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Influence of deposit on spray behaviour under flash boiling condition with the application of closely coupled split injection strategy

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HIGHLIGHTS

- Deposit causes small cone angle and long penetration due to poor atomization.
- Deposit raises SMD by increasing droplet size and lowering breakup potential.
- Split injection strategy effectively lowers the impingement possibility.
- Split injection alleviates the adverse effect of deposit under flash boiling.

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ABSTRACT

The effects of deposit on the spray macroscopic characteristics and droplet behaviour under flash boiling condition were investigated through high speed imaging and Phase Doppler Particle Analyzer (PDPA) techniques. Closely coupled split injection strategy was tried to alleviate the negative effect of deposit on spray characteristics. It was found that with single injection strategy, deposit led to smaller cone angle and longer penetration due to poorer atomization and dispersion. Deposit also resulted in larger droplet size by introducing large droplets and lowering the potential of further breakup into small ones. When split injection strategy was employed under non-flash boiling condition, the effects of deposit of on the over-penetration and the resultant high potential of impingement were alleviated, while the negative effect of deposit on droplet size was enhanced. However, when split injection was used under strong flash boiling condition, the negative influence of deposit on the spray over-penetration was significantly alleviated and the negative impact on the droplet size was almost eliminated although reduced potential for large droplets to further break up was still found. The employment of optimal split injection strategy is believed to be important for the alleviation of the adverse effect of deposit on the spray characteristics and the emissions.

1. Introduction

The application of multi-hole injector for direct injection spark ignition engine to achieve spray guided control becomes increasingly welcomed. The direct injection system with multi-hole injector is more flexible to control the fuel injection and mixture preparation through the control of hole orientation and the resultant spray pattern [1,2]. Quicker engine respond and better drivability can also be achieved since fuel is directly injected into the cylinder rather than into the intake manifold. Apart from that, the cooling effect of direct injection increases the volumetric efficiency and reduces the tendency of knock. However, the ambient condition for GDI injector becomes harsher due to the high pressure and high temperature, resulting in the formation of deposit on the injector [3–5]. High temperature (higher than the 90% distillation temperature of fuel) causes the crack and pyrolysis of gasoline, introducing the deposit precursors which form deposit [3,5].

It is widely reported that the injector deposit substantially affects fuel mass delivered, spray morphology, engine performance and engine emissions [3,6–9]. Researchers pays increasing attention on the injector deposit due to the high tendency of the formation and the resultant baneful effects. By comparing the performance of three types of injectors, Preusser et al. [10] reported that the outward opening injector showed high resistance to the formation of deposit while the inward opening multi-hole injector was highly vulnerable to the deposit formation. In [3],

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up to 7.2% fuel mass reduction was found with fouled injector. In [9], it was pointed out that the DISI engine performance (drivability, fuel consumption and emissions) shows up to 90% correlation to the deposit of the injector. Generally, emissions increase when employing fouled injector [11,12]. In [11], the reduction of fuel flow rate due to deposit is up to 22% and the resultant increase of CO and HC is up to 190% and 30% respectively. Wang [13] studied the emission sensitivity when fouled injector was employed by adopting various fuels, including gasoline, ethanol and DMF. The results suggested that for gasoline fuelled engine, the fouled injector obviously increased the PM emissions [13]. Lindgren et al. [7] reported that deposit led to higher plume velocity and larger droplet size. The weakened spray atomization was believed to be the main reason for the considerable increase of HC. That is to say the long penetration length and poor atomization increased the tendency of fuel impingement (thereby HC, CO and particle emissions).

Injection event for DISI engine is generally performed in the intake stroke where hot sub-atmospheric condition, the so called flash boiling condition, is created [14]. The low gas density exerts marginal drag force on the spray plume and impingement is likely to ensue. The employment of fouled injector deteriorates the wall wet because of longer spray penetration caused by the poorer atomization and evaporation [14]. In this case, the closely coupled split injection becomes a good way to combat this problem. Pereira et al. [15] investigated the impact of multiple-injection strategy on SI engine emissions. Three-split injection strategy was tried under the engine speed of 1500 RPM. The result illustrated that the optimized split injection strategy is effective to decrease the emissions and soot particles by enhancing fuel mixture preparation and avoiding impingement. However, the studies on spray characteristics of closely coupled split injection under flash boiling condition are not available. The effect of injector deposit on the spray behaviour when split injection strategy is employed under flash boiling condition also requires to be investigated. In the present study, the high speed imaging and PDPA techniques were used to study the influence of deposit on spray characterises under flash boiling condition with the employment of split injection strategy.

2. Experimental setup

The spray macroscopic characteristics were investigated by high speed imaging technique with the application of a high speed camera (Phantom V12) complete with a 105 mm Nikon lens. The frame speed of the employed camera was set to 18,000 frames per second and the resultant interval between two subsequent images is approximate 55 μs. To sufficiently illuminate the spray, a 500 W exon lamp was used and positioned at the back of spray, as shown in Fig. 1(a). PDPA technique was employed to study droplet characteristics, including droplet velocity, droplet size and droplet size distribution. At shown in Fig. 1(b), a PC was employed to control the PDPA processor. The main parameters of PDPA are listed in Table 1.

An ECU was used to control the injection parameters and trigger both PDPA processor and the camera through a TTL signal. A high pressure vessel with the pressure limit of 7 bars was used to maintain the ambient condition. Four side windows with quartz glasses allowed the visualization of the spray and optical tests. The pressure in the vessel was controlled through a needle valve and a vacuum pump whereas the temperature was regulated by a heating system. 8 ha which were controlled by a controller with a PID close control loop were installed at the corners to heat the vessel when necessary.

Two geometrically identical 6-hole GDI injectors, one clean injector and one fouled injector, were employed in this study. The fouled injector went through 6 warmups and 30 h engine operation with the engine speed of 2000 rpm and load of 5 bar net IMEP. It then went through another 10 h dirty-up process with the engine speed of 1500 rpm and engine load of 4 bar IMEP. As presented in Fig. 2, the 3 sets of symmetric plumes (plumes 1–6) are oriented with the same inclination angles. Because of the symmetry of the 3 sets of plumes, the injectors were carefully oriented so that only three plumes can be seen, as presented in Fig. 2(b). This is to simplify the images for high speed imaging tests and image processing with in-house built Matlab code. This is very useful, especially for the case under strong flash boiling condition where the plumes are collapsed and deformed. For macroscopic characteristics, only spray morphology and the vertical penetration length in the vertical plane (Fig. 2(b)) are studied. For the penetration, the authors focused on the overall overall axial penetration of all plumes because the fuel impingement is more likely to happen in this direction under flash boiling condition where the plumes move forward. As presented in Fig. 2(b), the overall vertical pene-

Table 1
PDPA settings.

Wavelength	Scattering mode	Scattering angle	Beam diameter	Optic focus
514.5/488 nm	Refractive	70°	2.2	310 mm

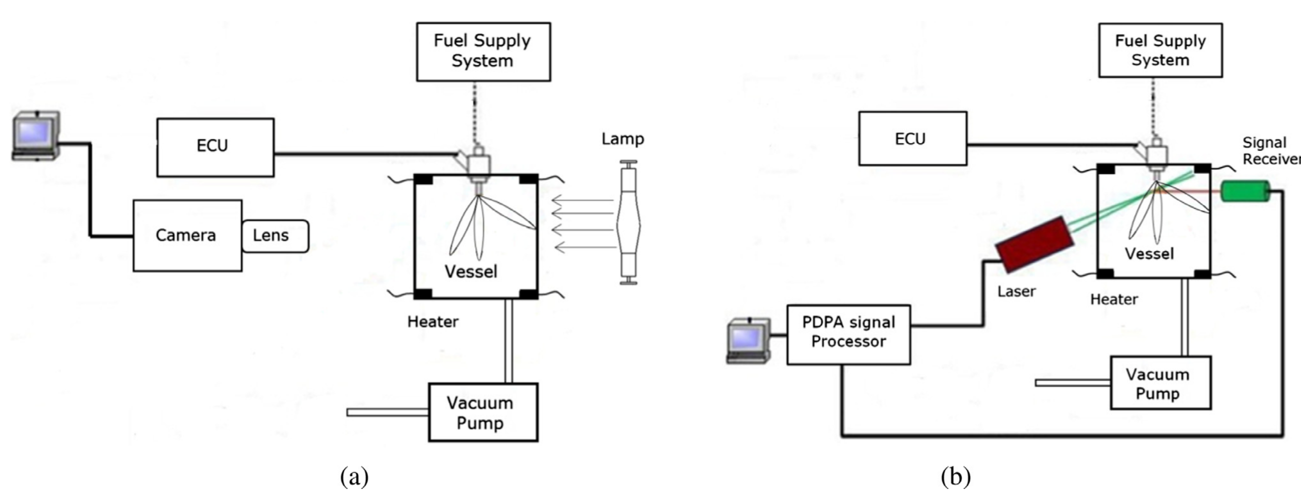

Fig. 1. The experimental setups for (a) high speed imaging test and (b) PDPA test.