Experimental Thermal and Fluid Science 68 (2015) 452–458

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Correlation analysis of superheated liquid jet breakup to bubble formation in a transparent slit nozzle

Shiyan Li [a], Yuyin Zhang [a,b,*], Bin Xu [b]

[a] School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Vehicle & Motive Power Engineering College, Henan University of Science and Technology, Luoyang 471023, China

ARTICLE INFO

Article history:
Received 17 February 2015
Received in revised form 21 April 2015
Accepted 24 April 2015
Available online 1 June 2015

Keywords:
Superheated liquid jet
Fuel property
Transparent nozzle
Breakup
Flash boiling spray

ABSTRACT

This investigation is to evaluate and quantify the influence of bubble formation inside the nozzle on breakup characteristics of a superheated liquid jet outside the nozzle. The effect of fuel properties was examined using methanol, ethanol and butanol. A unique optically-transparent slit nozzle with a high-speed micro-imaging system were utilized for quantifying the bubble formation inside and the liquid jet breakup outside the nozzle. Correlation between bubble number density and breakup of superheated liquid jet was obtained for all the fuel. The bubble is demonstrated as the main driving forces enhancing the breakup of superheated liquid jet. By introducing a parameter K, it is easier to correlate the superheated liquid jet breakup to the bubble number density as $\Delta f = K \cdot n$. K is related with the superheat degree, Reynolds number, Weber number, and the ratio of liquid to ambient gas viscosities, which has different form at the transition stage ($0.2 < P_a/P_s \leqslant 0.3$) and the flare flashing stage ($P_a/P_s \leqslant 0.2$), implying different breakup regimes.

1. Introduction

Over the conventional high pressure injection system, the flash boiling atomization, which is one of the hot topics in atomization and spray area at present, has several advantages, such as (1) more efficient to improve atomization by slightly elevating the fuel temperature, (2) lower cost, (3) higher evaporation rate, especially at low temperature, (4) more easily to diminish wall-wetting [1].

The process and mechanism of flash-boiling spray was tried to reveal earlier by Brown and York [2] and Lienhard [3]. Since then, a number of studies have been performed on flash-boiling atomization phenomena which can be divided into two aspects, one focused on observation of the atomization characteristics of flash-boiling spray outside real DI injectors [4–7], however, characteristics of superheated flow inside the nozzle cannot be observed. The other one focused on two-phase flow characteristics [8–11]. According to above studies, the superheated fluid inside the nozzle undergoes the nucleation process, bubble growth process and finally departures from the orifice as flash-boiling spray. Mechanism of nucleation and bubble growth process have also been investigated and several models have been proposed [12], but few experimental data are available for validation especially the process when two-phase flow leaves the orifice with flash-boiling, in specific, the correlation between bubble formation inside and superheated liquid jet breakup outside the nozzle was not reported.

Until recently, Park and Lee [13] reported a comprehensive study on the internal and external flow behaviors for the first time for attempting to correlate the two-phase flow inside the nozzle with breakup characteristics outside the nozzle. Günther and Wirth [14] extended the studies of the superheated atomization and its impact on the spray using nozzle capillary, Serras-Pereira et al. [15] carried out an experimental imaging investigation based on a transparent injector with multi-fuels, experimental studies [16,17] related to the behavior of boiling water discharging through a cylindrical nozzle into the atmosphere and disintegration of liquid jets under high and limit superheating were conducted in recent years. These studies proved that for a superheated spray, energy released from bubble burst due to a sudden pressure drop near the nozzle exit, which is transferred to the surrounding liquid, is therefore important in the production of new ligaments and yielding a disintegration of the jet, which would promote the breakup and atomization process of fuel spray. However, because of difficulty in quantitatively measuring of the bubbly flow inside the nozzle and the breakup characteristics in the vicinity of the nozzle exit based on above complicated 3-D transparent nozzle, the two-phase flow inside the nozzle and

* Corresponding author at: School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China. Tel./fax: +86 21 3420 4449.
E-mail address: yuyinzhang@sjtu.edu.cn (Y. Zhang).

http://dx.doi.org/10.1016/j.expthermflusci.2015.04.023
0894-1777/© 2015 Elsevier Inc. All rights reserved.

Nomenclature

Roman symbols
- D nozzle diameter (mm)
- K a correlation parameter (–)
- f area fraction (–)
- Δf area fraction variation (%)
- c constant
- L nozzle length (mm)
- N bubble number (–)
- n bubble number density (mm^{-3})
- P pressure (kPa)
- R radius (mm)
- Re Reynolds number (–)
- SD superheat degree (–)
- SMD sauter mean diameter (μm)
- SIDI spark-ignition-direct-injection (–)
- T Temperature (°C)
- V observation volume in the channel (mm^3)
- We Weber number (–)
- x undetermined correlation index

Greek symbols
- ρ density (kg m^{-3})
- σ surface tension (N m^{-1})
- μ viscosity (Pa s)

Subscripts
- a ambient gas
- b boiling-point
- f fuel
- s saturation
- x at certain location

breakup characteristics outside the nozzle were only correlated qualitatively to the superheat degree up to date. The correlations between bubbling inside nozzle and jet breakup characteristics in the vicinity of nozzle exit was not clear yet.

Because of the afore-mentioned limitations of the round orifice of transparent nozzle, an optically-transparent slit nozzle was developed for simultaneous observation on the internal flow inside nozzle and the spray characteristics in the vicinity of nozzle exit using high-speed microscopic photography in our previous study [18]. It was found that for methanol fuel, there exists a strong relationship between the bubble number density inside the nozzle and the breakup of superheated jet outside the nozzle exit. However, since the results were obtained only from methanol fuel, the effect of fuel properties on the bubble formation and liquid jet breakup characteristics are not clear. In other words, the quantitative correlation of superheated liquid jet breakup to bubble formation characteristics in the nozzle has not been revealed.

It was well-known that, for bubbly flow inside the nozzle, the inertia force, surface tension force and viscous force were closely related to bubble nucleation and growth process, which can be described by the Rayleigh–Plesset-equation as in Eq. (1) [12]:

$$R\ddot{R}+\frac{3}{2}\dot{R}^2=\frac{1}{\rho_f}\left(P_s-P_x-\frac{2\sigma}{R}-\frac{4\mu}{R}\dot{R}\right), \quad (1)$$

where R is the radius of the bubble. P_s is the saturation pressure and P_x is the pressure at certain location inside the nozzle. σ and μ are the surface tension and the viscosity of liquid fuel respectively.

For a non-superheated spray, the breakup process is usually correlated to the following non-dimensional parameters, namely Reynolds number, Weber number, the viscosity and density ratios of liquid to gas. One of the classical correlation of non-superheated spray was proposed by Hiroyasu and Arai [19] given in Eq. (2), where Eq. (2a) is the dimensionless SMD for an incomplete spray (LS) with low injection velocity, Eq. (2b) for the complete spray (HS), and the greater should be taken. This indicates that the atomization characteristic of non-superheated spray can be determined by these parameters.

$$\frac{\bar{x}_{32}^{LS}}{D}=4.12Re^{0.12}We^{-0.75}\left(\frac{\mu_f}{\mu_a}\right)^{0.54}\left(\frac{\rho_f}{\rho_a}\right)^{0.18}, \quad (2a)$$

$$\frac{\bar{x}_{32}^{HS}}{D}=0.38Re^{0.25}We^{-0.32}\left(\frac{\mu_f}{\mu_a}\right)^{0.37}\left(\frac{\rho_f}{\rho_a}\right)^{-0.47}, \quad (2b)$$

where D is the nozzle hole diameter, μ_f and μ_a is the viscosity of the liquid fuel and the ambient gas, respectively.

It is believed that for internal flashing jet, Hiroyasu's correlation is not applicable any more as the intensity of bubble burst has not been considered [14–17].

In this work, methanol, ethanol and butanol fuels will be used to examine the effect of fuel properties on characteristics of bubble formation inside the orifice and liquid jet breakup outside the transparent slit nozzle using high-speed microphotography. Based on the digital micro-image data, a correlation analysis between the bubble formation inside and the superheated liquid jet outside the nozzle exit will be implemented, for which a parameter representing the bubble burst intensity is proposed. It will be proven that bubble burst intensity parameter is the main factor dominating the breakup of superheated liquid jet. This correlation reveals the breakup mechanism of superheated liquid jet.

2. Experimental apparatus and technique

For quantitatively observing the physical processes of superheated liquid jet inside and the breakup characteristics outside nozzle when it undergoes big pressure drop, an optically-accessible nozzle and a micro-imaging system are required. The transparent nozzle must also be adequately thin so that the bubbles formed inside will not overlap each other in at least one of the view directions, i.e., with 2 dimensional feature. The micro-imaging system must be capable of clear simultaneous observation of individual bubble inside and individual droplets outside nozzle.

2.1. Optically-transparent slit nozzle

The newly-developed transparent slit nozzle, shown in Fig. 1, consists of two clamps (glass window holders), a precision gasket, two optical glasses (quartz) windows inside the clamps, two expansion optical glasses (quartz) windows outside the clamps and a few sealing sheets. The two inner surfaces of the quartz windows inside the clamps and the precision gasket formed an optically-transparent slit flow channel. A detailed description of transparent nozzle can be referred to Ref. [18]. Over the previous transparent nozzles of cylindrical holes [14,15,20], this slit transparent nozzle has three advantages: (1) much easier to focus exactly on the 2-D flow which contains 40 μm thickness layer of