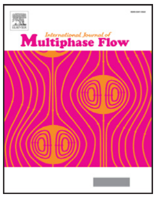
International Journal of Multiphase Flow 000 (2017) 1–10

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow



Theoretical breakup model in the planar liquid sheets exposed to high-speed gas and droplet size prediction

Li-zi Qin, Ran Yi, Li-jun Yang*

School of Astronautics, Beihang University, 100191 Beijing, PR China

A R T I C L E   I N F O

Article history:
Received 22 February 2017
Revised 6 August 2017
Accepted 29 September 2017
Available online xxx

Keywords:
Air-blast liquid sheet
Theoretical breakup model
Droplet size

A B S T R A C T

This paper makes an effort to describe the atomization in the air-blast breaking liquid sheet, with an emphasis on the establishment of the theoretical model capable of quantitatively predicting the performance of the atomizer. The phenomenological two-staged breakup model for a cylindrical jet exposed to the high-speed gas has been extended to the planar sheet, combined with a classical linear stability analysis whether gas compressibility and viscosity are included. By means of the full-wave integral, explicit expression of the Sauter Mean Diameter (SMD) for incompressible gas is obtained, as well as implicit ones for compressible and viscous gas conditions. Based upon the breakup model, results of the SMD are shown to coincide favorably with previous experimental data. Typically, the gas compressibility and viscosity in the first breakup stage have almost no influence on the ultimate value of mean droplet size, elucidating the validity and applicability of the explicit expression of the incompressible gas in the breakup model.

1. Introduction

Liquid jets flowing into gases are ubiquitously encountered in various applications such as propulsion and combustion systems, agricultural sprays and pharmaceutical industry. Based on the cross-sectional geometry of the liquid jet, atomizers could be generally categorized into planar sheet, cylindrical and annular jets, etc. When accompanied by a co-flowing high-speed gas stream, jets in this design are usually known as air-blasted or air-assisted atomizers, which can significantly enhance the specific energy of air per unit volume of liquid flow rate and thus produce fine water mist. Generally, in the case where the liquid jets of bulk mean velocity U_l are injected into the external gaseous flow with a mean velocity U_g (Usually, $U_g \ll U_l$), instabilities formed on the liquid surface often dictate the atomization characteristics.

Given the importance of atomization in affecting practical application performances, numerous studies have endeavored to establish links between atomization characteristics and the injector design, as well as different flowing conditions (Dombrowski and Jones, 1963; Mansour and Chigier, 1991, 1990; Lozano et al., 1996; Park et al., 2004; Kourmatzis and Masri, 2015). However, clarifying the atomization process is an extremely challenging task because it is an inherently multi-scale problem which has eluded a clear physical understanding. The process of atomization in coaxial air-blast atomizers involves various mechanisms which are likely to interact with each others, particularly Kelvin–Helmholtz instabilities and Rayleigh–Taylor instabilities (Varga et al., 2003; Kourmatzis and Masri, 2015). The basic physical mechanisms leading to eventual breakup are essentially the same in both axisymmetric and planar configurations (Lozano et al., 2001), except that the kind of instability caused by surface tension found in round jets (Rayleigh, 1878) does not exist in the planar sheets. A sketch of the atomization in a typical two-dimensional air-blast nozzle is depicted in Fig. 1. It is precisely because of the two-dimensional geometries in the thin planar sheets making it much easier to visualize without overlapping of the sight lines, it has been popular to investigate large-aspect-ratio liquid sheets since about 1990s (Mansour and Chigier, 1991, 1990; Söderberg and Alfredsson, 1998; Lozano and Barreras, 2001; Sivadas et al., 2007; Tammisola et al., 2011). Recently, motivated by atomization experiments with air and water, the instability problems of a parallel two-phase mixing layer have been studied by a series works. Both inviscid and viscous theories were considered by Boeck and Zaleski (2005), and the viscous theory introduced different instability mechanisms termed as three modes, which was further discussed by Otto et al. (2013) illustrated by the energy budget. Based on the spatio-temporal linear theory introduced by Otto et al. (2013) and numerical simulation, Fuster et al. (2013) illuminated the effect of the velocity deficit induced by the splitter plate on the nature of instability and the frequency spectra for different dynamic pressure ratios.

---

* Corresponding author.
E-mail address: yanglijun@buaa.edu.cn (L.-j. Yang).

https://doi.org/10.1016/j.ijmultiphaseflow.2017.09.010

Please cite this article as: L.-z. Qin et al., Theoretical breakup model in the planar liquid sheets exposed to high-speed gas and droplet size prediction, International Journal of Multiphase Flow (2017), https://doi.org/10.1016/j.ijmultiphaseflow.2017.09.010

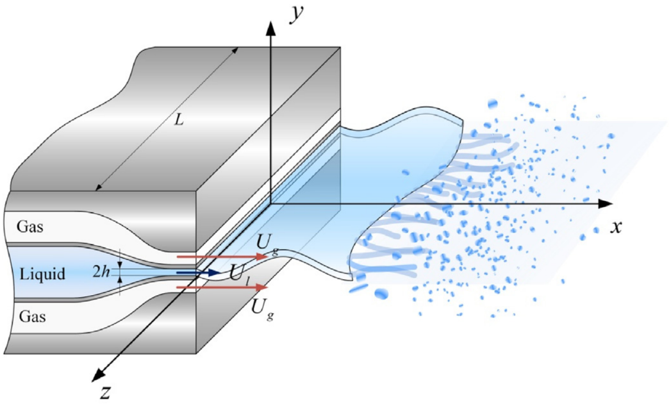


Fig. 1. Sketch of a typical two-dimensional air-blast atomizer in the working state.

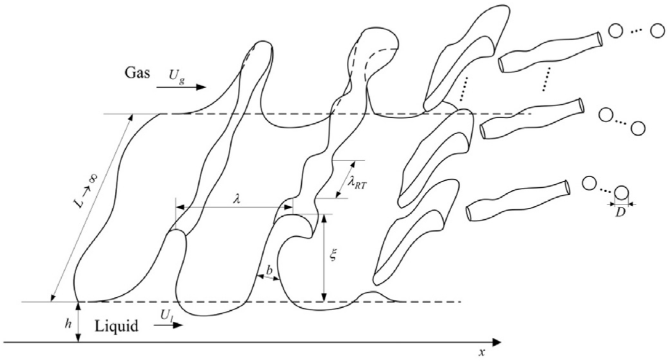


Fig. 2. Schematic of the sheet disintegration and breakup process.

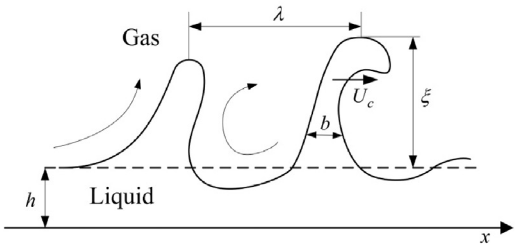


Fig. 3. Schematic of the formation of crests caused by primary Kelvin–Helmholtz instability.

In practical applications, one of the most frequently concerned parameters tracked in the atomization process is the droplet size, typically referring to the Sauter mean diameter (SMD) which corresponds to the ratio of volume to surface of the whole spray. The dependencies of the SMD on the physical parameters of fluids as well as flow conditions are generally focused on. Particularly, the SMD is usually expressed by a power law dependency on the gas velocity U_g (i.e. $SMD \propto U_g^{-n}$). A fair number of expressions with SMD are totally empirical, obtained by fitting the experimental data sets directly in specific given coefficients. Thus, this empirical approach, while practical in some conditions, makes it difficult to give corresponding physical explanations for individual parameters in those formulas. Under the circumstances, investigating the fundamental physical mechanisms hidden behind the relationship between the droplet sizes and the fluid properties or conditions of air-assisted atomizers has triggered interest in theoretical research.

The drop formation model proposed by Dombrowski and Johns (1963) has been widely used in the case of the drop formation process of planar sheets. They speculated that the drop sizes may have connection with the most unstable wavelengths growing on the surface of the sheet based on their experimental observations. It is assumed that half-waves are torn off the disturbed sheet when the amplitude of the surface reaches a critical value, then contract into spanwise ligaments, which are subsequently broken into droplets. However, it should be noted that abundant investigators studying the planar air-blast sheets observed other breakup mechanisms such as “cellular breakup” regime and “stretched streamwise ligament breakup” regime (Stapper and Samuelsen, 1992), and a more detailed summary of the classification of the sheet fragmentation can be found in the review paper of Dumouchel (2008). These various regimes suggest that it might be unlikely to use a universal breakup model to describe the process of atomization in all flow conditions and atomizer configurations. Typically, as to the most concerned air-blast atomization where the relative velocity between airstream and the liquid jet is fairly high, a corresponding theoretical breakup model needs reestablishing. In the last decade, a dual-instability breakup regime proposed by Varga et al. (2003), i.e., a primary shear instability followed by Rayleigh-Taylor instability (RTI), were satisfactorily consistent with experiments in the round liquid jet accelerated by a high-speed gas stream. This two-staged mechanism had been further consolidated and expanded to atomization of viscous and non-Newtonian fluids (Aliseda et al., 2008) and conditions of planar mixing layer (Rayana et al., 2006).

Yet, there is no appropriate breaking model for planar air-assisted sheet, with both upper and lower surfaces of the sheet exposed to high-speed airstreams. So far, few explicit and unified explanations have been proposed to link the “stretched streamwise” regime mentioned above observed in experiments with physical atomization mechanisms. In this paper, a theoretical breakup model based on the dual-instability regime is presented to investigate the SMD in planar sheets of air-blast atomizers. The first stage of primary instability wavelength λ_1 induced by Kelvin–Helmholtz instability (KHI) is acquired from the classical linear stability analysis for viscous liquid sheets, respectively, in the case of compressible or incompressible inviscid gas streams. Besides, the condition of viscous gas in the modified Stokes velocity profile model is investigated in the first instability stage. In addition, a full-wave assumption, similar to what was proposed by Mayer (1961), is applied when calculating the droplet size of the atomization.

2. Prediction of SMD in theoretical breakup model

2.1. Phenomenological breakup model

According to photos taken experimentally in previous literatures (Stapper and Samuelsen, 1992; Lozano et al., 1996), there existed a distinct change in the form of sheet disintegration when the relative velocity of gas and liquid sheet is fairly large. That is, streamwise ligaments will produce instead of spanwise ligaments before a large number of droplets are generated. Based on this physical phenomenon, we naturally came up with a schematic of the experimentally observed breakup process of liquid sheet under a co-flowing, high-speed gas stream, which is shown in Fig. 2. Similar to the breakup model raised by Varga (2003), on the effect of KHI, waves of length λ are formed at the gas-liquid interface. Liquid tongues of the primary instability, of thickness b, are prone to be caught by RTI just like a flattened droplet exposed to a high-speed gas stream, thus forming corrugations with the most unstable wavelength λ_{RT}. With the tongues peeling from the liquid surface, streamwise ligaments generate owing to the contraction of surface tension, and ultimately collapse into small droplets with a typical size D, where $D \propto \lambda_{RT}$.

The initial stage of this atomization model is represented graphically in Fig. 3 from a two-dimensional perspective. A full-wave ap-

Please cite this article as: L.-z. Qin et al., Theoretical breakup model in the planar liquid sheets exposed to high-speed gas and droplet size prediction, International Journal of Multiphase Flow (2017), https://doi.org/10.1016/j.ijmultiphaseflow.2017.09.010