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Determination of the aerodynamic droplet breakup boundaries based on a total force approach

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ABSTRACT

The determination of the critical We_g number separating the different breakup regimes has been extensively studied in several experimental and numerical works, while empirical and semi-analytical approaches have been proposed to relate the critical We_g number with the Oh_l number. Nevertheless, under certain conditions, the Re_g number and the density ratio ε may become important. The present work provides a simple but reliable enough methodology to determine the critical We_g number as a function of the aforementioned parameters in an effort to fill this gap in knowledge. It considers the main forces acting on the droplet (aerodynamic, surface tension and viscous) and provides a general criterion for breakup to occur but also for the transition among the different breakup regimes. In this light, the present work proposes the introduction of a new set of parameters named as $We_{g,eff}$ and Ca_l monitored in a new breakup plane. This plane provides a direct relation between gas inertia and liquid viscosity forces, while the secondary effects of Re_g number and density ratio have been embedded inside the effective We_g number ($We_{g,eff}$)

1. Introduction

The aerodynamic droplet breakup has been extensively studied in experimental and numerical works due to its importance in spray systems. Depending on the relative strength of the main forces acting on the droplet (aerodynamic, surface tension and viscous forces), different breakup types can be observed such as the bag breakup, the transitional breakup (including several sub-types), the sheet-thinning breakup and the catastrophic breakup. A complete description of these breakup modes can be found in the review article of Guildenbecher et al. (2009) among others.

Increasing the gas phase inertia results in the successive transition between the aforementioned breakup regimes. The parameters affecting droplet breakup are grouped into dimensionless numbers, such as the We_g, the Oh_l and the Re_g numbers, but also the density and viscosity ratios of the liquid/gas phase (ε and N respectively); see Section 2.1 for a complete description of these numbers. Among them, the We_g number is the most influential, while the liquid viscous damping becomes important only when $Oh_l > 0.1$; see for example the breakup map of Hsiang and Faeth (1995).

The We_g number leading to droplet breakup (or generally separating different breakup regimes) is called critical We number ($We_{g,cr}$) and in the limit of negligible liquid viscosity (i.e. low Oh_l), we call it in the present work as $We_{g,cr,0}$ (the subscript 0 denotes negligible viscosity). Having also in mind that the experimental data are characterized by high Re_g numbers, the $We_{g,cr,0}$ generally represents negligible viscosity effects both in the gas and liquid phases. In the following paragraphs, the various approaches found in literature to relate $We_{g,cr}$ with $We_{g,cr,0}$ will be presented.

In Guildenbecher et al. (2009) it is stated that breakup is observed for $We_{g,cr,0} = 11 \pm 2$, indicating that there is a scatter in the results of experimental works; in Hanson et al. (1963) an even lower value of ~ 7 is reported. Regarding the dependency between the $We_{g,cr}$ and Oh_l numbers (the two most influential), this is generally expressed through the empirical Eq. (1), where C and n are fitting coefficients:

$$\frac{We_{g,cr}}{We_{g,cr,0}} = 1 + C \cdot Oh_l^n \qquad (1)$$

Abbreviations: CAJ, Continuous Air Jet; R–T, Rayleigh–Taylor; ST, Shock tube; TFR, Total Force Ratio; VOF, Volume of Fluid

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Nomenclature

Roman symbols

Symbol (Units)	Description
C (-)	Adjustable coefficient
Ca (-)	Capillary number $Ca = \mu U/\sigma$
D (m)	diameter
f (-)	Correction factor
F (N)	force
n, ng, nl	Adjustable exponent
Oh (-)	Ohnesorge number $Oh = \mu/\sqrt{\rho\sigma D}$
Re (-)	Reynolds number $Re = \rho UD/\mu$
t (s)	time
U (m/s)	reference velocity
We (-)	Weber number $We = \rho U^2 D/\sigma$

Greek symbols

Symbol (Units)	Description
ε (-)	density ratio $\varepsilon = \rho_l/\rho_g$
μ (kg/ms)	viscosity
N	Viscosity ratio $N = \mu_l/\mu_g$
ρ (kg/m^3)	density
σ (N/m)	surface tension coefficient

Subscripts

Symbol	Description
0	Reference value
br	breakup
cr	critical
DEF	deformation
eff	effective
g or gas	gas
l or liq	liquid
RES	restore
vis	viscosity

A list of the coefficients C, n which were determined in past works is given in Table 1. Brodkey (1967) and Gelfand (1996) obtained these coefficients by fitting experimental data, while Cohen (1994) assumed that the energy required for breakup, is that of an inviscid droplet plus the energy required to overcome the viscous dissipation (see details in Section A.3); this resulted in $n = 1$, while the coefficient C was determined by fitting experimental data.

In Hsiang and Faeth (1995) the droplet momentum equation was used and adopting the viscous timescale of Hinze (1949) (Eq. (14) in Section 2.1), they derived Eq. (2). Assuming an average value of the drag coefficient $\overline{C_D}$, they determined the coefficient C (without mentioning its value) by comparing against experimental data and the model performance was very good.

$$\frac{We_{g,cr}}{We_{g,cr,0}} = \frac{1}{4}\left(1 + C\cdot\frac{\overline{C_D}}{\sqrt{\varepsilon\cdot We_{g,cr,0}}}Oh_l\right)^2 \tag{2}$$

Another approach for the estimation of the critical We_g number, is to assume that the breakup is ought to Rayleigh–Taylor (R–T) instabilities as in Zhao et al. (2011) and Yang et al. (2017). According to this model, when the droplet deformation (usually the cross-stream diameter) exceeds the critical wavelength of the R–T instability (which depends on liquid properties and droplet acceleration), then breakup occurs. The resulting equation (e.g. in Zhao et al. (2011)) has the form of Eq. (3), where C is an adjustable coefficient, in the range 1.18–1.48.

$$\left(\frac{We_{g,cr,0}}{We_{g,cr}}\right)^{1/2} + C\left(\frac{Oh_l^2}{We_{g,cr}}\right)^{1/3} = 1 \tag{3}$$

The concept of R–T instabilities has been considered as the main mechanism for breakup in other works as in Joseph et al. (1999),Theofanous and Li (2008) and Theofanous et al. (2012). The group of Prof. Theofanous considered also a different characterization of breakup, with Rayleigh–Taylor piercing (RTP) happening at lower We_g numbers and shear-induced entrainment (SIE) above a transition We_g. Generally, the aforementioned correlations are in qualitative agreement between them, but they do not give insight into the effects of Re_g and ε numbers

Turning now to the effect of the Re_g number and density ratio ε, this has not been in detail examined in experimental works due to technical limitations in obtaining low Re_g and ε numbers. On the other hand, their effect has been examined in a few numerical works but without providing correlations similar to the aforementioned for the Oh_l number (e.g. as in Eq. (1)). As a general remark, they have all concluded that the critical We_g number increases for low Re_g and ε numbers. More specifically, Aalburg (2002) found that there is no effect on breakup for $Re_g > 100$ and $\varepsilon > 32$. Nevertheless, their numerical model could not predict the actual breakup and they assumed that breakup happens when the cross-stream deformation exceeds 60%; despite this limitation, they were able to reproduce the breakup map of Hsiang and Faeth (1995). In Han and Tryggvason (2001) the authors examined low density ratios ($\varepsilon < 10$) and found that the Re_g effect is minimal for $Re_g > 200$, while decreasing the Re_g and keeping the other parameters constant can lead to different breakup modes. A similar conclusion was also drawn when the density ratio decreases and approaches unity. In Jing and Xu (2010) it is stated that shear breakup is observed only for $\varepsilon > 100$, while for Re_g numbers in the range 10^2 up to 10^6 there are slight differences in the topology of the bag and the rim. Regarding the effect of density ratio they found different breakup modes for $\varepsilon = 10$ and 1000 (forward bag and sheet-thinning respectively for $We_g = 27.5$) and also significantly lower droplet acceleration and displacement as the density ratio increases. Recently, Yang et al. (2016) used a 3D model to study breakup at highly unstable conditions ($Re_g \sim 10^4$) and found that breakup is affected even for $\varepsilon > 32$ (the limit proposed by Aalburg (2002)), and a lower density ratio results in a higher deformation rate but less intensive fragmentation. Finally, Kékesi et al. (2014) examined various combinations of Re_g and ε numbers (generally low values) and identified new breakup regimes that have not been observed in experiments.

The aim of the present work is to provide a simple but reliable methodology to relate the critical We_g number with all the actual dimensionless numbers affecting droplet breakup, as there is a lack of such a model in literature. In the text follows there is a description of the methodology and then the model results are presented. In the appendix, the derivation of correction factors for the effect of Re_g number and density ratio is presented along with a correlation to predict the breakup initiation time. Finally in the appendix, the present methodology is related to a modified version of the energy approach of Cohen (1994), showing that both concepts are equivalent.

Table 1
List of the coefficients C, n of Eq. (1) proposed by different sources for the bag breakup regime.

source	coeff. C	coeff. n	derivation	comments
Brodkey (1967)	1.077	1.6	Empir.	$Oh_l < 10$
Cohen (1994)	1–1.8	1	Semi-Anal.	$10 < We_{g,cr,0} < 100$
Gelfand (1996)	1.5	0.74	Empir.	$Oh_l < 4$