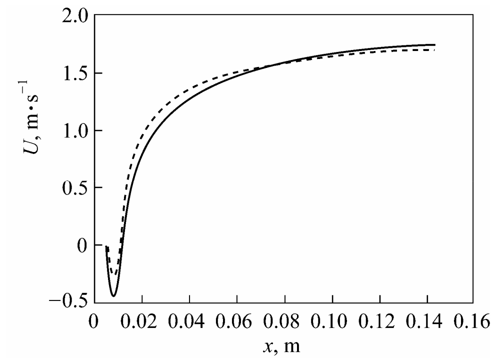


Figure 2 The gas time-averaged streamwise velocity behind the particle on the axis
– – – LES; —— RANS

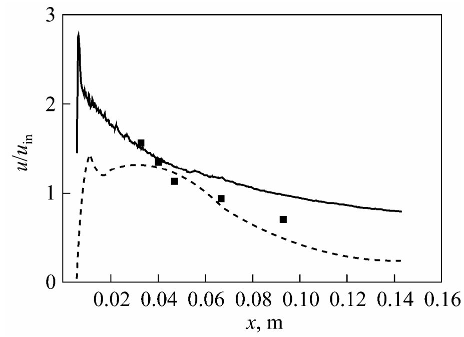


Figure 3 The RMS fluctuation velocity behind the particle on the axis
■ Exp.; – – – LES; —— RANS

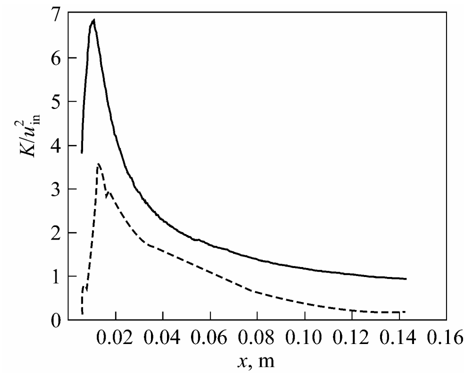
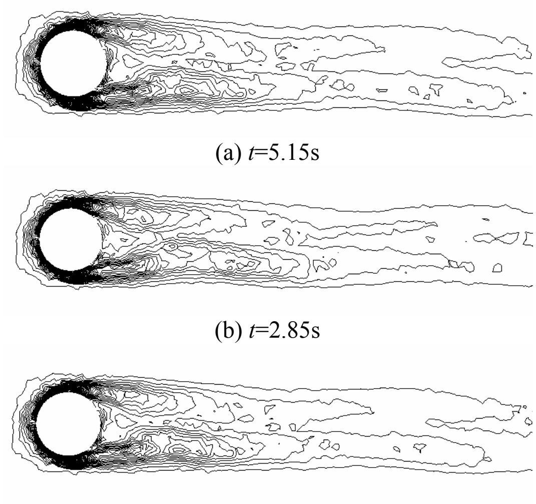


Figure 4 The turbulence kinetic energy behind the particle on the axis
– – – LES; —— RANS

such as d_p=1.0mm, the magnitude of the turbulence enhancement due to the wake effect increases with the increase of inlet velocity, it is approximately expressed by $\Delta K \propto U_{rel}^2$, where ΔK is the difference between the maximal turbulent kinetic energy behind the particle and the inlet turbulent kinetic energy. In Fig.7, when the inlet velocity keeps constant, such as U_{rel}=10 m·s^{-1}, the magnitude of turbulence enhancement increases with the increase of particle size roughly in a linear way, $\Delta K \propto d_p$. The increase of turbulence intensity by the particle wake effect for different inlet velocities and particle sizes can thus be summarized as



(a) t=5.15s

(b) t=2.85s

(c) t=0.58s

Figure 5 Vorticity maps

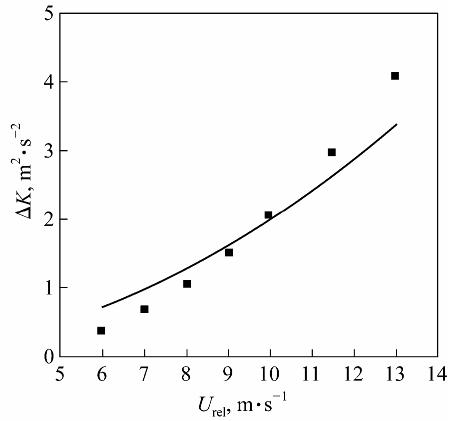


Figure 6 Turbulence enhancement for various inlet velocities (d_p=1.0mm)
■ calculation; —— fit line

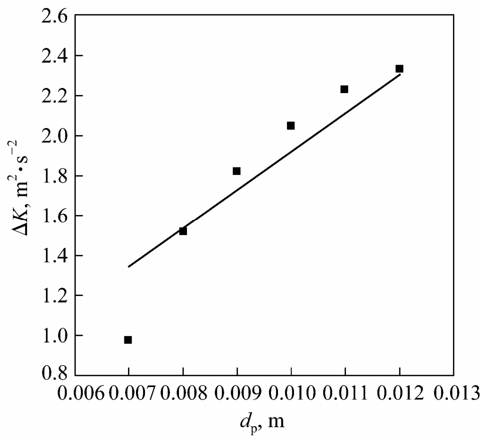


Figure 7 Turbulence enhancement for various particle sizes (U_{rel} = 10m·s^{-1})
■ calculation; —— fit line

$$\Delta K \propto U_{rel}^2 \cdot d_p$$

Based on the above-obtained results, accounting for the effect of both particle size and inlet velocity, we have the turbulence enhancement by a particle as

$$G_{pw} \propto U_{rel}^2 d_p \tag{3}$$

Equation (3) is valid for the effect of a single particle. For practical gas-particle flows with multiple particles, the production term should be directly proportional to number density n_p or the particle volume fraction:

$$\alpha_p = n_p \pi d_p^3 / 6 ,$$

so we have

$$G_{pw} \propto n_p U_{rel}^2 d_p \propto \frac{\alpha_p U_{rel}^2}{d_p^2}$$

The conventional particle source term (production/dissipation term) due to the existence of particles in the gas turbulent kinetic energy equation or Reynolds stress equation, in which particles are treated as point sources[10,11], is

$$G_p = \frac{\alpha_p \rho_p}{\tau_{rp}} \left(2\overline{v_{pi} v_i} - 2k_f \right) \tag{4}$$

Performing dimensional analysis and using the form given in Eq.(4), we proposed the following semi-empirical turbulence enhancement model by the particle wake effect as

$$G_{pw} = C \frac{\rho_p \alpha_p U_{rel}^2}{\tau_{rp}} \tag{5}$$

where the empirical constant C is taken as C=3.0. τ_{rp} is the particle relaxation time:

$$\tau_{rp} = \frac{\rho_p d_p^2}{18\mu_f \left(1 + Re_p^{2/3}/6\right)}$$

Re_p is the particle Reynolds number:

$$Re_p = \frac{\alpha_f \rho_f d_p \left| \boldsymbol{U}_f - \boldsymbol{U}_p \right|}{\mu_f} .$$

5 SIMULATION OF PRACTICAL GAS-PARTICLE FLOWS USING RANS MODELING WITH THE PARTICLE WAKE EFFECT

Now, as the second step, the turbulence enhancement model is incorporated into the second-order moment two-phase turbulence model[11,12] for simulating practical gas-particle flows. In the present model, the gas Reynolds stress equation with the particle source terms accounting for the wake effect should be

$$\frac{\partial\left(\overline{\alpha_f}\rho_f \overline{u_{fi}u_{fj}}\right)}{\partial t} + \frac{\partial\left(\overline{\alpha_f}\rho_f U_{fk} \overline{u_{fi}u_{fj}}\right)}{\partial x_k} = D_{f,ij} + P_{f,ij} + \Pi_{f,ij} - \varepsilon_{f,ij} + G_{fp,ij} + G_{pw}\delta_{ij} \tag{6}$$

The transport equation of the dissipation rate of gas turbulent kinetic energy is

$$\frac{\partial\left(\overline{\alpha_f}\rho_f \varepsilon_f\right)}{\partial t} + \frac{\partial\left(\overline{\alpha_f}\rho_f U_{fk} \varepsilon_f\right)}{\partial x_k} =$$

$$\frac{\partial}{\partial x_k}\left(C_{\mathrm{f}}\overline{\alpha_{\mathrm{f}}\rho_{\mathrm{f}}}\frac{k_{\mathrm{f}}}{\varepsilon_{\mathrm{f}}}\overline{u_{\mathrm{f}k}u_{\mathrm{f}l}}\frac{\partial \varepsilon_{\mathrm{f}}}{\partial x_l}\right)+$$
$$\frac{1}{\tau_{\mathrm{e}}}\left[C_{\varepsilon 1}\left(P_{\mathrm{f}}+G_{\mathrm{f,fp}}\right)-C_{\varepsilon 2}\bar{\alpha}_{\mathrm{f}}\rho_{\mathrm{f}}\varepsilon_{\mathrm{f}}\right]+\frac{\varepsilon_{\mathrm{f}}}{k_{\mathrm{f}}}C_{\varepsilon 3}G_{\mathrm{pw}} \quad (7)$$

where

$$C_{\varepsilon 3}=1.8^{[13]},\quad \tau_{\mathrm{e}}=\min\left(\tau_{\mathrm{rp}},k_{\mathrm{f}}/\varepsilon_{\mathrm{f}}\right).$$

The terms on the right-hand side of Eqs.(6) and (7) are given in Ref.[10,11]. The boundary conditions can be found in Ref.[13,14], taking into account the particle collision with rough walls.

6 SIMULATION RESULTS FOR GAS-PARTICLE FLOWS

The proposed model is at first used to simulate vertical gas-particle flows, measured by Tsuji *et al.*[15]. The pipe inner diameter is D=30.5mm, the mean air velocity is in the range of 8—20m·s^{-1}, three kinds of particles (0.2mm, 0.5mm, 1mm) were used as the particle phase with the particle density 1020kg·m^{-3}, and the mass loading ratio up to 5. The measurements were performed at a distance of 5.11m from the entrance. Figs.8 to 10 give the RMS gas fluctuation velocities for different sizes of particles. It is found that the results obtained using the model accounting for the particle wake effect are in much better agreement with the experimental results than those obtained using the model not accounting for the particle wake effect in predicting the following phenomena: 0.2mm particles attenuate gas turbulence, 0.5mm particles enhance or attenuate gas turbulence at different locations, and 1mm particles enhance gas turbulence intensity.

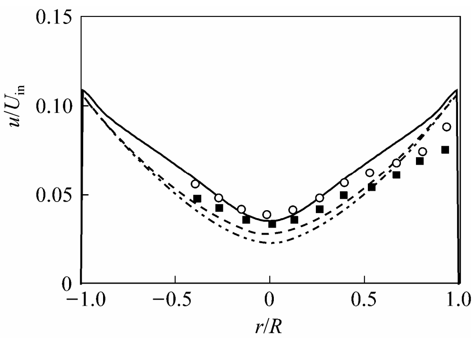


Figure 8 Air turbulence intensity of 0.2mm particles
○ experiment m=0, U_{in}=13.4m·s^{-1}; ■ experiment m=0.5, U_{in}=13.1m·s^{-1}; —— m=0, U_{in}=13.4m·s^{-1}; - - - m=0.5, U_{in}=13.1m·s^{-1} (wake effect); - - - - m=0.5, U_{in}=13.1m·s^{-1} (no wake effect)

The proposed model is then used to simulate horizontal gas-particle channel flows for low roughness, measured by Kussin and Sommerfeld[16]. The channel is 6m long with height of 35mm, particles have a density of 2500kg·m^{-3}, mean particle diameter of 100μm, mass loading of 0.3, the average inlet velocity is $\bar{u}_{\mathrm{in}}$ =19.7m·s^{-1}. The measurements were performed near to the end of the channel at a distance

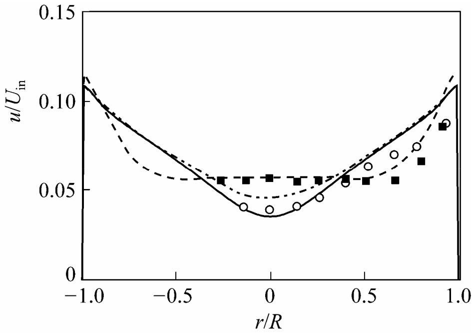


Figure 9 Air turbulence intensity of 0.5mm particles
○ experiment m=0, U_{in}=13.4m·s^{-1}; ■ experiment m=3.4, U_{in}=10.7m·s^{-1}; —— m=0, U_{in}=13.4m·s^{-1}; - - - m=3.4, U_{in}=10.7m·s^{-1} (wake effect); - - - - m=3.4, U_{in}=10.7m·s^{-1} (no wake effect)

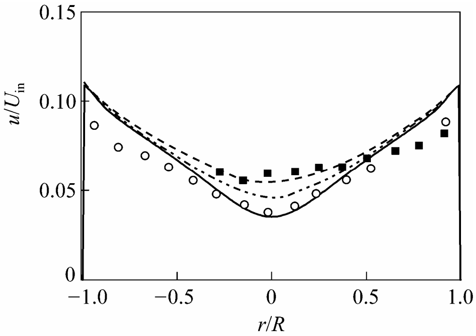


Figure 10 Air turbulence intensity of 1mm particles
(U_{in}=13.4m·s^{-1})
○ experiment m=0; ■ experiment m=0.6; —— m=0; - - - m=0.6 (wake effect); - - - - m=0.6 (no wake effect)

of 5.8m from the entrance, to ensure almost fully developed flow conditions.

Figures 11 to 13 show the predicted gas streamwise time-averaged velocity and RMS streamwise and transverse fluctuation velocities respectively. The particle wake effect almost has no effect on the gas time-averaged velocity (Fig.11). For the gas RMS fluctuation velocities, the present model gives much better simulation results than the model not taking into account the particle wake effect (Figs.12 and 13).

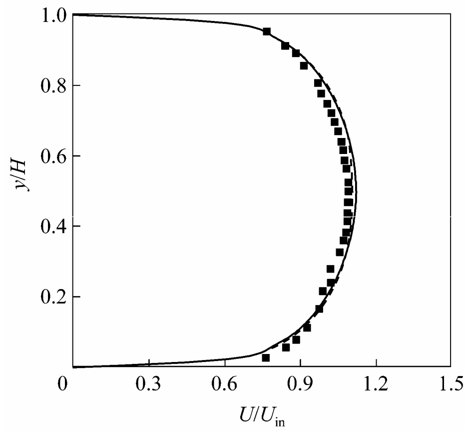


Figure 11 Gas streamwise time-averaged velocity
■ experiment; —— without wake effect; - - - with wake effect

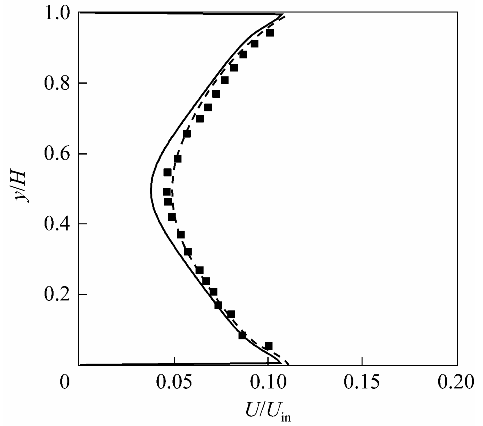


Figure 12 Gas streamwise RMS fluctuation velocity
■ experiment; —— without wake effect; - - - with wake effect

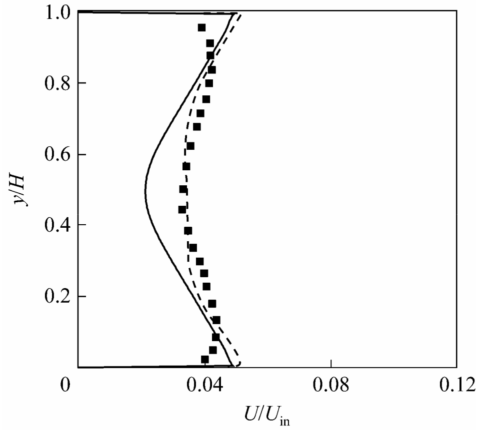


Figure 13 Gas transverse RMS fluctuation velocity
■ experiment; —— without wake effect; - - - with wake effect

7 CONCLUSIONS

(1) The LES of gas turbulent flow passing a single particle gives reasonably the wake effect on gas turbulence.

(2) A semi-empirical turbulence enhancement model is proposed

(3) For practical gas-particle flows, the model accounting for the particle wake effect can simulate well the gas turbulence modulation, giving much better prediction results than the model not accounting for this effect.

NOMENCLATURE

C	model constant
D, d	diameter, m
G	source term in equation
H	height, m
K	turbulent kinetic energy, $m^2 \cdot s^{-2}$
m	mass loading ratio
R	radius, m
Re	Reynolds number
t	time, s
U	mean velocity components, $m \cdot s^{-1}$
u, v	fluctuation velocity components, $m \cdot s^{-1}$
$\overline{u}$	pressure-strain term
x,y,r	coordinates, m
α	volume fraction
ε	turbulent kinetic energy dissipation rate, $m^2 \cdot s^{-3}$
μ	molecular viscosity, Pa·s
ρ	density, $kg \cdot m^{-3}$
τ_e	effective character timescale, s
τ_{rp}	particle relaxation time, s

Superscripts

—	temporal average

Subscripts

f	gas phase
i,j,k,l	dimensional index
in	inlet
p	particle phase
rel	relative

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