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Study on gas-particle heat transfer in oscillating flows

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ABSTRACT

A numerical study of the gas-particle cluster interphase heat transfer in oscillating flows is conducted by using the one-dimensional Eulerian-Eulerian model. The effects of flow oscillation on the two-phase flow, particle concentration and as well the interphase heat transfer rate are investigated. The results show that the heat transfer between the gas and particle clusters can lead to the increases of the average particle concentration and the corresponding oscillation amplitude, but the decrease of the oscillation wavelength, which are closely related to the interphase heat transfer during the particle velocity relaxation process. Convective particle clustering is the primary cause of the oscillation of the two-phase mixture equilibrium temperature. Particle initial velocity and gas inlet velocity have great influences on the particle concentration and temperature. Increases in the gas inlet mean velocity and oscillation frequency are beneficial for the reduction in particle and gas temperature oscillation amplitudes. Particle diameter has an insignificant influence on the averaged values of the two-phase equilibrium mixture parameters but a noted impact on the oscillation amplitude of particle concentration. The increase in particle diameter is helpful for the reduction of the oscillation amplitude of the two-phase mixture equilibrium temperature.

1. Introduction

Particle laden flows are of relevant interest in many industrial processes in mechanical and chemical engineering, powder transport, thermal pollutant in atmosphere, solid and liquid fuel combustion, heat exchangers and many other examples [1,2]. In many of these industrial processes a striking feature of the two-phase flows is the tendency of particles to inhomogeneously distribute in space, forming clusters by virtue of flow oscillation, turbulence, centrifugal force, and etc. [3–7]. Particle clustering necessarily implies high particle concentration regions and a vast of researches have been conducted in the past few decades for its strong theoretical and practical engineering relevance. These studies focused on multiple aspects including clustering formation, cluster structure and size, drag law, flow characterization, heat transfer enhancement, turbulence modulation and combustion instability [8–16]. Among them, the heat transfer between gas and cluster attracted more and more attentions of researchers, although the computation cost is still high. As the earliest efforts, Marthelli and Boelter [17] studied the effects of flow oscillation and particle clustering on the rate of gas-particle interphase heat transfer to investigate the mechanism of the enhancement of the transport phenomena due to flow oscillation. Also, Tong and Sirignano [18] investigated the influence of oscillating gas pressure and velocity on single size gas-droplet heat transfer in presence of flow oscillation. Such early attempts confirm that the gas-droplet heat transfer play a decisive role in influencing self-sustained acoustical oscillations. Later, with the fast development of fluidized bed, the studies of particle clustering also become one of the hottest research areas, including the heat transfer [19–24]. In general, researchers commonly agree that there are three main modes of heat transfer, surface-bed, gas-particle cluster, particle-particle heat transfer, occur in gas-solid fluidized beds [19]. In particular, the studies related to gas-particle cluster heat transfer have the focus on the heat conduction taking place between particle clusters and the wall surface for that the particles are major heat carriers between the core and the wall of a fluidized bed riser and a higher concentration of particles results in a higher heat transfer [20]. To reveal the further detail of the gas–particle clusters heat transfer, direct numerical simulations (DNS) and multiscale modeling approaches exhibit the incomparable capability to model the prevailing flow and transport phenomena [21]. However, huge computational costs resulting from the need to perform unsteady multi-scale calculations raise doubts as to its suitability for solving complex physical processes. Therefore, to keep the computational cost on an acceptable level, in the previous studies the heat transfer between gas and particle clusters is often neglected despite the fact that it is an important element of the heat transfer in fluidized beds [20,21]. Studies have proved that the thermal transport mechanisms of particle clusters are strikingly different from that of the dispersed particles [22]. It is expected that the gas-particle clusters heat transfer should also be different from that between gas and dispersed particles. To our knowledge, limited results exist for the gas-particle cluster heat transfer.

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The main objective of this work is to investigate the gas-particle cluster heat transfer in dilute two-phase flows. As a matter of fact in fluidized beds and turbulent gas-particle flows the flow fields are multi-dimensional and the distributions of particles in clusters are generally uneven. This inhomogeneity in particle distribution can pose considerable challenges and introduce great difficulties and inaccuracies in quantifying gas-particle clusters heat transfer. In previous studies, the authors studied the particle clustering phenomenon in oscillating flows and elucidated the formation mechanism of particle cluster. In current work, particle clusters are generated by modulating the gas inlet velocity. An Eulerian-Eulerian two-phase numerical model is employed to investigate the gas-particles cluster heat transfer in one-dimensional flows. The remainder of this paper is organized as follows. Section 2 documents the Eulerian-Eulerian two-phase model and numerical method. Section 3 reports the numerical results and discussions. The main results of the paper are summarized in Section 4.

2. Mathematical model

In this work, an Eulerian-Eulerian (EE) two-phase flow model has been adopted to study the gas-particle cluster interphase heat transfer in oscillating gas flows. For the simplicity, the numerical simulation is carried out in a one-dimensional space and only energy coupling between the two phases is included.

2.1. Gas-phase governing equations

The governing equations for the laminar compressible flow are shown as following [25]:

$$\frac{\partial}{\partial t}(\rho) + \frac{\partial}{\partial x_j}(\rho u_j) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_j}(\rho E u_j) = \frac{\partial}{\partial x_j}\left(-p u_j + u_i \tau_{ij} - q_j\right) + S_e \tag{3}$$

where $\rho(x,t)$, $u_j(x,t)$, $p(x,t)$ and $E(x,t)$ are the fluid density, velocity component, pressure and total energy, respectively. The total specific energy is computed as $E = e + {u_i^2}/{2}$, where e denotes the specific energy. τ_{ij} is the stress tensor which can be derived from kinetical gas theory. q_j denotes heat conduction and is modeled by Fourier's law. The fluid follows the ideal gas law and the dynamic viscosity is evaluated by a standard power law. S_e is the source term accounting for the interphase heat transfer.

2.2. Discrete-phase governing equations

In the EE approach, the dispersed phase is treated as a continuum flow, for which the transport equations can be formulated by defining the mesoscopic quantities, denoted by $\breve{}$. In this study, the discrete particles are assumed to be monodisperse and only small volumetric loadings (~10^{-3}) are considered. The conservation equations for the dispersed phase mesoscopic quantities read:

$$\frac{\partial}{\partial t}N_p + \frac{\partial}{\partial x_j}N_p u_{p,j} = 0 \tag{4}$$

$$\frac{\partial}{\partial t}N_p u_{p,i} + \frac{\partial}{\partial x_j}N_p u_{p,j} u_{p,i} = -\frac{N_p}{\tau_p}(u_{p,i} - u_i) \tag{5}$$

where N_p, $u_{p,i}$ are the particle concentration and velocity component. The particle velocity relaxation time τ_p is evaluated by the empirical correlation proposed by Bird et al. [26] which is used to correct the relaxation time given by the Stokes model when the droplet Reynolds number is not small.

The convective heat flux Φ_g from the gaseous side to the particles is calculated as $\Phi_g = \pi N_p d_p \lambda N_u (T_p - T_g)$ [27], where T_p and T_g are particle and gas temperatures, d_p is the particle diameter, λ is the gas phase conductivity and Nu is the Nusselt number expressed as:

$$Nu = 2.0 + 0.55 Re_p^{1/2} Pr^{1/3} \tag{6}$$

where Re_p is the particle Reynold number and Pr is the Prandtl number.

2.3. Numerical methods

The discretization of the governing equations is based on the finite volume method. The fully explicit finite volume solver uses a cell-vertex discretization with a two-step Taylor–Galerkin finite element scheme developed by Colin and Rudgyard [28] Characteristic boundary conditions (NSCBC) [25] are used for the gas phase along the streamwise direction. Gas velocity oscillation is imposed at the inlet by the Inlet Wave Modulation (IVM) approach [29].

In this paper only the convective particle clustering is involved for it is the one generally encountered in practical applications. The computational domain is a simple 1D channel as shown in Fig. 1.

At the inlet, a velocity oscillation is imposed on the boundary of continuous phase, which can be expressed as:

$$u_g(0,t) = u_a + u_b \sin(\omega t) \tag{7}$$

where u_a is the inlet mean gas velocity, u_b is the velocity oscillation amplitude, ω is the angular velocity, $T = 2\pi/\omega$ is the time period of oscillation, $f = 1/T$ is the oscillation frequency. The particle is assumed to be monodisperse and it is assumed that $St \ll 1$ where St is the particle Stokes number and defined as $St = \tau_p/T$. The numerical simulations are carried out with different particle initial velocity and gas boundary velocity while the gas-particle mass ratio remains at 2.46 at the inlet. The main parameters used in the present simulation are listed in Table 1.

3. Results and discussions

Based on the conditions presented above, the gas-particle cluster interphase heat transfer in oscillating flows is conducted. As the primary characteristics, the particle concentration and particle temperature distribution are analyzed and discussed in detail. Then the main parameters are studied and evaluated to demonstrate the effects.

3.1. Characteristics of the two-phase equilibrium mixture

Characterizations of gas-particle two-phase flows subjected to acoustic forcing are examined. Fig. 2(a) plots the spatial distributions of the normalized particle concentrations $N_p/N_{p,0}$ at the initial instance of one acoustic forcing cycle, where $N_{p,0}$, $u_{p,0}$ are the particle concentration and velocity at the inlet. For convenience, particle relaxation zone (PRZ) is introduced and defined as the region particle travels in the period of τ_p following the particle injection. The curves show that in downstream of the inlet, $N_p/N_{p,0}$ relaxes rapidly from 1.0 to the respective

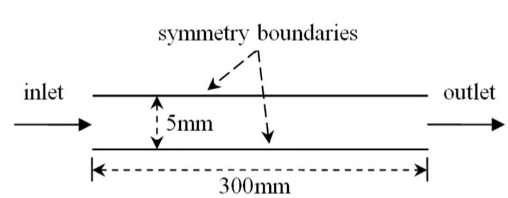

Fig. 1. Schematic of computational domain.