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Interaction of two drops in the bag breakup regime by a continuous air jet

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ABSTRACT

Fuel atomization characteristics are important in the performance of gasification and combustion. This work concerns the interaction of two drops in a continuous air jet stream. Morphological classifications of interaction modes have been analyzed using high speed camera. Behaviors of drops group and the isolated drop in the airflow are significantly different. Experimental photos show that there are four main interaction modes, which are coalescence mode, puncture mode, side by side mode and no direct contact mode. Influence of dimensionless distance on drops interaction mode is researched. Then the drops interaction regime map is obtained. The model prediction is in good agreement with the experimental results. The total dimensionless breakup time of puncture mode is the longest, then the coalescence mode, and the third the side by side mode. Results present an evaluation of the role of proximity to other drops in affecting the outcome, which are useful in understanding atomization mechanism and improving simulation model.

1. Introduction

Atomization is an important phenomenon taking place in natural and many industrial processes, such as combustion, gasification, automobile engine and propellant injector [1–3]. In atomization, the influence of two drops interaction on drop size distribution is great, and the two drops interaction also has a quantity of significant practical importance for a wide range of applications [4–6]. Many theoretical, experimental and numerical simulation studies have been performed on the two drops interaction in quiescent air environment. Several modes of two drops interaction are distinguished and researched, including coalescence, stretching separation, bouncing, and reflexive separation, etc [7–21]. The coalescence and bouncing regimes at small relative velocity are governed by the drainage of gas film between the approaching drops. The drops collide if their surfaces in the collision region approach the distance comparable with the characteristic size associated with the van der Waals forces. The reflexive separation is observed at the relatively high relative velocity. Such collision leads to an axial stretching followed by its radial deformation. This axially stretching jet is bounded by two drops. These drops move first apart and then recede. Such collisions lead to the drops separation. The stretching separation is usually related to the head-off collision. Such collision produces two moving drops connected by a stretching filament, which then breaks up.

The work on the two drops interaction in quiescent gas is rich [7–21]. However, the research on the two drops interaction in a continuous air jet is limited, which is also a common phenomenon in a variety of scientific and engineering applications [22]. The liquid atomization by airflow (the air-blast atomization) can be summarized commonly as two steps: primary and secondary atomization [23–25]. Primary atomization removes liquid mass from the surface to form big liquid drops. And secondary atomization is the breakup of isolated drop in airflow.

The important intermediate step between primary and secondary atomization is the interaction of drops, which has an important impact on this final atomization performance. It constitutes the link between the flow issuing from the atomizer and final spray. Due to the presence of airflow, the interaction of two drops now evolves in a highly interactive and variable manner. The interaction of two drops in the airflow yield even more rich morphologies and mechanisms, which have not been completely known.

So this study is to discover the modes of two drops interaction and describe the morphologies of different drops interaction modes. The interaction mechanism is analyzed by energy approach, and then the effect of drop position on interaction mode and time is also studied.

2. Experimental set-up

Interaction of two drops is studied with the help of Fastcam APX-RS camera (Photron, 3000 images/s, 1024 × 1024 pixels). The image

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Nomenclature

u_g	air velocity
u_i	the drop internal flow velocity
u_{il}	the drop internal flow velocity of the left-hand end
u_{ir}	the drop internal flow velocity of the right-hand end
$\overline{u_l'}$	$u_{il}/2$ approximately
$\overline{u_r'}$	$(u_{ir} + u_g\sqrt{\rho_g/\rho_l})/2$ approximately
u_i	drop internal flow velocity
u_u	the drop internal flow velocity of the upper part
$\overline{u_u'}$	$u_u/2$ approximately
w_g	the characteristic velocity in the wake of first drop

resolution is 75.3 µm per pixel. Fig. 1 is the schematic of two drops test system, this rig is similar to our earlier research [26,27].

There are two water drop generators and one air nozzle (outlet diameter 68.00 mm whose uncertainty is ± 0.02 mm) with the converging outlet in this test. The circular nozzle combined with the flow meter and air blower. The uncertainty of flow meter is ± 1.5%. The flow field of the air jet is measured in detail in our early work [26]. Air velocity u_g for this experiment is 18.4 m/s. Drop diameter D_0 is 2.12 mm. The ratio of droplet diameter to air jet diameter is very small. The horizontal distance between the initial drops and the nozzle exit is 20 mm. The drop Reynolds number is 2680,

$$Re = u_g D_0 \rho_g/\mu_g \tag{1}$$

and Weber number is 12.3,

$$We = \rho_g D_0 u_g^2/\sigma \tag{2}$$

where ρ_g and μ_g are the density and viscosity of test gas, respectively, and σ is the surface tension. Weber number (We) is the ratio of the aerodynamic forces to the surface tension forces and is the most important dimensionless parameter in liquid breakup and atomization. Definition of drop position and the air flow direction is shown in Fig. 2, the horizontal distance of two drops is X, and the vertical distance of two drops is Y. Here we proposal that along the direction of airflow as shown in Fig. 2, the right drop is named the first drop, and the left drop is named the second drop. Here Ohnesorge number (Oh $<$ 0.1) is very small, thus it is not playing role. Here all drops are in the same plane. The distance Y is controlled by drop generators, and there is a time lag. The X distance is controlled by adjusting the position of the droplet generators. In this test the ranges of parameters X and Y examined are $X/D_0 < 3$ and $Y/D_0 < 3$.

3. Results and discussion

3.1. Coalescence mode

As illustrated in Fig. 3, the coalescence mode appears when the location of two drops is very close to each other. Before airflow can play a leading role, the velocity and deformation of two drops is little, two drops merge into one gradually. The coalescence stage is dominated by surface tension. And we can find the capillary waves traveling along the surface of two drops. After the coalescence stage, aerodynamic force drives the deformation and aero-breakup processes of the new large drop. The new large drop deforms to the disk shape, the center of disk deforms into thin membrane with the thicker basal ring structure and some nodes. Finally, the bag results in a larger number of small size fragments. And the ring structure and node results in a smaller number of large size fragments.

Based on the research work of Rayleigh [28], if the length-to-diameter ratio of liquid column is π, it would become unstable. For the coalescence drop as shown in Fig. 4, it will be

$$\frac{d/2 + l}{d} \approx \pi \tag{3}$$

Here assumed that the right part of the liquid structure of Fig. 4 is nearly flat and it is ignored. Based on the mass conservation principle in this study, the relationship between initial two spherical drops and coalescence drop is $\frac{1}{3}\pi D_0^3 \approx \frac{1}{12}\pi d^3 + \frac{1}{4}\pi d^2 l$. So we can obtain that $d \approx \left(\frac{8}{6\pi - 1}\right)^{1/3} D_0 \approx 0.77 D_0$.

We could take the control volume at the left-hand end of this cylinder, the force balance will be

$$\frac{d}{dt}\int u_l' \rho_l dV_l - \rho_l u_{il}^2 A = (p_b - p_a)A \tag{4}$$

where V_l is the volume of the left-hand end, u_{il} is the drop internal flow velocity of the left-hand end, A is the cross sectional area, $p_a \approx 4\sigma/d$, $p_b \approx 2\sigma/d$ [6]. The unsteady term could be estimated as $\overline{u_l'}\rho_l dV_l/dt$, where the average velocity, $\overline{u_l'}$, is approximated by $u_{il}/2$. The term dV_l/dt is just $u_{il}A$ [6]. So the velocity would be

$$u_{il} = \sqrt{\frac{4\sigma}{\rho_l d}} \tag{5}$$

We then take the control volume at the right-hand end of this cylinder, the force balance would be

$$\frac{d}{dt}\int u_r' \rho_l dV_r = (p_d + p_g - p_c)A \tag{6}$$

where V_r is the volume of this right-hand end, u_{ir} is drop internal flow velocity of this right-hand end, $p_c \approx p_d \approx 2\sigma/d$, $p_g \approx \frac{1}{2}\rho_g u_g^2$. Here the unsteady term could be estimated as $\overline{u_r'}\rho_l dV_r/dt$, where the average velocity, $\overline{u_r'}$, is about $(u_{ir} + u_g\sqrt{\rho_g/\rho_l})/2$. The term dV_r/dt is just $u_{ir}A$. So the velocity would be

$$u_{ir} = \frac{\sqrt{5}-1}{2} u_g \sqrt{\rho_g/\rho_l} \tag{7}$$

If ignoring this middle cylinder part of Fig. 4, we can find that it becomes the analysis of secondary atomization of single drop. So the critical condition of secondary atomization is $u_{il} \leqslant u_{ir}$, which will be $We_d = \frac{\rho_g d u_g^2}{\sigma} \geqslant 10$. It is in well agreement with those reported in these literatures [25–27,29–32]. In order to sustain the shape of cylindrical drop and breakup, the estimation on the drop internal flow velocity should be

$$u_i = \max(u_{il}, u_{ir}) \tag{8}$$

The energy approach is often used in the analysis of drop breakup and atomization [6,33,34]. First, the surface tension is the energy required to increase the surface area of liquid due to the intermolecular forces. Then the surface tension is also the ratio of change in the energy

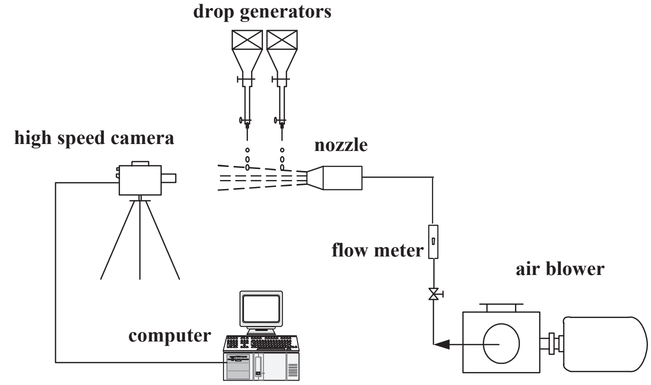

Fig. 1. Schematic of two drops test system.