Full Length Article

Transition Weber number between surfactant-laden drop bag breakup and shear breakup of secondary atomization

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ABSTRACT

Fuel spray and atomization characteristics play an important role in the performance of internal combustion engines and many applications of industry. In drop aerobreakup, there are two main breakup modes: general bag breakup and shear breakup, which are induced by Rayleigh-Taylor instability and Kelvin-Helmholtz instability, respectively. Influence of surfactant on drop deformation and breakup is remarkable. So the transition condition of surfactant-laden drop between general bag breakup and shear breakup will be different from pure liquid. In this work, we investigate the influence of surfactant on drop breakup morphology in a continuous air jet stream, and find the physical mechanism of surfactant-laden drop atomization. Finally the predicted expression of transition Weber number is obtained.

1. Introduction

Atomization is a subject of practical interest in numerous industrial applications and the physics of natural precipitation, such as fuel combustion, automobile engine, propellant injector, material preparation, food processing, inkjet printing, spray drying, agriculture and medicine [1–11]. When the spherical drop encounters an ambient flow field moving at a velocity relative to it, aerodynamic force will cause the drop to deform and break apart into fragments. This process is referred to as aero-breakup or secondary atomization [12–15]. In addition to theoretical and experimental researches, drop breakup has also been researched computationally by many groups [16–22].

Weber number (*We*) is one of the most important parameters in secondary breakup, which represents the ratio of disruptive hydrodynamic forces to the stabilizing surface tension force,

$$We = \rho_g u_g^2 D_0 / \sigma \qquad (1)$$

where ρ_g is the air density, u_g is the air velocity, D_0 is the initial diameter of drop, σ is the surface tension. Based on morphological classification, as the Weber number increases, bag breakup, bag-stamen breakup, dual-bag breakup, bag/plume breakup, etc. occurs in turn. These breakup types which have the characteristic bag structure are all governed by the Rayleigh-Taylor instability. These breakup types can be named as Rayleigh-Taylor piercing (the combined RT/aerodynamic drag mechanism, general bag breakup). At higher Weber number, the

thin sheet is continuously drawn from the periphery of the deforming drop. The sheet disintegrates a short distance downstream from the drop. These breakup types which have continuing shearing and entraining action are all governed by the Kelvin-Helmholtz instability. These breakup types can be named as shear-induced entrainment (sheet-thinning breakup, shear breakup) [14,23–28].

The presence of surfactants at the liquid interface can significantly change the interfacial properties, which can be used to control the process of atomization and combustion, such as emulsified fuels, slurry fuels, coating, painting, electroplating, gluing, and cleaning [29–37]. As the interface is created quickly in the deformation process of liquid, the diffusion of surfactant is limited near the interface. Our previous work [38,39] examines surfactant in the transition between no breakup and bag breakup regime at the low gas velocity. The instantaneous surfactant concentration at the liquid-air interface plays an important role in the drop breakup mode and morphology.

As the air speed increases, the atomization performance will gradually improve, which is useful in fuel combustion. So the influence of high gas velocity on surfactant distribution and interface instability is important in the surfactant-laden drop breakup process. This paper could be considered that work in examining the transition between general bag and shear breakup regime at the high gas velocity. We try to research the transition *We* between general bag breakup and shear breakup. However in the presence of surfactant, the transition *We* is found to be nonlinear at different concentrations of the surfactant in

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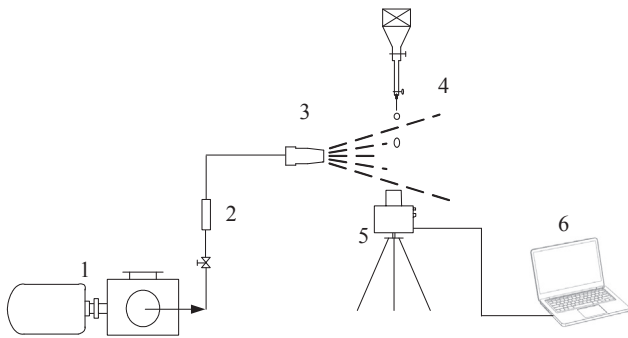 E-mail address: hfliu@ecust.edu.cn (H.-F. Liu).

Fig. 1. Sketch of drop breakup experimental apparatus. 1-air compressor; 2-flow meter; 3-nozzle; 4-drop generator; 5-high-speed camera; 6-computer.

Fig. 2. The dynamic surface tension at different surfactant concentrations by dynamic surface tensiometer, t is the bubble lifetime.

this study. By the competition analysis between Rayleigh-Taylor instability and Kelvin-Helmholtz instability, we obtain the relationship between concentrations of surfactant and transition *We* theoretically. The rest of the paper is organized as follows. In Part 2, we describe the details of experimental methods. Results are presented and discussed in Part 3, followed by concluding remarks in Part 4.

2. Experiment

We study the surfactant-laden drop breakup with the help of the high-speed digital camera (Fastcam SA2 by Photron Limited). Fig. 1 presents the sketch of experimental set-up, which is similar to our earlier work [38,39]. A drop generator and a circular air nozzle with a converging exit are arranged in the cross flow pattern. The circular nozzle combined with an air compressor is used to form a continuous air jet. The airflow rate is regulated by a rotameter. The drop generator, including a cylinder liquid chamber and a small-diameter tube, is fixed at the bottom of the liquid chamber. Drops drip from the tip of the tube under the action of gravity and fall into the air jet.

In the present study, the surfactant is sodium dodecyl benzene sulfonate (SDBS). The equilibrium values of SDBS surface tension are measured by Wilhelmy plate method (Shanghai Fangrui Instrument Co., Ltd., Model: QBZY). Based on Sheludko model [40] and our early work [38,39], the surface tension at different surfactant concentrations would be

$$\sigma = \frac{\sigma_0}{\left\{1 + \frac{c}{c+0.025}\left[\left(\frac{\sigma_0}{\sigma_m}\right)^{1/3}-1\right]\right\}^3} \tag{2}$$

where σ_0 and σ_m are the surface tensions of a surfactant-free fluid and of maximal surfactant concentration, respectively, c is the mass concentration of surfactant.

Dynamic surface tensiometer (SITA science line t100 by SITA Messtechnik GmbH, Germany) can measure the dynamic surface tension of liquids according to the bubble pressure method. The minimum bubble lifetime of this tensiometer is 15 ms. Due to internal attractive forces of a liquid, the gas bubble within the liquid is compressed. The resulting pressure (bubble pressure) rises at a decreasing bubble radius. The bubble pressure method makes use of this bubble pressure which is higher than in the surrounding environment (liquid). A gas stream is pumped into a capillary that is immersed in a fluid. The resulting bubble at the end of the capillary tip continually becomes bigger in surface; thereby, the bubble radius is decreasing. The pressure rises to the maximum level. At this point the bubble has achieved its smallest radius (capillary radius) and begins to form a hemisphere. Beyond this point the bubble quickly increases in size and soon bursts, tearing away from the capillary, thereby allowing a new bubble to develop at the capillary tip. It is during this process that a characteristic pressure pattern develops, which is evaluated for determining the surface tension. The bubble lifetime is the time period from the bubble minimum pressure to the bubble maximum pressure.
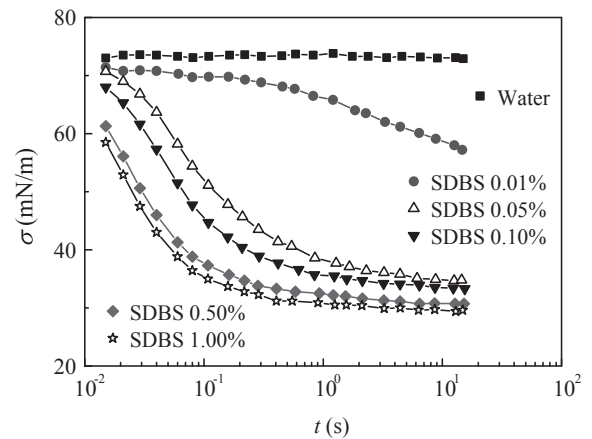
3. Results and discussion

The experimental results on the dynamic surface tension at different surfactant concentrations are shown in Fig. 2. The dynamic (instantaneous) surface tension increases with the decrease of bubble lifetime. Note that t is the bubble lifetime in Fig. 2. This shows the diffusion rate of surfactant is limited. Finally the dynamic surface tension of different surfactant concentrations will all tend to the surface tension of pure water when the bubble lifetime tends to the level of millisecond.

In the traditional atomization research, under a certain initial condition, surface tension and *We* are considered to be constant. Under the action of high-speed airflow, the shape of the gas-liquid interface changes rapidly. Here due to the influence of surfactant, surface tension and *We* are variable in the process of fast drop deformation. So there are some new definitions on the different Weber numbers. Traditional Weber number *We* is shown in Eq. (1), whose surface tension σ is obtained by Wilhelmy plate method before doing the atomization experiment. It is very important in industrial applications. Then the real Weber number (We_r) is proposed when the surfactant appears,

$$We_r = \rho_g u_g^2 D_0/\sigma_r \tag{3}$$

where σ_r is the real (dynamic or instantaneous) surface tension. We_r can show the physical mechanism of drop breakup more intuitively than *We*. It is very important in scientific research. However, σ_r is hard to obtain during the process of drop deformation and breakup, so we try to find the relationship between We_r and *We* in this paper. We hope that the atomization results can be predicted by these initial conditions, such as surfactant concentration, fluid properties and gas velocity etc.

The main feature of general bag breakup is the bag structure as shown in Fig. 3. Here the general bag breakup includes bag breakup, bag-stamen breakup, dual-bag breakup, etc., whose difference is the number of bags. The general bag breakup is induced by Rayleigh-Taylor instability, so it can be named as Rayleigh-Taylor piercing (RTP) breakup regime [14]. The bag geometry is composed of thin hollow bag attached to thicker rim.

In the shear breakup, the films and ligaments are continuously eroded from the drop surface, then they disintegrates rapidly after being removed as shown in Fig. 4. The peeling action of shear breakup is induced by Kelvin-Helmholtz instability, so it can be named as Shear-induced entrainment (SIE) breakup regime [14].

The competition between Rayleigh-Taylor instability and Kelvin-Helmholtz instability in secondary atomization would decide the final breakup mode of drop [14,23–28]. The exact solutions of these