Large Eddy Simulation of Particle-Laden Turbulent Channel Flow Considering SGS Coupling*

(A Proposal of Dynamic SGS Model for Two-Way Coupling)

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The paper presents a new dynamic SGS model of two-way coupling for large eddy simulation of particle-laden turbulent flow based on Yuu's model (1997). The advantage of this new model is that coupling of fluid-particles SGS components is taken into account and at the same time the coefficient of proposed SGS model can be optimized by Germano's (1991) dynamic procedure. To investigate the capability of this model, numerical simulations of particle-laden turbulent flow at $Re=644$ in a vertical channel were performed using this new dynamic SGS model and using Van Driest wall function. By comparing the calculation results with that of using single-phase SGS models, in which the coupling of SGS components was not considered, the present dynamic SGS model for two-way coupling was verified. In addition, the roles of particles GS and SGS components played in the turbulence modulation of fluid flow were clarified for particle-laden channel turbulent flows.

Key Words: Numerical Analysis, Multi-Phase Flow, Turbulent Flow, Computational Fluid Dynamics, Large Eddy Simulation, Dynamic SGS Model, Two Way Coupling, Turbulence Modulation

1. Introduction

In recent years, direct numerical simulation (DNS) and large eddy simulation (LES) have become powerful tools for the study of multiphase flow. Especially, the Eulerian-Lagrangian method has been

playing an important role in predicting the fluid turbulence modulation and particles diffusion for particle-laden turbulent flows. Rousson & Eaton (1994) performed DNS⁽¹⁾ of wall-bounded turbulent flow, and Wang & Squire (1996) carried out LES⁽²⁾ of that. They were all called one way coupling both of them didn't investigate the turbulence modulation by particles. Concerning two-way coupling LES of channel turbulent flows, Yamamoto & Tsuji⁽³⁾ (1999) studied the turbulence modulation by only considering the coupling of grid scale (GS) components. However, the effects of sub-grid scale (SGS) components coupling on turbulence modulation still remains an open question.

In LES of single-phase turbulent flows, one major deficiency of the Smagorinsky⁽⁴⁾ sub-grid scale (SGS) stress models is their inability to represent correctly with a single universal constant to different turbulent fields in rotating or sheared flows, near solid walls, or in transitional regimes. Usually additional modifications to the Smagorinsky model were made in

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the near-wall region to force the sub-grid scale stresses to vanish at the wall boundary with a standard Van Driest⁽⁵⁾ damping function. The dynamic SGS model proposed by Germano⁽⁶⁾ et al.(1991) overcomes these deficiencies by locally calculating the eddy viscosity coefficient to reflect closely the state of the flow. In LES of multi-phase turbulent flows, it is being expected that the fluid turbulence modulation SGS model can be evaluated by Germano's dynamic procedure as in the single-phase turbulent flows.

In particle-laden turbulent flow, a kind of multi-phase turbulent flows that occur in a wide range of engineering and scientific research, interaction of particles and gas-phase turbulent carrier flow is a problematic research topic of both fundamental importance and practical interest. In addition, it is the most interesting problem in developing numerical simulation models. A two-way coupling SGS model was presented by Yuu^{(7),(8)} (1997, 2000), in which the coupling of fluid-particles SGS components was considered. However, the model coefficient was simply decided in the same way as previous works for the single-phase turbulent flows.

We present here a new dynamic SGS model for two-way coupling LES of particle-laden turbulent flow based on Yuu's SGS model. The couplings of fluid-particles SGS component on fluid turbulence modulation in LES was taken into account and at the same time the coefficient of proposed SGS model can be dynamically decided by assuming that the small scales are in equilibrium, so that energy production, dissipation and interaction of fluid-particles are in balance.

The main objective of this paper is to introduce this model and at the same time to report the results of investigation on the capability and limitation of present SGS mode in predicting the fluid turbulence modulation for particle-laden turbulent flows through numerical simulations, which were performed in downward particle-laden turbulent flows at $Re=644$ in a vertical channel using Van Driest wall function model and the proposed new dynamic SGS model.

2. Governing Equation of Two-Way Coupling

2.1 Equation of particle motion

The motion of a small rigid sphere in a turbulent flow field is described by a complicated integro-differential equation. However, if the density of the particle is substantially larger than the density of the carrier fluid, and the diameter of particle is smaller compared to the Kolmogorov scale, we can suppose the particles are driven only by gravity and drag force, and then the equation of particle motion can be simplified. The dimensionless equation of particle

motion used in these simulations is

$$\frac{du_{pi}}{dt} = -\frac{f(u_{pi} - \bar{u}_i)}{\tau_p} + g_i \delta_{1i} \quad (1)$$

Where $\bar{u}_i$ are grid-scale (GS) velocity of fluid flow, u_{pi} are velocity of particles, $\tau_p = (\rho_p d_p^2) / (\rho_f 18\nu)$ is relaxation time of particle, $f = 1 + 0.15 Re_p^{0.687}$ is corrected Stokes coefficient, $Re_p = (d_p |u_p - u|) / \nu$ is particle Reynolds number, and g_i is acceleration due to gravity.

2.2 Equation of fluid flow

For dilute particle-laden flow, the particle volume fraction is very small but the particle mass loading ratio is large, in this case, the governing equation of particle-laden turbulent flow between plane channels driven by uniform pressure gradient and particles gravity can be described by using the incompressible Navier-Stokes equations with the particle source term.

$$\begin{aligned} \frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} (u_i u_j) &= -\frac{1}{\rho_f} \frac{\partial p}{\partial x_i} + \frac{\mu}{\rho_f} \frac{\partial^2 u_i}{\partial x_j \partial x_j} \\ &\quad - \frac{1}{\rho_f \Delta V} \sum_{p=1}^{n_p} \frac{f m_p (u_i - u_{pi})}{\tau_p} \\ &\cong -\frac{1}{\rho_f} \frac{\partial p}{\partial x_i} + \frac{\mu}{\rho_f} \frac{\partial^2 u_i}{\partial x_j \partial x_j} - n F (u_i - u_{pi}) \end{aligned} \quad (2)$$

In which $m_p = \pi \rho_p d_p^3 / 6$ is particle mass, n is particle number density, $F = 3\pi \mu d_p f / \rho_f$ is coefficient. Here the reaction of average drag force was added as a source term.

Filtering the N-S equations Eq.(2) orients the equations governing transport of the large eddies as following Eq.(3). Similar to the LES of the single-phase turbulence, the Leonard term and Cross term are neglected here.

$$\begin{aligned} \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j) &= -\frac{1}{\rho_f} \frac{\partial \bar{p}}{\partial x_i} + \frac{\mu}{\rho_f} \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} \\ &\quad - \frac{\partial \tau_{ij}}{\partial x_j} - F [N(\bar{u}_i - \bar{u}_{pi}) + \overline{n' u'_i} - \overline{n' u'_{pi}}] \end{aligned} \quad (3)$$

The last term on the right hand side of Eq.(3) is the particle source term, which indicates the two-way interaction from particles to fluid, and the effect of SGS on the resolved eddies in Eq.(3) is represented by SGS stress $\tau_{ij} = \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j$.

2.3 Modeling of SGS diffusion flux terms

In this study, the SGS diffusion flux terms $\overline{n' u'_i}$ and $\overline{n' u'_{pi}}$ adopt gradient model as presented in Eqs. (4) and (5).

$$\overline{n' u'_i} = -\nu_{TS} \frac{\partial N}{\partial x_i} \quad (4)$$

$$\overline{n' u'_{pi}} = -\nu_{TP} \frac{\partial N}{\partial x_i} \quad (5)$$

Where ν_{TS} is scalar diffusion coefficient of turbulence, it is modeled by turbulence Schmidt number σ_s and movement diffusion coefficient ν_T as follows.

$$\nu_{TS} = \frac{\nu_T}{\sigma_s} \quad (6)$$

The particle turbulence diffusion coefficient ν_{TP} is parameterized with Hinze's proposal⁽⁹⁾ below

$$\nu_{TP} = \frac{f T_{Li}}{f T_{Li} + \tau_p} \nu_T \quad (7)$$

Where f and τ_p are same as they are before. We suppose the eddy concerned in particle motion is energy contain eddy, then T_{Li} , the Lagrange continuance time of energy contain eddy could be modeled by Corrsin's expression⁽¹⁰⁾

$$T_{Li} = \frac{L_e}{(2k/3)^{1/2}} = \frac{\alpha_1}{C_\epsilon} \left(\frac{2}{3} k \right)^{1/2} \quad (8)$$

Because only the large eddies (GS component) are directly available in LES computation, the SGS turbulence energy k can be modeled as follows according to dimensional analysis⁽¹¹⁾

$$k = -\frac{C_\nu}{C_\epsilon^{2/3}} \Delta^2 (2 \bar{S}_{ij} \bar{S}_{ij}) = -\frac{C_\nu}{C_\epsilon^{2/3}} \Delta^2 |\bar{S}|^2 \quad (9)$$

Where $|\bar{S}| = \sqrt{2 \bar{S}_{ij} \bar{S}_{ij}}$ is the magnitude of strain velocity $\bar{S}_{ij}$, the filter width Δ is defined as $\Delta = (h_x h_y h_z)^{1/3}$, where h_x , h_y and h_z are the grid spacing in the x , y , z directions, respectively. Then substitute k into formula (8), the Lagrange continuance time T_{Li} can be parameterized below.

$$T_{Li} = \frac{\alpha_1}{C_\epsilon^{2/3} C_\nu^{1/2} \sqrt{2/3} |\bar{S}|} \quad (10)$$

Where L_e is the length scale of energy contain eddy, α_1 , C_ν , C_ϵ are the coefficients of model T_{Li} , in this study, we take the constant values of $\alpha_1 = 0.165$, $C_\nu = 0.05$ and $C_\epsilon = 1.0$.

2.4 Modeling of SGS stress

Similar to the LES of the single-phase turbulence, in this work, SGS stress τ_{ij} is parameterized using an eddy viscosity hypothesis as Eq.(11).

$$\tau_{ij} - \frac{1}{3} \delta_{ij} \tau_{kk} = -2 \nu_T \bar{S}_{ij} \quad (11)$$

Therefore, the problem here is how to model the eddy viscosity when the interaction between fluid and particle is taken into account.

3. Improvement of Two-Way Coupling SGS Model

The governing equation of kinetic energy k for sub-grid scale flow considering the interaction of fluid and particles can be derived as follows.

$$\begin{aligned} \frac{Dk}{Dt} = & \frac{\partial k}{\partial t} + \bar{u}_j \frac{\partial k}{\partial x_j} = -\bar{u'_i u'_j} \bar{S}_{ij} - \frac{\partial}{\partial x_j} \left(\frac{1}{2} \bar{u'_j u'_i u'_i} \right. \\ & + \frac{1}{\rho_f} \bar{u'_j p} - \nu \frac{\partial k}{\partial x_j} \Big) - \nu \frac{\partial \bar{u'_i}}{\partial x_j} \frac{\partial \bar{u'_i}}{\partial x_j} \\ & - F [N(\bar{u'_i u'_i} - \bar{u'_i u'_{pi}}) + \bar{n' u'_i} (\bar{u}_i - \bar{u}_{pi}) \\ & + \bar{n' u'_i} (\bar{u'_i} - \bar{u'_{pi}})] \end{aligned} \quad (12)$$

From Eq.(12), Yuu⁽⁷⁾ (1997) proposed a two-way coupling SGS model applying a local equilibrium assumption expressed as Eq.(13) that energy production, dissipation and interaction of fluid-particles are

in balance.

$$\begin{aligned} 2 \nu_T \bar{S}_{ij} \bar{S}_{ij} - C_\epsilon k^{3/2} \Delta^{-1} - 2NF \frac{1-b}{a T_{Li} + 1} k \\ + F \frac{\nu_T}{\sigma_s} \frac{\partial N}{\partial x_i} (\bar{u}_i - \bar{u}_{pi}) = 0 \end{aligned} \quad (13)$$

From Eq.(13), the eddy viscosity taking into account of fluid-particles interaction was derived and expressed as Eq.(14) by Yuu⁽⁷⁾.

$$\nu_T = C_{\nu T} C_\epsilon^{1/3} \Delta \left[\frac{-A_2 + \sqrt{A_2^2 + 4A_1(A_3 + A_4)}}{2A_1} \right] \quad (14)$$

Where $A_1 = C_\epsilon \Delta^{-1}$, $A_2 = 2NF \frac{1-b}{a T_{Li} + 1}$, $A_3 = 2C_{\nu T} C_\epsilon^{1/3}$

$\times \Delta \bar{S}_{ij} \bar{S}_{ij}$, $A_4 = F C_{\nu T} C_\epsilon^{1/3} \frac{\Delta}{\sigma_s} \frac{\partial N}{\partial x_i} (\bar{u}_i - \bar{u}_{pi})$

Here, the third order fluctuating terms is neglected, and the Hinze's expression⁽⁹⁾ of $\bar{u'_i u'_{pi}}$ below is employed.

$$\bar{u'_{pi} u'_i} = \frac{a T_{Li} + b}{a T_{Li} + 1} \bar{u'_i u'_i} = 2k \frac{a T_{Li} + b}{a T_{Li} + 1} \quad (15)$$

Where $a = f/\tau_p$, $b = \rho_f/\rho_p$ and T_{Li} is same as before.

However, it is difficult to decide the coefficient $C_{\nu T}$ dynamically in Yuu's model, because the filter widths Δ are mixed in Eq.(14). In this study, we take the place of Eq.(13) T_{Li} with Eq.(8) and get Eq.(16) as follows.

$$\begin{aligned} 2 \nu_T \bar{S}_{ij} \bar{S}_{ij} - C_\epsilon k^{3/2} \Delta^{-1} - 2NF \frac{1-b}{a \frac{\alpha_1}{C_\epsilon^{2/3} C_\nu^{1/2} \sqrt{2/3} |\bar{S}|} + 1} k \\ + F \frac{\nu_T}{\sigma_s} \frac{\partial N}{\partial x_i} (\bar{u}_i - \bar{u}_{pi}) = 0 \end{aligned} \quad (16)$$

Substitution the SGS turbulence energy k of Eq.(9) into the third term denominator of Eq.(16) and put it in order, the new eddy viscosity is then given by

$$\nu_T = C_{\nu T}^{3/2} \Delta^2 \left[\frac{|\bar{S}|^2 + \frac{F}{\sigma_s} \frac{\partial N}{\partial x_i} (\bar{u}_i - \bar{u}_{pi})}{1 + \frac{2NF(1-b)}{\sqrt{3/2} \alpha_1 a + \sqrt{C_\nu C_\epsilon} |\bar{S}|}} \right]^{1/2} \quad (17)$$

Because the filter width Δ appears at only one place in the Eq.(17) similar to the standard Smagrinisky model of single-phase turbulent flows, the coefficient $C_{\nu T}$ of proposed model can be easily decided by Germano's (1991) dynamic procedure⁽⁶⁾.

4. A Proposal of New Dynamic SGS Model for Two-Way Coupling

Now substitute Eq.(17) into the eddy viscosity hypothesis Eq.(11) to get the new dynamic eddy viscosity sub-grid scale stress expressed as Eq.(18), which takes into account of the interaction of particles-fluid SGS components in LES.

$$\begin{aligned} \tau_{ij} = & \bar{u}_i \bar{u}_j - \bar{u}_i \bar{u}_j = -2 \nu_T \bar{S}_{ij} \\ = & -2 C_{\nu T}^{3/2} \Delta^2 \left[\frac{|\bar{S}|^2 + \frac{F}{\sigma_s} \frac{\partial N}{\partial x_i} (\bar{u}_i - \bar{u}_{pi})}{1 + \frac{2FN(1-b)}{\sqrt{3/2} \alpha_1 a + \sqrt{C_\nu C_\epsilon} |\bar{S}|}} \right]^{1/2} \bar{S}_{ij} \end{aligned}$$

$$= -2(C_{ms}\Delta)^2 g(\bar{u}_i, \bar{u}_{pi}, N) \bar{S}_{ij} \quad (18)$$

According to the Germano's dynamic procedure⁽⁶⁾, the test filter level SGS stress can be defined as

$$\begin{aligned} T_{ij} &= \widetilde{\widetilde{u_i u_j}} - \widetilde{\widetilde{u_i}} \widetilde{\widetilde{u_j}} \\ &= -2C_{\nu T}^{3/2} \Delta_s^2 \left[\frac{|\bar{S}|^2 + \frac{F}{\sigma_s} \frac{\partial \bar{N}}{\partial x_i} (\bar{u}_i - \bar{u}_{pi})}{1 + \frac{2F\bar{N}(1-b)}{\sqrt{3/2} \alpha_1 a + \sqrt{C_\nu C_\varepsilon} |\bar{S}|}} \right]^{1/2} \bar{S}_{ij} \\ &= -2(C_{ms}\Delta_s)^2 g(\bar{u}_i, \bar{u}_{pi}, \bar{N}) \bar{S}_{ij} \end{aligned} \quad (19)$$

Where Δ is the characteristic filter width associated with the grid level filtering operator, and Δ_s is the filter width associated with the test level filtering operator. Considering the similarity between the SGS stresses at the grid and test levels, therefore, they could be modeled using the same functional expression, and it is assumed that the coefficient $C_{\nu T}$ or C_{ms} in Eq. (18) and Eq. (19) are same, then grid filter stress τ_{ij} , test filter stress T_{ij} and resolved turbulent stress can be related in algebraic relation Eq. (20)

$$\begin{aligned} T_{ij} - \tau_{ij} &= \widetilde{\widetilde{u_i u_j}} - \widetilde{\widetilde{u_i}} \widetilde{\widetilde{u_j}} \\ &= 2C_{\nu T}^{3/2} \Delta^2 [g(\bar{u}_i, \bar{u}_{pi}, N) \bar{S}_{ij} \\ &\quad - \alpha^2 g(\bar{u}_i, \bar{u}_{pi}, \bar{N}) \bar{S}_{ij}] \end{aligned} \quad (20)$$

Where $\alpha = \Delta_s/\Delta$ is a unique parameter for dynamic SGS model, in this study, we take the value of $\alpha = 2$, which was proposed by Germano⁽⁶⁾.

From Eq. (20), $C_{\nu T}(x, y, z, t)$ can be obtained in principle. The quantity in square brackets, however, can become zero, which would make $C_{\nu T}$ indeterminate or ill conditioned. For the channel flow, therefore, it is assumed that $C_{\nu T}$ is only a function of distance from wall y and time t . The average of both sides of Eq. (20) are taken over a plane parallel to the wall to yield

$$\begin{aligned} C_{ms} &= C_{\nu T}^{3/4} \\ &= \left[\frac{\langle \widetilde{\widetilde{u_i u_j}} - \widetilde{\widetilde{u_i}} \widetilde{\widetilde{u_j}} \rangle}{2\Delta^2 \langle g(\bar{u}_i, \bar{u}_{pi}, N) \bar{S}_{ij} - \alpha^2 g(\bar{u}_i, \bar{u}_{pi}, \bar{N}) \bar{S}_{ij} \rangle} \right]^{1/2} \end{aligned} \quad (21)$$

Here, similar to single-phase turbulent flow, the modification of least squares technique proposed by Lilly⁽¹²⁾ is adopted to minimize the difference between the closure assumption and the resolved stresses.

The new dynamic eddy viscosity sub-grid scale stress model, which takes into account of the interaction of particles-fluid SGS components in LES, is then given by

$$\begin{aligned} \tau_{ij} &= \left[\frac{\langle \widetilde{\widetilde{u_i u_j}} - \widetilde{\widetilde{u_i}} \widetilde{\widetilde{u_j}} \rangle}{\langle \alpha^2 g(\bar{u}_i, \bar{u}_{pi}, \bar{N}) \bar{S}_{ij} - g(\bar{u}_i, \bar{u}_{pi}, N) \bar{S}_{ij} \rangle} \right] \\ &\quad \times g(\bar{u}_i, \bar{u}_{pi}, N) \bar{S}_{ij} \end{aligned} \quad (22)$$

5. Simulation Overview

5.1 Calculation of fluid phase

The particle-laden turbulent flow between plane

channels driven by uniform pressure gradient and particles gravity was calculated by large eddy simulations at Reynolds numbers based on friction velocity and channel half-width of 644. Van Driest damping function model and dynamic SGS models with (the present model) or without (Germano's model) couplings of SGS components were applied respectively. The governing equation Eq. (3) and continuity equation were solved numerically by SMAC method on a staggered grid. Second-order central difference scheme was used for the advection and diffusion terms, and second-order Adams-Bashforth method was adopted for time advancement. The Poisson equation for pressure was solved using ICCG method. The flow was resolved using $32 \times 64 \times 32$ grid points in the x, y and z directions, respectively. The channel domain for the calculation was $\pi\delta \times 2\delta \times \pi\delta/2$ which was about 50 times volume of the minimal flow unit⁽¹³⁾ for appropriate Reynolds number. The grid spacing in wall coordinates in the x, y and z directions was $\Delta x^+ = 63$, $\Delta z^+ = 32$ and $\Delta y^+ = 2 \sim 72$, this spatial resolutions of LES was about 10 times of that of DNS⁽¹⁴⁾ in concerned Reynolds number. The time increment Δt used in the simulation was 4.082×10^{-5} second. For fully developed channel flow, periodic boundary conditions for the dependent variables were applied in the stream wise and span wise directions, whereas the no-slip condition was applied on the channel walls.

5.2 Calculation of particle phase

The motion of particles was integrated using second-order Adams-Bashform method in time, and third order Lagrange polynomials were used to interpolate the fluid velocity to the particle position since it was only by chance that a particle was located at a grid point where the Eulerian velocity was available. For particles that moved out of the channel in the stream wise or span wise directions, the periodic boundary conditions were used to introduce them into the computational domain. The channel walls were perfectly smooth and a particle was assumed to contact the wall when its center was one radius from the wall. Elastic collisions were assumed for particles contacting the wall. In this work, the effect of SGS components of fluid flow on particle motion was neglected, only the turbulence GS component was taken into account in particles tracing.

The initial condition of single phase Eulerian velocity field was given by a statistically fully developed solution. Then the particles were assigned to random locations throughout the channel, where the initial particle velocity was arranged to be uniform distribution from zero to maximum velocity of fluid flow by generating random numbers. Particles were then timely advanced in the flow field up to a new

Table 1 Particle calculation parameters

Material	Copper
Diameter $d_p [\mu m]$	70
Density $\rho_p [kg/m^3]$	8800
Relaxation time $\tau_p [ms]$	130
Terminal velocity $v_t [m/s]$	0.93
$St_k \equiv \tau_p / (\delta / U_{cl})$	70
Mass loading ratio Φ_m	1.0
Volume fraction $\Phi_v [\times 10^{-4}]$	1.36
Number of particles n_p	60000
$d_p^+ = d_p / \delta$	0.0035
$d_p^+ = d_p^* Re_\tau$	2.254
$\tau_p^+ = \tau_p / (\delta / u_\tau)$	3.185
$\tau_p^+ = \tau_p^* Re_\tau$	2050

equilibrium condition in which particle motion was independent of initial condition. Similar to the fluid flow, statistics of the particle velocity were averaged over two homogeneous directions, both channel halves and time. After 10 times of particles relaxation time, which was assumed that an equilibrium condition had been reached, the fluid and particles statistics were accumulated by $20\delta/u_\tau$ dimensionless time data. The particle calculation parameters are shown as Table 1. To distinguish the effect of two-way coupling, the 70 μm Copper particles were blended at mass loading ratio 1.0.

6. Calculation Results and Analysis

6.1 Mean velocities and Reynolds stresses

The numerical simulations of two-way coupling were carried out using Van Driest wall function and the present dynamic SGS model, while the SGS coupling was taken into account or not respectively. The stream wise mean velocities of fluid GS components are shown in Fig. 1, the root-mean-square velocity fluctuations of fluid GS components in stream wise and in wall normal are shown in Fig. 2, Fig. 3, the Reynolds stress of GS components are shown in Fig. 4, respectively. As observed in figures above, in spite of the SGS coupling was taken into account or not, the mean velocities were shifted upward in the logarithmic layer, and the root-mean-square velocity fluctuations were also slightly larger using proposed dynamic SGS models than using Van Driest wall function. Since this characteristic is similar to single-phase turbulent flow using standard dynamic SGS model, it is clear that the present SGS model has proper asymptotic behavior near the wall without the use of *ad hoc* damping function in case of multiphase turbulent flow. As shown in Figs. 2–4, the calculated

Fig. 1 Profile of stream wise mean velocity of fluid

Fig. 2 Turbulence intensity of fluid in stream wise

Fig. 3 Turbulence intensity of fluid in wall normal

results agree with the conclusion reported by Yamamoto⁽³⁾ et al., the turbulence intensities of particle-laden flow were clearly decreased than ones of particle-unladen flow for the coupling of GS components of particle-laden flow, but the turbulence intensities of particle-laden flow are hardly decreased when the SGS coupling was taken into account. These results are against previous conjecture⁽³⁾ that the couplings of SGS components should cause the

Fig. 4 Reynolds shear stress of fluid

Fig. 5 Profile of mean model coefficients

decreased turbulence intensities of particle-laden flows in high frequency sphere.

6.2 Coefficient of SGS model and SGS eddy viscosity

The eddy viscosity model coefficients that were calculated by using proposed dynamic SGS model are shown in Fig. 5. In the channel buffer region, the dynamic SGS model coefficient of particle-laden flow was smaller than that of particle-unladen flow. On the contrary, in the channel center area, the former was higher than the latter. Since the effects of two-way coupling of GS and SGS components correspond the profile of turbulence intensity of fluid in wall normal, the coefficient of proposed dynamic SGS model obtained the correct asymptotic behavior in the near-wall region. In logarithm law region ($y^+ \sim 100$), where concentration of the local particles was lowest, the proposed model obtained the fittest value $C_{ms} \sim 0.1$ in single-phase channel turbulent flows. It reflected the local structure of small eddies, showing that the capability of proposed model is validated.

The mean distributions of eddy viscosities are shown in Fig. 6. In the near-wall region ($y^+ < 30$), as the effects from SGS components to GS components

Fig. 6 Profile of mean SGS eddy viscosity

Fig. 7 Profile of GS turbulent energy budget by dynamic model with SGS coupling

are relatively small, the distributions of model coefficients correspond the profile of eddy viscosity as they are. While in the logarithm law region, though the model coefficients were roughly same, the effect of two-way coupling of GS components is significant, which may result from the difference of strain velocities S . As a result of taking into account of two-way coupling of SGS components, the model coefficients become bigger, which is agreed with the tendency that dissipation of turbulence is enhanced in high frequency.

6.3 Turbulence energy budget and spatial spectra of fluctuation energy

The results above suggest that two-way coupling maybe affect the balance of GS energy in the particle-laden channel flow. Figure 7 shows the energy budgets of GS components calculated by proposed dynamic model of two-way coupling. (The symbols in Fig. 7 represent the terms as followings: conv.: convective term, prod.: stress production term, prst.: pressure strain correlation term, disp.: viscosity dissipation term, tdif.: GS turbulence diffusion term, pdif.: pressure diffusion term, bdif.: viscosity diffusion term, sdif.: SGS model diffusion term, casc.: cascade term,

Fig. 8 Production profile of GS turbulent energy

Fig. 9 Dissipation profile of GS turbulent energy

pft.: particle-fluid interaction term, respectively). The stress production and viscosity diffusion terms associated with main energy budgets are shown as Figs. 8 and 9, the Figs. 10 and 11 pick up the cascade and particle-fluid interaction terms which directly respond the effects of two-way coupling.

As observed in Fig. 7, the direct contribution of particle-fluid interaction was small relatively, and the qualitative distributions of each term were not clearly different compared with the single-phase flow. They suggest that SGS components have the same distributive pattern as GS components, therefore, it is implied that the assumption of local energy equilibrium was proper as in the development of single-phase turbulence SGS model. On the other hand, it suggests that the decrease of turbulence intensity due to two-way coupling of GS components not only comes from particle-fluid interaction, but also mainly attributes to the alteration of stresses production term.

The cascade profiles of GS turbulence energy with or without SGS components coupling are shown in Fig. 10, the energy cascade becomes slightly stronger owing to SGS coupling as expected. This indicates that the contribution of SGS components to GS components is shown as dissipation of GS compo-

Fig. 10 Cascade profile of GS turbulent energy

Fig. 11 Profile of interaction of particles and fluid for GS turbulent energy

nents. In this study, since the effects of SGS two-way coupling on the energy cascade from GS to SGS components are directly represented by SGS eddy viscosity ν_t , the simulation results agree with the mechanism (Eq.(13)) that minuteness particles enhance dissipation of fluid turbulence energy in sub-grid scale. Therefore, it can be concluded that availability of presented dynamic two-way coupling model is verified. On the other hand, attending the difference of vertical axis scale, the stress production term (Fig. 8) and viscosity dissipation term (Fig. 9) are much more different than cascade term at the same case, which suggests that slight enhancement (Fig. 3) of GS turbulent intensity can be resulted from the balance of stress production, viscosity dissipation and other terms.

Fig. 12 shows the stream wise spatial spectra of fluctuation energy in the near wall region ($y^+=5$), and Fig. 13 shows that in channel center area ($y^+=600$). The effects of two-way coupling on turbulence intensities are noticeable in near wall region as expected, and the profiles of spatial spectra of fluctuation energy are regularly changed over all frequency domains in

Fig. 12 Stream wise spatial spectra of fluctuation energy at $y^+ = 5$

Fig. 13 Stream wise spatial spectra of fluctuation energy at $y^+ = 600$

all the cases. According to this simulation result, the effects of two-way coupling of GS components are reasonable in agreement with the simulation analysis by Yamamoto⁽³⁾ et al., and are qualitatively in accordance with the experimental measurements of Kulick⁽¹⁵⁾ et al. though the simulation evaluation was smaller than experiments. Intriguingly, contrary to the conjecture of Yamamoto⁽³⁾ et al., as mentioned above, the spatial spectra of fluctuation energy were slightly increased due to the two-way coupling of SGS components.

From analysis above, it is known that the turbulence attenuation of particle-laden turbulent channel flow is arisen from the decrease of total turbulence production, which is mainly attributed to the change of external force distribution. In this study, the wall shear stress is set up to a constant, so the average pressure gradient forced on fluid flow and the gravity of particles are in balance. However, because the distributions of particle number density are not homogeneous in particle-laden channel turbulent flow, the preferential concentrations are generated in the near

Fig. 14 Profile of particles number density

wall region, and so the external force added on particle-laden flow becomes bigger in near wall but smaller in channel center area to form non-uniform distribution. Consequentially the fluid flow in narrow range near wall was powerfully accelerated to strengthen the wall shear stress, and the contribution to turbulence production for whole flow field becomes relatively weaker. This conclusion supports the observation⁽¹⁶⁾ of non-decreased turbulence intensity that is resulted from the calculation of a constant pressure gradient condition.

6.4 Distribution of particle number density

The investigations above suggest that the particles distribution could make strong effect on turbulence modulation. Fig. 14 shows the distributions of particle number densities calculated in LES, here the particle-unladen case means the calculation of one-way coupling. The preferential concentrations of particles took place in near wall region, and the particle number densities were minimum in the logarithmic layer, then the particle number distributions were recovered in channel center area. The region where particles are concentrated is close to $y^+ = 100$ in case of one-way coupling, whereas, in cases of two-way coupling of GS components, that region is shifted to far less than about $y^+ = 200$ and the whole distributions of particles are mitigated. The difference of particle distributions caused by SGS models was hardly observed in near wall region, only in channel center area, the particle distributions become a little bigger due to the two-way coupling of SGS components. These non-uniform distribution phenomena of particles are generally considered as that particles are gathered in the weak turbulence region attributing to the gradient of particle fluctuation velocity as a result of interaction between turbulence and particles. However, according to the indication of Yamamoto^{(3),(17)} et al., the inter-particle collision encourages transverse mixing, and the effect of the

mixing flattens the profiles of particle velocity and particle concentration in particle-laden channel flow, the effect of inter-particle collision occurred in particle concentration area cannot be disregarded even in very dilute solid volume fraction condition. Since the inter-particle collision could be considered to take place in sub-grid scale as in physical term, the effect of SGS model including inter-particle collision should be investigated in detail.

7. Concluding Remarks

In this study, we improved the two-way coupling SGS stress model proposed by Yuu^{(7),(8)}, and presented a new dynamic SGS model for two-way coupling LES of particle-laden turbulent flow. Then large eddy simulations were performed in downward particle-laden turbulent flows at $Re=644$ in a vertical channel using Van Driest wall function model and the proposed new dynamic SGS model in order to investigate the capability and limitation of present SGS model in predicting the fluid turbulence modulation. From the evaluation in particle-laden turbulent channel flow, the following points should be remarked.

(1) A new dynamic SGS model has been proposed for two-way coupling LES of particle-laden turbulent flow based on Yuu's SGS model, in which the coupling of fluid-particles SGS components on fluid turbulence modulation was taken into account and at the same time the coefficient of proposed SGS model could be dynamically obtained as the calculations progress rather than input *a priori*.

(2) As a result of taking into account of two-way coupling of SGS components, the dynamic model coefficients become bigger, and in the channel buffer region, the proposed dynamic model coefficient of particle-laden flow is smaller than that of particle-unladen flow, on the contrary, the former is higher than latter in the channel center area.

(3) On modulation of particle-laden turbulent channel flow, the contributions of GS components and SGS components were clarified respectively. That is to say, the turbulence intensities were overall decreased by two-way coupling of GS components, at the same time, the turbulence energy cascade was increased by SGS components coupling. They offset against variety of stress production at turbulence energy budgets, and make little contribution to alteration of turbulence intensity all in all.

(4) As results of this simulation, the turbulence modulation of particle-laden was mostly caused by decrease of stress production, which was resulted from the non-uniform distribution of external force due to the particle preferential concentration in near wall region. On the other hand, because the fully

developed channel turbulent flow are in equilibrium at every moment, the effects of two-way coupling on turbulence energy budgets were relaxed, so these actions should be discussed distinctively.

(5) From investigations above, we can predict that the distribution of particle number density affect turbulence modulation in a big way, therefore, the SGS model that includes inter-particle interaction occurred in preferential concentration region remains to be developed.

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