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Characteristics of jet droplet produced by bubble bursting on the free liquid surface

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ABSTRACT

Droplet formation that follows gas bubble bursting at a free liquid surface, being known as "entrainment", is a common phenomenon in many fields. Though there were a couple of investigations focusing on entrainment, specific characteristics of jet drops produced by bubble bursting on free surface are still unknown in the current stage. Efforts were performed to try to determine the expression of critical bubble size, above which the bubble does not produce any drops by bursting on liquid surface. Dimensionless analyses show that in air–liquid systems, $\mathbf{ReFr}^{-0.5}$, $\mathbf{ReWe}^{-0.5}$ and $\mathbf{WeFr}^{-0.5}\mathbf{Re}^{-1}$ can be readily correlated to **Mo**. Error analysis demonstrated the following expression: $D_{cr}=10^{0.1914}\sigma_L^{0.5517}\rho_L^{-0.4830}g^{-0.5170}\mu_L^{-0.0688}$ can give the most accurate prediction of D_{cr} as a universal expression. Further, for correlating the number of droplets to bubble diameter in air–water and air–iron system, D_{cr} was used as the length scale to normalize the bubble diameter. Through curve fitting, a universal expression has been obtained to predict the number of droplets produced by bubble bursting on free liquid surface in any air–liquid system: $N_{dr}=7.9\exp(-D_B/(0.338D_{cr}))-0.41$. Comparison shows that this expression is able to give more accurate prediction than the previous empirical expressions. The most significant innovation is that it is a universal model that can be used in various gas–liquid systems.

1. Introduction

Liquid entrainment is a phenomenon associated with systems in which liquids and gases are in relative motion. It is common in ocean and geophysical fields as well as in many chemical processes such as aeration, boiling, degassing distillation and evaporation. It plays an important role in mass transfer (Newitt et al., 1954), and causes serious liquid mass loss or contamination of the gas phase in many cases (Georgescu et al., 2002).

Liquid entrainment process depends mainly on the gas flux. In a low gas flux regime, i.e., so-called single bubble low, bubbles steadily rise in a continuous liquid and droplets are formed during the burst of single bubbles. When a single bubble reaches the surface of the liquid it usually rebounds back and forth with decreasing amplitude and then it comes to rest with its upper part projecting above the surface in the form of a hemispherical dome (Newitt et al., 1954). The thinning of the liquid film on the dome top results in its failure and the liquid of the former film is released in form of film droplets (t_1, Fig. 1a). Following the rupture of the bubble cap, liquid streams retrieve back into the remaining cavity, forming a liquid jet (t_2), which disintegrates into droplets, called jet droplets (t_3) (Koch et al., 2000). As the size of jet droplet is a few orders larger than the size of film droplet, the former dominates the entrained liquid volume primarily.

With the increase of gas flux, a few bigger bubbles would be formed due to the coalescence of the original bubbles, which forms the so-called bubbly flow. As a result, there is a decrease in the number of jet droplet compared to an increase in the number of film droplet, though the liquid entrainment mechanism does not change (Günther et al., 2003).

At high gas fluxes (churn turbulent flow, Fig. 1b), bubbles rise unsteadily and chaotically in a highly turbulent manner. In such a way, liquid is drawn up above the surface in the shape of an inverted hollow cone (t_1). The upper part of it extends into several ligaments, which continue to move upward (t_2). These ligaments become unstable under the effect of surface tension and quickly neck down to form individual droplets (t_3).

A number of investigations have been carried out to try to classify liquid entrainment. Because the droplet generation in the churn turbulent flow is simply the result of direct momentum exchange mechanisms, a couple of general models have been put forward to correlate the liquid entrainment rate to gas flow rate (superficial velocity) and liquid properties statistically by dimensionless analyses (Kataoka and Ishii, 1984). However, as the mechanism of droplet generation by single bubble bursting on the liquid surface is much more complicated and sensitive to

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many parameters, it is very difficult to improve a universal model to classify this phenomenon.

Characteristics of jet droplets attracted investigators' concentrations as it is jet droplets that dominate the liquid entrainment in single bubble flow when the bubble size is less than the critical value. Various gas–liquid systems were involved in experimental as well as numerical ways. Table 1 gives an overview of the representative investigations on bubble bursting on liquid surface.

Throughout these literatures, there were a couple of widely recognized conclusions regarding the characteristics of jet droplet produced by single bubble bursting on water surface, including droplet number, mean size and droplet velocity. In air–liquid system, the number of droplets produced by bubble bursting increases as the bubble size decreases. There were a couple of correlations of droplet number versus bubble size that have been approved in air–water system, which will be discussed below. In air–water system, there were a few published data concerning the mean size of jet droplets, for which Koch et al. (2000) approved Eq. (1) to correlate the mean droplet diameter to bubble size.

$$D_{dr} = \begin{cases} 0.1D_B & 0.1\,\mathrm{m} \le D_B \le 0.9\,mm \\ 3.34(0.001D_B)^{1.5} & 0.9\,\mathrm{m} \le D_B \le 5.5\,mm \end{cases} \tag{1}$$

A series of studies on the initial velocity of the jet droplet were drawn out. Spiel (1995, 1997) approved exponential-wised correlations between initial velocity of droplet and parent bubble

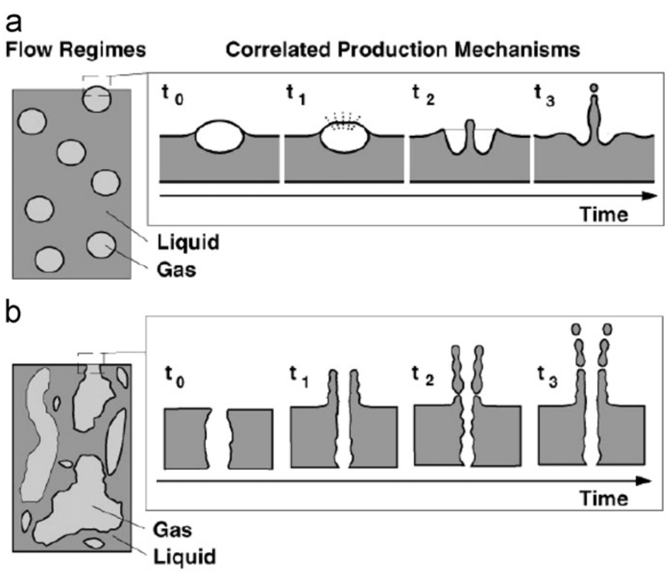

Fig. 1. Liquid entrainment phenomena for various gas flow rate (Koch et al., 2000).

based on his experimental data for the 1st to the 5th droplets, where the initial velocity of the 1st droplet is higher than the 2nd one, higher than the 3rd one, etc.

In air–water system, though there were a couple of common cognitions on the characteristics of jet droplets, e.g., droplet size, there were a couple of contradictions among the reference data concerning the number of jet drops and size distribution and a lack of data concerning the velocity of jet droplets. The most significant thing is, conclusions from the literatures cannot get universal usage. Further, in other air–liquid system, this problem is far from clear as there were only a few available experimental data (Guézennec et al., 2004, 2005; Han and Holappa, 2003). As entrainment is an important phenomenon in many cases and obviously it is not practical to perform similar experiments in every air–liquid system, thus a possibility may exist: can we normalize the previous experimental data and put forward more universal expressions to predict the characteristics of jet drops in every air–liquid system?

The present study especially concentrates on single bubble flow, where the consistent flow pattern can be defined according to the experimental conditions belonging to the studies listed in Table 1. In these studies, experimental conditions involved: (1) the next bubble would not be generated through the orifices until the bursting of the previous one; (2) the submerging depths of the orifices were deep enough (2.5 cm for air–water system) to make the terminal velocity of bubbles independent of the size (Newitt et al. 1954); (3) the diameters of the bubbles were all less than 1 cm, very small compared to the vessel, where the first condition could be extended to "without bubble coalescence" in the application. In the present study, critical bubble size will be discussed; in addition the normalized expression will be tried to put forward to predict the number of jet drops produced by bubble bursting on various liquid surfaces through dimensionless analyses.

2. Dimensionless analyses on critical bubble diameter

2.1. Overview

Georgescu et al. (2002) investigated the process of bubble bursting on the free liquid surface using boundary element method in a manner of dimensionless scheme, and the effect of viscosity was also considered. Conclusion showed that after bubble bursting, jet dimensionless velocity increases sharpely and reaches a maximum when the droplet starts to form. Then the velocity decreases to an almost constant level that corresponds to the first droplet rupture from the jet. After that the jet velocity suddenly declines and rises again, in accordance with the

Table 1
Overview of the representative investigations on bubble bursting on liquid surface.

Reference	Systems	Technique	Motive
Newitt et al. (1954)	W/A 25–45 °C	CS & MS	Mean size, number
Garner et al. (1954)	W/A Benzene/A Alcohol/A	CS & MS	Mean size, distribution, entrainment rate
Hayami and Toba (1958)	SW/A 4–30 °C	Filter & MS	Size distribution, height, number
Boulton-stone and Blake (1993)		Numerical	Droplet size, velocity
Spiel (1994)	FW/A	PMS & OAP	Mean size, distribution, number
Spiel (1995)	FW/A SW/A	PMS & OAP	Mean size, distribution, number, velocity
Spiel (1997)	FW/A SW/A	PMS & OAP	Mean size, distribution, number, velocity
Koch et al. (2000)		Numerical	Size, velocity
Georgescu et al. (2002)		Numerical	Size, velocity, critical bubble size
Han and Lolappa (2003)	MI/A	Plate receiver	Entrainment rate, number
Guézennec et al. (2004)	MI/A	HSC	number
Guézennec et al. (2005)	MI/A	HSC	Number

W = water; A = air; CS = covered slide; MS = microscope; FW = fresh water; SW = sea water; PMS = particle measuring system; OAP = optical array probe; MI = Molten iron; HSC = High speed camera.