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Influence of energy spectrum distribution on drop breakage in turbulent flows

Luchang Han*, Shenggao Gong, Yongqiang Li, Ningning Gao, Jin Fu, He′an Luo*, Zhifen Liu

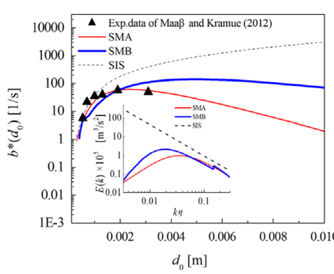
School of Chemical Engineering, Xiangtan University, Hunan 411105, PR China

HIGHLIGHTS

- The influence of energy spectrum on drop breakage was studied.
- Drop breakage should be modeled in the wide energy spectrum range.
- A breakage model in terms of general energy spectrum function was presented.
- This model can explain the recent experimental phenomena theoretically.

GRAPHICAL ABSTRACT

As shown in this figure, the breakage frequency predicted by the proposed model coupled with energy spectrum function SMA or SMB increases to a maximum and then decreases with increasing parent drop diameter. Furthermore, SMA or SMB showed a non-monotone distribution with wave number. However, the breakage frequency predicted by the proposed model coupled with energy spectrum function SIS monotonously increases with parent droplet diameter and the energy spectrum always increases with decreasing wave number.



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ABSTRACT

This work focused on the influence of energy spectrum distribution on drop breakage in turbulent flows. An improved breakage model in terms of general energy spectrum function was presented. It can be coupled with available forms of energy spectrum and can be applied to the wider operating conditions such as the wider size range of drops. Unlike previous work that only considered the inertia subrange spectrum, this work simulated the breakage in the framework of wide energy spectrum and accounted for the necessity of considering the wide energy spectrum distribution. The improved model coupled with wide energy spectrum function can theoretically explain the recent experimental phenomena observed by Maaß and Kraume, 2012. Determination of breakage rates using single drop experiments. Chem. Eng. Sci. 70, 146–164. That is, breakage frequency increases to a maximum and then decreases with increasing parent drop size. This is because the non-monotone energy spectrum function can distinguish three spectrum ranges, i.e., containing-energy range, inertia subrange and dissipation range, and the treatment that parent drop size always falls in the inertia subrange is no longer required in this work. While when only the energy spectrum of inertia subrange is applied to the whole size range of eddies, the predicted breakage frequency monotonously increases with parent drop diameter. Therefore, the energy spectrum distribution has a crucial influence on the evolution of the breakage frequency with parent drop size.

* Corresponding authors. Tel./fax: +86 731 58293549.
E-mail addresses: han_119_lulu@163.com (L. Han), hluo@xtu.edu.cn (H. Luo).

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1. Introduction

The breakage of fluid particles usually determines interfacial area, volume fraction and size distribution of dispersed phase. Thus, it plays an important role in design and optimization for many industrial processes such as chemical reaction, polymer blending, emulsification, absorption and extraction. In past decades, many studies have focused on the breakage of fluid particles (Coulaloglou and Tavlarides, 1977; Lee et al., 1987; Prince and Blanch, 1990; Hesketh and Etchells, 1991; Kumar et al., 1992, 1998; Tsouris and Tavlarides, 1994; Luo and Svendsen, 1996; Colella et al., 1999; Martínez-Bazán et al., 1999a, 1999b; Lehr and Mewes, 2001; Lehr et al., 2002; Hagesaether et al., 2002; Lasheras et al., 2002; Alopaeus et al., 2002; Diemer and Olson, 2002; Wang et al., 2003, 2006; Sarimeseli and Kelbaliyev, 2004; Chen et al., 2005; Kostoglou and Karabelas, 2005, 2007; Galinat et al., 2005; Podgórska, 2006; Kerdouss et al., 2006; Andersson and Andersson, 2006a, 2006b; Zhao and Ge, 2007; Azizi and Al Taweel, 2007, 2011; Laakkonen et al., 2007; Liao and Lucas, 2009; Patruno et al., 2009a, 2009b; Marchetti et al., 2010; Marchetti and Svendsen, 2012; Jo and Revankar, 2011; Liao et al., 2011; Han et al., 2011a, 2013; Fu et al., 2012; Maniero et al., 2012; Bak and Podgórska, 2013; Daub et al., 2013; Solsvik et al., 2013; Solsvik and Jakobsen, 2013), a number of mathematical models for the breakage frequency (or rate) and daughter size distribution have been presented.

1.1. Previous work on breakage frequency

Coulaloglou and Tavlarides (1977) proposed that the breakage frequency of drop can be expressed as the product of the inverse of breakage time and the fraction of the total number of breaking drops. They argued that drop will break if the kinetic energy transmitted to the drop by turbulent eddies exceeds the surface energy of parent drop. That is, $e(d_0) \geq c_1 \sigma d_0^2$, where d_0 denotes the parent particle diameter. The fraction of breaking drops was assumed proportional to the fraction of the eddies that have a turbulent kinetic energy greater than the surface energy of parent drop, and the breakage time was assumed proportional to the lifetime of the eddies in the inertia subrange. Their model contains two unknown and adjusted parameters which need to be fitted from the experiment.

Prince and Blanch (1990) proposed that the breakage rate can be written as the product of breakage efficiency and collision frequency between fluid particle and eddy with appropriate size. They took the breakage efficiency as the fraction of the eddies that have sufficient energy to cause breakage, i.e., $\exp(-u_c^2/u_{te}^2)$. Where, u_c is the critical eddy velocity required for fluid particle breakage, and was determined from the critical Weber number $(=1.52(2\sigma/d_0)^{0.5})$.

Martínez-Bazán et al. (1999a) argued that the surface of gas bubbles has to deform and the deformation energy was mainly provided by the turbulent stresses produced by the surrounding fluid. The minimum energy required for deforming the gas bubble of size d_0 was $\pi d_0^2 \sigma$, and the surface restoring pressure was $6\sigma/d_0$. The breakage constraint was that the turbulent stress resulting from the turbulent velocity fluctuations must be greater than the surface restoring pressure, i.e., $1/2\rho_c \Delta \bar{u}^2(d_0) > 6\sigma/d_0$. They proposed that the breakage frequency was inversely proportional to the difference between the turbulent stress and the surface restoring pressure. The unknown parameter contained in this breakage frequency model was fitted from their experiment.

In the literature, the breakage frequency or rate models show two different trends with increasing parent particle diameter (please see Table 1). That is, ones show that the breakage frequency monotonously increases with increasing d_0 such as the models of Tsouris and Tavlarides (1994), Luo and Svendsen (1996), Lehr et al. (2002), Wang et al. (2003), Zhao and Ge (2007), and Han et al. (2011a). However, the other ones show the non-monotone behavior. That is, the breakage frequency increases to a maximum and then decreases with increasing d_0 such as the models of Coulaloglou and Tavlarides (1977), Lee et al. (1987), Prince and Blanch (1990), Martínez-Bazán et al. (1999a) and Andersson and Andersson (2006b). It is worth to be noted that the model of Coulaloglou and Tavlarides (1977) can also give a monotone relation between the breakage frequency and the parent drop diameter in the condition of given physical properties and turbulent dissipation rate, which depends on the values of the two unknown parameters contained in this model.

The non-monotone trend was already considered likely questionable by some investigators (Tsouris and Tavlarides, 1994; Chen et al., 1998), nevertheless several experiments seem to support this trend. Martínez-Bazán et al. (1999a) measured the breakage frequency of gas bubbles in a fully developed turbulent water flow. They found that the breakage frequency of gas bubbles of size larger than about 1.6 mm decreases with increasing d_0. Maaß and Kraume (2012) measured the drop breakage probability and the breakage time in a breakage cell. The breakage frequency, which was expressed as the product of the inverse of breakage time and the breakage probability, increases to a maximum and then decreases with increasing d_0. They adopted the model of Coulaloglou and Tavlarides (1977) and modified the two unknown parameters contained in this model according to the measured breakage frequency. Nevertheless, the experiment of Andersson and Andersson (2006b) showed that the breakage frequency of the drops of size smaller than about 1.0 mm in a turbulent pipe flow monotonously increases with increasing d_0.

It can be seen from Table 1 that the breakage constraints seem to have a certain relation with the evolution of breakage frequency with d_0. In Table 1, the breakage constraints contained in the monotone breakage frequency models depend on both the size of parent particle and the sizes of daughter particles, and the breakage constraints contained in the non-monotone breakage frequency models seem to be dependent on the size of parent particle. Most of the above models considered that the size of parent particle falls in the inertia subrange and the eddies contributing to the parent particle breakage can be modeled by the energy spectrum in this range. That is, the energy spectrum function $E(k) = C\varepsilon^{2/3}k^{-5/3}$ and the turbulent velocity $\bar{u}_\lambda \sim (\varepsilon\lambda)^{1/3}$ in inertia subrange were usually used to establish the breakage frequency model. Where, k is wave number, λ is eddy diameter $(2\pi/k)$ and C is the universal Kolmogorov constant. This spectrum function describes a Kolmogorov $-5/3$ spectrum, and the available experimental data support this trend (Sreenivasan, 1995; Lee and Yianneskis, 1998; Pope, 2000).

However, according to turbulence theory, the width of inertia subrange usually depends on turbulent dissipation rate and physical properties of fluid (such as viscosity and density). It means that the size of eddies in the inertia subrange may not be always comparable to d_0, even it is possible that d_0 falls in the energy-containing range or in the dissipation range. Therefore, the effect of the wide energy spectrum distribution on the breakage needs to be studied.

1.2. Purpose of this work

As seen from the above review, the influence of energy spectrum on the breakage needs to be studied in depth since the condition that the size of parent particle falls in the inertia subrange may not be always satisfied in actual applications. Furthermore, the evolution characteristic of breakage frequency with parent drop size needs to be studied further since the