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**Hydrodynamic modeling of turbulence modulation by particles in swirling
gas-particle two-phase flow**

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Abstract

Turbulence modulations by particles of swirling gas-particle two-phase flow the axisymmetric chamber is investigated. To fully consider the preferential concentrations and anisotropic dispersions of particle, a second-order moment model coupling particle-particle collision model was improved based on the Eulerian-Eulerian two-fluid approach and the kinetic theory of granular flow. Proposed model, algorithm and in-house codes are validated and they are in good agreement with the experiment. Effects of ultralight expanded graphite and heavy Copper particles with large spans of Stokes number on gas velocity and fluctuations, Reynolds shear stress and tensor invariants, turbulence kinetic energy, and vortices structures are numerically simulated. Results show turbulent modulation exhibits strongly anisotropic characteristics and keeps in close relationship with flow structure. The disturbances of modulations, the alternations of vortex evolution are enforced by heavy-large particle with higher Stokes numbers. Preferential accumulations of light particle at shear stress regions in low vortices are weaker than those of heavy particle. For axial turbulence modulations, heavy particle plays the primary role on inhibition action due to larger inertia and light particle contributes to enhancement effect due to excellent followability.

Keywords: Turbulence modulations; particle-particle collision; swirling gas-particle turbulent flow; second-order moment model

1. Introduction

Swirling gas-particle two-phase turbulent flow exists in all kinds of the natural phenomena and the industrial processes, such as the air ventilation and distribution in building, environment protection, etc. Gas turbulence plays an important role in the transfers of mass, momentum, and energy between gas and particle phases. It is very indispensable to obtain further understandings for flow mechanisms of complex two-phase turbulence, as well as the turbulence modifications by the effects of particle property, particle dispersion, interaction and turbulent flow structure^[1-5].

Experimental investigations by means of the particle image velocity (PIV), the laser Doppler anemometry (LDA), the phase Doppler particle analyzer (PDPA) and the high speed camera (HSC) have been measured successfully the hydrodynamics of gas-particle turbulent flows^[6-17]. As for the LDA technique, [Kulick et al. 1994^{\[6\]}](#) studied the interactions between small-dense Copper and glass beads with diameter of 70 μm , 50 μm and 90 μm and gas turbulence behaviors in fully developed channel. They disclosed that particle could response to some specific scales of turbulent motion and gas turbulence was attenuated by the addition of particle. [Fessler et al. 1994^{\[7\]}](#) revealed that streamwise gas turbulence modulation reaches up to approximately 35% in decrease along the channel-flow extension regions. [Ljus et al. 2002^{\[8\]}](#) observed that turbulence intensity is significantly changed in the higher particle concentration, and turbulence intensity increases closely to the center of the pipe. [Mora et al. 2019^{\[9\]}](#) quantified the impact of inertial particle on turbulent kinetic energy, and turbulent kinetic energy dissipation in particle-laden flows. By using of the PIV instrument, [Kiger et al. 2002^{\[10\]}](#) found that the presence of particle noticeably alters the carrier phase turbulence properties through an effective increase in the wall friction velocity of approximately 7%, and an increase of the normal and shear Reynolds stress by approximately 8-10% in the outer flow. [Wu et al. 2006^{\[11\]}](#) denoted that particle inertia are of great

importance for gas turbulence modification, even if the lower mass loading ratio of 5×10^{-4} . It is attenuated with increasing particle size and mass loading. Swirling two-phase hydrodynamics using PDPA were performed by Sommerfield et al. 1991,1993^[12,13]. In recent years, the direct numerical simulation (DNS)^[18-23], the large eddy simulation (LES)^[24-31], the Reynolds averaged Navier-Stokes simulation (RANS)^[32-41], have been applied to model and simulate the hydrodynamics of two-phase flows has been rapidly developed based on the computational fluid dynamics (CFD) technique. Gore et al.1989^[42] characterized the turbulence modification into augmentation and attenuation categories using a developed intuitive parameter, which is the ratio of the particle diameter to a characteristic size of large eddies. Elghobashi 1994^[43] firstly proposed the thresholds of particle volume fraction (α) to characterize effects of particle on gas turbulence, which were termed as the one-way coupling ($\alpha < 10^{-6}$), the two-way coupling ($10^{-6} < \alpha < 10^{-3}$) and the four-way coupling ($\alpha > 10^{-3}$). By using DNS algorithm, Eaton et al. 1994^[18] indicated that gas turbulence was attenuated by fine particle in developing boundary layer and fully developed channel flows when mass loading ratios are greater than 10%. Nan et al. 2010^[19] demonstrated that the turbulence modulation is more highly sensitive to the effect of mass loading rather than the particle response. Yan et al. 2014^[20] presented the turbulence modulation are determined by a group of parameters rather than a sole factor, i.e. combination of swirling number, mass loading, particle size and density etc, which mass loading was considered as the leader order. Moreover, turbulent kinetic energy that determined by the intermediate and the small scale vortices is smaller than of in single swirling jet^[21]. Wang et al. 2019^[22] studied the effects of inertial particle on self-sustained, turbulent coherent structures in plane Couette flow at low Reynolds number. Low-inertia particle triggers the laminar-to-turbulent instability whereas high-inertia particle tends to stabilize turbulence due to the extra dissipation induced by particle-fluid coupling. Regarding the LES application, Wang et al. 2013^[23]

clarified the turbulence modulations have stronger anisotropic characteristic and closely determined by flow structure in the backward facing step two-phase flows, especially, smaller size and lower density particle enhanced the turbulence modulation. For the first time, [Apte et al. 2003^{\[24\]}](#), [Oefelein et al. 2007^{\[25\]}](#) numerically simulated the swirling particle-laden flows in coaxial-jet combustor for the experimental measurement by Ref.[\[12\]](#). The two-phase hydrodynamics, i.e. particle dispersion characteristics, particle residence time of different particle sizes, evolution coherent structures, and particle-diameter correlation were obtained. However, the trend gas turbulence modulations by particle has not been provided completely. [Elghobashi et al. 2019^{\[31\]}](#) suggested that the experimental data to validate the DNS results are virtually nonexistent due to the complexity of gas-particle two-phase turbulent flows and the current measurement approaches. In regard to LES algorithm, the most challenge is that how to establish the accurate subgrid scale (SGS) models and carry out the priori verifications. Compared to DNS and LES, RANS is the compromised way for industrial applications due to economic computation, robust turbulent model, and practically empirical coefficient, even if it was failed to disclose the instantaneous flow behavior and coherent turbulent structure. [Anagnostopoulos et al. 1992^{\[32\]}](#) used a standard k- ϵ two equations turbulence model the effects of particle size, mass loading, and swirling number on gas turbulence modulation at the internal recirculation region. [Sommerfield et al. 1992^{\[33\]}](#) solved the gas phase by a standard k- ϵ turbulence mode and discrete particle models for tracking the particle trajectory in swirling two-phase turbulence flow. [Zhang et al. 2003^{\[34\]}](#) developed a k- ϵ particle collision model for dilute gas-particle vertical flows containing high-inertia particle. They found that interparticle length scale has a significant effect on gas turbulence. [Tanaka et al. 2008^{\[35\]}](#) proposed a new dimensionless particle moment number of particle-laden Navier-Stokes equations. The turbulence attenuation was observed between the augmentation regions with two critical particle momentum numbers according to

the mapped of Re-Pa numbers. [Lin et al. 2014^{\[36\]}](#) developed a probability density function to describe the cylindrical particle orientation. He found that turbulence intensity enhancement caused by cylindrical particles is smaller in the streamwise than that of near the nozzle exit, as well as directly proportional to particle concentration, Reynolds number and particle aspect ratio. [Pakhomov et al. 2015^{\[37\]}](#) improved a two-phase turbulent Reynolds stresses model to predict the swirling particle dispersions in behind a sudden tube expansion. Fine particle attenuates the gas turbulence of up 25%. [Zhou et al. 2017,2018^{\[38,39\]}](#) and [Liu et al. 2019^{\[40\]}](#) proposed a series of the second-order moment gas-particle turbulent model to simulate the anisotropic dispersions of particle and hydrodynamics of swirling two-phase flows. The anisotropic characteristics, the redistributions of Reynolds stresses of two phases, the mixing and separation behaviors have been successfully demonstrated,

Up to now, the mechanism of turbulence modulation by particles in swirling gas-particle flows have not been revealed clearly. The aim of the present study is to explore the turbulence modulations by the effects of particle density and size using ultralight expanded graphite (EG) and heavy Copper particles, as well as the Stokes number. A second-order moment gas-particle turbulence model was developed, which the Reynolds stress transport equation and the particle temperature equation based on the kinetic theory of granular flow are used to describe the anisotropic characteristics and particle -particle collisions. The measurement data of glass bead in experiments were used to validate proposed mathematical model, algorithm, and in-house code^[12]. Effects of particles on gas turbulence modulations are analyzed in detail.

2. Theoretical formulation and governing equations

The gas and the dispersed particle phases are modelled by the Eulerian-Eulerian two-fluid approach, which treats both gas and particulate phase as each continuous medium. It involves the solution of a

two-phase set of Navier-Stokes equations using the four-way coupling correlation. The particle takes effects on two-phase hydrodynamics, especially for gas turbulence modulation. Anisotropic characteristics of gas and particle dispersion were solved by the two-phase Reynolds stresses transport equations and particle-particle collision was modelled by particle temperature equation. Conservation laws of mass and momentum are satisfied for each phase, no mass and heat transfer occurred between gas and particle phases. The governing equations in relation with correlations and closure transport equations are given in Table 1.

3. Description and computational method

3.1 Experimental and simulation settings

Coaxial cylindrical chamber in experiment consists of the primary core zone and the secondary annular jet zone. Diameters of primary inject, annulus jet and main outer chamber are 32.0 mm, 64.0 mm and 194.0 mm. Total length test-section that oriented vertically with gravity acting in the direction of the flow is 960.0 mm. Prediction are laden with the ultralight expanded graphite (EP) and the Copper beads with the density of 21.9 kg/m³ and 8900.0 kg/m³ with the each diameters of 45.0 μm and 1000.0 μm, respectively. Glass bead is used to verify the simulation result, which has 2500.0 kg/m³ in density and 45μm in diameter, and Stokes number St=0.025. The primary central flow rate is 9.9 g/s, annular flow rate is 38.3 g/s, inlet Reynolds number is 26,200 and particle loading is 0.034, which is defined as the ratio of particle to gas phase mass flow rates in Equation (1).

$$\eta = \frac{\dot{m}_p}{\dot{m}_{air}} \quad (1)$$

Swirling number is given by Equation (2) and it is set to 0.47 in this simulation. The data output positions are obtained at the length of 3.0 mm, 52.0 mm, 155.0 mm, 195.0 mm, and 315.0 mm along the streamwise directions. Detailed schematic diagram is shown in Figure 1.

$$s = \frac{2 \int_0^{d_a} \rho_g w_g u_g r^2 dr}{d_a \int_0^{d_a} \rho_g u_g^2 dr} \quad (2)$$

A dimensionless parameter, Stokes number St is defined by $St = \tau_s / \tau_f$ as Equation (3) and (4), which is used to classify the degree of particle entrainment into the gas flow. τ_s is the particle relaxation time and τ_f is the fluid time scale, respectively.

$$\tau_s = \frac{1}{18} \frac{\rho_s d_s^2}{\mu_g} \quad (3)$$

$$\tau_f = \frac{d_{inner}}{u_{jet}} \quad (4)$$

The experimental parameters and simulation settings are summarized in Table 2. Moreover, the interim value of $St = 1.11$ in between 43.6 and 0.002 using Copper particle with diameter of 160.0 μm is also simulated to investigate the trend of the effect of Stokes number in-between on turbulence modulations.

2 Numerical algorithms

The finite volume method and the staggered grid technique is utilized to solve transport equations and Reynolds stress models in a generalized coordinate space. Quadratic upstream interpolation for convective kinematics (QUICK) procedure and the central difference scheme (CDS) for the diffusion terms are employed as well. Computational domain is firstly divided into a finite number of control volumes and then was integrated over this certain control volume. The semi-implicit for pressure linked equations correction (SIMPLEC), the tri-diagonal marching algorithm (TDMA), the line-by-line iteration and the under-relaxation are served for the velocity corrections to meet the requirements of continuity criteria, which are set to the of 1.0×10^{-4} for residual mass sources. The distributions of gas inlet velocity are uniform and those of particles are parabolic. Isotropic profiles for normal components of Reynolds stresses and the eddy viscosity hypothesis for shear stress are assumed. Non-slip wall conditions are set for gas velocity and the gas Reynolds stresses were determined by the production

terms. Tangential particle velocity and granular temperature at the wall are calculated by the [Johnson's](#) boundary model^[44] (see Equations (5) and (6)). In-house computational codes are compiled by the Fortran 77 with approximately 22,000 statements.

$$u_{s,wall} = -\frac{6\mu_s \alpha_{s,max}}{\pi \rho_s \alpha_s g_0 \sqrt{3\theta}} \frac{\partial u_{s,wall}}{\partial n} \quad (5)$$

$$\theta_{wall} = -\frac{k_s \theta}{e_w} \frac{\partial \theta_{wall}}{\partial n} + \frac{\sqrt{3} \pi \rho_s \alpha_s u_s g_0 \theta^{3/2}}{6 \alpha_{s,max} e_{wall}} \quad (6)$$

4. Results and discussion

4.1 Experimental validations

Mathematical model, numerical algorithm and in-house code were validated by experimental measurements using glass bead with density of 2500.0 kg/m³ and diameter of 45.0 μm by [Sommerfeld et al.1991](#)^[12]. The grid independences for axial particle velocity by means of the coarse (6.0 mm×1.9 mm), the medium (2.0 mm×0.48 mm) and the fine (1.3 mm×0.33 mm) grid sizes were tested (see Figure S1). Medium grid size is acceptable due to the economic CPU time and satisfied results, which was adopted for the grid scheme. The swirling flow exhibits the considerably anisotropic, especially in the shear layer and flow core regions. Focusing on the key flow features including primary corner and secondary recirculation zones with cores that centered at the (x,r) coordination of (117.4 mm, 61.1 mm) and (50.4 mm, 73.3 mm), the reattachment point centered at approximately (53.8 mm, 93.0 mm), and the highest negative velocities within the primary recirculation region are found at the coordinates of x=117.4 mm, respectively (see Figure 2 and Table 3). These values are complied with the measured results by [Sommerfeld et al. 1991](#)^[12] within 5% errors, as well as the LES simulations by [Apte et al. 2003](#), [Oefelein et al. 2007](#)^[24,25]. Predictions of axial and tangential two-phase velocities at the streamwise sections in comparisons with the PDPA data are shown in Figure 3. The W-shaped profiles

at annular flow regions and the typical Rankine vortex structure along axial tangential direction are captured in the shear layers, respectively. These findings correlate well with the experimental results even if there have slightly overestimated at near wall zone at $x=155.0$ mm. The reason is the fact that RANS algorithm fails to describe the instantaneous flow and the coherent structure for swirling two-phase flow. Although LES algorithm can overcome these drawbacks to some extents, it was confined strictly by the accurate subgrid scale models and reasonable wall boundaries, as well as DNS limitations due to unaffordable CPU time^[24, 25, 31, 38, 39].

4.2 Flow modulations by particles

Figure 4 and Figure 5 demonstrate the modulations of gas streamlines and vorticities by laden and unladen particles with large spans of Stokes number values ranging from $St=0.0002$ to $St=43.6$. As we can see that flow status has significantly been changed because of the effect of the sudden expansion geometry section. Typical two recirculating regions were observed, that is the central primary jet region at near-axial region as a result of the appearance of return flow with negative velocity, and corner recirculating region at wall-bound region as a result of the two-phase flow reattachment production under the combination effects of sudden expansion, turbophoresis force and particle inertia. Density and diameter of particle is function of Stokes number and they greatly impacted on the evolution processes of flow and vortex structures. When Stokes number is far less than unity, it means that the particles are well entrained into the gas turbulence. These have excellent followability in the carrier gas and two-phase flow could be treat as homogeneous phase. Especially, particle is significantly responsive to gas fluctuations. When St is greater than unity, particles are unresponsive to gas-phase fluctuations and move unaffected through the gas eddies due to large inertia of particle. Table 4 indicates the effects of particle on flow characteristics under different Stokes number values. Ultralight

particle quickly responds gas flow in recirculation leading to more entrainment in the secondary recirculation zone due to strong followability. Shedding vortices from inlet region that rolled up by the boundary layer with vortices from the shear layer underwent a process of pairing, merging and breakup. Large-heavy particle are easier to penetrate the central reversed flow regions instead of undergoing toward wall-normal region due to the large inertia and lagging velocity with gas inlet velocity. Therefore, distinctly vortex structures were not generated because of the perturbation of inertia particle. In order to consider the effects of in-between or interim Stokes number values, the $St=1.11$ using heavy particle with diameter of $d_s=160.0\ \mu m$ was studied (see Figure S2). The flow status shows the apparently transition characteristics in terms of primary and secondary circulation, and vortex evolution etc.

4.3 Modulations of mean velocities by particles

Figure 6 shows the modulations of the axial, radial and tangential gas mean velocities by laden particles. Negative velocities are observed at the near centerline and wall recirculation regions except for tangential swirling velocity. The decay of axial velocities along streamwise centerline, the shift toward wall region of their maximums are revealed, as well as the maximums of radial velocities at central flow and decrease in the boundary of primary jet. Meanwhile, significant decreasing peaks along streamwise direction, flatten profiles over the cross sections are presented and the similar trend for tangential velocities as well. With the disappearance of inlet effect, velocities have seriously changed after the streamwise section of $x=155.0\ mm$, and the effects of smaller Stokes number on axial and tangential velocities can be negligible even if near inlet region. As a matter of the fact that the attenuation of gas turbulence by heavy-large particle is remarkable. At near inlet region, light-small particle were subjected to be thrown out from central reversed flow zone then moved toward the outer

region by centrifugal force. In sharp contrast, intensified modulations by heavy-large particle with higher St number had seriously disturbed the gas turbulence due to lagging velocity and higher inertia. At the far downstream locations, axial velocities are significantly enhanced, and radial and tangential velocities are slightly weakened even though for small Stokes number. Moreover, preferential accumulation of light particle is weaker than those of heavy particle flow at the section of $x > 155.0$ mm due to anisotropic dispersions and excellent followability. The behaviors of transition particle with $St=1.11$ are closely to those of heavy-large particle with adjacent to the threshold of $St=1.0$ (see Figure S3).

4.4 Modulations of root-mean-square (RMS) fluctuation velocities by particles

Figure 7 shows the modulations of the root-mean-square (RMS) fluctuation velocities of gas turbulence by laden particles, which is defined by $\overline{u'_g} = \sqrt{(u'_g)^2}$. Significantly anisotropic characteristics of gas fluctuations can be observed in the shear regions, in which the corresponding highest velocity gradient decreases toward the centerline and jet boundary. With the development of flow, modulations by particles seems to be weaken than near inlet regions due to lower local particle mass flux. Effects of larger Stokes number are always strengthened and attenuated for small Stokes number of light-small particles since they have experienced the different histories. Due to the initial inertia, particles firstly are entrained into the central recirculating zone, then being gradually decelerated, stopped and turned backward flow. Radial and tangential velocities became more dominant and particles gradually move toward wall driven by centrifugal force. Light-small particles with small Stokes number are strongly controlled and decelerated by reversal flow in primary recirculating jet leading to the decrease in central fluctuations. Heavy-large particle with high Stokes number reinforces the turbulence fluctuations at all directions. The compromise characteristics of modulations for $St=1.11$ are provided

in Figure S4.

4.5 Modulations of turbulence kinetic energy (TKE) by particles

Modulations of turbulence kinetic energy (TKE) by particles is given in Figure 8, which is defined by

$$TKE = \frac{1}{2} (\overline{u_s'^2} + \overline{v_s'^2} + \overline{w_s'^2}) .$$

The enhancement at centerline regions by heavy particle is obtained, as well as those at near wall regions by light particle after the sections of $x > 155.0$ mm. Noticeably, the degree to modulate of light particle are larger than those of heavy particle due to quick absorption of the kinetic energy from the different flow processes. [Mohanarangam et al. 2007^{\[45\]}](#) indicated that the particle trajectory, slip velocity, and drag force transferred to gas phase are all uniquely determined by particle time constant or Stokes number under a large ratio of particle to fluid material density when particle diameters approximately are smaller than the Kolmogorov scale. When the diameter of particle is smaller than the Kolmogorov scale, it has a small distortion to moderate scale turbulent eddies. Thus, particles with the same Stokes number including different diameters and densities to modulate gas turbulence may conduct the different fashions. Stokes number is suitable parameter to judge modulations rather than either diameter or density individuals+.

4.6 Modulations of the shear Reynolds stresses by particles

Figure 9 shows that the modulations of the shear Reynolds stress by laden particles. The distributions of shear stresses demonstrate the significantly anisotropic characteristics. Large values located at shear regions due to higher velocity gradients, and axial-axial value that larger than those of axial-radial and radial-tangential are observed. At the position of $x=50.4$ mm and $r=93.0$ mm, it reaches up to the maximum and then decreased towards the centerline and the boundary of jet. The values at near inlet region are larger than those of development flows. It can be explained that heavy particle is readily to penetrate the central reversed region, however light particle is able to quickly response to reversed flow

with negative velocity. Overall, modulations of shear stresses are very complicated under the combination effects of centrifugal force, turbulent diffusion and moment transfer between gas and particle phases. The degrees in axial-radial modulations are stronger than those radial-tangential and axial-tangential directions. The enhancement by light-small particle and the reduction by large-heavy particle are acquired because higher preference accumulation concentration is easier to generate at lower vorticity regions. Figure S5 predicted the modulations by heavy particle with $St=1.11$, as well as the transition trends in-between Stokes number values.

4.7 Modulations of the tensor invariants of the Reynolds stress by particles

The tensor invariants of Reynolds stress imply the geometrical and physical information of turbulence fluctuations, which are denoted as $I_{g,x}$, $I_{g,y}$ and $I_{g,z}$ using the components of normal and shear Reynolds stress, see Equations (7), (8) and (9). Now that invariants indicate the fundamental geometrical and physical characteristics of turbulence fluctuations related with stress components, it is more reasonable to observe the modulations on the invariants than those of any individuals.

$$I_{g,x} = \lambda_{g,x} + \lambda_{g,y} + \lambda_{g,z} = u'_{g,x}u'_{g,x} + u'_{g,y}u'_{g,y} + u'_{g,z}u'_{g,z} \quad (7)$$

$$I_{g,y} = \lambda_{g,x}\lambda_{g,y} + \lambda_{g,x}\lambda_{g,z} + \lambda_{g,z}\lambda_{g,y} = \begin{vmatrix} u'_{g,y}u'_{g,y} & u'_{g,z}u'_{g,y} \\ u'_{g,y}u'_{g,z} & u'_{g,z}u'_{g,z} \end{vmatrix} + \begin{vmatrix} u'_{g,x}u'_{g,x} & u'_{g,z}u'_{g,x} \\ u'_{g,x}u'_{g,z} & u'_{g,z}u'_{g,z} \end{vmatrix} + \begin{vmatrix} u'_{g,x}u'_{g,x} & u'_{g,y}u'_{g,x} \\ u'_{g,y}u'_{g,y} & u'_{g,y}u'_{g,y} \end{vmatrix} \quad (8)$$

$$I_{g,z} = \lambda_{g,x}\lambda_{g,y}\lambda_{g,z} = \begin{vmatrix} u'_{g,x}u'_{g,x} & u'_{g,x}u'_{g,y} & u'_{g,x}u'_{g,z} \\ u'_{g,y}u'_{g,x} & u'_{g,y}u'_{g,y} & u'_{g,y}u'_{g,z} \\ u'_{g,z}u'_{g,x} & u'_{g,z}u'_{g,y} & u'_{g,z}u'_{g,z} \end{vmatrix} \quad (9)$$

Figure 10 shows the modulations of the stress tensor invariants $I_{g,x}$, $I_{g,y}$ and $I_{g,z}$ by particles.

Modulations along axial-radial, radial-tangential, and axial-tangential directions are enhanced with Stokes number increase. It means that flow structures and vortex rotations can be changed by particles

although the same geometry and space configuration.

In summary, larger-heavy particles with large Stokes number have excellent ability to resist the centrifugal force and penetrate the central reserved flow leading to reduction of their dispersions. As a matter of fact, swirling flow structures are complicated and their mechanism have not been understood due to complex multiphase turbulent diffusion, interaction between gas and particle, turbulence scale, and Stokes numbers etc. The key parameters related to modulations need to be further validated by experiment.

3. Concluding remarks

In this work, gas turbulence modulations of swirling gas-particle flow by particles with different diameters and densities was investigated with large spans of Stokes number ranging from 0.0002 to 43.6. A second-order moment model was developed to fully consider the two-phase anisotropic characteristics using Reynolds stress transport equation. Particle-particle collision model based on the kinetic theory of granular flow was also coupled to describe the preferential accumulation at shear stress regions. Modulations of gas turbulence by laden or unladen particles, i. e. mean velocity and fluctuations, Reynolds shear stress, turbulence kinetic energy, stress tensor invariants, and vortices structure were quantitatively analyzed, and they showed strongly anisotropic. Generally, heavy-large particles with $St > 1.0$ significantly enhanced the gas turbulence in comparison with light-small particle with $St < 1.0$, except for of axial velocity and axial-radical shear stress, the anisotropic characteristics by preferential accumulations at low vortices are disclosed as well. However, better understandings for the mechanism of turbulence modulations and determinations for the most dominant factors from a group of Stokes number, density, diameter and Reynold number of particles, still need to be further clarified.

Conflict of Interest:

The authors declare that they have no conflict of interest

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Collected Figure Captions

Figure 1 The schematic diagram of coaxial swirling chamber

Figure 2 Predictions of gas-particle flow characteristics using glass bead experiment^[12]

Figure 3 Validation of the time-averaged axial and tangential velocities of gas and particle using glass bead in experiment, $St=0.025$ ^[12]

Figure 4 Modulations of gas streamline by particles

Figure 5 Modulations of gas vorticities by particles (1/s, r-w plane)

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(a) axial direction, gas

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(c) axial direction, particle

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Figure 3 Validation of the time-averaged axial and tangential velocities of gas and particle using glass bead in experiment, $St=0.025$ ^[12]

(a) unladen particle, $St=0.025$

(b) ultralight particle, $d=45.0 \mu m$, $St=0.0002$

(c) ultralight particle, $d=1000.0 \mu m$, $St=0.11$

(d) heavy particle, $d=45.0 \mu m$, $St=0.087$

(e) heavy particle, $d=1000.0 \mu m$, $St=43.6$

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(a) eigenvalues of $I_{g,x}$

(b) eigenvalues of $I_{g,y}$

(c) eigenvalues of $I_{g,z}$

Figure 10 Distributions of stress tensor invariants of gas turbulence

Table 1 Mathematical model of gas-particle swirling flow in chamber

A: Conservation equations

(a) Continuity equations

Gas phase
$$\frac{\partial}{\partial t}(\alpha_g \rho_g) + \frac{\partial}{\partial x_j}(\alpha_g \rho_g \overline{u_{gj}}) = 0 \quad \text{T1-1}$$

Particle phase
$$\frac{\partial}{\partial t}(\alpha_s \rho_s) + \frac{\partial}{\partial x_j}(\alpha_s \rho_s \overline{u_{sj}}) = 0 \quad \text{T1-2}$$

(b) Momentum equations

Gas phase
$$\frac{\partial(\alpha_g \rho_g \overline{u_{gi}})}{\partial t} + \frac{\partial(\alpha_g \rho_g \overline{u_{gk} u_{gi}})}{\partial x_k} = \alpha_g \rho_g g - \alpha_g \frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_k}(\tau_{gik} - \alpha_g \rho_g \overline{u'_{gi} u'_{gk}}) + \beta_{gs}(\overline{u_{si}} - \overline{u_{gi}}) \quad \text{T1-3}$$

Particle phase
$$\frac{\partial(\alpha_s \rho_s \overline{u_{si}})}{\partial t} + \frac{\partial(\alpha_s \rho_s \overline{u_{sk} u_{si}})}{\partial x_k} = \alpha_s \rho_s g - \alpha_s \frac{\partial \overline{p}}{\partial x_i} - \frac{\partial \overline{p}}{\partial x_i} - \frac{\partial}{\partial x_k}(\tau_{sij} - \alpha_s \rho_s \overline{u'_{sk} u'_{si}}) + \beta_{sg}(\overline{u_{si}} - \overline{u_{gi}}) \quad \text{T1-4}$$

(c) Equation of particle fluctuating energy

$$\frac{3}{2} \left[\frac{\partial(\alpha_s \rho_s \overline{\theta})}{\partial t} + \frac{\partial(\alpha_s \rho_s \overline{u_{sk} \theta})}{\partial x_k} \right] = \frac{\partial}{\partial x_k} \left(C_s \alpha_s \rho_s \frac{\kappa_s^2}{\varepsilon_s} \right) + \frac{\partial}{\partial x_k} \left(\kappa_s \frac{\partial \overline{\theta}}{\partial x_k} \right) + \mu_s \left(\frac{\partial \overline{u_{sk}}}{\partial x_i} + \frac{\partial \overline{u_{si}}}{\partial x_k} \right) \frac{\partial \overline{u_{si}}}{\partial x_k} + \mu_s \varepsilon_s - \overline{p_s} \frac{\partial \overline{u_{si}}}{\partial x_i} + \left(\varepsilon_s - \frac{2}{3} \mu_s \right) \left(\frac{\partial \overline{u_{si}}}{\partial x_i} \right)^2 - \gamma_s \quad \text{T1-5}$$

B: Constitutive equations

(a) Reynolds stress equation of gas phase[51,52]
$$\frac{\partial(\alpha_g \rho_g \overline{u'_{gi} u'_{gj}})}{\partial t} + \frac{\partial(\alpha_g \rho_g \overline{u'_{gk} \cdot u'_{gi} u'_{gj}})}{\partial x_k} = D_{g,ij} + P_{g,ij} + \Pi_{g,ij} - \varepsilon_{g,ij} + \sum_{s=1}^M G_{g,s,ij} \quad \text{T1-6}$$

(b) Reynolds stress equation of particle phase[51,52]
$$\frac{\partial(\alpha_s \rho_s \overline{u'_{si} u'_{sj}})}{\partial t} + \frac{\partial(\alpha_s \rho_s \overline{u'_{sk} \cdot u'_{si} u'_{sj}})}{\partial x_k} = D_{s,ij} + P_{s,ij} + \Pi_{s,ij} - \varepsilon_{s,ij} + \sum_{s=1}^M G_{s,s,ij} \quad \text{T1-7}$$

(c) Turbophoresis force
$$D_{s,ij} = \frac{\partial}{\partial x_k} \left(C_p \alpha_s \rho_s \frac{k_s}{\varepsilon_s} \overline{u'_{sk} u'_{si}} \frac{\partial \overline{u'_{si} u'_{sj}}}{\partial x_i} \right) \quad \text{T1-8}$$

(d) Particle shear production
$$P_{s,ij} = -\alpha_s \rho_s \left(\overline{u'_{sk} u'_{sj}} \frac{\partial \overline{u_{si}}}{\partial x_k} + \overline{u'_{sk} u'_{si}} \frac{\partial \overline{u_{sj}}}{\partial x_k} \right) \quad \text{T1-9}$$

(e) Particle pressure-strain
$$\Pi_{s,ij} = \Pi_{s,ij,1} + \Pi_{s,ij,2} = -C_{p1} \frac{\varepsilon_s}{k_s} \alpha_s \rho_s \left(\overline{u'_{si} u'_{sj}} - \frac{2}{3} k_s \delta_{ij} \right) - C_{p2} \left(P_{s,ij} - \frac{2}{3} P_s \delta_{ij} \right) \quad \text{T1-10}$$

(f) Particle dissipation
$$\varepsilon_{s,ij} = \frac{2}{3} \delta_{ij} \alpha_s \rho_s \varepsilon_s \quad \text{T1-11}$$

(g) Two-phase interaction
$$\sum_{s=1}^M G_{s,g,s,ij} = \frac{\alpha_s \rho_s}{\tau_{rs}} \left(\overline{u'_{si} u'_{gj}} + \overline{u'_{gj} u'_{si}} - 2 \overline{u'_{si} u'_{sj}} \right) \quad \text{T1-12}$$

(h) Equation of gas-particle interphase Reynolds stress[51]
$$\frac{\partial \overline{u'_{si} u'_{gj}}}{\partial t} + (\overline{u_{gk}} + \overline{u_{sk}}) \frac{\partial \overline{u'_{si} u'_{gj}}}{\partial x_k} = D_{gs,ij} + P_{gs,ij} + \Pi_{gs,ij} - \varepsilon_{gs,ij} + T_{gs,ij} \quad \text{T1-13}$$

(i) Interphase diffusion
$$D_{gs,ij} = \frac{\partial}{\partial x_k} \left(C_{gs3} \left(\frac{k_s}{\varepsilon_s} \overline{u'_{pk} u'_{pl}} + \frac{k_g}{\varepsilon_g} \overline{u'_{gk} u'_{gl}} \right) \frac{\partial \overline{u'_{si} u'_{sj}}}{\partial x_i} \right) \quad \text{T1-14}$$

(j) Interphase shear production
$$P_{gs,ij} = -\overline{u'_{si} u'_{gk}} \frac{\partial \overline{u_{gj}}}{\partial x_k} - \overline{u'_{sk} u'_{gj}} \frac{\partial \overline{u_{si}}}{\partial x_k} \quad \text{T1-15}$$

(k) Interphase pressure-strain
$$\Pi_{gs,ij} = \Pi_{gs,ij,1} + \Pi_{gs,ij,2} = -\frac{C_{gs1}}{\tau_{rs}} \left(\overline{u'_{si} u'_{gj}} - \frac{2}{3} k_{gs} \delta_{ij} \right) - C_{gs2} \left(P_{gs,ij} - \frac{2}{3} P_{gs} \delta_{ij} \right) \quad \text{T1-16}$$

(l) Interphase dissipation	$\varepsilon_{gs,ij} = \frac{\overline{u'_{si}u'_{gj}}}{\min\left(\tau_{rs}, k_s/\varepsilon_s\right)}$	T1-17
(m) Interphase interaction	$T_{gs,ij} = \frac{\beta}{\alpha_g \rho_g \alpha_s \rho_s} \left(\alpha_s \rho_s \overline{u'_{si}u'_{sj}} + \alpha_g \rho_g \overline{u'_{gi}u'_{gj}} - (\alpha_g \rho_g + \alpha_s \rho_s) \overline{u'_{gi}u'_{sj}} \right)$	T1-18
(n) Conductivity coefficient of granular temperature	$\kappa_s = \frac{150}{384(1+e)g_0} \rho_s d_s \sqrt{\pi\theta} \left[1 + \frac{6}{5}(1+e)g_0\alpha_s \right]^2 + 2\alpha_s^2 \rho_s d_s g_0 (1+e) \sqrt{\frac{\theta}{\pi}}$	T1-19
(o) Translational fluctuation energy dissipation rate	$\gamma_s = 3(1-e^2)\alpha_s^2 \rho_s g_0 \theta \left[\frac{4}{d_p} \sqrt{\frac{\theta}{\pi}} - \frac{\partial u_{k,s}}{\partial x_k} \right]$	T1-20
(p) Bulk particle viscosity	$\xi_s = \frac{4}{3} \alpha_s^2 \rho_s d_s g_0 (1+e) \sqrt{\frac{\theta}{\pi}}$	T1-21
(q) Radial distribution function	$g_0 = \left[1 - \left(\frac{\alpha_s}{\alpha_{s,\max}} \right)^{1/3} \right]^{-1}$	T1-22
(r) Particle relax time	$\tau_{rs} = d_s^2 \rho_s \left(1 + \frac{\text{Re}_s^{2/3}}{6} \right)^{-1} / 18\mu_g$	T1-23
(s) Particle viscosity	$\mu_s = \frac{10\rho_s d_s \sqrt{\pi\theta}}{96\alpha_s(1+e)g_0} \left[1 + \frac{4}{5}(1+e)g_0\alpha_s \right]^2 + \frac{4}{5} \alpha_s^2 \rho_s d_s g_0 (1+e) \sqrt{\frac{\theta}{\pi}} + \mu_s^f$	T1-24
Frictional stress	$\mu_s^f = \frac{p_s^f \sin \phi_f}{2\sqrt{I_{2D}}}$	T1-25
	$I_{2D} = -\frac{1}{2} \left[\frac{1}{2} (\nabla u_s + \nabla u_s^T) - \frac{1}{3} (\nabla \cdot u_s) I \right] : \left[\frac{1}{2} (\nabla u_s + \nabla u_s^T) - \frac{1}{3} (\nabla \cdot u_s) I \right]$	T1-26
	$p_s^f = \begin{cases} 0.05 \frac{(\alpha_s - \alpha_{s,\min})^2}{(\alpha_{s,\max} - \alpha_s)^5} & \alpha_s > \alpha_{s,\min} \\ 0 & \alpha_s \leq \alpha_{s,\min} \end{cases}$	T1-27
(t) Interphase momentum exchange coefficient		
Ergun model	$\beta_{\text{Ergun}} = 150 \frac{\alpha_s(1-\alpha_g)\mu_g}{\alpha_g(\phi d_s)^2} + 1.75 \frac{\alpha_s \rho_g \overline{u_g} - \overline{u_s} }{\phi d_s}$	T1-28
Wen-Yu model	$\beta_{\text{Wen,Yu}} = \frac{3}{4} C_D \frac{\alpha_s \alpha_g \rho_g \overline{u_g} - \overline{u_s} }{d_s} \alpha_g^{-2.65}$	T1-29
Huilin-Gidaspow model	$\beta_{sg} = (1-\phi)\beta_{\text{Ergun}} + \phi\beta_{\text{Wen-Yu}}$	T1-30
	$\phi = \frac{\arctan[150 \times 1.75(0.2 - \alpha_s)]}{\pi} + 0.5$	T1-31
	$C_D = \frac{24}{\text{Re}_s} (1 + 0.15 \text{Re}_s^{0.687}) \quad \text{Re}_s \leq 1000$	T1-32
	$C_D = 0.44 \quad \text{Re}_s > 1000$	T1-33
Particle Reynolds number	$\text{Re}_s = \frac{\alpha_g \rho_g d_s \overline{u_g} - \overline{u_s} }{\mu_g}$	T1-34

Table 2 Parameters of experiment and numerical simulation

Parameters	Unit	Value
Diameter of expanded graphite and Copper particles, d_s	μm	45/1000 45,160/1000
Density of expanded graphite and Copper particles, ρ_s	kg/m^3	21.9, 8900
Diameter of glass bead for CFD validation, d_{sg}	μm	45
Density of glass bead for CFD validation, ρ_{sg}	kg/m^3	2500
Density of gas, ρ_g	kg/m^3	1.225
Viscosity of gas, μ_g	Pa.s	1.8e-05
Restitution coefficient of particle-wall, e_w	-	0.96
Restitution coefficient of particle-particle, e	-	0.95
Particle sphericity, ϕ	-	0.96
Diameter of primary inject, d_{jn}	mm	32
Diameter of annular jet, d_{an}	mm	64
Diameter of chamber, d_o	mm	194
Total length, L	mm	960
Particle loading, η	-	0.034
Swirling number, s	-	0.47
Flow rate in primary jet, Q_s	g/s	9.9
Flow rate in annular jet, Q_{an}	g/s	38.3
Inlet Reynolds number, Re_{in}	-	26,200
Stokes numbers of the Copper St , $d_s=45,160,1000 \mu\text{m}$	-	0.087, 1.11, 43.6
Stokes numbers of expanded graphite St , $d_s=45,1000 \mu\text{m}$	-	0.0002, 0.11
Stokes number of glass bead for CFD validation St , $d_s=45 \mu\text{m}$	-	0.025

Table 3 Comparisons with LES and experimental data^[12,24]

	In this simulation	LES	Experiment data
Primary circulation zone, (x, r)	(50.4 mm, 73.3 mm)	(49.8 mm, 76.8 mm)	(52.0 mm, /)
Secondary circulation zone, (x,r)	(117.4 mm, 61.1mm)	(115.4 mm, 64.0 mm)	(112.0 mm, /)_
Reattachment point, (x,r)	(53.8 mm, 93.0 mm)	(52.2 mm, 94.7 mm)	(52.0 mm, /)
Maximum relative error with experiments, %	4.8	3.1	

Table 4 Comparisons of hydrodynamic characteristics by particles

	Ultralight particle		Heavy particle	
	$d_s=45.0\ \mu\text{m}$	$d_s=1000.0\ \mu\text{m}$	$d_s=45.0\ \mu\text{m}$	$d_s=1000.0\ \mu\text{m}$
Stokes number	0.0002	0.11	0.087	43.6
Followability	Excellent	Good	Excellent	Worse
Second recirculation	Entrainment	Entrainment	Entrainment	Penetration
Length of primary and secondary circulation	Enlarge	Enlarge	Enlarge	Weak
Preferential accumulation	Increase	Increase	Increase	Decrease
Vortex formation	Helpful	Helpful	Unhelpful	Destructive

Nomenclature

C_D	Drag coefficient, (dimensionless)
d_s	Diameter of particle, (m)
D	Diffusion term, (dimensionless)
e	Restitution coefficient of particle, (dimensionless)
e_w	Restitution coefficient of wall, (dimensionless)
g	Gravitational acceleration, (m/s ²)
g_o	Radial distribution function, (dimensionless)
$\mathbf{I}$	Unit tensor, (dimensionless)
k_g	Turbulent kinetic energy of gas, (m ² /s ²)
k_s	Turbulent kinetic energy of particle, (m ² /s ²)
p	Thermodynamic pressure, (Pa)
p_p	Particle phase pressure, (Pa)
p_p^f	Particle frictional pressure, (Pa)
P	Production term, (dimensionless)
Q	Flow rate, (g/s)
Re_p	Particle Reynolds number, (dimensionless)
s	Swirling number, (dimensionless)
St	Stokes number, (dimensionless)
t	Time, (s)
T	Interaction term, (dimensionless)
u_g	Gas velocity, (m/s)
u_s	Particle velocity, (m/s)

Greek Alphabets

α_g	Gas volume fraction, (dimensionless)

α_s	Particle volume fraction, (dimensionless)
$\alpha_{s,max}$	Maximum particle volume fraction, (dimensionless)
β_{gs}	Inter-phase drag coefficient, (dimensionless)
γ	Collisional dissipation rate, (kg/ms ³)
λ	eigenvalues of the tensor, (dimensionless)
δ	Kronic-Delta unit tensor, (dimensionless)
ρ_g	Gas density, (kg/m ³)
ρ_s	Particle density, (kg/m ³)
ε_g	Turbulent energy dissipation rate of gas, (m ² /s ³)
ε_s	Turbulent energy dissipation rate of particle, (m ² /s ³)
μ_g	Gas dynamic viscosity, (Pa.s)
μ_s	Particle shear viscosity, (Pa.s)
τ_g	Stress tensor of gas phase, (Pa)
τ_p	Stress tensor of particle phase, (Pa)
ζ_s	Particle bulk viscosity, (Pa.s)
θ	Particle temperature, (m ² /s ²)
Π	Pressure-strain, (dimensionless)
φ	Particle sphericity (dimensionless)
ϕ	Blending function, (dimensionless)

Superscripts

'	Fluctuation
-	Averaged

Subscripts

<i>an</i>	Annular
<i>i,j,k</i>	Coordinates directions
<i>in</i>	Inlet
<i>f</i>	Frictional, flow

g,s	Gas and particle
l	Laminar
L	Length
o	Outer
r	Relax

Figures

Figure 1

The schematic diagram of coaxial swirling chamber

Figure 2

Predictions of gas-particle flow characteristics using glass bead experiment[12]

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(b) tangential direction, gas

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Figure 3

Validation of the time-averaged axial and tangential velocities of gas and particle using glass bead in experiment, $St=0.025$ [12]

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Distributions of stress tensor invariants of gas turbulence

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