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Study on gas-droplet heat and mass transfers in oscillating flows

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ABSTRACT

A numerical study on the dynamics of evaporating droplets in oscillatory flows is performed by using an Eulerian-Eulerian model including two-way couplings. The diluted liquid fuel-gas two-phase flow is assumed to be laminar. The droplet is assumed to be spherical during its lifetime and its thermal conductivity is also assumed to be infinite. Heat and mass transfer of this two-phase flow is characterized by analyzing the effects of acoustic fields on the two-phase temperatures, droplet diameter and concentration, spray evaporation rate and vaporizing species mass fraction. Results show that acoustic forcing can substantially influence the dynamics of the two-phase flow. The presence of droplet clustering as a consequence of acoustic forcing affects the two-phase flow in two aspects. The first is the oscillation of the two-phase flow parameter which roots in the periodic variation of droplet concentration. The second is the enhancement of the droplet evaporation rate at all conditions. The maximal relative increase in spray evaporation rate can be up to 72.9% in the parameter range studied. The mechanism for the enhancement of droplet evaporation rate is the optimal distribution of the heat in the liquid phase whose direct cause is droplet clustering. The enhancement of evaporation rate is highly dependent on the acoustic oscillation amplitude; however, there is no significant relationship between the acoustic oscillation frequency and the evaporation rate. Additionally, the oscillation amplitudes of the two-phase flow parameters are found to decrease with the growth of acoustic forcing frequency. It is made clear that the evaporation of droplets has a negligible effect on the occurrence of droplet clustering despite its marked influence on the two-phase flow through the reduction of the droplet relaxation timescale. Increasing the droplet initial concentration is also found to be beneficial for the enhancement of droplet evaporation rate.

1. Introduction

Spray combustion has received significant attention because of its wide range of applications in many industrial and practical systems especially in liquid-fueled combustors [1–3]. In many of these combustors including industrial burners and gas turbines, the liquid fuel is injected into the combustion chamber as fine droplets through a spray nozzle, and the downstream carrier flow is oscillatory [4]. Understanding the dynamic interactions between the droplets and the flow oscillations are important, and it allows for further insight into the knowledge of two-phase combustion instabilities [5,6]. However, the in-depth study of two-phase flow dynamics is a challenging task due to the complex interactions of several phenomena that occur at different temporal and spatial scales, such as inter-phase heat and mass transfers, heating and evaporating of droplets, and momentum exchange [3]. A great deal of efforts have been described in the literature to study the effects of flow oscillations on the evaporation of a single liquid droplet since that a comprehensive understanding of the effects of pulsations on a single droplet is very important in understanding their effects on sprays [7–9]. These studies showed that the evaporation of a single droplet is modified in an oscillating field and it has been experimentally demonstrated that the evaporation rate of a droplet (diameter: 100 μm) increases at least 160% with a sound pressure level of 174 dB over steady flow at the same mean Reynolds number [8]. Gurubaran and Sujith [9] conducted an experimental investigation on evaporative spray under various acoustic forcing conditions, and their experiment results conclude that the enhancement of evaporation rate of ethanol droplet can be up to 100% in the presence of an externally imposed acoustic field at 160 dB. In general, the enhancement of evaporation rate is more significant in oscillatory flows than in quiescent air, and another common understanding is that the evaporation rate is strongly correlated to the acoustic amplitude; however, it weakly varies with frequency [10–12]. There are two reasons for the enhancement of evaporation rate of a single droplet under the presence of an axial acoustic field: (1) The acoustic field increases the convective heat and mass transfer to and from the droplet, respectively; (2) The presence of an acoustic field decreases the terminal velocity

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of the droplet, thereby increases its residence time [12]. These prior research achievements on single liquid droplet offer a practical and efficient approach to decrease the time required for droplet evaporation.

Apart from the single droplet evaporation study, there are several works [13–15] were done to understand the effects of acoustic forcing on the enhancement of evaporation rate in sprays. In 1996, Dubey et al. [13] investigated the combustion characteristics of an ethanol spray-fired Rijke tube under various acoustic forcing conditions. They observed that the ethanol droplet diameter in the spray-fired Rijke tube is reduced by 15% on the average by the acoustic oscillations. After conducting several systematic studies [14,15], the researchers confirmed that the size reduction of droplet diameter was due to spray evaporation, but not due to atomization process. A similar spray characterization study [16] was performed in a pulse combustor when combustion occurs at steady and unsteady-state conditions. The results showed the evaporation rate of water droplets can be increased up to 25–30% during the unsteady-state condition. Later, Balachandran et al. [17] reported that the evaporation rate of droplets can be increased up to 107% for a sound pressure level of 156 dB. Due to the acoustic oscillations, the spray velocity is considerably reduced, thus indicating the presence of smaller droplets. The spray characteristics are much influenced by the acoustic velocity rather than the acoustic pressure, which can be understood by the fact that the influence of acoustic oscillations on the spray is stronger when the spray nozzle is located at an acoustic velocity antinode than the acoustic velocity node [12]. The reason for the enhancement of spray evaporation is believed to be closely related to the increase in the convection and interphase heat transfer at the acoustic velocity antinode of a standing wave [12].

When a spray of droplets is introduced into an acoustic field, droplet clustering takes place and is exhibited by alternate regions of high and low droplet concentrations. Several studies show that the droplet clustering influence the turbulence modulation, spray dynamics, and the interphase heat transfer [18-21]. Katoshevski [22,23], Greenberg [24] and Sazhin [25] studied the clustering of non-evaporating and evaporating droplets in an oscillating gas flow fields. They reported that the droplet and gas velocities have considerable effects on the occurrence of droplet clustering. For evaporating droplets, the variation of droplet diameter can influence the occurrence and transition of droplet clustering. However, Heinlein and Fritsching [26] experimentally showed that there is no obvious relationship between the occurrence of droplet clustering and the droplet size. Dwyer et al. [27] numerically studied the vaporization of heptane droplet cluster, and they have reported the evaporation rate of droplet cluster could be reduced due to the influence of velocity and temperature of the droplets and gas. In our recent work, the dynamics of dispersed particles in oscillating flows are studied and two types of particle clustering are identified and characterized. We also clarified the formation mechanisms of particle trapping/dispersion and clustering [19]. The influence of particle clustering on heat transfer of gas and particles is also studied in oscillating flows [20].

Table 1
Parameters used in the present simulation.

Parameter	Symbol	Value
Gas pressure	p_g	1.013×10^5 Pa
Gas heat capacity	C_g	1.004 kJ/kg K
Gas boundary temperature	$T_{g,0}$	450.0 K
Particle initial temperature	$T_{p,0}$	300.0 K
Gas inlet velocity mean value	u_a	1.0 m/s
Gas inlet velocity oscillation amplitude	u_b	0.2 m/s
Gas inlet velocity oscillation frequency	f	20.0 Hz
Droplet initial diameter	$d_{p,0}$	20.0 μm
Droplet density	ρ_p	782.3 kg/m^3
Droplet heat capacity	C_p	3.007 kJ/kg K

To sum up, the evaporation of droplets in acoustic fields is still an open question and the key issue of many studies. Previous studies on single droplet and spray evaporation in acoustic fields are mostly carried out in standing waves and several points are not clear and generally agreed. Firstly, it is not clear if traveling waves can enhance the spray evaporation rate; and it is also not clear whether the mechanisms for the spray evaporation in standing and traveling waves are the same. Secondly, the influence of droplet clustering on the gas-droplet heat and mass transfer is not clear and has not been extensively investigated. Thirdly, there is a discrepancy in the effect of droplet clustering on spray evaporation rate. The present work is mainly motivated by these three aspects. In the present work, an Eulerian-Eulerian two-phase numerical model is employed to investigate the complicated interactions between flow oscillations and the gas-droplet interphase heat and mass transfers in traveling waves. Especially, we address the influences of flow oscillations on the gas-droplet heat and mass transfers in aiming to elucidate the mechanism for the droplet evaporation rate enhancement. The remaining parts of this paper are organized as follows. Section 2 documents the Eulerian-Eulerian two-phase model and numerical method utilized, followed by numerical validation in Section 3. Section 4 introduces the simulation conditions and main parameters. Section 5 reports the numerical results and discussions. The main results of this paper are summarized in Section 6.

2. Mathematical models

In this work, an Eulerian-Eulerian (EE) two-phase flow model has been adopted to study the droplet clustering and its effects on the two-phase heat and mass transfers in oscillating gas flows. For the simplicity, the numerical simulation is carried out in a one-dimensional case.

2.1. Gas-phase governing equations

The governing equations for the laminar compressible flow are shown as following [28]:

$$\frac{\partial}{\partial t}(\rho Y_k)+\frac{\partial}{\partial x_j}(\rho Y_k u_j)=-\frac{\partial}{\partial x_j}J_{j,k}+S_{v,k}\quad \text{for } k=1,2\ldots N_s \tag{1}$$

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

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

where $\rho(x,t)$, $u_j(x,t)$ and $E(x,t)$ are the fluid density, velocity vector, and total energy, respectively. $Y_k(x,t)$ is the mass fraction of species indexed by k. The above equations state the conservation of partial density, momentum and total non-chemical energy over N_s species. The fluid follows the ideal gas law. 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, $J_{j,k}$ is diffusive species flux and is approximated by the Hirschfelder-Curtis relation with a correction velocity ensuring mass conservation [28], the heat flux vector q_j is composed of two terms denoting heat conduction (modeled by Fourier's law) and the heat flux through species diffusion. The dynamic viscosity of ideal gases is evaluated by a standard power law. The species diffusion coefficients are evaluated by assuming constant Schmidt numbers for all species. The heat conduction coefficient is computed from the