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Transitions of deformation to bag breakup and bag to bag-stamen breakup for droplets subjected to a continuous gas flow

Wei Yang [a], Ming Jia [b], Zhizhao Che [a], Kai Sun [a], Tianyou Wang [a,*]

[a] State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China
[b] School of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, China

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ABSTRACT

The transitions of deformation/squeezing breakup to bag breakup and bag to bag-stamen breakup modes for liquid droplets are studied numerically and theoretically. The multiphase flow model is based on the solution of the Navier-Stocks equations and a coupled volume-of-fluid and level-set method. By employing the adaptive mesh refinement technique, the computational cost is significantly reduced. The simulation is validated against published experimental results for the bag breakup and the bag-stamen breakup, which proves that the present model is adequate for capturing qualitatively the breakup processes. The transitions of different modes are investigated at a wide range of Ohnesorge (*Oh*) numbers (0.001–2). Results indicate that the breakup modes in the bag-type regimes are determined by the ratio of the cross-stream diameter of the flattened droplet to the wavelength of the most unstable Rayleigh-Taylor (RT) wave. The increase of *Oh* numbers leads to an increasing insensitiveness of the transition behaviors to the Weber (*We*) number. Furthermore, according to the RT instability, a new theoretical model for predicting transition *We* numbers is derived in a more reasonable approach. Results further indicate that the present theoretical model could predict the transition behaviors more accurately by comparing with the present numerical results and the experimental data of earlier studies.

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1. Introduction

The fragmentation of liquid droplets is of fundamental importance in many industrial applications such as sprays in medical and agricultural applications and combustion in engines. In engines, droplet fragmentation plays a crucial role in determining the spray characteristics, which further affects the mixture formation and combustion process significantly [1,2]. Therefore, a good knowledge of droplet fragmentation is of great importance for the development of high-efficiency and low-emission engines.

The atomization process commonly consists of the initial breakup of liquid jet to form large droplets and further breakup of these droplets into tiny ones, which are known as primary and secondary breakup, respectively. In secondary breakup, the Weber number (*We*) and the Ohnesorge number (*Oh*) are two controlling parameters defined as $We = \frac{\rho_g U_g^2 D_0}{\sigma}$ and $Oh = \frac{\mu_l}{\sqrt{\rho_l D_0 \sigma}}$, respectively. The categorization of breakup modes and the boundaries between the different breakup modes were investigated in many experimental studies [3–11]. For a low *Oh* number ($Oh < 0.1$), the droplet breakup is mainly controlled by the *We* number. With increasing the *We* number progressively, the following breakup modes occur: deformation/vibrational breakup, bag, intermediate, sheet-thinning, and catastrophic breakup modes as shown in Fig. 1.

Besides these typical breakup modes, the intermediate breakup can be divided into more detailed modes such as bag-stamen [4,10,11], bag-jet [3], bag-plume [7,11], dual-bag [8,10], multi-bag [11], plume/shear [7], and multimode/transition breakup [3,5,6,9,10]. Regarding the transitions between two contiguous regimes, most of the earlier studies have suggested that the criticalities of transitions are mainly function of *We* number and *Oh* number. It should be noted that an important consensus is the critical *We* number 11 ± 2 of the initial bag breakup under low *Oh* number ($Oh < 0.1$), while the transition *We* numbers in the intermediate breakup regime are somewhat arbitrary as shown in Fig. 1.

Several experimental maps were proposed to describe the related transition behaviors for the droplet breakup modes at different *Oh* numbers [3,4,12,5]. However, the quantitative correlations were mainly established to focus on the transition from deformation to bag breakup [13,14,1]. Despite aforementioned studies, these empirical correlations determined by experiments were not in consistent with each other when the viscous effect is important ($Oh > 0.1$). Therefore, the theoretical analyses and the

* Corresponding author.
E-mail address: wangtianyou@tju.edu.cn (T. Wang).

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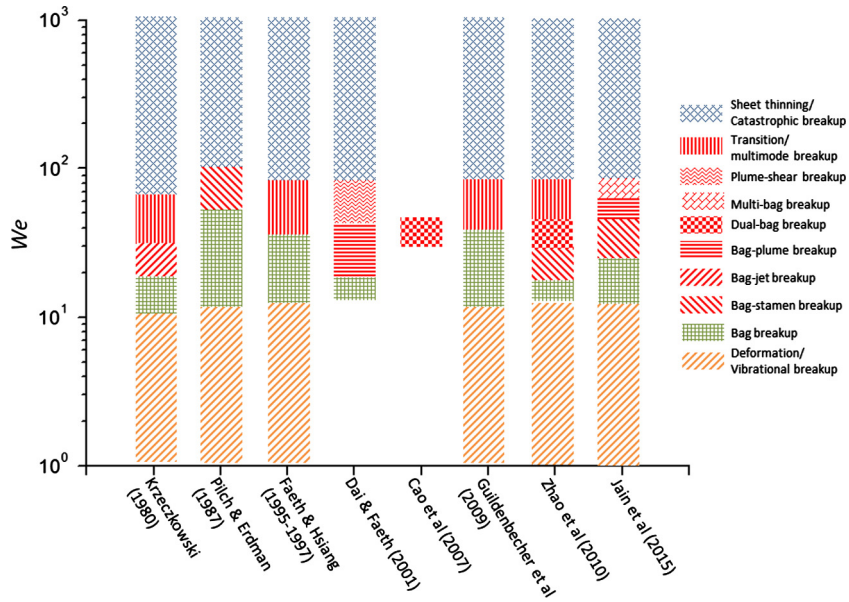

Fig. 1. Basic breakup regimes corresponding to Weber numbers.

numerical simulations are necessary to reveal the underlying physics of the breakup mode transitions.

From a theoretical perspective, the Rayleigh–Taylor (RT) instability has been argued to play an important role in the droplet breakup process [10,15–18]. The RT instability is the instability of an interface between two fluids of different densities, which occurs when the heavier fluid is accelerated by the lighter fluid [19,20]. Relevant investigations on the relationship between the RT instability and the droplet breakup can be found in the literature [9,15–18,21–23]. Joseph et al. [15] investigated the effect of acceleration on the drop breakup due to the RT instability under widely varying viscosity, and performed an RT stability analysis for Newtonian droplets. The results demonstrated that the fragmentation by the RT instability was impossible when the diameter of the droplet was smaller than the critical wavelength of the RT instability, and the wavelength of the most unstable wave increased strongly with the droplet viscosity. Subsequently, Joseph et al. [16] extended their work to include an RT stability analysis for three viscoelastic droplets. Theofanous et al. [17] derived a relationship between the diameter of the flattened droplet and the RT instability wavelength based on the classical inviscid analysis, and elucidated that the fragmentation of droplets was essentially attributed to the RT piercing (RTP) mechanism. Afterwards, Theofanous et al. [18] further studied that the aerobreakup physics of Newtonian droplets of any viscosity, neglecting the surface tension and the shear stress in the viscous regime. The key physics of RTP (first criticality) and of shear-induced entrainment (SIE, terminal criticality) were verified and quantified by new viscosity-based and capillarity-based scales for fluids of any viscosity. Guildenbecher et al. [9] summarized that the growth of RT instability created an initial surface disturbance which was intensified by the aerodynamic effects, and defined it as the combined RT instability and aerodynamic drag mechanism. Despite aforementioned theoretical researches, the theoretical calculations for the criticalities of different transition regimes are still deficient. Besides the predicting model by Theofanous et al. [17,18], the theoretical calculation derived by Zhao et al. [21], taking the viscous and surface tension effects into consideration based on the simplified correlation ($\lambda_{\max} = 2\pi\left[\left(\frac{3\sigma}{\rho_l a}\right)^{1/2} + A_2\left(\frac{\mu_l^2}{\rho_l^2 a}\right)^{1/3}\right]$) of Aliseda et al. [22], offered a best prediction of the critical values. However, the correlation by Aliseda et al. [22] was established based on simplifications and approximations rather than a strong theoretical derivation. Moreover, in order to obtain good agreements in the theoretical calculation and the experimental data, the ratios of the flattened droplet diameter to the wavelength of the most unstable wave (D_f/λ_{RT}) were fixed at $1/\sqrt{3}$ for all the transition processes by Zhao et al. [23] without providing sufficient supporting information. Based on the RT instability theory of droplet breakup, we aim to improve the theoretical model to predict the criticalities of deformation to bag breakup and bag to bag-stamen breakup from a more reasonable approach.

In addition to the experimental and theoretical studies, some computational studies have been performed, providing us more details of the breakup processes. In such simulation, an accurate prediction of the complex interface deformation and breakup is always challenging. Various multiphase interface tracking/capturing methods have been developed, such as Volume of Fluid (VOF) [24–26], Level Set (LS) [27,28], Front Tracking (FT) [29,30], Moving Mesh Interface Tracking (MMIT) [31], Lattice Boltzmann Method (LBM) [32–34,49,50], and Coupled Level Set and Volume of Fluid (CLSVOF) [35–38] methods. Many studies of droplet breakup with these methods have been reported in the literature. By using the FT method, Han and Tryggvason [30] studied the deformation of 2D axisymmetric droplets at low density ratios (1.15 and 10). Two regime maps were presented for the different density ratios, and the results showed that the transition *We* numbers between the different breakup modes decreased with increasing *Re*. Aalburg [27] investigated the breakup dynamics of droplets using a 2D axisymmetric LS method, and a regime map including the deformation and breakup was presented ($We^{1/2}/Oh \sim 1/Oh$), which demonstrated that the criticality remained almost linear increasing tendency for $Oh > 1$. Kékesi et al. [26] used the VOF method to study the droplet breakup in various conditions (density and viscosity ratios, and Reynolds number) for $We = 20$, and a new breakup map was proposed in the coordinates of $Re \sim A$ ($A = C_1 \frac{\mu_l}{\mu_g}\sqrt{\frac{\rho_g}{\rho_l}}$). Recently, Jain et al. [11] studied the droplet breakup in the moderate Weber number range (20–120) with the experimental and numerical (VOF) methods, and a multi-bag breakup mode was observed both in the numerical and experimen-

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