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Original Research Paper

Effects of specularity and particle-particle restitution coefficients on the hydrodynamic behavior of dispersed gas-particle flows through horizontal channels

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ABSTRACT

Specularity coefficient (ϕ) and particle–particle restitution coefficient (e) are two important parameters governing the flow physics of dispersed gas-particle flows. In this work, a detailed numerical analysis is carried out to get an insight into the effects of these two parameters in the flow hydrodynamics of dispersed gas-particle flows through horizontal channels. Investigations have also been carried out to find the ϕ-e pair for which the phase velocities become an extremum. It has been found that at a particular value of e, both gas and particle velocities at the centerline of the channel increase with increase in the value of ϕ, whereas near the wall, they tend to decrease. At a fixed non-zero value of ϕ, both gas and particle velocities tend to increase with increase in the value of e. For ϕ equal to zero, which corresponds to free-slip boundary condition for particle velocity, there is no significant variations in gas and particle velocities with changes in e. Out of all combinations of values of ϕ and e investigated herein, it is found that both gas and particle velocities attain a maximum value when both the values of ϕ and e are maximum.

1. Introduction

In dispersed gas-particle flows, there exist two phases which are not separated by any sharp interface and are thoroughly mixed with each-other. The flow physics of this type of flows are governed mainly by the interactions between the individual phases [1] and these interactions between the individual phases are taken into account by introducing drag force term in their respective governing equations. Different drag models proposed by different researchers [2–4] are used in this regard. In addition to the interphase drag force, particle-particle and particle-wall interactions also play important roles in this type of flows. In practical flow situations such as those encountered in pneumatic conveying or in flow of particles in gas-solid fluidized beds where particle volume fraction is high, there is always a loss of particle momentum due to collisions among the particles which effects the overall flow hydrodynamics. This loss in particle momentum is quantified by introducing particle-particle restitution coefficient (e) which is a measure of momentum loss due to particle-particle collisions. A value equal to unity refers to perfectly elastic collisions where no momentum is lost and a value of e equal to 0.8 means that 20% of the particle momentum is lost due to collisions. Again, there are collisions between the particles and the wall and depending on the wall roughness, some amount of particle momentum is lost due to this. To quantify this loss, a parameter termed as specularity coefficient (ϕ) is introduced which is the ratio of the momentum loss due to particle-wall collisions to the total momentum of the particles. A value of ϕ equal to zero refers to a perfectly smooth wall where there is no loss of particle momentum due to particle-wall collisions (specular collisions, leading to free-slip condition for particle velocity) and a value equal to unity leads to totally diffusive collisions where the particle momentum is completely lost due to collisions with the wall. In two-fluid model, based on the value of ϕ, the wall boundary conditions for the particle velocity is derived using Johnson and Jackson [5] model.

Study of effects of particle-particle and particle-wall collisions in dispersed gas-particle flows has been carried out in gas-solid fluidized beds, vertical and horizontal channels as well as for recirculating flows. Sommerfeld and Kussin [6] carried out experimental study on pneumatic conveying of spherical particles in a narrow horizontal channel using two-component phase Doppler anemometry (PDA) where wall roughness was considered in the range of

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Nomenclature

C_d	interphase drag coefficient
d_s	particle diameter
e	particle-particle restitution coefficient
K_{gs}	momentum exchange coefficient
p	hydrodynamic pressure
p_s	solid pressure
Re_p	particle Reynolds number
St	Stokes number
u_g, v_g, w_g	gas phase velocity components in x, y, z directions respectively
u_s, v_s, w_s	particle phase velocity components in x, y, z directions respectively
V_s	characteristic velocity of a system
x, y	dimensionless Cartesian coordinates

Greek symbol

α	volume fraction
ϵ_g	rate of dissipation of turbulent kinetic energy of gas phase
θ	granular temperature of particle phase
κ	conductivity coefficient of granular temperature
μ_g	dynamic viscosity of the gas phase
μ_s	solid phase shear viscosity
ρ	material density of a phase
τ	shear stress
ϕ	wall specularity coefficient

Subscript

g	gas
s	particle

Abbreviations

FVM	Finite Volume Method
CGNS	CFD General Notation System
KTGF	Kinetic Theory for Granular Flows

2–17 μm. It was found that increasing the degree of wall roughness resulted in higher loss of particle momentum near the wall. A similar study has been carried out by Lain and Sommerfeld [7] both numerically and experimentally considering a wide range of particle diameter and wall roughness value. Zhu et al. [8] concluded that particle-wall interactions had a more significant effect on the flow dynamics for particles with higher diameter than for smaller particles. Eskin [9] numerically carried out study on dilute turbulent gas-particle flows in flat horizontal channels using an approach of tangential restitution coefficient, but the study was done for low particle phase volume fractions. Passalacqua and Fox [10] used the solver MFIX to simulate dilute gas-particle flow in a vertical channel with particle phase volume fractions between 0.0001 and 0.01. The wall boundary conditions are set to be specularly reflective, i.e., no particle momentum is lost due to collisions with the wall and the particle-particle collisions are considered to be perfectly elastic. Loha et al. [11] studied the influence of specularity coefficient (ϕ) on the hydrodynamic behavior of gas-solid fluidized beds. It was found that different values of ϕ resulted in different particle velocity, granular temperature and particle volume fraction both close to the wall and in the central region. A similar type of study was done by Loha et al. [12] to check the effect of variation of particle–particle restitution coefficients on the flow characteristics of gas–solid fluidized beds at particular values of specularity coefficient ϕ. Some other noted works in this area have been carried out by Hartge et al. [13], Li et al. [14] and Lan et al. [15] etc. Soleimania et al. [16] modified the twoPhaseEulerFoam solver of OpenFOAM-2.2x using the modified boundary conditions given by Li and Benyahia [17] and studied the effects of these modifications in the particle phase velocity profiles in channels. Li et al. [18] observed that the simulations carried out considering particle-particle interactions showed closer agreement with experimental results for dispersed gas-particle flows through a sudden expansion. Zhao et al. [19] proposed a new semi-analytical and flow-dependent model for specularity coefficient based on the measurable particle properties and the model was integrated to the open-source code MFIX.

It is seen that several researchers have done studies in the field of dispersed gas-particle flows both numerically and experimentally, considering the effects of specularity (ϕ) and particle-particle restitution coefficient (e). It has also been reported that ϕ and e have more significant effects on flow hydrodynamics for higher particle volume fractions and higher values of particle diameters [8]. But to the best of the authors' knowledge, very few studies have been carried out till date where the effects of variations of these two parameters have been studied individually (as done by Loha et al. [11,12] for bubbling gas-solid fluidized beds) as well as in combination for dispersed gas-particle flows through horizontal channels. Moreover, discussions on the consequent effects of variations of these two parameters on the phase velocities, volume fractions as well as on the wall shear stress profiles are also very limited. So, as a step towards precise understanding of hydrodynamics in such flow scenarios, this study has been taken up in this work to find the effects of ϕ and e on the phase velocities and volume fraction profiles for gas-particle flows through horizontal channels. Simulations have been carried out for three different values of ϕ at a particular value of e and also for three different values of e at a particular value of ϕ. Four possible combinations of maximum and minimum values of ϕ and e are considered from the values considered for the simulations in order to find out the maximum and minimum values of phase velocities that can be obtained from those combinations. In addition to these, variations in the wall shear stress for both the phases with change in the value of ϕ have also been studied keeping all other parameters constant which has been previously reported in very few literature.

2. Governing equations and discretization

In this work, an inhouse numerical solver has been developed to simulate dispersed gas-particle flows using finite volume method where the entire solution domain is sub-divided into a number of non-overlapping cells (finite volumes). Collocated grid arrangement has been used where all the dependent variables are defined at the centroid of each individual cell. Both phases are treated using Eulerian approach where the conservation equations for mass and momentum are solved for the gas and particle phases separately and interaction is taken care by inter-phase exchange term. The governing equations for both the phases can be written as,

Gas phase Continuity Equation

$$\frac{\partial(\alpha_g \rho_g)}{\partial t} + \nabla \cdot (\alpha_g \rho_g \mathbf{u}_g) = 0 \tag{1}$$

where α_g is the gas phase volume fraction, ρ_g is the gas phase material density and $\mathbf{u}_g$ is gas phase velocity vector. There is no mass