Dynamics of Droplets Impulsively Accelerated by Gaseous Flow: A Numerical Investigation

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Abstract

The dynamics of droplets in gaseous flow is of importance in nature and in engineering application, such as rain, sprays, and combustions. The most fundamental interactions in such flows are the coupling between the droplet and the gas, and the interaction between droplets. However, the knowledge of these interactions is very limited. In this paper, two droplets, which stand side by side along the free stream direction, subjected to impulsive acceleration by the surrounding gaseous flow are simulated using a moving mesh interface tracking scheme coupled with finite volume method. This numerical method was used to simulate a single droplet impulsively accelerated by gaseous flow, and the results compared well with the existing experimental work ("Direct numerical study of a liquid droplet impulsively accelerated by gaseous flow", *Phys. Fluids*, **18**, 2006). By varying the distance between the two droplets, the interaction between drops are examined. It is found that for small distance, the two droplets' shapes are much different from the single droplet case. The front drop is even more deformed, and the rear one has a cone shape. This can be explained by the fact that for these small distances, the back droplet is in the wake of the front drop. The back droplet slows down the acceleration of the front drop, resulting in a smaller drag. The wake of the front drop pulls the front of the back drop, and thus a bell shape is formed. Finally, the two drops form a mushroom shape.

Introduction and problem setup

Transient dynamics of droplets in another fluid flow is important in a variety of natural phenomena and engineering applications, such as in rainfall, sprays, and inkjet printings. However, the knowledge of the interaction between droplets and the surrounding fluid, especially the momentum transfer in unsteady state, such as droplets impulsively accelerated by a gaseous flow, is rather limited. During such process, the droplets might undergo large deformation as they are translated. For single droplet, Temkin and his co-workers [1-2] experimentally investigated the droplet dynamics in an accelerating and decelerating flow. They found that for an almost spherical droplet in decelerating relative flows, the unsteady drag is always larger than the steady state drag at the same Reynolds number, while in accelerating relative flows, the unsteady drag is smaller. Helenbrook and Edwards [3] numerically studied the quasi-steady deformation and drag of a liquid drop. The effect of the deformation on the drag is examined numerically by Aalburg et al [4], Quan and Schmidt [5], and Wadhwa et al [6]. Droplet pair interaction in an unsteady flow is experimentally investigated by Temkin and Ecker [7], and the deformation of the droplet is small. They showed that the front (or upstream) droplet is not affected by the rear droplet; however, the downstream droplet experiences significant reductions of drag forces.

In this paper, the moving mesh interface tracking method [8-9] is used to simulate the droplet pair interaction subject to an impulsively acceleration by the surrounding gaseous flow. The numerical method has been validate against a number of experimental observations and theoretical results; especially, comparison between the numerical results [5] and the experimental predictions [1] shows high fidelity of our numerical simulations for a droplet accelerated by a gaseous flow. In this work, the two droplets are initially spherical with a diameter of r_0, and are aligned with the free stream, which is shown in Fig. 1. The distance between the centroids of the front (upstream) droplet and the rear (downstream) droplet is denoted as d_0. The outer domain is a box with length (L) of $50r_0$, width (W) of $16r_0$, and height (H) of $16r_0$ to minimize any wall effects. The upstream free gas flow is $8r_0$ away from the centroid of the front droplet. Moving wall boundary conditions are applied to the top and bottom walls, and the two sides are slip walls. A free stream with velocity of U_0 is imposed in the inlet, and an outflow boundary condition is applied for the right-end. The droplets have a viscosity of μ_d, density of ρ_d, and the viscosity and density for the suspending fluid are μ_s and ρ_s, respectively. A density ratio is defined as $\eta = \rho_d/\rho_s$, and a viscosity ratio is $\lambda = \mu_d/\mu_s$.

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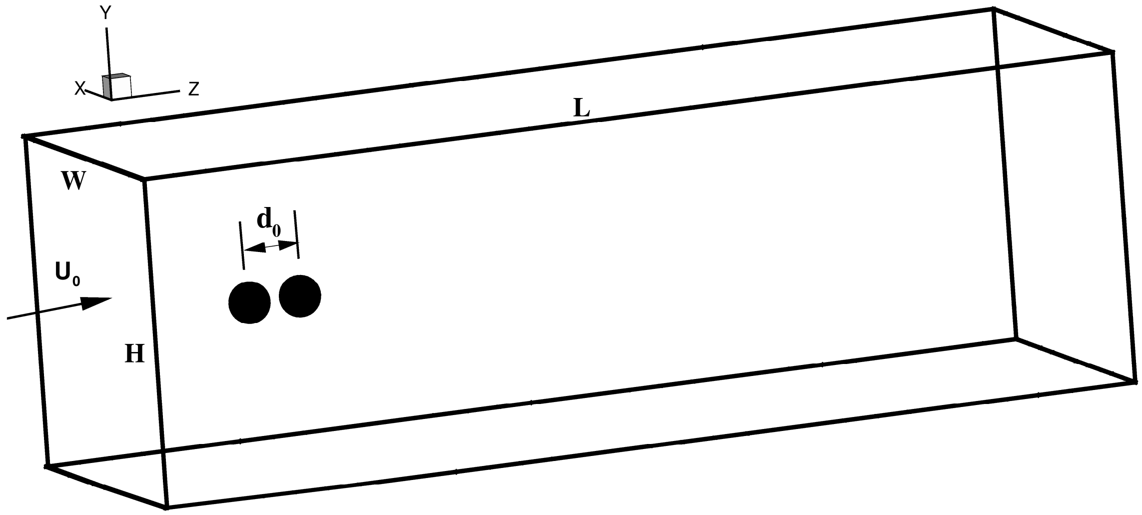


Figure 1. Sketch of the initial setup for the droplet pair impulsively accelerated by a gaseous flow.

Governing Equation and Numerical Methods

The integral form of the Navier-Stokes equations is used for the two-fluid system, as the interface is a natural control surface (CS) for a control volume (CV) near the interface.

$$\frac{d}{dt}\iiint_{CV} dv = \iint_{CS} \mathbf{v}\cdot\mathbf{n}ds, \quad (1) \qquad \frac{d}{dt}\iiint_{CV} \rho dv + \iint_{CS} \rho(\mathbf{u}\text{-}\mathbf{v})\cdot\mathbf{n}ds = 0 \quad (2)$$

$$\frac{d}{dt}\iiint_{CV} \rho\mathbf{u}dv + \iint_{CS} \rho\mathbf{u}(\mathbf{u}\text{-}\mathbf{v})\cdot\mathbf{n}ds = \iiint_{CV} \rho\mathbf{f}dv - \iint_{CS} p\cdot\mathbf{n}ds + \iint_{CS} \mu(\nabla\mathbf{u}+\nabla\mathbf{u}^T)\cdot\mathbf{n}ds \quad (3)$$

where **u** is the fluid velocity, **v** is the surface velocity of the control volume, **n** stands for the unit vector of the face normal, **f** denotes the body force per unit mass, and the superscript *T* stands for the transpose.

The governing equations are discretized by a finite volume method in a strongly conserved form. It should be noted that in the moving mesh interface tracking method, the Lagrangian motion of the interface atuomatically eliminates the convection terms in Equations (2) and (3) on the interface. The interface is zero thickness, and thus there is no smoothing of the fluid properties across the interface using Delta functions. For the convection terms other than on the interface, they are calculated by a central differencing in time and a predictor corrector scheme, and viscous terms are also computed in a similar approach. A three-step, second order, Runge-Kutta scheme is used for time integral. The resulted linear system is solved by Conjugate Gradient method. As mesh moves, mesh quality can not be guaranteed. Mesh adaptation methods, such as, mesh smoothing, edge flipping, edge contraction, edge bisection, are applied to the elements which the mesh quality is bad. For the details of the numerical schemes and the mesh adaptations, see [8-11].

Results and Discussion

A smooth initial velocity distribution is necessary to obtain reasonable results for the simulations. The same approach as the one in [5] is used to set up the initial velocity field and the velocity field for the two droplets and the surrounding flow is shown in Fig. 2. It can be seen that the velocity inside the droplet are very small compared to the suspending flow. In order to observe the fluid flow inside the droplets, streamlines are displayed. There are vortex rings inside the droplets. It is believed that this velocity field mimics the droplet impulsively accelerated by a gaseous flow.

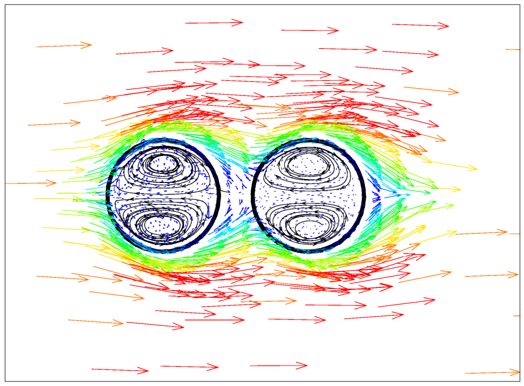


Figure 2. Initial velocity field for two droplets impulsively accelerated by a gaseous flow.

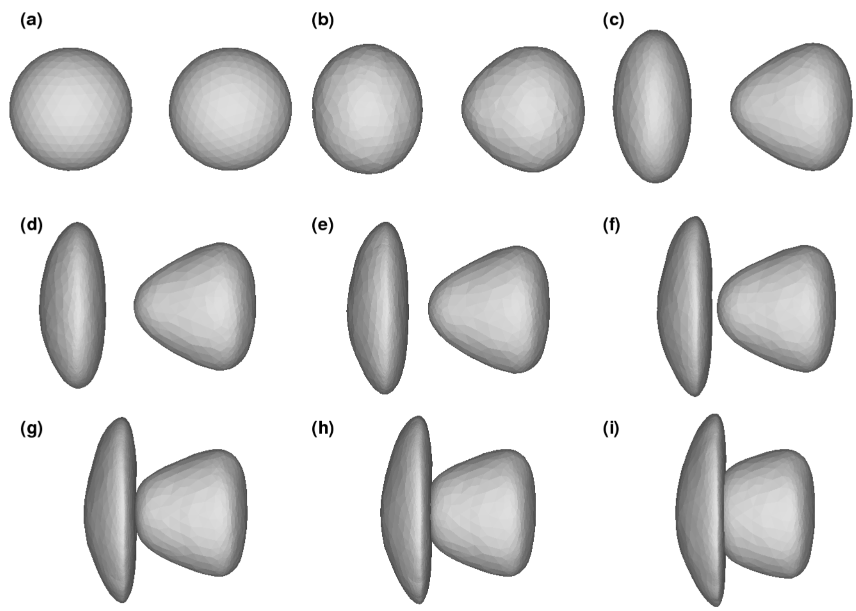


Figure 3. Shape evolution of the two droplets. We_i=40, Re_i=40, λ=50, η=50. Non-dimensional time sequence from (a) to (i) is 0.0, 2.50, 7.50, 10.00, 11.25, 13.01, 14.01, 14.51, and 15.51.

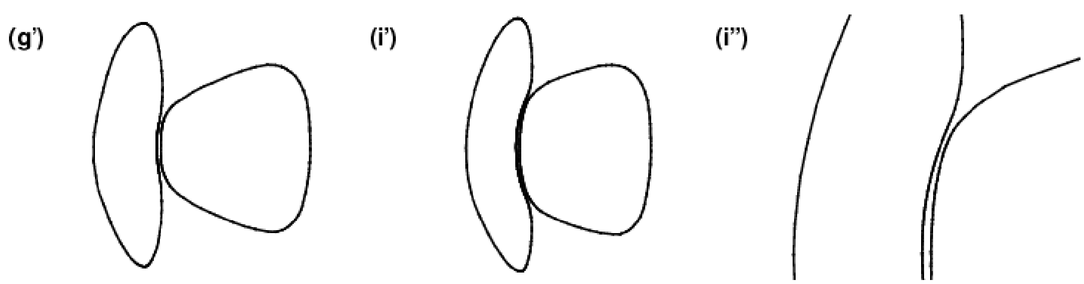
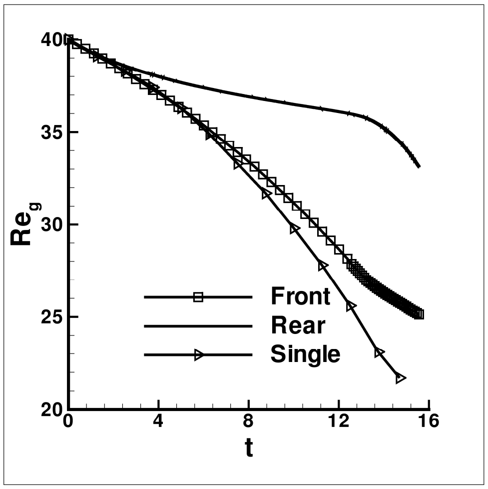


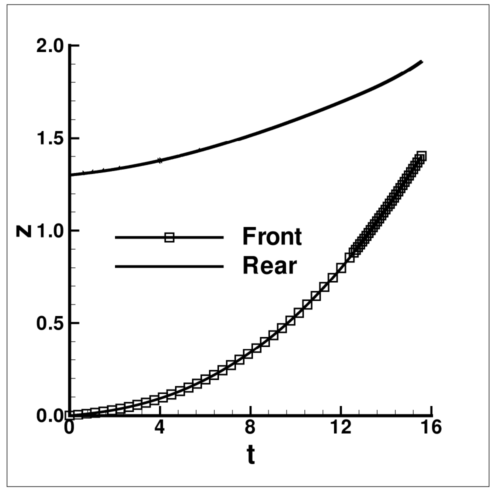
Figure 4. A yz-plane cut of (g) and (i) in figure 3. The superscript prime stands for the corresponding cut. (i'') is the zoom-in of (i').

Fig. 3 shows the shape evolution of the two droplets as they are accelerated by the suspending flow, and the time is non-dimensionlized by r_0/U_0. As time progresses the upstream droplet deforms almost symmetrically in the front portion and the back region, see Fig. 3 (a)-(c). However, the downstream droplet behaviors differently, the front part become much more curved, and the rear part is more flattened. The first droplet has an ellipsoidal shape, while the second droplet is bell–shaped. The back portion of the upstream droplet is becoming more flattened for

Figs. (d)-(f), and the front part is curving. The front part of the second droplet is becoming blunt, while the rear portion is continuing flattened. The distance between the two droplets is increasingly shortened. This trend continues for Fig. 3 (g)-(i), and finally the two droplets form a mushroom shape. It can be noticed that in (g)-(i), the back of the upstream droplet might be dimpled, this is clearly shown in Fig. 4. It can also be observed that our mesh adaptation is capable in capturing small length scale in the thin film of between the two droplets, see Fig. 4 (i') and (i'').



(a)



(b)

Figure 5. (a) Relative Reynolds number based on the surrounding fluid versus non-dimensional time t for the front drop, the rear drop, and a free single drop with We_i=40, Re_i=40, λ=50, η=50. (b) The centroid positions, Z is non-dimensionlized by $2r_0$.

Fig. 5(a) show the history of the relative Reynolds number (Re_g) based on the surrounding fluid; $Re_g = \rho_s(U_0-U_c)2r_0/\mu_s$, where U_c is the centroid velocity of the corresponding droplet. It can be seen that the rear droplet is the one which is slowest, while the free single droplet is more quickly accelerated. Fig. 5 (b) shows the position of the two droplets. The initial distance between the two drops is 1.3 diameters, which mean the smallest distance between the droplets is 0.6 radii. As time progesses, the distance become smaller and smaller, and at time of 16, the distance is less one diameter. It is shown in Fig. 4 that the smallest distance between the two drops is very tiny. Fig. 6 displays the comparison of the drag coefficient between the front droplet and the free single droplet. For the time less than 4, the drag coefficients are almost the same, however, for the time after 4, the upstream droplet moves slower than the free single one. After t=13.0, the acceleration of the second droplet is abruptly deceased, this may due to the formation of a thin film between the two droplets. To explain why the two droplets moves slower than a free single droplet, an examination of the velocity field is necessary.

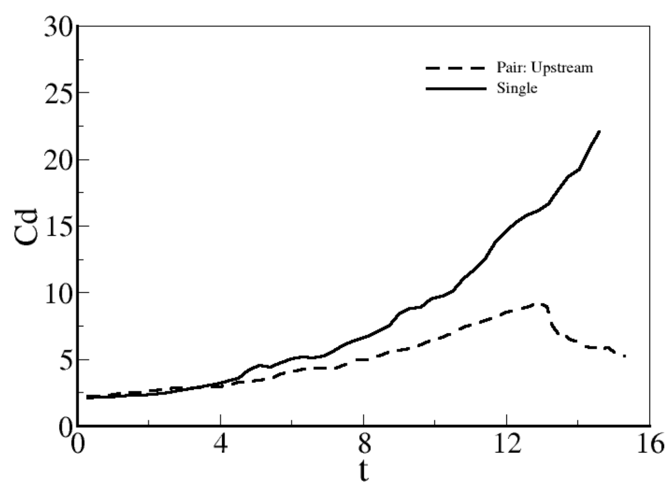


Figure 6. Drag coefficients of the upstream droplet and the free single droplet.

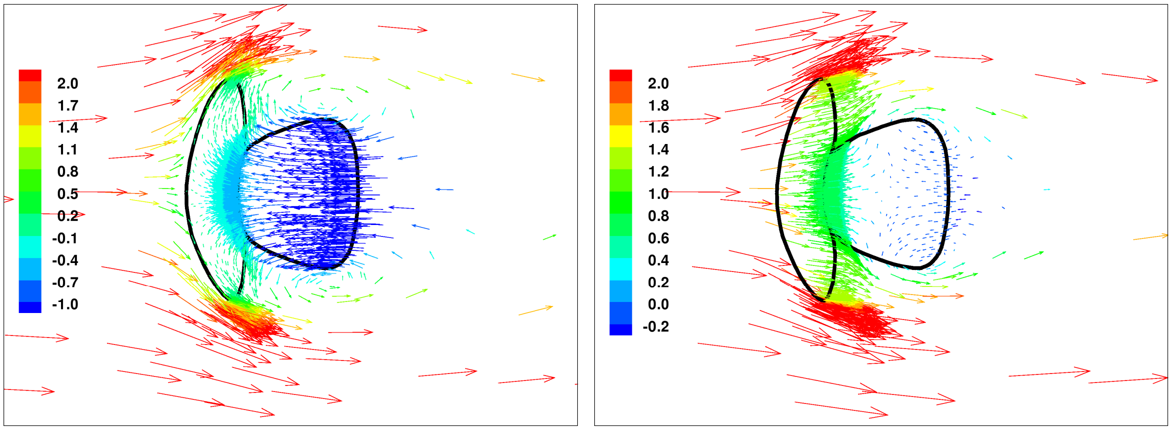


Figure 5. Velocity field in xy-plane of (i) in figure 3. The left figure is at the reference of the upstream droplet centroid, while the right one is at the reference of the second droplet centroid.

Fig. 5 displays the velocity field, where the figure on the left is at the reference of the first droplet centroid, and the one on the right hand side is at the reference of the downstream droplet centroid. It can seen from the left figure that the second droplet is totally inside of the first droplet weak, and the second one moves towards the first one with a significant speed. This explains why the second droplet is much more slowly accelerated than the free single droplet and the first droplet. The rear part of the upstream drop is moving upstream, this results in a dimple in this region. From the right figure, it is observed that the upstream droplet moves toward itself, and the flow field at the front of the second droplet is distinct different from the one of a free single drop impulsively accelerated by a gaseous flow. A much smaller weak appears behind the second droplet, and this leads to a slower motion of the droplet. It can also be seen that the weak of these two droplets is affected by the presence of the other droplet.

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