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Microscopic and macroscopic characterization of spray impingement under flash boiling conditions with the application of split injection strategy

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ABSTRACT

Microscopic and macroscopic impingement characteristics of a single jet were investigated under various flash boiling conditions. The influences of split injection strategy and the related interaction between split injections were studied. The fuel concentration distribution during the impingement process was also quantified. It was found that non-flash boiling condition lead to large secondary droplets and ligaments, resulting in a large amount of liquid fuel deposited on the impact surface. The boosted flash boiling could effectively reduce the sizes of primary droplets and secondary droplets and the resultant deposited fuel. The employment of split injection strategy could further decrease the deposited fuel. The second split injection built up the fuel film more quickly than the first injection due to the existence of the built fuel film by the first injection, however, increasing flash boiling strength decreased the building-up rate by improving dispersion and evaporation. In addition, the concentration of the deposited fuel on the surface could effectively be reduced by enhanced flash boiling and the lifetime of dense fuel was shortened by increasing dwell interval between split injections.

1. Introduction

Spray impingement is a hot topic for GDI engines since the combustible fuel mixture preparation, combustion performance and emissions are adversely affected [1–4]. The lubrication characteristics and lubricant quality can also be influenced if the impinged fuel mixes with the engine oil. The spray injection event is generally carried out in the intake stroke where the low in-cylinder pressure increases the overall spray penetration and the possibility of impingement on liner wall or piston. In addition, the modern GDI injectors tend to suffer from the formation of deposit in the nozzle holes due to the exposure to the harsh working conditions [5]. The appearance of the deposit generally leads to poorer dispersion and prolonged penetration, increasing the overall penetration length and the mass of fuel deposited on the surfaces of combustion chamber [6]. It is therefore of great importance to investigate the impingement characteristics and the ways to alleviate or eliminate the adverse effects of spray impingement.

The impingement regimes and characteristics for single droplet are widely accessible in the literature [2,4,7]. The impact regimes and the droplet morphologies for single droplet have been deeply investigated in Ref. [2]. The boundary conditions and quantified dimensionless parameters for the impact regimes, for instance, critical Webber number and splash number, also have been studied under various conditions [2,8,9]. The most interesting boundary condition is the one for splash regime since this regime generally leads to small secondary droplets although some liquid fuel still deposits on the surface [4]. The effects of various factors, including the droplet velocity, size, viscosity, surface tension, topographies of the impact surface, and impact surface wettability on the impingement characteristics were also studied [2,4,10]. It was reported that high viscosity and surface tension constraint the breakup of the primary droplets and consequently increased the size of secondary droplets [10]. However, the high velocity thus high inertia of the primary droplets boosts the impingement quality. Besides, the disintegration of the primary droplets can also be promoted by rougher surface [11]. The temperature of impact surface is another parameter that can affect the impingement characteristics by heat transfer and the heat transfer is thought to alter the boundary conditions for various impingement regimes [4].

The above studies mainly focus on the behaviour of single droplet or a few droplets with controlled droplet properties. However, for real gasoline sprays, numerous droplets are involved and the impingement process is very dynamic due to continuous change of boundary conditions and the building-up of the fuel film. Furthermore, for a large proportion of GDI engine operation conditions, the high fuel

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temperature and the in-cylinder sub-atmospheric condition in the intake stroke generally result in the occurrence of flash boiling which can significantly alter the spray behaviour and the resultant impingement characteristics. How the impingement characteristics are affected by the flash boiling is still unknown. These questions need to be answered to provide useful information for the design and calibration of injection system. In addition, split injection strategy is reported to shorten the overall spray penetration [12,13] and its effectiveness to alleviate or eliminate the adverse effects of spray impingement need to be studied. In this study, the microscopic impingement characteristics in the near field are studied by employing a long distance microscope and an ultrahigh speed camera whereas the macroscopic characteristics are investigated by the application of high speed imaging technique. The effectiveness of the closely coupled split injection strategy is checked by quantifying the concentration of deposited fuel on the impact surface. This paper aims to explore the three aforementioned unknown questions, namely, the highly dynamic impingement characteristics, the influence of flash boiling condition and how the closely coupled split injection strategy affects the impingement characteristics.

2. Experimental setup

The employed test system consists of the impingement system, test condition control system, ultrahigh speed imaging system and fuel injection system, as shown in Fig. 1. The main component of the impingement system is the steel impact plate which is horizontally fixed at 40 mm below the injector tip and this impingement location is used for all the tests in the present study. The roughness of the steel plate is 6.3 μm (Ra). The test condition control system includes a high pressure vessel, 8 heating elements located at the corners of the vessel and a vacuum pump. The high pressure vessel has two inline glass windows which allow the visualization of the spray to be realized. The heating system is used to control the vessel temperature and the fuel temperature is correspondingly controlled by the heat conduction. The temperature feedback for the heating system is measured by a thermocouple which is installed on the metal of the vessel close to the injector. The high heat capacity of the vessel can sufficiently maintain the system and it requires up to 2 h to heat the system from 20 °C to 100 °C. This feedback temperature is treated as the fuel temperature although small difference between the real fuel temperature and the measured metal temperature can be expected. When carrying out the tests, the injection rate is set to one injection per minute to allow the fuel temperature to recover to the required one.

The flash boiling condition is created by heating the liquid fuel and depressurization of the ambient condition which is realized through a vacuum pump. The ambient air temperature was controlled at around 20 °C by keeping the vacuum pump running consistently during the tests. The air temperature increase after flowing through the vessel is round 11 °C when the vessel temperature is set to 100 °C. This small increase is ignored because of the insignificant effect on the spray evaporation. In addition, the impact metal plate is fixed in the vessel after the vessel is heated so that surface temperature of the impact plate can be kept as close as to 20 °C. It can be expected that the impact plate experience a small temperature increase due to the temperature increase of the ambient air (around 11 °C). However, this small temperature is ignored due to its marginal effects on the evaporation.

The used injector in the present study is a single hole gasoline injector with the nozzle diameter of 0.15 mm. The possible interference and interaction from other plumes are therefore not concerns in this study. The visualization system includes an ultrahigh speed camera (Shimadzu HPV2), a long distance microscope (QM 100) and the light source. To study the microscopic impingement characteristics and development of droplets, a frame speed of 500,000 fps is used to obtain high temporal resolution. The employment of the long distance microscope allows the view field of $1.4 \times 1.73\,mm^2$ just on the top of impact surface to be investigated and the constant camera resolution of 260×320 pixels^2 gives the spatial resolution of 5.4 μm/pixel for the images. A magnifying lens with the amplification of 2 is also employed. The working distance of the microscope is set to around 18 cm and this gives a field depth of approximate 32 μm. The specifications of the employed long distance microscope are presented in Table 1. For the macroscopic impingement characteristics, the frame speed is set to 63,000 fps and the long distance microscope is replaced with a 105 mm lens. In addition, the convex lens used to focus the light for microscopic imaging is not used and the direct backlighting is used for the high speed imaging.

3. Test fuel and conditions

Isooctane (ISO) whose physical properties have been well studied is used in the present study to investigate the impingement characteristics under various conditions. ISO is an important part of gasoline fuel and can represent the gasoline spray characteristics quite well. Some physical properties are shown in Table 2.

In this study, the variation of vapour pressure with increasing temperature is of great interest to show the phase of the fuel, as presented in Fig. 2. The region above the blue line denotes the liquid state of isooctane due to its high vapour pressure while the region below the

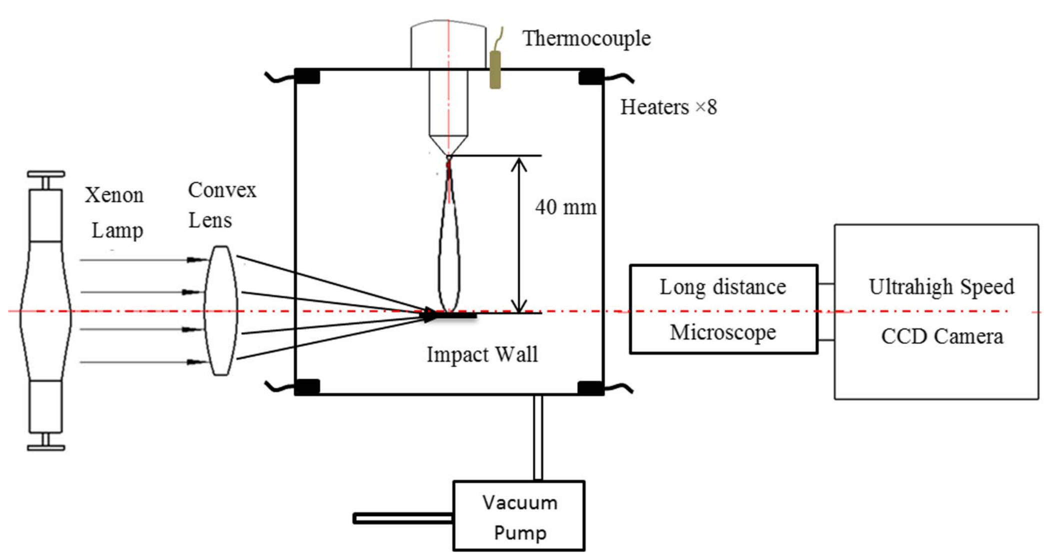

Fig. 1. Experimental setup.