Chinese Journal of Chemical Engineering 23 (2015) 262–267

Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

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

Energy, Resources and Environmental Technology

Instability and breakup of cavitation bubbles within diesel drops☆

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ARTICLE INFO

Article history:
Received 18 April 2013
Received in revised form 19 July 2013
Accepted 15 September 2013
Available online 1 November 2014

Keywords:
Stability
Diesel droplet
Cavitation bubble
Secondary breakup

ABSTRACT

A modified mathematical model is used to study the effects of various forces on the stability of cavitation bubbles within a diesel droplet. The principal finding of the work is that viscous forces of fluids stabilize the cavitation bubble, while inertial force destabilizes the cavitation bubble. The droplet viscosity plays a dominant role on the stability of cavitation bubbles compared with that of air and bubble. Bubble–droplet radius ratio is a key factor to control the bubble stability, especially in the high radius ratio range. Internal hydrodynamic and surface tension forces are found to stabilize the cavitation bubble, while bubble stability has little relationship with the external hydrodynamic force. Inertia makes bubble breakup easily, however, the breakup time is only slightly changed when bubble growth speed reaches a certain value (50 m·s^{-1}). In contrast, viscous force makes bubble hard to break. With the increasing initial bubble–droplet radius ratio, the bubble growth rate increases, the bubble breakup radius decreases, and the bubble breakup time becomes shorter.
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1. Introduction

Cavitation phenomenon in injection nozzles has a strong impact on spray formation and atomization, which are directly correlated to the efficiency of the combustion process and extents of pollutant emission [1–4]. Study on the stability of cavitation bubbles has important significance and value. Cavitation phenomenon in injection nozzles is divided into two types, onset of cavitation and supercavitation [5–7]. Supercavitation in the process of fuel injection refers to a kind of phenomenon that cavitation bubbles exist in the fuel jet leaving the nozzle. Some experiments have proved that more efficient atomization occurs in the liquid jet with the stronger supercavitation [8–16]. However, supercavitation turns the fuel jet into gas–liquid two-phase mixture flow, which increases the instability of fuel jet and has an important impact on the breakup and atomization of fuel injection process so that the spray breakup and atomization mechanism under the condition of supercavitation is still unclear. Therefore, the study on how the ligament breaks up from the spray and when the secondary breakup of diesel droplet happens under the condition of supercavitation is meaningful.

Cavitation bubbles, which always exist in diesel droplets generated from breaking jet as a result of cavitation of the diesel, increase the instability of jet and droplets in part due to the two-phase mixture [17], while the mechanism and degree of this effect is uncertain. Due to the small scale of diesel droplets and cavitation bubbles, and the high jet speed of several hundred meters per second, experimental studies on the breakup of cavitation bubble within the droplet are very limited. Likewise, numerical modeling results are not exact in the case of the limited quantitative data, especially for the breakup process of secondary droplets. Therefore, it is obvious that theoretical analysis is promising to explain some observations of practical atomizer performance and improve the understanding of the breakup problem of cavitation bubbles within diesel drops.

Zeng and Lee [18] applied linear stability analysis method to develop a simple mathematical model to solve the secondary droplet character of dimethyl ether, with the atomization being considered as the result of two competing mechanisms: the hydrodynamic force and the bubble growth. In the regimes with intermediate superheating degrees their study considered that sprays are atomized by bubble growth, which produces smaller Sauter mean diameter than hydrodynamic forces alone. However, they neglected the viscous forces of fluids and the surface tension force. In this paper, based on their studies, a modified mathematical model considering the effect of fluids viscosity is used to study the effects of various forces (viscous force, inertial force, internal and external hydrodynamic forces, and surface tension force) on the stability and breakup of cavitation bubbles within the diesel droplet, which is helpful in studying the breakup mechanism of the secondary diesel droplet under the condition of supercavitation.

2. Mathematical Model

Fig. 1 shows that the schematic of cavitation bubble within a diesel droplet. Three modeling objects are present for this bubble/droplet system: stationary diesel droplet, stationary air and expanding cavitation

☆ Supported by the National Natural Science Foundation of China (51276011), the National High Technology Research and Development Program of China (2013AA065303), Beijing Municipal Natural Science Foundation of China (3132016), and the Opening Foundation of State Key Laboratory of Engines (K2013-3).
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http://dx.doi.org/10.1016/j.cjche.2014.10.009
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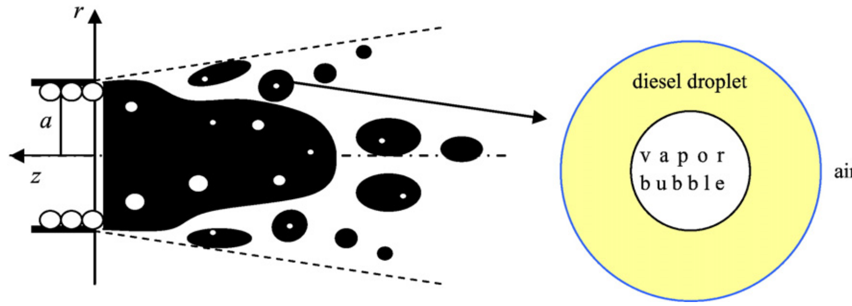

Fig. 1. Schematic of cavitation bubble within the diesel droplet.

bubble with the velocity of 2 $\mathrm{m\cdot s^{-1}}$ in radial direction. Three assumed conditions for building the mathematical model of instability of radial expansion of a droplet and an inside bubble are: only one cavitation bubble within a diesel droplet, no evaporation on the surface of diesel droplet, and the disturbances on the bubble surface are assumed to be spherically symmetric. It is further assumed that the ambient air and the diesel droplet are viscous and incompressible while the cavitation bubble is viscous and compressible.

2.1. Mathematical model

Spherical coordinate system is used in this work. The effects of viscosity including ambient air, diesel droplet and cavitation bubble are considered in this study. For the limit of paper length, the detailed derivation process of mathematical model [19] is omitted, and here is the final form of mathematical model derived by the authors.

For ambient gas outside the droplet, the diesel droplet, and the cavitation bubble, we can get the linearized disturbance governing equations. To establish the mathematical model describing the temporal stability of cavitation bubbles within the diesel droplet, we should give the initial conditions and the corresponding boundary conditions at the interface and at the infinity. Substituting disturbance governing equations into the boundary conditions, which leads to

$$\begin{aligned}&\rho_2\left(\omega^2\bar{R}_o-\omega\bar{V}_o\right)-3\bar{\rho}_v c^2\frac{\omega}{\omega\bar{R}_i+3\bar{V}_i}\frac{\bar{R}_o^2}{\bar{R}_i^2}\\&-\rho_2\left(\omega^2\frac{\bar{R}_o^2}{\bar{R}_i}-\omega\bar{V}_o\frac{\bar{R}_o^4}{\bar{R}_i^4}\right)+\frac{2\sigma\bar{R}_o^2}{\bar{R}_i^4}-4\mu_2\frac{\omega\bar{R}_o^2}{\bar{R}_i^3}\\&+4\mu_v\frac{\omega\bar{R}_o^2}{\bar{R}_i^3}-\rho_1\left(\omega^2\bar{R}_o-\omega\bar{V}_o\right)+\frac{2\sigma}{\bar{R}_o^2}+4\mu_2\frac{\omega}{\bar{R}_o}-4\mu_1\frac{\omega}{\bar{R}_o}=0.\end{aligned}\tag{1}$$

Eq. (1) is the mathematical model, which can be used to describe the disturbance growth rate of the diesel bubble growth instability. For the purpose of generality and convenience to research, Eq. (1) can be normalized as

$$\begin{aligned}&\left(\delta-\delta^2-\psi_o\delta\right)\omega^{*2}+\left[-1+\delta^4+\psi_o-\frac{4\delta^3}{Re_2}+\frac{4\psi_i}{\delta Re_v}\left(\frac{We_i}{We_o}\right)^{1/2}\right.\\&\left.+\frac{4}{Re_2}-\frac{4\psi_o}{Re_1}\right]We_o^{1/2}\omega^*\\&+2\delta^2+2\delta^{-2}-3\psi_i\frac{We_i}{Ma_i^2}\frac{\omega^*}{\omega^*+3We_i^{1/2}}\delta^2=0.\end{aligned}\tag{2}$$

where $\delta=\bar{R}_o/\bar{R}_i$, is the liquid–bubble radius ratio, $\psi_o=\rho_1/\rho_2$, is the air–liquid density ratio, $\psi_i=\bar{\rho}_v/\rho_2$, is the bubble–liquid density ratio, $Ma_i=\bar{V}_i/c$, is the bubble Mach number, $\omega^*=\sqrt{\rho_2\bar{R}_i^3/\sigma}\omega$, is the non-dimensional disturbance growth rate, $Re_2=\rho_2\bar{V}_o\bar{R}_o/\mu_2$, is the liquid Reynolds number, $We_i=\rho_2\bar{V}_i^2\bar{R}_i/\sigma$, is the bubble Weber number, $We_o=\rho_2\bar{V}_o^2\bar{R}_i/\sigma$, is the liquid Weber number, $Re_v=\bar{\rho}_v\bar{V}_i\bar{R}_i/\mu_v$, is the bubble Reynolds number, and $Re_1=\rho_1\bar{V}_o\bar{R}_o/\mu_1$, is the air Reynolds number.

Eq. (2) is a cubic equation about plural number ω^* and characterized by 10 non-dimensional variables and can be solved analytically or numerically. Three roots exist for the mathematical model. The root with the largest real part represents the disturbance growth rate, and the corresponding imaginary part represents the frequency of oscillation. The effects of viscosity including ambient air, diesel droplet and cavitation bubble are considered in this study. So Eq. (2) is more complete than that derived in [18].

Assuming all viscosity coefficients are equal to zero, all terms related to Reynolds numbers disappear, then Eq. (2) degenerates to

$$\begin{aligned}&\left(\delta-\delta^2-\psi_o\delta\right)\omega^{*2}+\left(-1+\delta^4+\psi_o\right)We_o^{1/2}\omega^*\\&+2\delta^2+2\delta^{-2}-3\psi_i\frac{We_i}{Ma_i^2}\frac{\omega^*}{\omega^*+3We_i^{1/2}}\delta^2=0\end{aligned}\tag{3}$$

which is the mathematical model used by Zeng and Lee [18].

2.2. Bubble breakup criterion

Experimental studies display that the jet spray is atomized primarily by bubble breakup under cavitation conditions, but the exact atomization mechanism concerning when and how the bubble breakups is not very clearly identified up to now.

The breakup model proposed by Zeng and Lee [18] for a bubble–droplet system is used in this study. The breakup is assumed to occur when the disturbance grows larger than a certain characteristic length. The film thickness (*i.e.*, the difference between droplet radius R_o and bubble radius R_i) is chosen. So, the breakup variable K is defined as

$$K(t)=\frac{\eta(t)}{R_o(t)-R_i(t)}=\frac{\eta_0\exp(\omega t)}{R_o(t)-R_i(t)}$$

where η_0 is the initial disturbance, for the time being, linear stability analysis method cannot be used to solve the value of η_0. The initial disturbance η_0 is assumed to be proportional to the initial droplet radius R_{o0} in this paper, $\eta_0=fR_{o0}$, where f is a constant, which can be determined from experimental data. In this study, f is taken as 0.05. The breakup criterion is chosen to be

$$K(t_b)=1$$

namely when the disturbance is up to the fuel thickness, her t_b represents the breakup time.

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