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Three-dimensional numerical investigation and modeling of binary alumina droplet collisions

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ABSTRACT

The off-center collision of binary equal-sized alumina droplets has been investigated by employing a three-dimensional direct numerical simulation method which involves the volume of fluid (VOF) and adaptive mesh refinement method. The simulations of tetradecane droplet collision are carried out to validate the numerical method. The results show good agreement with experiments. The off-center collisions of alumina droplet with diameter 10 μm are numerically investigated at various Weber numbers (30–400) and impact numbers (0.1–0.7). The Ohnesorge number is 0.1151. Four collision outcomes are obtained, coalescence after substantial deformation, reflexive separation, coalescence after long extension, and stretching separation, respectively. Bouncing is achieved by employing the double VOF functions method. In addition, as to the collision at various impact parameters, the critical Weber number of separation is obtained. And the collision regimes of alumina droplet are mapped out. Furthermore, alumina droplet collisions are modeled with the consideration of viscous dissipation, including the model of coalescence after minor deformation, bouncing model, reflexive separation model, stretching separation model, as well as the model for calculating the droplet parameters after separation. Bouncing model, reflexive separation model and stretching separation model are in good agreement with the present numerical results.

1. Introduction

With the development of space technology, deep space exploration has become the competitive project of many national aerospace departments in recent years, such as the Moon, Mars exploration and manned landing. In order to explore the deep space, the large thrust rocket engine is essential. Due to the easy realization of large thrust, simple structure, and high reliability, solid rocket motor has become the popular candidate power of heavy launch vehicle, such as space launch system (SLS), Ariane-6, and Chinese solid launch rocket CZ-11. The cost of large size solid rocket motor is extremely expensive. In order to reduce it and time, three-dimensional multi-physics numerical simulation is one of the preferred solutions. Through the numerical simulation, physical parameters are obtained to predict the problem and performance of the motor, and then improve the motor design, so as to reduce the number of trials and cut down the cost. Three-dimensional full-physics numerical calculation has always been one of the objectives of the study of solid rocket motor. In the last decades, the research around it has made a great progress resulting from the development of heavy launch vehicle, and at present it is still a hot spot in rocket power academic and engineering [1].

The physical processes in solid rocket motor are really complicated, involving propellant combustion, gas-droplet two-phase flow, ablation of insulation, as well as fluid-structure coupling between gas and the inhibitors for multi-segmented rocket motor. The productions of aluminum particle after combustion are fine alumina (Al_2O_3). Since the combustion temperature of propellant is between the melting point and boiling point of alumina, the alumina phase is liquid, which means that fine alumina is droplet. The flow of alumina droplets with gas is a typical gas-droplet two-phase flow. The diameter of droplets in the combustion chamber is of bimodal distribution, and alumina droplets mainly vary in size from submicron to tens of microns [2–4]. A large number of alumina droplets with different sizes will collide with one another when they are flowing at different velocities, and the outcomes of collision include bouncing, coalescence and breakup, which will change the size and velocity distribution of droplets, resulting in the change of flow field. It clearly shows that alumina droplet collision is one of the physics of solid rocket motor and very important for the prediction of the performance of motor, such as

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combustion instability [5], slag accumulation in submerged nozzles [6], and ablation of internal insulation [7]. If the multi-physics numerical simulation is used to predict these physical parameters, it is necessary to study the collision of alumina droplets and model the collision outcomes.

Up to the present, because of the cruel conditions of high temperature and pressure, only a few studies on droplet collision in solid rocket motor are reported in the literature. According to the approximate surface tension of mercury and alumina droplet, Salita [8] simulated the gas-droplet two-phase flow in the nozzle of Space Shuttle booster with mercury droplet collision model, and the result was similar to the experiment. However, the viscosity of mercury is much lower than alumina droplet, which causes the collision of alumina droplet is different from mercury droplet. And the model of alumina droplet collision cannot be similar to mercury droplet. Averin et al. [9] embedded a collision model similar to O'Rourke model into a numerical code, and carried out simulations of two-phase flow with allowance for coagulation and fragmentation of droplets in the combustor duct of a solid rocket motor with a sudden change in its cross-sectional area. The O'Rourke model is suitable for inviscid or low viscosity fluids but cannot accurately predict the high viscous fluid that alumina droplet belongs to. In the last few years, the Center for Simulation of Advanced Rocket (CSAR) has conducted a three-dimensional multi-physics numerical program named Rocstar. The Rocstar program is developed for reused solid rocket motor, such as the booster of Ares V and SLS. Researchers in CSAR have done a great deal of excellent numerical work with Rocstar [10,11]. But one of the weaknesses of their work is that the multi-physics model does not incorporate the collision model of alumina droplets. That is not because they could not add the model but there is no appropriate model for them to add. It is clear that alumina droplet collision is still not well understood.

2. Droplet collision

In contrast to alumina droplet collision, water and hydrocarbon droplet collisions are well understood, and there are many studies reported in the literature. But before the literature review, let us briefly introduce the description of binary droplet collision. Fig. 1 shows the collision of two droplets, where D_S, D_L, R_S, R_L, U_S, U_L are the diameters, radii, and velocities of the small and large droplets, respectively, and b is the distance between the centers of the droplets projected onto the direction perpendicular to the relative velocity at the moment of impact. In the present numerical simulation, D_S and D_L are equal, and $D_S = D_L = D_0$. U_S and U_L are equal, and $U_S = U_L = U_0$, and then the relative velocity is $U_r = U_S + U_L = 2U_0$. For the non-parallel collision, the velocity vectors can be decomposed into the parallel velocities shown in Fig. 1. Generally, the outcome of such a droplet collision can be described by five non-dimensional parameters: the Weber number *We*, the impact parameter *B*, the droplet size ratio Δ, the Reynolds number *Re*, and the Ohnesorge number *Oh*. These parameters are defined as follows:

$$We = \frac{\rho_l U_r^2 D_0}{\sigma} \quad B = \frac{b}{R_S + R_L} \quad \Delta = \frac{D_S}{D_L} \tag{1}$$

$$Re = \frac{\rho_l U_r D_0}{\mu_l} \quad Oh = \frac{\mu_l}{\sqrt{\rho_l \sigma D_0}} \tag{2}$$

where ρ_l, σ, μ_l are the density, surface tension, and dynamic viscosity of the droplets, respectively. Here, for equal-sized droplets $\Delta = 1$. The impact parameter is in the range $0 \le B < 1$, and $B = 0$ is the head-on collision, while $0 < B < 1$ means the off-center collision.

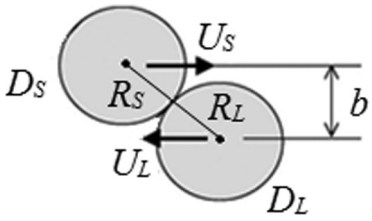

Fig. 1. The collision of two droplets.

The literature shows that binary droplet collision is of interest to the studies of atmospheric raindrop formation, nuclear fusion, emulsion polymerization, and fuel spray in internal combustion engines. Fig. 2 reviews the development of droplet collision study. In the early, droplet collision study focuses on the water droplet collision for the interest of atmospheric raindrop formation, on which Adam et al. [12], Park [13], Brazier-Smith et al. [14], Ashgriz and Poo [15], and Brenn et al. [16] are pioneers. They experimentally investigated the effect of diameter, size ratio, impact parameter, as well as Weber number on water droplet collision. It has to note that Ashgriz and Poo [15] obtained three collision outcomes of water droplet, namely coalescence, reflexive separation, and stretching separation, and also proposed a reflexive separation model and a stretching separation model based on the inviscid fluid theory. Those models greatly promoted the development of current droplet collision model.

Since droplet collision is very important to fuel spray in internal combustion engines, hydrocarbon droplet collisions have attracted lots of interests of study. Law et al. [17–20] have been working on hydrocarbon droplet collisions since 1990s. They experimentally studied the collision of different hydrocarbon droplets, and found five different collision outcomes, namely (I) coalescence after minor deformation, (II) bouncing, (III) coalescence after substantial deformation, (IV) coalescence followed by separation for near head-on collisions, and (V) coalescence followed by separation for off-center collisions, and the collision regimes was delineated on a *We-B* map shown in Fig. 3. Ashgriz and Poo [15] named outcome (IV) "reflexive separation" and outcome (V) "stretching separation" that are used in the present paper. The results show that boundaries between the various regimes of collision outcome are significantly influenced by the fluid properties of the droplets and the conditions of the ambient gas. For the head-on collision of various hydrocarbon droplets, the critical Weber number between different outcome regimes varies linearly with μ/σ. The difference in collision behavior is caused by the difference in the rheological properties of the fluids, especially the surface tension and the viscosity coefficient. Additionally, a theoretical model was developed to predict the head-on critical Weber number between regimes (III) and (IV), with considering the influence of size-ratio and fluid properties. The collision dynamics of ethanol droplet were investigated experimentally by Estrade et al. [21], and a bouncing model was proposed based on inviscid fluid dynamics, which is the first bouncing model for droplet collision.

As the development of oil industry, the studies of droplet collision were extended to high viscous fluids. Wills and Orme [22] conducted an experimental investigation of viscous binary droplet collisions in a vacuum environment. The viscosity of various droplets ranges from 10 to 30 mPa·s, which is much higher than water (1.003 mPa·s). And the Weber numbers are 761–3200. The results show that only two outcomes, coalescence and reflexive separation, are observed, and the critical Weber number between coalescence and reflexive separation $We_{c\text{-}r}$ is more than 100 times greater for a 30-cSt fluid than for water. With the increase of droplet viscosity, the viscous dissipation energy gradually increases, and the