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Original Research Paper

A parametric study of dispersed laminar gas-particle flows through vertical and horizontal channels

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A B S T R A C T

Particle diameter, particle phase material density and inlet particle volume fraction are three important parameters governing the flow physics of dispersed gas-particle flows. In this work, an inhouse numerical solver is developed to investigate the effects of particle diameter (Stokes number), particle phase material density, inlet particle volume fraction and inlet phase velocities in the flow characteristics of gas-particle flows through vertical and horizontal channels and also in open domains. It is found that, for a constant inlet particle volume fraction, lower diameter particles attain a higher steady state velocity at any section inside the channel than the higher diameter particles; while the corresponding steady state gas velocity at any section increases with increase in particle diameter. On the other hand, for a constant particle diameter, the steady state gas phase velocity at any section decreases with increase in inlet particle volume fraction. Significant changes in both gas and particle velocity and volume fraction profiles have also been observed with inlet slip, i.e., when the velocities of both the phases at inlet are distinct as opposed to being equal, keeping all other flow and physical parameters invariant.

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1. Introduction

Dispersed gas-particle flow is a specific case of two phase flow in which both the phases are thoroughly mixed in each-other and not separated by a distinct interface. The particle phase may be solid or liquid. The particles are called the dispersed phase and the fluid in which the particles move is called the continuous phase. In dispersed gas-particle flows, the interactions between the particle phase and gas phase play an important role in governing the physics of the flow [1]. This interaction between the phases is termed as phase coupling. One way coupling means that the particle phase is affected by the fluid, but the fluid is not affected by the particle phase. It is applicable in case of dilute gas-particle flows in which the particle concentration is sufficiently low. As the particle concentration increases, a two way coupling is needed which means that both the phases are affected by each other. In case of dense gas-particle flows, the particle concentration is very high and particle-particle interactions resulting from inter-particle collisions also play an important role in addition to the two way coupling. This involves a three way coupling for modeling the effect of gas on particles, the effect of particles on gas and the effect of neighboring particles on one another. On the other hand, dilute gas-particle flows do not require the consideration of particle-particle interactions. In such a case, depending upon the particle concentration, a one or two way coupling would suffice. The dispersed gas-particle flow has attracted the attention of the researchers due to its existence in a wide variety of applications ranging from the flow of dust-air mixture in the atmosphere to industrial applications like chemical reactors, fluidized beds, pneumatic conveying, IC engines, etc. [2]. As a result, the research in this type of flow is gaining pace along with other types of two phase flows over the years.

Study of particle dispersion and deposition in dispersed gas-particulate flows has been carried out extensively. Li and Ahmadi [3] studied the dispersion and deposition of particles from a point source in a turbulent channel flow. Effects of Brownian diffusion on particle dispersion along with the effects of variation in particle density and particle-surface interaction are carried out in this work. Rahimi-Gorji et al. [4] carried out CFD simulations of airflow behavior and particle transport and deposition in different breathing conditions such as light breathing condition (15 L/min), normal breathing condition (30 L/min) and heavy breathing condition (60 L/min) through the realistic model of human airways. Similar type of study has been carried out by Rahimi-Gorji et al. [5] in which a detailed two-phase flow modeling of airflow, transport

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Nomenclature

C_d	interphase drag coefficient
d_s	particle diameter
K_{gs}	momentum exchange coefficient
L_s	characteristic length of a system
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
μ_g	dynamic viscosity of the gas phase
μ_s	solid phase shear viscosity
ρ	material density of a phase
τ	shear stress
τ_f	characteristic fluid time scale
τ_p	particle relaxation time
ϕ	wall specularity coefficient

Subscript

g	gas
s	particle

Abbreviations

FVM	finite volume method
CGNS	CFD General Notation System

and deposition of micro-particles of range 1–10 μm in a realistic tracheobronchial airway geometry is carried out and it has been found that more particle deposition in tracheobronchial airways can be achieved by enhancing inhalation flow rate and particle size.

Volume fraction and particle Stokes number are two very important physical parameters related to this type of flows. The volume fraction of a particular phase is defined as the ratio of volume occupied by that phase to the total volume under consideration. The value of particle phase volume fraction determines whether the flow is dilute or dense. Some limiting values for particle phase volume fraction α has been suggested in [6] according to which if α is less than 10^{-3}, the particle phase has no influence on the gas phase. The flow in this case is referred to as dilute and so, a one way coupling is enough for modeling such kind of flows. But when the particle phase volume fraction increases above 10^{-3}, the flow no longer remains dilute and the effect of particle phase on the gas phase should also be taken into account. This is the range in which a two way coupling is to be considered between the phases. If the particle phase volume fraction increases above 0.1, particle-particle interactions should also be considered along with the two way coupling. The other important parameter is the particle Stokes number which is a dimensionless number corresponding to the behavior of particles suspended in a fluid flow. It physically determines how readily the particles tend to adapt in the changes in gas phase flow field. These two parameters have significant effects in the hydrodynamics of dispersed gas-particle flows and so studies to find out the effects of these parameters have been carried out by many researchers.

The numerical simulation of dispersed gas-particle flow with dispersed phase consisting of solid particles of finite size has been extensively carried out by Barton [7–9]. Laminar particle laden flows were analyzed for a classical backward-facing step geometry using orthogonal grids. The particle phase was treated with Lagrangian approach in which each particle is tracked individually inside the computational domain. The change in the recirculation lengths for various inlet values of Reynolds number, particle Stokes number and void fraction was mainly studied in these works. Significant work in simulations of dilute laminar gas-particle flows was carried out by Passalacqua and Fox [10]. In this work, a third-order quadrature based moment method coupled with a fluid solver has been applied to simulate dilute gas-particle flow in a vertical channel with particle phase volume fractions between 0.0001 and 0.01. The effect of particle phase volume fraction on particle velocity has been studied. Similar work was carried out by Passalacqua et al. [11] in which numerical simulations of laminar gas-particle flows were carried out for particle Stokes numbers 0.061 and 0.61 in a 2-D vertical channel and results are compared with those obtained from two-fluid model. Deshmukh et al. [12] used Particle Image Velocimetry (PIV) to study the velocity distribution and profiles of mean velocities and volume fractions of particles in a gas-solid mixture through horizontal channels. It was found from the experiments that the small diameter particles are better dispersed in the channel than the larger ones.

Like particle Stokes number and particle phase volume fraction, ‘inlet slip’ (which means the difference of velocities between the phases at the inlet of the domain) also effects dispersed gas-particle flow through open and wall bounded domains. Yu et al. [13] studied the effects of inlet slip between the phases in case of dispersed gas-particle flow in a single-side backward facing step flow and found out that inlet slip has significant effects both on recirculation lengths and vortex structure of the gas phase. Zhao et al. [14] studied the effects of particle slip velocity in wall bounded turbulent flows and found that the slip velocity fluctuations exhibit a monotonic increase with increasing particle Stokes number.

It is seen that several researchers have done some studies in the field of dispersed gas-particle flows through channels both numerically and experimentally in order to find out the effects of particle Stokes number, inlet particle phase volume fraction, etc. But very few have carried out a complete parametric study of this type of flows which involves the study of effects of particle diameter (Stokes Number), particle phase material density, inlet particle phase volume fraction and difference of inlet phase velocities taken together. So, in the present study, we have carried out a complete parametric study of laminar dispersed gas-particle flows considering all the above aspects and a detailed analysis of the influence of all these parameters in the flow physics of dispersed gas-particle flows is presented based on the obtained results. The present study has been carried out in an extensive manner for a wide range of volume fractions for the dispersed phase which varies from a very low value (falling in dilute range) to a moderately high value (falling in the dispersed range) and a wide range of particle diameters (Stokes number) in horizontal and vertical channels as well as in

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