Chapter

Breakup Morphology and Mechanisms of Liquid Atomization

Hui Zhao and Haifeng Liu

Abstract

Fuel atomization, the transformation of bulk liquid into sprays, is of importance in jet engines. In this chapter, we will introduce the latest research advances on breakup morphology and mechanism of liquid atomization. On primary atomization, based on the morphological difference, the twin-fluid atomization could be classified into different regimes. The influence of Kelvin-Helmholtz and Rayleigh-Taylor instability on breakup morphology and fragment size is great and nonmonotonic. On secondary atomization, Rayleigh-Taylor instability is considered as the main driving mechanism in different bag-breakup modes; for higher Weber number, it will be in concurrence with the shear instability. Based on ligament-mediated spray formation model, ligament breakup is found to be well represented by the gamma distributions. Atomization of complex fluids has special characteristics and mechanisms. There are also a lot of research advances recently in this field.

Keywords: atomization, sprays, breakup, drop, instability

1. Introduction

Transformation of bulk liquid fuel into sprays is of importance in many engines. Most fuels employed in engines are liquid that must be atomized before being injected into combustion zone. Atomization could produce a very high ratio of surface to mass in the liquid phase, thereby promoting rapid reaction and combustion. In addition, liquid atomization is also common in a wide array of applications, such as agriculture, coatings, gasification, water scrubber, pharmaceuticals, metal powder production, 3D printing, spray drying, fire suppression, and cooling.

Atomization quality can be described in terms of mean drop size and distribution. Important factors in atomization include the flow conditions, liquid properties, gas properties, atomizer (or nozzle, injector) dimensions, and environment conditions. So, there are many atomizer types in the industry and laboratory, such as pressure atomizers, air-blast atomizers, air-assist atomizers, rotary atomize, effervescent atomizers, electrostatic atomizers, ultrasonic atomizers, etc. Then, the key is to select the suitable atomizers for the given application, which can have a well performance in operating conditions.

Atomization process usually consists of the initial removal of liquid mass from the surface to form large liquid drops and the subsequent breakup of these drops into tiny droplets; the phenomena are, respectively, known as primary and secondary atomization. Atomization has been quantitatively studied for more than a century. However, liquid atomization is a complicate, multiparameter two-phase flow process, which is not well understood. Many empirical theories and equations have been developed and used in atomization. So, there is still a lot of unknown work to be done [1–15].

2. Dimensionless number

The physical processes and fluid properties are important in atomization morphology and performance, and the mathematical and numerical analysis of atomization is very challenging, so a number of dimensionless numbers are used. First of all, the most important one is Weber number, which represents the ratio of disruptive hydrodynamic forces to the stabilizing surface tension force,

$$We = \frac{\rho_g (u_g - u_l)^2 D}{\sigma}, \tag{1}$$

where ρ_g is the gas density, u_g is the gas velocity, u_l is the liquid velocity, D is the characteristic size (in general, nozzle diameter in primary atomization and drop diameter in secondary atomization), and σ is the surface tension. Liquid viscosity will hinder deformation and dissipates energy supplied by aerodynamic forces. The viscosity effect is highly correlated with the Ohnesorge number,

$$Oh = \frac{\mu_l}{\sqrt{\rho_l D \sigma}}, \tag{2}$$

where μ_l is the liquid viscosity, and ρ_l is the liquid density. Other important dimensionless groups are gaseous Reynolds number

$$\mathrm{Re}_g = \frac{\rho_g u_g D}{\mu_g}, \tag{3}$$

liquid Reynolds number

$$\mathrm{Re}_l = \frac{\rho_l u_l D}{\mu_l}, \tag{4}$$

Mach number

$$Ma = u_g / c, \tag{5}$$

Strouhal number

$$St = \frac{fD}{u_l}, \tag{6}$$

the characteristic time [16]

$$T = \frac{t u_g}{D} \sqrt{\frac{\rho_g}{\rho_l}}, \tag{7}$$

gas-liquid momentum flux ratio

$$M = \frac{\rho_g u_g^2}{\rho_l u_l^2}, \quad (8)$$

momentum ratio

$$MR = \frac{\rho_g u_g^2 A_g}{\rho_l u_l^2 A_l} \quad (9)$$

and mass ratio

$$GLR = \frac{\rho_g u_g A_g}{\rho_l u_l A_l}. \quad (10)$$

Here μ_g is the gas viscosity, c is the speed of sound in the medium, f is the frequency, t is the real time, and A_g and A_l are the area of gas exit and liquid exit, respectively.

Complex fluid is usually a kind of complicated non-Newtonian fluid, which has more dimensionless groups on atomization. For example, in the Bingham model, the flow is characterized by the following constitutive equations,

$$\tau = \tau_0 + \eta\gamma \text{ and } \mu_l = \tau_0/\gamma + \eta, \quad (11)$$

where τ is the shear stress, τ_0 is the yield stress, η is the plastic viscosity, and γ is the shear rate. Hedstrom number is the useful nondimensional number, which depends only on material properties and geometrical parameters,

$$He = \frac{\tau_0 D^2 \rho}{\eta^2}. \quad (12)$$

The ratio of the yield stress to the stabilizing surface tension force is [17]

$$X = \tau_0 D/\sigma, \quad (13)$$

and the ratio of the aerodynamic force to the yield stress is [17]

$$Y = \rho_g u_g^2/\tau_0. \quad (14)$$

For viscoelastic fluids, Weissenberg number compares the elastic forces to the viscous forces

$$Wi = N_1/\tau \text{ or } Wi = t_R\gamma, \quad (15)$$

where N_1 is the first normal-stress difference, and t_R is the relaxation time. Another dimensionless number on the ratio of first normal stress difference to surface tension force could be defined as follows [18]

$$Z = \frac{N_1}{\sigma D}. \quad (16)$$

3. Primary atomization

Nozzle is generally used to produce spray. Fuel injection process plays a major role in many aspects of combustion performance. The influence of nozzle structure is remarkable on the atomization performance [19–22]. With the progress of technology

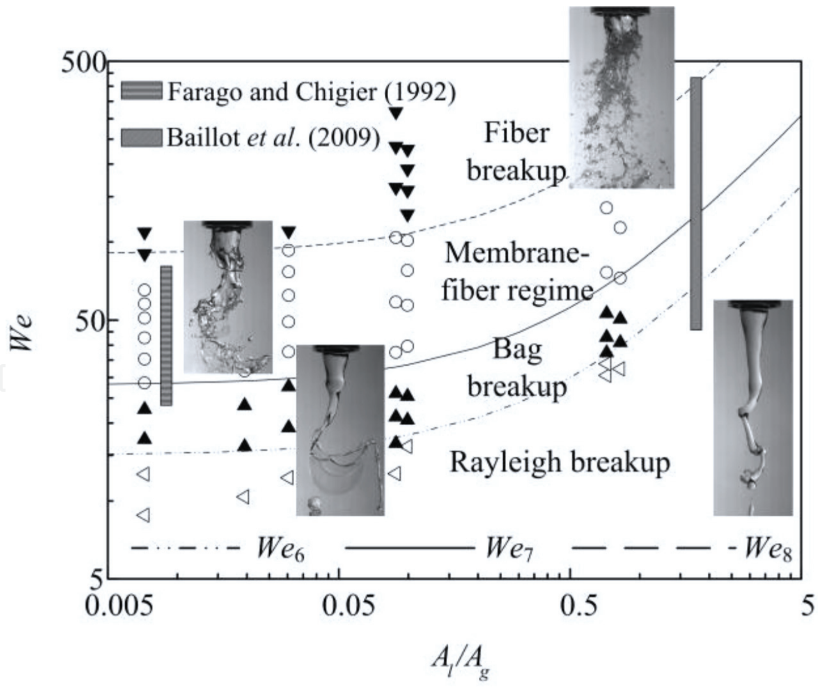

Figure 1.
Influence of A_g/A_l on atomization mode.

[23], it is found that the properties of breakup morphology and fragment distribution in different regimes are different [24–28]. Coaxial air-blast atomizers have many applications [29–31]. In order to obtain the desired results of atomization in the industrial scale, the suitable range of nozzle size and operating condition could be determined with the help of the regime map. There are two basic types on coaxial gas-liquid jets: (I) a cylindrical liquid jet surrounded by an annular gaseous stream and (II) an annular liquid sheet with an inner round gaseous stream [32–35].

In cylindrical liquid jet and annular gas jet, the common atomization modes are Rayleigh-type breakup (axisymmetric and non-axisymmetric), the membrane-type breakup (bag-type and membrane-fiber), fiber-type breakup, superpulsating breakup, atomization, and so on [36–42]. For the traditional classification, the

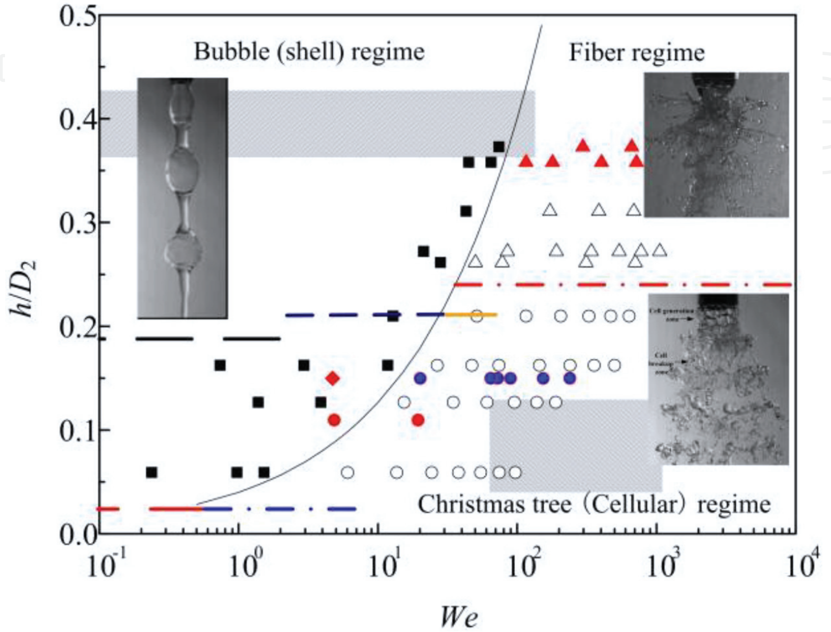

Figure 2.
Influence of h/D on atomization mode.

We-Re_l map or M-Re_g map is common. However, these criteria cannot reflect the impact of gas-liquid nozzle exit size. So, there is the modified map of classification by the gas-liquid nozzle exit area ratio A_g/A_l. **Figure 1** shows that atomization performance will improve with the increase of A_g/A_l, but the oversized value of A_g/A_l will produce very little effect and waste energy [41]. These results are conducive to the design of nozzles.

In cylindrical gas jet and annular liquid jet, the common atomization modes are bubble (shell) breakup, Christmas tree (cellular) breakup, fiber breakup, and so on [43–55]. Here, the characteristic size is the liquid film thickness h, which has an important impact on liquid film breakup. Then, there is the h/D-We map of breakup regimes based on the Rayleigh-Taylor instability is proposed, which is in well agreement with the experimental results as shown in **Figure 2**. Note that outlet wall thickness of nozzle can affect the flow field at nozzle outlet [56–61].

4. Secondary atomization

Drop is subjected to aerodynamic forces when there is the relative velocity between drop and gas. This force results in drop deformation and, if sufficiently large, will lead to breakup and fragmentation. Differing gas flow conditions can lead to differing drop breakup modes. Based on the morphology, as We increases, the vibrational, bag, bag-stamen, multimode, sheet-thinning, shear, and catastrophic breakup mode appear in turn [62–66]. This classification method would lack the quantitative physical mechanism, which may result in the criterion of mode based primarily on subjective experience.

The mechanism of drop breakup is a key and hot research area of secondary atomization. The investigation [67] shows the structure and location of turbulent eddies, which do not appear to correlate with drop breakup morphology. The average gas flow fields show no significant differences of drop morphology between bag breakup and sheet-thinning breakup. The results show that the wake structure of gas is unlikely to be the dominant mechanism of secondary atomization. These results agree well with experimental photos that the morphological transition of drop breakup is a strong function of We, and the influence of Re_g is little [68].

Interfacial instability is very important in atomization [69, 70]. Rayleigh-Taylor (RT) instability is considered as the main driving mechanism responsible for drop breakup in the general bag breakup or Rayleigh-Taylor piercing (including bag breakup, bag-stamen breakup, dual-bag breakup, bag/plume breakup, multibag breakup, etc.) [65, 71–77]. All of these breakup modes have the same characteristic bag structure. With the increase of Weber number, the thin sheet (or membrane) at the periphery of deforming drop appears and breaks up continuously. These breakup types that have continuing shearing and entraining action are all governed by the Kelvin-Helmholtz (KH) instability mainly. This mode can be named as shear breakup (or sheet-thinning breakup, shear-induced entrainment) [65, 78]. So based on the instability in secondary atomization, there are two main modes: general bag breakup and shear breakup.

In order to classify the submode of general bag breakup, a dimensionless number of RT instability wave number is proposed [71]

$$N_{RT} = D/\lambda_{RT}, \tag{17}$$

where λ_{RT} is the wavelength of the most R-T unstable wave. N_{RT} is the number of R-T wave on the windward side, which can also be considered as the bag number

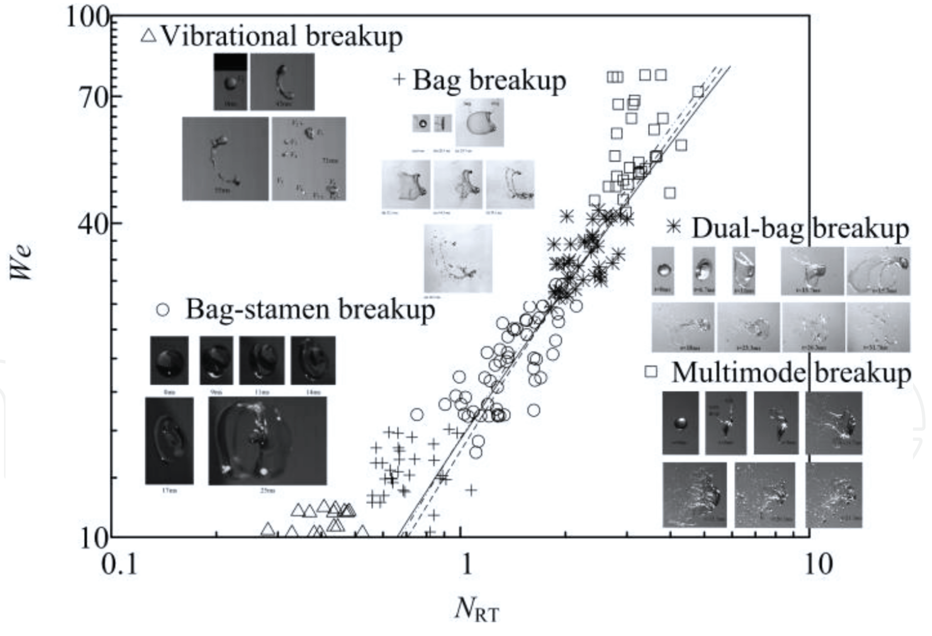

Figure 3.
Theoretical criterion N_{RT} for general bag breakup.

approximately. So the theoretical criterion N_{RT} could be the new criterion instead of *We* in the range of general bag breakup as shown in **Figure 3**.

When the viscosity of liquid cannot be neglected, *Oh* will be another key parameter [79–84]. Many researches show that the *We* range of drop breakup mode will increase with the increase of *Oh* nonlinearly. The most important transition *We* is the critical Weber number We_c occurring at the start of bag breakup. It can establish the criteria for the onset of secondary atomization. Based on the RT instability, the theoretical formula for predicting We_c is [81]

$$\left(\frac{We_0}{We_c}\right)^{1/2} + C\left(\frac{Oh^2}{We_c}\right)^{1/3} = 1, \tag{18}$$

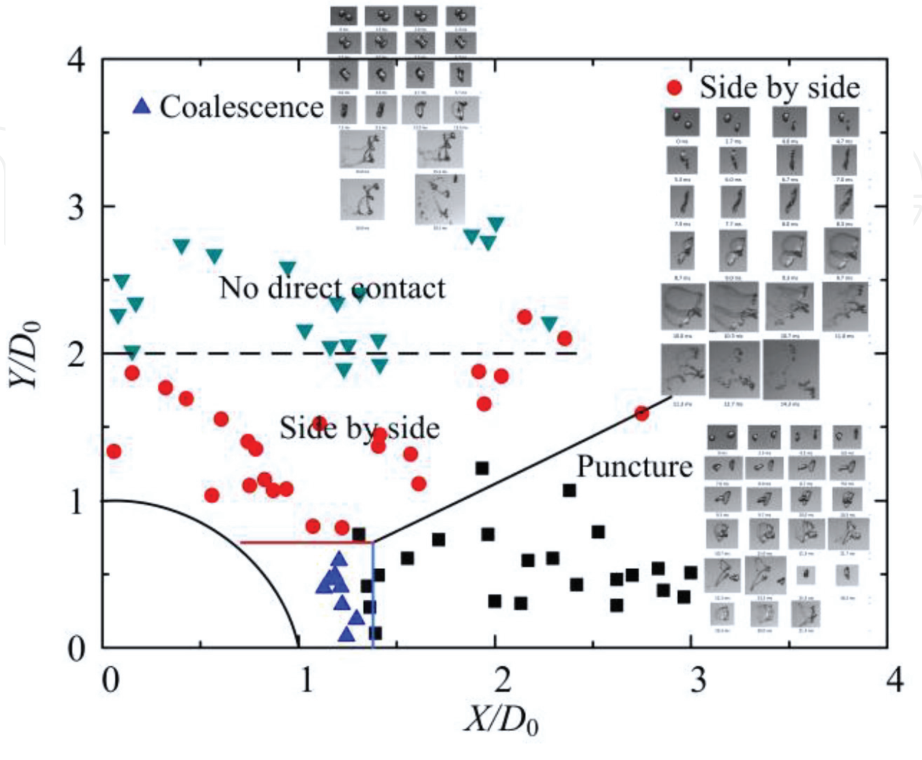

Figure 4.
Drop interaction regime map.

where We_0 is the critical Weber number when Ohnesorge number tends to zero, $We_0 = 11 \pm 2$, and C can be considered as a constant 1.48.

Drop interaction in the continuous gas jet is the important atomization process between primary atomization and secondary atomization [85]. It is the important link between the jet breakup and final spray. Due to airflow, the interaction of two drops evolves in a highly interactive and variable manner. The drop interaction in the airflow yields even more rich atomization morphologies and mechanisms. Behaviors of drop group and the isolated drop in the airflow are significantly different. Experimental photos in **Figure 4** show that there are four main interaction modes, which are coalescence mode, puncture mode, side by side mode, and no direct contact mode [86].

5. Fragment size and distribution

Drop size in atomization is a key parameter that is needed for a lot of fundamental researches and applications [87]. Due to the complicated nature of atomization, most nozzles cannot produce sprays of uniform droplet size. Instead, the spray can be regarded as a spectrum of drop sizes distributed about some defined mean drop size. Now, the most widely used mean diameter is Sauter mean diameter,

$$D_{32} \;\text{ or } SMD = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \tag{19}$$

where n_i is the number of droplets per unit volume in size class i, and d_i is the droplet diameter [7, 88–91].

The liquid in prefilming air-blast nozzle is first spread into a very thin sheet or film, which is then exposed to gas operating at the high velocity causing breakup and atomization. By spreading bulk liquid into film, contact area between liquid and gas increases. Generally speaking, SMD will decrease with the increase of gas velocity. However, under some conditions of prefilming atomization, the droplet size increases with the increase of gas velocity, and then decreases with the increase of gas velocity. So, the classical KH-RT atomization model [92–94] is modified and extended to the prefilming air-blast atomization [95].

Droplet size distribution is a crucial parameter of atomization process besides droplet mean diameter. Atomization and spray presents a wide distribution of fragment sizes. Many empirical relationships have been proposed to characterize the distribution of droplet sizes in atomization, for example, Rosin-Rammler, Nukiyama-Tanasawa, log-normal, root-normal, and log-hyperbolic. Atomization process involves a succession of changes of liquid topology, the last being the elongation and capillary breakup of ligaments torn off from the liquid surface. Breakup of liquid ligament (filament or fiber) is the key in primary atomization and secondary atomization, so ligament-mediated spray formation model is proposed [96, 97]. Drop fragments after ligament breakup is found to be gamma distribution. Then, the broad statistics of atomization shows Marshall-Palmer exponential shape of overall distribution in spray [98–101].

6. Complex fluids

Complex fluids are mixtures that have a coexistence between two or multiphases, which are common in our society and industry [102–104]. Many complex fluids are non-Newtonian fluid, whose characteristics of breakup and atomization are unusual [82, 105–107].

The particle concentration in the pinch-off zone of suspension or slurry decreases as its minimal diameter decreases, resulting in a pure liquid interstitial fluid. There are three successive stages during suspension pinch-off, referred to as suspension, transition, and liquid stages, which is different from pure liquids [108–111].

For evaluating the breakup of non-Newtonian fluid, the mean apparent viscosity of liquid during deformation and breakage is the key parameter. Three methods for determining the apparent viscosity of non-Newtonian fluid have been presented: (1) calculation of mean apparent viscosity according to the shear rate equal to $\gamma = u_g/D$ [112], (2) increase the constant k determined by other test parameters, $\gamma = ku_g/D$ [17, 113], and (3) numerical analysis or analytical solution of energy and motion equations to determine dynamic shear rate [114–117].

Based on morphology, the breakup regimes of slurry jet can be classified into different modes: Rayleigh-type breakup, fiber-type breakup, superpulsating breakup, and atomization [113, 118, 119]. The particles in slurry will make membrane breakup very fast, so the membrane structure is not obvious in slurry atomization as shown in **Figure 5**. The dimensionless slurry jet breakup length can be correlated by the KH-RT hybrid model [92, 93, 113, 120]. There are two kinds of periodic structures, which are shear wave and jet oscillation. The deformation and breakup regimes of slurry drops can be classified into different modes: deformation, multimode breakup (including two submodes: hole breakup and tensile breakup), and shear breakup [17, 117].

Atomization of solution is a common phenomenon in numerous practical applications [121–124]. In the breakup of surfactant-laden liquid, critical micelle concentration (CMC) has an important influence [125–129]. The micelle can be considered as the source term, which can supply the monomers [130]. The diffusion rate of surfactant is limited, and liquid breakup is very fast sometimes. So, dynamic surface tension will change with the process of liquid deformation and atomization. According to the competition of the amplification rate of KH instability ω_{km} and RT instability ω_{Rm}, the criterion on transition Weber number between general bag breakup and shear breakup is obtained [131],

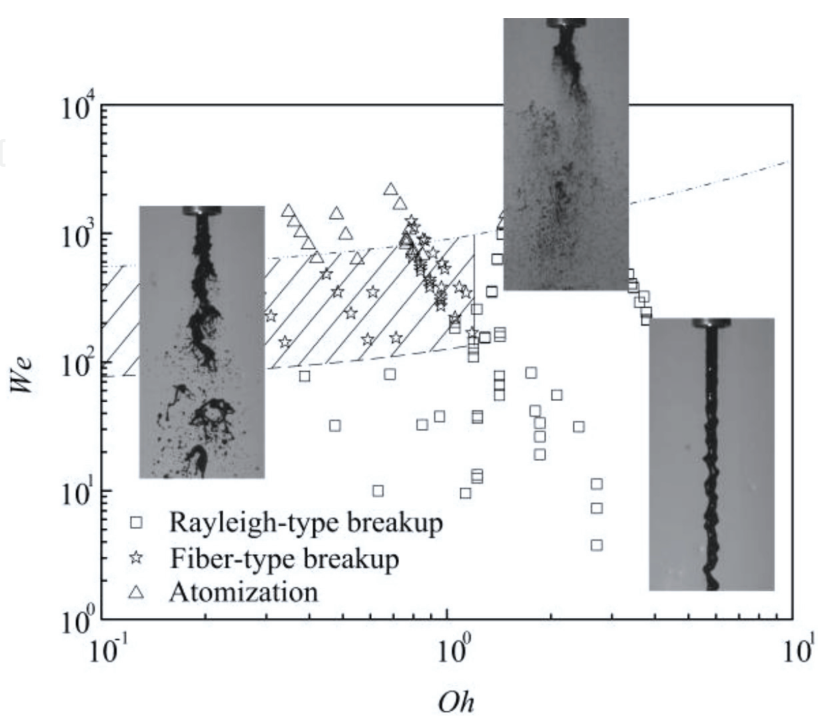

Figure 5.
The breakup regimes of slurry jet.

$$\omega_{km}/\omega_{Rm} = 1. \tag{20}$$

Atomization of viscoelastic liquids is widely known to be more difficult to atomize than typical Newtonian liquids [18, 132–138]. The addition of viscoelasticity is found to stabilize the rim of liquid. Viscoelasticity can enhance the growth of the bead and delay pinch off. Viscoelasticity increases the mean drop diameter and broadens the size distribution. Liquids with atypical properties, such as gels, liquid metal, and strain-thickening liquids, are also studied widely [139–147].

7. Conclusions

The available literature on liquid atomization is countless. Many researchers and engineers have done a lot of excellent work in this field. Unfortunately, the clear physical mechanisms on atomization have not yet been fully revealed. Some topics have received only cursory attention, such as non-Newtonian liquids, charged liquids, and turbulence influence. There are many challenges ahead for research in atomization and spray technology [148, 149]. On the other hand, it is lucky for us. Due to the fundamental nature of the problem and its many important applications, we can expect great progress in the fields of atomization and spray technology in the future.

Acknowledgements

This work was supported by the National Key R&D Program of China (2018YFC0808502-02), National Natural Science Foundation of China (21506059), Shanghai Engineering Research Center of Coal Gasification (18DZ2283900), and Fundamental Research Funds for the Central Universities.

Conflict of interest

The authors have declared that no conflict of interest exists.

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