A Multi-Threshold Image Process for Analyzing Transient Characteristics of A Flash-Boiling Spray

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Abstract
This work is to investigate the flash-boiling spray behaviors of Dimethyl ether using image processing and atomization performance analysis of the spray injected through a plain-orifice nozzle under atmospheric conditions. The spray images were analyzed at various times after the start of actuation using a visualization system consisting of a high speed digital camera and an Nd-YLF laser as the illumination source. The light intensity level implies the local relative density level of droplets in the spray. From the spray images, spray characteristics such as the transient continuous cone angle, transient contour plots at various light intensity levels were analyzed using a multi-threshold image process. The results were compared with the turbulent round jet of diesel and showed that the relative concentration distribution and continuous cone angles of the spray at the start, development and end of the atomization. The light intensity levels at the outer and end regions of the sprays were lower compared to those at the center regions, because the droplets at the outer and end regions were well-atomized by the volatile nature of the material and the friction between the injected droplets and the surrounding gas. The continuous spray cone angle was defined to represent the flash-boiling spray, which showed a significant variation in the expansion region of the spray.

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Introduction

As means of reducing or eliminating the dependency on petroleum, it is proposed to use fuels derived from natural gas, biomass, or coal. Dimethyl ether (DME) is a potential energy to replace petroleum-based fuels\(^\text{[1]}\). The middle-east part of China was blanketed in a thick haze in these years, which was mainly cause by the emissions from vehicles. DME has been considered as a clean, efficient alternative fuel for use in a diesel engine, with almost smoke-free combustion \(^\text{[2-5]}\). Sorenson states in his work\(^\text{[2]}\) that DME performs well in combustion and emissions, however, due to its physical properties it is required to change if it is to be used in traditional diesel fuel injection systems. It has indicated that the most challenging aspects of DME operation are related to its physical properties, and not to its combustion behavior\(^\text{[3]}\).

Suh et al. (2006)\(^\text{[6]}\) analyzed spray development, spray tip penetration, spray cone angle of DME injected through a common-rail injection system in a diesel engine. Kim et al. (2009) studied the macroscopic spray behaviors of DME at an ambient pressure of 0.1MPa and an ambient temperature of 293 K, and a flash-boiling phenomenon was observed. Xiao et al. (2009)\(^\text{[7]}\) measured the spray velocity vector and droplet size field of (DME) blended fuels by phase doppler anemometry (PDA). Kim et al. (2010) analyzed the DME spray characteristics according to the light intensity level of the images. However, the quantitative analysis of the relative concentration distribution in the spray has not been mentioned.

For the reasons of health and safety, we replace DME with HFC 134a to characterize the flash-boiling spray. Evaporation and boiling are the main thermodynamics processes that govern phase change during flash-boiling atomization\(^\text{[8]}\). Figure 1 shows the variations of the saturated vapour pressure of DME and HFC 134a are similar, which indicates that it is feasible to replace DME with HFC 134a. This work is to investigate the flash-boiling spray behaviors of HFC 134a spray injected through a plain-orifice nozzle under atmospheric conditions. The spray images were analyzed at various times after the start of actuation using a visualization system consisting of a high speed digital camera and an Nd-YLF laser as the illumination source. The light intensity level implies the local relative density level of droplets in the spray. Spray characteristics such as the transient continuous cone angle, transient contour plots of HFC 134a at various light intensity levels were analyzed using a multi-threshold image process\(^\text{[9]}\), and the results are compared with those of diesel\(^\text{[10]}\).

Experimental Setup and Methodology

This section introduces a simple spray visualization system, presents a multi-threshold method to analyze the spray images and proposes to use continuous cone angle to characterize the flash-boiling spray.

Spray visualization system setup

A schematic layout of the experimental apparatus to visualize the flash-boiling spray is shown in Figure 2. The system consists of a pressure vessel for storage of HFC 134a, an observation chamber, a plain-orifice (single-hole) atomizer with the diameter of 0.2mm, and a solenoid electric valve (ASCO SC B223A125) which is controlled by a data acquisition (DAQ) card of the PC. Sprays were imaged using laser-based high-speed visualization to reveal the atomization. The system comprised an Nd-YLF (yttrium lithium fluoride) laser (Darwin-Duo-527-40-M) as the illumination source in conjunction with a FASTCAM- high-speed digital camera for image recording. The laser provides a pulsed light source with a frequency of 0.1-10kHz. The camera provided 1024×1024 pixel resolution images and was operated with a SIGMA (105mm, F/2.8) lens to image the global spray development.

Multi-threshold method for spray image analysis

A raw image of a HFC 134a spray is presented in Figure 3(a), and the distribution of its local relative density is illustrated in Figure 3(b). The amount of the HFC 134a spray within each relative concentration is proportional to the pixels with the corresponding light intensity of the image. It can easily be seen that the spray becomes sparse from the core to the boundary, because the droplets at the outer and end regions were well-atomized by the volatile nature of the material and the friction between the injected droplets and the surrounding gas. Here, the relative concentration is represented by the normalized light intensity of the image from 0 to 1. The amount of the spray within each relative concentration is quantified by the pixel area (A) of the corresponding light intensity. The multi-threshold method proposed by Ju et al. (2012)\(^\text{[10]}\) is implemented here to analyze the spray images.

Transient continuous cone angles of a spray

The cone angle is often defined as the angle formed by two straight lines drawn from the discharge orifice to cut the spray contours at some specified distance from the virtual origin of the nozzle\(^\text{[11]}\). In order to describe the expansion region of a flash-boiling spray, Ju et al. (2012)\(^\text{[12]}\) used the cone angles at two positions to characterize it. With the purpose to quantify the flash-boiling spray, especially for the expansion region, it is proposed here to implement continuous cone angles.
which are defined from the virtual origin along the axis-x to characterize the spray, as shown in Figure 3 where three representative cone angles of the spray are illustrated at the start, expansion, and entrainment regions of the atomization. All the continuous cone angles presented in this paper are half angles, such as $\theta_1$, $\theta_{10}$, $\theta_n$ in Figure 4.

Results and Discussion

There are two parts to the results. First we compare the external atomization characteristics of a flash-boiling spray and a normal turbulent round jet of a non-volatile component. The visualizations of the flash-boiling spray are generated from HFC 134a by the rig presented in Figure 2, where the pressure and the temperature in the observation chamber are 0.1MPa and 297K respectively. The images of the turbulent round jet was reported are from the work of Xiao et al. (2009)[10], where the test fuel (diesel) was actuated under an injection pressure of 7.5MPa through a plain-orifice nozzle, into an observation chamber, with an ambient pressure of 0.1MPa and an ambient temperature of 293 K.

Secondly, we focus on the expansion region of the flash-boiling spray to find the variation of the spray structure for one pulsation of the actuation.

 Result part A: comparison of a flash-boiling spray and a turbulent round jet

Three sets of images are presented in Figure 5 to show the spray structure of HFC 134a and diesel at the start, development and end of the actuation. It is obvious that the flash-boiling phenomenon of HFC 134a is violent, while the diesel is “quiet”. Quantitative variations of the spray characteristics of HFC 134a and diesel at transient time points are illustrated in Figure 6. At the start of the actuation, the temperature of HFC 134a dropped rapidly due to the consumption of latent heat energy for the phase change. It restrained the violent expansion phenomena of the flash-boiling due to the lower saturated vapor pressure of the HFA 134a with lower temperature. Therefore, the variations of the continuous cone angle are similar for both HFC 134a and diesel at the start of the actuation. The amount of HFC 134a within each relative concentration is uniformly distributed in the spray. However, for the spray of diesel at the start of the actuation, there is a peak of $\text{A/A}_{0.55}$ around the relative concentration of 0.9, which indicates the dense fluid dominates the spray. During the development period of the actuation, the continuous cone angles of HFC 134a are nearly the twice of those of diesel. It is caused by the volatile property of HFC 134a to expand the spray from the core to the boundary. The continuous cone angles of the diesel almost stayed constant along the jet, which follows the trends of the “self-similar" property of a turbulent round jet described in Pope (2000)[13]. However, the volatile property made the continuous cone angles of HFC 134a fluctuate severely. During the development period, the HFC 134a at the boundary of the spray evaporated rapidly into the ambient, the remaining dense fluid slowed the evaporation rate of HFC 134a and accumulated in the core of the spray to from another denser region. The $\text{A/A}_{0.55}$ of HFC 134a during the development period was lower than that at the end of actuation when the spray had more time for evaporation. In addition, the diesel within the relative concentration of 0.7 dominated the development period and it was 0.85 at the end of the actuation. It indicates that the spray was sparser during the develop period of the actuation.

Result part B: the characteristics of the HFC 134a jet in the expansion region.

Domnick et al. (1995)[14] concluded that the periodic behavior (pulsation) is the result of the bubble growth process which only depends on the evaporation process at and the location of bubble creation. Figure 7 shows a sequential pulsation of the flash-boiling HFC 134a in the expansion region. The continuous cone angle varies sharply from the start to the end of pulsation. For the start of the pulse [ER (1)], the continuous cone angles stayed around 18° along the axis-x. ER (2): the continuous cone angle decreased from 30° to 10° at x=5~20mm, which indicated the pulse formation. ER (3): the continuous cone angles stayed around 23° at x=5~20mm, which indicated the pulse entrainment. ER (4): the continuous cone angles returned to the original state around 18°.

Conclusion

With the purpose to investigate the flash-boiling spray behaviors of flash-boiling atomization, image processing was implemented to analyze the spray injected through a plain-orifice nozzle at an ambient pressure of 0.1MPa and an ambient temperature of 293 K. The light intensity level of the image represents the local relative concentration of droplets in the spray. Spray characteristics such as the transient continuous cone angles, relative concentration distributions of HFC 134a (a replacement of dimethyl ether) and diesel were compared using the multi-threshold image process. The results showed those characters of the sprays at the start, development and end of the atomization. At the start of the actuation, the variations of the flash-boiling spray and the non-flash spray are similar, because there was a rapid pressure drop of the flash-boiling spray. During the development period, the continuous cone angles of
HFC 134a are twice of those of the diesel, due to the volatile property of HFC 134a to expand the spray. Different from the diesel, the amount of HFC 134a within each relative concentration is uniformly distributed in the spray, due to the rapid evaporation of HFC 134a into the ambient. The cone angles of the flash-boiling spray varied significantly at the expansion region of one pulsation.

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References

Figure 1. Definition of transient continuous cone angle of a spray at a certain time point of actuation.

Figure 2. Schematic layout of the spray visualization facility

Figure 3. (a) A raw image of the interested HFC 134a spray; (b) Relative concentration distribution of the HFC 134a spray
Figure 4. Definition of transient continuous cone angle (half) of a flash-boiling spray at a certain time point of actuation.

Figure 5. External spray visualizations of HFC 134a (top row) and diesel\(^{[10]}\) (bottom row) at the start, development and end of the actuation.
Figure 6. Quantitative variations of continuous cone angles and relative concentration distribution of the sprays in Figure 5. Left column: continuous cone angle; Right column: the amount of the spray within different relative concentrations ($A$: the pixel area of the spray within the corresponding relative concentration; $A_{0.55}$: the total pixel area of the spray within the relative concentration higher than 0.55.)
Figure 7. (a) Sequential visualizations [from ER (1) to ER (4)] of the HFC 134a jet in the expansion region (ER) recorded at a frequency of 5HZ. (b) Variations of continuous cone angles for the pulsation in Figure 7(a).