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Study of spray collapse phenomenon at flash boiling conditions using simultaneous front and side view imaging

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ABSTRACT

Flash boiling has become a topic of interest to researchers due to its potential of achieving good fuel atomization and negative influence on GDI engine emissions when spray collapses and spray-wall impingement exists. Under flash boiling conditions, the accompanying spray collapse phenomenon and plume interaction are not clearly elucidated. Simultaneous side view diffused back illumination (DBI) and front view Mie-scattering were implemented in this work to capture transient plume to plume interaction of iso-octane fuel spray from a 10 hole gasoline direct injection (GDI) injector at flash boiling conditions. Fuel temperature and ambient gas pressure were varied in a wide range to cover collapse, transitional and non-flashing regimes. Two new criteria named 'spray collapse percentage', defined based on the front view Mie-scattering technique and 'optical thickness' based on the side view DBI technique, were developed for classification of different spray regimes. These two criteria distinguish the collapsing and transitional regimes well from the non-collapsing regime compared to other criteria used in the literature.

1. Introduction

In gasoline engines, flash boiling is a common phenomenon [1] that liquid fuel boils suddenly when it goes through a fast depressurization process to a pressure level lower than its saturated vapor pressure [2]. Flash boiling has the advantage of achieving proper atomization at a lower cost compared with increasing fuel injection pressure [3]. Droplet size has been reported [4,5] to decrease when flash boiling occurs. But heavy flash boiling, which should be avoided, would cause spray collapse [3,5], wall impingement [6] and reduces internal nozzle fuel flow rate [7]. Wang et al. [8] studied the closely coupled split injection strategy at flash boiling condition and concluded that it can shorten the spray penetration length and reduce the potential of spray impingement. Either to utilize or to prevent flash boiling, a better understanding of this complex process is required. Flash boiling and its accompanying spray collapse phenomenon have become an exciting topic among researchers recently.

Three commonly used variables to control the flash boiling intensity are the fuel temperature, ambient gas pressure, and saturation vapor pressure of the fuel. To study the influence of these factors on flash boiling and give general criteria, R_p (ratio of ambient gas pressure to saturation vapor pressure) and ΔT (superheat degree) are the two mainly used parameters [9–12]:

$$R_p = P_a/P_s \tag{1}$$

$$\Delta T = T_f - T_s \tag{2}$$

where P_s is the saturation pressure at fuel temperature T_f, P_a is the ambient gas pressure, and T_s is the saturation temperature of the fuel at the ambient gas pressure P_a.

Different indicators have been used to distinguish three different regimes including flare flash regime, transitional regime, and non-flashing regime. Some researchers have studied flash boiling using an 8-hole GDI injector with 60° spray angle [3,9,13]. In their studies, penetration length, plume width, vapor quantity, droplet size and plume to plume distance (the two opposite plumes on the central cross section) were used as indicators to differentiate the regimes based on R_p. They classified the regimes as flare flashing regime ($R_p < 0.3$), the transitional regime ($0.3 < R_p < 1$) and the non-flashing regime ($R_p > 1$). Lacey et al.[10] studied propane flashing sprays using ECN spray G injector and proposed a new indicator D_n, with nozzle geometry taken into consideration, and generalized the flashing criteria to be

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$D_n \geqslant 1$, $d_t/d_{collapse} < D_n < 1$, $D_n \leqslant d_t/d_{collapse}$ from collapse regime to non-flash regime.

Spray collapse can happen both at non-flash boiling condition, and flash boiling condition for multi-hole GDI sprays. Guo et al. [14] explained them as jet induced collapse and condensation induced collapse, respectively. In both cases, plume to plume interaction is a vital precedent phenomenon. Wang et al. [15] studied the near nozzle single hole spray pattern under flash boiling conditions and observed increased cone angle and spray area when flash boiling occurs. Wu et al. [16] studied 1-hole, 2-holes, and 6-holes sprays at near nozzle region from flare flash to sub-cooled conditions. It was revealed that the single plume swells and multi-plume interactions occur when flash boiling phenomenon takes place. Heldmann et al. [17] studied the separate single plume of the 5-hole injector and interaction between single plumes from two different 5-hole injectors. These above mentioned single plume and multi-plume interaction studies help to understand the spray pattern change in a multi-hole GDI injector under flash boiling conditions. Investigation of plume interaction is mandatory for better understanding of the complex collapse process.

Most reported experimental work on spray collapse phenomenon were through side view and volume illumination (backlight imaging) [11,18–24], Mie-scattering [10,25,26] or schlieren [10,12,22,25]), which has the advantage of capturing transient spray included cone angle or spray width and reporting directly whether spray collapse happens or not. But it inevitably has the drawback of overlapping of plumes and is not capable of illuminating inner structure of spray and demonstrating plume to plume interaction. It's challenging to explain that merge of plumes on the image is due to plume interactions or due to overlapping along the line of sight, especially when the number of holes is relatively high.

Few works [9,13,18,27] have been reported with laser sheet illumination to show the cross-sectional view of the spray (either through central plane showing spray inner structure or perpendicular to injector axis showing plumes cross section at a fixed distance from the nozzle). However, a very recent publication has reported laser sheet imaging for a 2-hole nozzle [28] showing plume to plume interaction. Again the setback of these laser sheet based imaging techniques is that it is very challenging to capture the interaction between adjacent plumes for a real multi-hole GDI injector.

For multi-hole injector sprays, Mie-scattering images taken from the front view (ahead of spray cone) can be an attractive choice to visualize the transition from segregated plumes to connected plumes or collapsed plumes, without the issue of overlapping between plumes. While minimal work has been done with this method on plume to plume interaction under spray collapsing conditions and particularly direct simultaneous comparison between side view and front view images, have not been done so far for flashing sprays. Sphicas et al. [21] have implemented front view Mie-scattering in the study of spray collapse at non-flashing conditions for ECN spray-G. Mojtabi [29] studied plume to plume interaction under flash boiling conditions on GDI injectors solely from front view. Gutierrez [30] studied ECN spray-G morphology in a single cylinder engine under flash boiling conditions using front view Mie-scattering.

Considering minimal work that has been done using front view imaging for plume interaction studies, this work bridges the gap by visualizing the spray from both the side view (DBI) and the front view (Mie-scattering) simultaneously with two high-speed cameras. It gives a clear image showing how the transient plume to plume interaction is related to the collapsing phenomenon usually observed from the side. Two new criteria based on front view Mie-scattering and side view DBI images were proposed to segregate spray behavior into strong collapse regime, transitional regime, and non-flashing regime. These criteria were compared with widely used conventional indicators based on liquid penetration length and spray width.

2. Experimental setup and diagnostics

Experiments were carried out in KAUST Spray Lab. Fig. 1(a) shows the setup alignment for simultaneous DBI and Mie-scattering imaging techniques. The chamber used in this study is capable of handling gas pressure from the sub-atmospheric condition to 10 bar absolute pressure. The large chamber volume of 27 liters benefits the study of spray at low ambient gas density conditions, like flash boiling, without encountering the problem of wall interactions. A 10-hole GDI injector was mounted horizontally on one side, and optical windows on the other three sides allow the possibility to run diffused back illumination (DBI) and Mie-scattering at the same time. Two high-speed cameras (Photron SA-X2) were mounted facing towards the injector tip and from side for Mie-scattering and DBI imaging, respectively. A high power LED was used in a high-speed repetitive pulse mode to ensure sufficient Mie-scattering intensity. At the same time, optimized aperture and neutral density (ND) filter were used for DBI imaging to avoid saturation of the camera. Two cameras were synchronized at 40 kfps frame rate to capture the same spray from different perspectives at a sufficiently high temporal resolution to obtain enough information of flashing sprays. Resolution of DBI and Mie-scattering images are 0.22 mm/pixel (512 × 512) and 0.28 mm/pixel (512 × 552), respectively.

An Aramco customized high-pressure multi-hole injector was studied in this work. The injector was fixed in a custom-made fixture, which has an internal channel connected with a heat exchanger, shown in Fig. 1(b). The internal volume of the fixture covers injector head thus that fuel temperature can be controlled. Fig. 1 (c) shows the orientation of 10 nozzle holes, each of diameter ϕ 165 μm. National Instruments Direct Injector Driver System (NI DIDS-2003) was used to drive the injector. The injector excitation duration was fixed at 1 ms throughout this study.

3. Experimental conditions

Table 1 shows the experimental conditions used for this study. In this work, a single component fuel iso-octane was studied as a surrogate of complex multi-component gasoline fuels. The injection pressure was fixed at 100 bar and excitation duration of 1 ms. Ambient gas temperature was kept at room temperature. Fuel temperature and ambient gas pressure are the two variables examined in this study. Fuel temperature was varied from 60 °C to 120 °C. Since R_p is of more interest rather than the absolute ambient gas pressure, R_p was varied in 15 levels (0.05–1.4) for each fuel temperature. As saturation vapor pressure varies with fuel temperature, the absolute ambient gas pressure was determined based on R_p and saturation vapor pressure accordingly as shown in Table 2. Iso-octane saturation vapor pressure was obtained using Antoine's equation (Eq. 3) from the NIST website [31].

$$\log_{10}(P) = A - \frac{B}{T + C} \tag{3}$$

where P is the vapor pressure in bar and T is the fuel temperature in K.

According to Xu et al. [3], R_p of 1 is the starting point of the transitional regime for their injector and fuel combination. Therefore in this study, R_p data points are refined below 1 and further refined when $R_p \leqslant 0.3$ to capture the change in plume interactions.

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