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Experimental characterization of closely coupled split isooctane sprays under flash boiling conditions

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HIGHLIGHTS

- The impact of flash boiling on primary breakup characteristics were probed.
- Primary breakup characteristics of split isooctane spray were investigated.
- The effect of flash boiling on interaction between split injections was studied.

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ABSTRACT

The characteristics of isooctane spray in the near field and far field were experimentally studied under various flash boiling conditions representing both low load and high load hot engine operation conditions. Closely coupled split injection strategy was also employed to study the influence of flash boiling on the primary breakup of split injections and the interaction between split injections. It was found that flash boiling considerably boosted the spray atomization, especially during the end of injection stage when a large amount of liquid fuel with low speed was observed. The interaction between split injections in liquid phase was significantly weakened under flash boiling condition due to the enhanced atomization but the interaction in gaseous phase was boosted because of the resultant quicker evaporation. The effect of dwell interval on the spray behavior under flash boiling condition was profound, causing significant variation for the delivered fuel mass and spray characteristics.

1. Introduction

Quick reduction of pressure for the pressurized bubbly mixture when discharged through an orifice leads to the expansion and explosion of the bubbles and the resultant disintegration of the liquid [1]. The bubbles in the liquid can be obtained from the intense nucleation caused by the superheating of liquid and flash boiling is produced when the pressure of the pressurized mixture decreases [1]. Flash boiling generally leads to the phase transfer from liquid phase to gas phase with the existence of both phases [2]. The increase of liquid temperature and the depressurization of the ambient condition for the liquid are two common ways to achieve flash boiling [3]. For modern direct injection gasoline engine (GDI), the two conditions, namely high temperature and depressurization, are widely available in the intake stroke when the fuel injection is carried out. The cylinder head metal temperature is generally more than 100 °C when engine is fully warm and the in-cylinder pressure is sub atmospheric at low load and part load [4]. The flash boiling is to ensue for gasoline spray under such conditions due to the considerably low vapor pressure of the gasoline. Under flash boiling, the plumes for commercial gasoline injector generally move towards the center of the spray, changing the designed spray pattern.

Some studies on the spray characteristics under flash boiling conditions with single injection strategy are available [4–7]. Flash boiling is reported to be beneficial to spray collapse and dispersion due to the formation, growth and explosion of the vapor bubbles [5,8]. Due to the improved atomization, small droplets and homogeneous air/fuel mixture are available at the spark timing. In [9], isooctane showed a 30% reduction of Sauter mean diameter (SMD) when temperature increased from 90 to 120 °C but kept at 15 μm when temperature was lower than 90 under the back pressure of 0.5 bar. By contrast, gasoline presented a nearly linear reduction from 15 to 9 μm as temperature rose from 20 to 90 °C. In Zhao's study [6], SMD was reduced by 50% when fuel temperature increased from 20 to 90 °C with rail pressure and ambient pressure of 11 MPa and 0.1 MPa respectively. The appearance of

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the flash boiling phenomenon was believed to be responsible for such obvious reduction. It is also expected that lower HC and soot particle emissions can be realized because of the improved spray breakup and atomization under flash boiling condition. In [10], it was reported that this favorable condition can effectively reduce the plume velocity and alleviate or eliminate the fuel impingement, resulting an obvious reduction of emissions.

One widely reported problem for gasoline direct injection engine is the formation of the deposit in the employed injector nozzle [11]. The fouled injector generally leads to higher spray penetration and poorer atomization, causing higher probability for fuel impingement and fire pool [11,12]. Emissions including HC, CO and soot consequently increase. To avoid the undesirable impingement and to make good use of the flash boiling effect, closely coupled split injection strategy appears to be promising. When delivering the same amount of fuel, the application of the closely coupled split injection can potentially boost the atomization and reduce the spray penetration compared with single injection. In [4], the influence of multiple-injection strategy on the spray and combustion characteristics was investigated under flash boiling condition. The intake manifold pressure varied between 0.5 and 1 bar while the coolant temperature ranged from 20 °C to 90 °C. Single and triple split-injection strategies were employed. For triple injection (0.3 ms + 0.3 ms + 0.32 ms), the start timings were 60, 70 and 80 crank angles after top dead center (ATDC) with the engine speed of 1500 RPM. The injection timing for the single injection (0.9 ms) was 80 crank angles ATDC. It was concluded that the optimized number of split injections and timings were effective to boost fuel mixing and flame propagation, avoid impingement and reduce gaseous emissions and soot particles.

The gasoline spray primary breakup in the near field under flash boiling condition is still not well understood. The spray behavior with closely coupled split-injection strategy under this typical condition is not available. The effect of flash boiling on the interaction between split injections also requires more studies. Aim to obtain a better understanding on these questions, the spray characteristics were experimentally investigated under various flash boiling conditions by employing a long distance microscope and an ultra-high speed camera. To avoid the interference from other plumes for multiple-hole injector, a single-hole solenoid diesel injector together with a modern diesel common rail injection system was employed. The employment of diesel injection system also allowed the tests to be carried out under high injection pressure.

2. Experimental setup

As shown in Fig. 1, the whole system included two parts, namely, the imaging system and the ambient condition control system. The ambient condition control system consisted a high pressure vessel with 2 inline glass windows (diameter of 10 cm), 8 heaters complete with a PID controller and a vacuum pump. The 8 heaters were fixed at the 8 corners of the vessel. The PID controller allowed the vessel temperature to vary between 20 °C and 100 °C. Meanwhile, the vacuum pump was used to vary the ambient pressure from 0.2 to 1 bar and a pressure gauge was adopted to monitor the ambient pressure. The employed injector was a cylindrical single-hole solenoid diesel injector with the nozzle diameter of 0.18 mm. This single-hole injector enabled the focusing work of the highly sensitive long distance microscope to be carried out and the potential interference from other plumes was avoided. A common rail injection system was adopted so that the tests can be carried out under high fuel pressure. It should be noted that the injector was installed on the metal plate of the vessel and it was heated up when heating the vessel. The fuel temperature is correspondingly controlled through the heating system. A thermocouple which was used to measure the vessel metal temperature was installed close to the injector. It took around 2 h to heat the vessel to 100 °C and the heat capacity of the vessel is sufficiently high to maintain the vessel temperature. Although some temperature difference between the vessel metal and fuel is expected, it is believed that the measured metal temperature can well represent the fuel temperature. In addition, when carrying out the tests, the injection rate was two injections per minute to allow the fuel temperature to recover. To minimize the effect of ambient temperature on the spray behavior, the needle valve for air inlet was kept partially open so that the air kept flowing during the test (vacuum pump kept running during the test to achieve the desired back pressure). The maximum ambient air temperature increase (measured at the outlet of the vessel) was approximate 11 °C and this small ambient temperature variation was ignored. The spray behavior is thought to be independent on such small temperature increase from 20 °C to around 31 °C and the ambient temperature was treated as 20 °C for all tests. In addition, the near nozzle primary breakup was focused in this study and the effects of ambient temperature can be ignored because the time for the spray to pass the view field is very short.

The diameter of the employed single hole injector is 0.18 mm with L/D of 4. It is a cylindrical hole injector.

The imaging system consisted of an ultra-high speed Shimadzu HPV2 camera complete with a highly resolved long distance microscope (QM 100) and the back-lighting system (a convex lens and a 500-Watt xenon lamp). Up to 1 million fps of ultra-high frame speed was used to capture the development of spray at microscopic level. This frame speed gave 1 microsecond interval between two adjacent images. The resolution of the camera was set to 312 × 260 pixel^2. More details about the experimental setup can be found in [13,14]. The working distance for the employed long distance microscope was set to 18 cm and this gave a 1.8 × 1.46 mm^2 view field. The resultant resolution was 5.7 μm per pixel. To obtain favorable illumination for the view field, the aforementioned convex lens was employed to focus the light from the lamp at the injector tip. When carrying out the high speed imaging, the long distance microscope was replaced with a 105 Nikon lens and the convex lens was not used.

3. Test fuel and conditions

The employed fuel in the present study is isooctane which represents a quite large part of the commercial gasoline. The low kinematic viscosity (0.72 mm^2/s @ 40 °C) and surface tension (18.77 × 10^{-3} kg/s^2 @ 40 °C) are beneficial to the spray breakup and dispersion [15,16]. The low vapor pressure presented in Fig. 2 suggests that increasing temperature and lowing back pressure (lower than the vapor pressure) enable the liquid fuel to transfer into gas phase quite easily.

The injection pressure was set to 400 bars for all the tests. Four ambient conditions, namely points A, B, C and D, were employed to investigate the influence of flashing boiling condition on the spray collapse and dispersion. At test point A, the low temperature (20 °C) and high back pressure (1 bar) lead to non-flash boiling condition. Point B where the fuel temperature was 100 °C with back pressure of 1 bar was at the boundary of flash boiling. This is referred to marginal flash boiling condition. Point C showed quite strong flash boiling when the fuel temperature was set to 100 °C and the back pressure was set to 0.5 bar. This was called medium flash boiling. When the ambient pressure further decreased to 0.2, flash boiling was very strong, as point D showed. The details of the conditions are shown in Table 1. To quantify the strength of flash boiling, the flash boiling strength is calculated by Eq. (1) [17].