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Microscopic level study on the spray impingement process and characteristics

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HIGHLIGHTS

- Droplets splash or fingering rebound in early stages due to high velocity.
- Droplets tend to stick in the end stage due to low velocity and existence of film.
- Higher surface temperature affects the initial stage but not steady and end stages.

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ABSTRACT

Spray impingement adversely affects fuel mixture preparation, combustion performance and emissions and more studies are required to understand this process. The isooctane spray impingement process and characteristics were investigated by ultrahigh speed imaging technique with the employment of highly spatially resolved long distance microscope. The effects of impact surface temperature were also studied. It was found that during the initial stage and steady stage of spray impingement, a large proportion of droplets splashed due to high velocity. The droplet size after impingement generally reduced because of the strong collision. For the end stage of impingement, droplets tended to stick on the impact surface and float on the fuel film due to the low droplet velocity and the existence of built liquid fuel film. It was also found that hot impact surface could only improve the impingement and reduced the film building-up rate in the initial stage. The steady stage and end stage of spray impingement were less affected by the variation in impact surface temperature.

1. Introduction

The spray impingement causes fundamental issues for IC engines by altering the fuel mixing, combustion and emissions [1,2]. If spray impingement occurs on the top of piston, the emissions due to unburn fuel are to increase [1–3]. The adverse effects of spray impingement for GDI engine are more obvious under cold start conditions where the evaporation is relatively poor due to low in-cylinder temperature. The formation of injector deposit deteriorates the influence of impingement due to the weakened atomization and prolonged penetration [4,5]. In addition, the engine oil will be brushed away and diluted if impingement occurs on the liner wall. This will change the lubrication characteristics and the resultant piston liner friction. The mixture of fuel and engine oil also results in the oil degradation when going through high temperature. The dynamics and characteristics of the impingement process consequently become hot topics for both academy and industry.

The studies on the fundamental impact characteristics of a single droplet and multi-droplets are widely available. Five impact regimes, namely, stick, spread, splash (including prompt splash, corona splash, receding breakup, partial rebound and finger breakup), rebound and fingering were identified [2,6]. When velocity is low, droplet would not breakup but stick on the surface, leading to the expanding and recoiling of the liquid lamella [2]. The increase of droplet velocity leads to disintegration of the periphery rim into 'fingers' and this process is governed by the impact surface roughness. Much higher velocity and inertia result in the instant disintegration of the droplet, termed 'prompt splash' [2]. Two regimes, namely, the 'splash' and 'stick-spread', are the common regimes reported for IC engines [3]. The characteristics of the secondary droplets after the impact were also investigated. It was reported that the diameter of the secondary droplet can be reduced by 90% compared with the original droplet size if splash occurs on

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cold surface and that the increase of surface tension raises the size of the secondary droplets [7,8]. For multiple-droplet impact, the impingement process is more complicated and the interaction between droplets results in different pictures compared with a single droplet impacting on surface [9]. The size of the secondary droplets from the sheet produced from interaction is larger than the size produced from single droplet impact [10,11].

The influences of various factors on the droplets impingement also have been deeply investigated. Moita et al. [3] studied the effect of temperatures, roughness and topographies of the impact surface with the variation of wettability, viscosity and topography. It was pointed out that rougher surface promotes the droplet disintegration and that the variation of the heat transfer mechanism could affect the impingement behaviours [3,12]. The increase of viscosity decreases the size of the crown and suppresses the secondary breakup of the droplets [3]. Some studies showed that hot surface results in a sudden rebound of droplets with low velocity after impingement due to the occurrence of vapour layer caused by the fuel evaporation at the periphery of the droplet [13,14]. In addition, the incident angle for the impact is believed to be important since it determines the momentum transfer. Results from Mundo [12] showed that the increase of incident angle causes the increase of reflection angle and vice versa.

The abovementioned studies mainly focused on single or a few droplets. However, for real dense spray impingement in IC engines, the impact characteristics are highly dynamic due to the variation of film thickness, impact surface temperature and the resultant boundary conditions for the impingement regimes [2]. So far, few studies have been carried out to show the interaction between primary droplets and film dynamics and how secondary droplets behave under the highly transient conditions. The dynamics of the fuel film building-up are still unknown. Aiming to answer these questions, both transient and steady impact characteristics, including droplet breakup and film building-up were investigated with the employment of ultrahigh speed CCD camera and long distance microscope. The effect of impact surface temperature was also investigated.

2. Impingement theory and experimental setup

2.1. Impingement theory

The impact regimes are classified based on the characteristics of the droplets before the collision and several dimensionless parameters are used to quantify the boundary conditions. Reynolds number is used to denote the effects of inertial force and can be calculated through Eq. (1).

$$Re = V * d_o / v \tag{1}$$

where V is the velocity, d_o is droplet diameter before the impact and v is viscosity

Weber number is employed to denote the breakup possibility of droplets.

$$We = \frac{\rho V^2 d_i}{\sigma} \tag{2}$$

where ρ is liquid density, d_i is critical diameter and σ is surface tension.

Moita et al. [3] defined the boundary for prompt splash and proposed the critical Weber number for the initiation of prompt splash, as shown in Equation (3).

$$We b_c = a \ln^b (d_0 / R_a) \tag{3}$$

where a and b are coefficients, d_0 is the droplet size and R_a is the roughness of the impact surface.

Mundo [12] also defined a critical parameter, K_c, for the boundary of splash, as presented in Equation (4).

$$K_c = Oh\ Re^{1.25} \tag{4}$$

where Oh is Ohnesorge number and can be calculated from Equation (5).

$$Oh = We^{1/2} / Re \tag{5}$$

These equations and the correspondingly calculated dimensionless numbers are used in the present study.

2.2. Experimental setup

The experimental setup mainly includes the illumination system, ultra-high speed camera together with the long distance microscope, injection system, the filter plate, the iron impact plate and heating system (not shown), as presented in Fig. 1. A 500 W xenon lamp was employed to provide strong light which was focused by a convex lens on the target area so that the droplets at the impact surface can be clearly observed. To capture the development of the droplets during the process of impingement, an ultrahigh speed camera was used and the frame speed was set to 0.5 million, giving an interval of 2 μs between two images. The camera resolution was fixed at 312 × 260 pixel^2. To capture the shape of the droplets clearly, a highly-spatially resolved long distance microscope (QM 100) was used to study the droplets behaviours in the region of 1.4 mm in height above the impact surface. The working distance of the microscope was set to 18 cm and the corresponding depth of field was around 32 μm. In addition, a magnifying lens with magnification coefficient of 2 was also used. Consequently, the resolution of the captured images is around 5.4 μm/pixel. More specifications about the imaging system can be found in [15,16] and Table 1.

A single hole gasoline injector with the nozzle diameter of 0.15 was used. The spray impingement occurred at 40 mm downstream of the injector and it can be expected that a large number of droplets will be seen at the collision point (the blue circle area shown in Fig. 1). The appearance of numerous droplets could significantly affect the observation of the impinging process. To obtain clear images for the droplets, a filter plate was therefore used to block most of the fuel at the periphery, only allowing part of the droplets in the plume centre to pass through and impact on the surface. The hole diameter in the filter plate was 2 mm, which is believed to be sufficiently big for the view field of 1.4 mm (height) and will not affect the droplet behaviours. In addition, before every test, the filter plate was cleaned and dried to make sure that there was no fuel film built in the hole which may affect the dynamics of the droplets. The filter plate was set to 30 mm downstream of the injector tip, giving a distance of 10 mm between the impinging plate and the filter plate. An impingement angle of 45° was employed for all tests. A heating system consisting of 8 heaters and a close loop controller was used to heat the impact surface according to the requirements of test conditions.

3. Test fuel and conditions

Isooctane, a frequently used surrogate liquid for gasoline, was used in the present study. The properties are shown in Table 2.

The tests were carried out under two conditions, as presented in Table 3. The cold surface condition was used as the reference and the hot surface condition was employed to study the effect of surface temperature. An injection pressure of 150 bars was used for all the tests. The roughness of the iron impact surface, Ra, is 6.3 μm. 15 repetitions were carried out for each test. The data of some figures (except the images and tables) shown in the present study are the