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Study on the clustering of dispersed particles in an oscillating flow field

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ABSTRACT

An Eulerian-Eulerian two-phase numerical model is employed to investigate the behavior of particles in oscillating gas flows with neglect of the effect of particles on gas flow field and the interphase heat and mass transfer. Meanwhile, a theoretical model for the analysis of particle clustering in oscillating gas flows is presented, in which the particles are tracked by the Lagrangian method and the particle concentration is calculated in the Euler frame. These two models complement each other with the aim to reveal the cause of formation and characteristics of particle clustering in oscillating flows. The results show that the occurrence of particle trapping/dispersion can be essentially attributed to the relaxation of particle velocity from its initial value to the mean value. The corresponding particle concentration shift is primarily determined by the particle initial velocity and mean velocity, but independent of the particle diameter and the gas oscillation. Two types of particle clustering are identified based on the different causes. The first type can be attributed to the relaxation of particle velocity from its mean value to the instantaneous gas velocity. The particle concentration oscillates with the same frequency of gas oscillation and travels at the local mean particle velocity which is equal to that of the gas. The second type is due to the modulation of particle velocity by the acoustic wave introduced at the inlet by gas velocity oscillation. The particle concentration oscillates at the frequency of gas oscillation and travels at the sound speed of the gas. The corresponding amplitude is much smaller than the first type. The results can also be extended to multidimensional space.

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1. Introduction

The complicated interaction of particles and non-evaporating droplets with an oscillating flow field can find a variety of mechanical, chemical, environmental, medical and agricultural applications [1,2]. In many of these applications the continuous carrier flow is oscillating. These flow oscillations can have substantial influences on the spatial and temporal concentrations of dispersed particles. The striking feature of the two-phase flow is the tendency of particles to inhomogeneously distribute in space, forming clusters by virtue of particle clustering [3–6]. Such interactions can also occur in mixing layers bordering particle streams and in other areas of two-phase flows [7–9]. Previous studies revealed that the clustering of particles or non-evaporating droplets can be attributed to a variety of reasons, such as particle-vortex interactions [10,11], particle-turbulence interactions [12,13], centrifugal force [14, 15] and particle-flow interactions. Pera and Reveillon [16] numerically studied the 2-D interactions between conical premixed spray flames and sinusoidal velocity modulations. They pointed out that there was a significant modulation on the flame due to droplets clustering. Katoshevski and coworkers [17–19] studied the clustering of particles in an oscillating gas flow field by a one dimensional model with neglect of the effect of particles on gas flow field. They reported that the particle clustering in an oscillating flow field can be caused by the change of local relative velocity of particles with respect to the oscillating carrier phase. The non-zero relaxation time for particles results in accumulation and separation of particles, and moreover the particle and gas velocities have considerable effects on the occurrence of particle clustering. Sazhin et al. [7] described the dynamics of grouping of spherical particles in an oscillating flow using a detailed analytical study and three types of trajectories were predicted. Mahapatra et al. [3] studied the grouping and segregation of particles numerically in both steady and oscillating flow fields by Eulerian-Eulerian multiphase model in one dimensional space. They reported the occurrence of particle trapping near the inlet and the grouping of different particle size classes, but the primary causes of particle trapping and clustering were not revealed. Heinlin and Fritsching [20] carried out an experimental investigation of droplet clustering in liquid sprays and compared clustering effects using two different types of atomizers. They found that for the pressure atomizer the clustering took place mainly in the central area of the spray, for the twin-fluid atomizer it was identified mostly in the outside spray area. It can be found that the interaction of particles with oscillating flows is the subject of many studies and it has been proven that the flow oscillation can efficiently influence the behavior

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of particles and lead to particle clustering. However, not much is known about the cause of formation and characteristics, and this constitutes the main subject of this paper.

In this study, an Eulerian-Eulerian two-phase numerical model is employed to investigate the behavior of particles in oscillating gas flows. A theoretical model for the analysis of particle clustering in oscillating gas flows is also presented. The results of the two methods are consistent and complementary, benefited from which the cause of formation and characteristics of particle clustering are investigated. The remainder of this paper is organized as follows. Section 2 documents the Eulerian-Eulerian two-phase model and the numerical method. Also the one-dimensional equation describing the dynamics of dispersed particle in an oscillating flow is presented. 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 and a theoretical model have been adopted simultaneously to study the particle clustering phenomena in oscillating gas flows. For the simplicity, the numerical simulation is carried out in a one-dimensional case. In order to deeply and clearly study the particle clustering phenomenon in oscillating gas flows, the numerical simulation and the theoretical calculation are carried out under the same boundary conditions for consistency. Consequently, the two results are expected to be the same and can validate and complement each other with the aim of demonstrating the underneath facts relating the formation of particle clustering and presenting the correlations of each important parameter.

2.1. Gas-phase governing equations

The governing equations for the laminar compressible flow are shown as follows [21]

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

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

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

where $\rho(x,t)$, $u_j(x,t)$, $p(x,t)$ and $E(x,t)$ are the fluid density, velocity vector, 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.

2.2. Liquid-phase governing equations

In the EE approach, the dispersed phase is treated as a continuum, for which the transport equations can be obtained. The conserved variables are defines for the so-called mesoscopic quantities, which is denoted by $\breve{}$ and represent the conditional ensemble average over all particle present in a given control volume. The conservation equations for the dispersed phase mesoscopic quantities read [21].

$$\frac{\partial}{\partial t}\breve{N}+\frac{\partial}{\partial x_j}\breve{N}\,\breve{u}_{l,j}=0 \tag{4}$$

$$\frac{\partial}{\partial t}\breve{N}\,\breve{u}_{l,i}+\frac{\partial}{\partial x_j}\breve{N}\breve{u}_{l,j}\,\breve{u}_{l,i}=-\frac{\breve{N}}{\tau_p}\left(\breve{u}_{l,i}-u_i\right) \tag{5}$$

where $\breve{N}$, $\breve{u}_{l,i}$ are the mesoscopic particle concentration and velocity component. In the numerical model the particle relaxation time τ_p is evaluated by the empirical correlation proposed by Bird et al. [22] which allows to correct the relaxation time given by the Stokes model when the particle Reynolds number is not small. In this study, the particle is assumed to be monodisperse and the particle volume fraction remains small (~10^{-4}) so that all particle interactions are negligible and that the fluid phase is undisturbed by the presence of the dispersed phase.

2.3. Numerical method

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 [23]. Characteristic boundary conditions (NSCBC) [22] are used for the gas phase along the streamwise direction. Gas velocity oscillation is imposed at the inlet by the Inlet Velocity Modulation (IVM) approach. The gas velocity imposed at the inlet is as

$$u_{g,in}=u_a+u_b\ sin(\omega t) \tag{6}$$

where $u_{g,in}$ is the inlet gas velocity at a time t, u_a is the mean gas velocity, u_b is the velocity oscillation amplitude, ω is the angular velocity of gas flow. In this way an acoustic wave is introduced into the flow field [24].

2.4. Theoretical solution of particle motion

Consider particle motion in a one-dimensional oscillating gas flow, described by the following equation [17]

$$u_g(x,t)=u_a-u_b\ sin(kx-\omega t) \tag{7}$$

where u_g is the gas velocity at a time t at a location x, k is the wave number of gas flow. Thus, $T=2\pi/\omega$ is the time period of oscillation, $f=1/T$ is the oscillation frequency. For that the effect of particles on gas flow field and the interphase heat and mass transfer are neglected, the quasi-steady state gas velocity fields are expected to be the same for the two approaches.

Adopting a Lagrangian approach, the one-dimensional governing equations for each particle can be expressed as [1]

$$\frac{du_p}{dt}=\frac{u_g-u_p}{\tau_p} \tag{8}$$

$$\frac{dx_p}{dt}=u_p \tag{9}$$

where u_p,x_p are the particle velocity and location. In this paper it is assumed that $St \ll 1$ where St is the particle Stokes number and defined as $St=\tau_p/T$ in this paper.

Generally, Eqs. (8) and (9) can be integrated by the straightforward ordinary differential equation (ODE) solver. However, in this paper the idea of exponential schemes is employed and the solution to Eq. (8) can be expressed in the integrated form as follows when ignoring the effect of particle on the gas [1]

$$u_p(t)=u_p(t_0)\ exp\left(-\frac{t-t_0}{\tau_p}\right)+\ exp\left(-\frac{t-t_0}{\tau_p}\right)\int_{t_0}^{t}\frac{u_g(x,t')}{\tau_p}\ exp\left(\frac{t'-t_0}{\tau_p}\right)dt' \tag{10}$$

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