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Investigation of deposit effect on multi-hole injector spray characteristics and air/fuel mixing process

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HIGHLIGHTS

- Effects of injector deposit on spray and air/fuel mixing process were investigated.
- Injector deposit altered the designed spray structure and droplet behaviours.
- Injector deposit led to severe fuel impingement in the late injection cases.
- Over rich zones found for the coked injector can lead to higher emissions.

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ABSTRACT

An optical-based experimental study of the injector deposit effect on a multi-hole GDI injector was performed first. After carefully calibrating the spray model with the experiment data, a three-dimensional computational fluid dynamics (CFD) simulation was then carried out to study the deposit effect on the air/fuel mixture preparation process in an optical research GDI engine. Six different injection timings were used for full-cycle simulations. The numerical engine condition was at stoichiometric ratio, 1200 rpm and 150 bar injection pressure. The experimental results showed that injector deposit would lead to lower fuel mass flow rate, with 5.4%, 5.7% and 6.1% loss at 50, 100 and 150 bar respectively. Injector deposit resulted in longer penetration length and the effect displayed hole to hole difference. The maximum increment was observed for the ignition jets with 11.6% at 150 bar. Injector deposit led to higher droplet velocity and larger droplet size and the difference increased with injection pressure. For the air/fuel mixing simulation, the injector deposit led to more fuel impingement on the piston and cylinder walls, as well as a lower mean equivalence ratio during late injection events. The distorted spray pattern led to higher fuel stratification level. In very late injection cases, the injector deposit led to a very lean mixture near the spark plug which could result in unstable engine performance; while the rich regions at the cylinder sides could result in higher emissions. Comparison of computed results with PLIF (planar laser induced fluorescence) images provided a satisfactory validation for the model.

1. Introduction

Gasoline direct-injection (GDI) engines provide benefits such as high efficiency, low fuel consumption and low emissions; however, injector deposit, otherwise known as the injector coking effect, is a serious issue for them [1]. The injector deposit could distort the carefully designed spray patterns which could lead to unstable combustion process and higher emissions. The situation is worse in GDI engines than in traditional port fuel injection (PFI) engines, due to their injectors being directly exposed to harsh in-cylinder conditions. Also, for traditional PFI engines, low levels of fuel rate loss and spray pattern distortion caused by injector deposit could be compensated by the engine control system; spray distortion is not a critical issue, as they commonly operate under a homogeneous-charge combustion mode and their air/fuel mixture process is completed in the intake port [2].

For the GDI engines, spray characteristics are more critical to retain good and stable engine performance. This is especially true when GDI engines are running in the stratified-charge combustion mode, where the formation of the desired air/fuel mixture relies

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heavily on a carefully designed spray pattern and its interaction with the intake charge flow. A relatively small amount of deposit accumulation on the injector can however distort such spray patterns and may lead to lower fuel economy, higher emissions, or even vehicle drivability problems such as misfire [1,3,4]. Thus, the injector deposit is a significant concern for GDI applications and needs great attention.

The effect of injector deposit on spray characteristics and engine performance has been widely reported [5–9]. Song et al. [5] investigated the effect of deposits on the spray behaviours of a six-hole GDI injector. Their coked injector had been used in a vehicle for 58,000 km. They found that the flow rate of the coked injector was decreased by about 10% and the deposits formed inside the GDI injector's nozzle influence its spray behaviours significantly. They reported that the deposit effect reduced the spray penetration length while increasing the spray cone angle; which contradicted the previous authors' conclusions. Lindgren et al. conducted an optical study of the deposit effect on the swirl injector and found that the fouled injector produced more dense and faster pre-jet compared to that of a clean one [6]. Joedicke et al. conducted an accelerated deposit formation test using a fuel with additives that could accelerate the deposit formation [7]. After 55 h dirty-up test, 23.5% fuel rate loss was observed together with 93% and 20% increase of CO and HC emissions respectively. Fuel consumption also increased with 2.45%. In the work of Sandquist et al., an 8.5% fuel rate reduction was observed together with 10% higher HC emissions under the work load of 5.5–8.5 bar IMEP compared with a clean injector [8]. Wang et al. used two fouled and one clean multi-hole injector in a single cylinder spray guided DISI research engine to study the effect of injector deposit on engine emissions [9]. It was found that the fouled injectors consistently produced higher emissions and the maximum difference was observed at highest engine load of 8.5 bar IMEP, where the fouled injectors produced 58% higher PN emissions and 300% higher PM emissions. In all these studies, while the final effect of injector deposit on engine performance was studied, its effect on the air/fuel mixing process was still poorly understood due to the lack of available experiment data.

In a recent work conducted by Xu et al. [10], a compensative review of injector deposit was conducted. After reviewing the mechanism of injector deposit formation, different methodologies used in the study of injector deposit, the effect of injector deposit on engine performance as well as different strategies for injector deposit reduction, the author concluded that while extensive work had been done, the mechanism of GDI injector deposit formation was still not fully understood. Xu et al. concluded that while CFD modelling can provide significant help in understanding the injector deposit effect, few work has been done as little information could be obtained about 3D deposit information inside the nozzle [10]. Also, it was pointed out that more optical work should been carried out on the deposit effects on spray patterns.

In order to gain a deeper understanding of injector deposit effects on spray characteristics and the in-cylinder air/fuel mixing process, both experimental and CFD investigations were carried out in this study. Detailed spray characteristic studies of a clean and coked injector were conducted first; including measurements of mass rates, spray penetration lengths, cone angles, as well as droplets' velocity and diameter distributions. Both high speed photography (HSP) and Phase Doppler Particle Analyzer (PDPA) techniques were applied. After carefully calibrating the spray model with the experimental results, a three-dimensional CFD study of the air/fuel mixing process inside the cylinder was then performed under different stratification levels. The CFD results were validated with PLIF data with a close match.

2. Experimental setup

2.1. Fuel injection system and test conditions

A clean and a typical coked Bosch multi-hole injector were used in this study. The coked injector was produced in the Future Engines Laboratory at the University of Birmingham, having been used for 54 h with various fuels under loads ranging from 3 to 8 bar IMEP, 150 bar injection pressure and 2000 rpm engine speed. The deposit was accumulated at the injector tip and also inside the counter bore to the nozzle hole. Another coked injector, exposed to similar conditions as those used for the tests, was split and its deposit formation on the ball pin and counter bore is presented in Fig. 1.

A schematic diagram of the test bench is shown in Fig. 2. Three sides of the constant volume vessel provided optical assess using 100 mm diameter windows. Fuel was pressurized by nitrogen and then fed to the multi-hole injector controlled by an electric control unit (ECU) with a power source of 24 V and a pulse delay generator. The test conditions are shown in Table 1.

2.2. HSP and PDPA system

First, a study of the deposit effect on the mass of injected fuel was conducted. Five injection pulse widths ranging from 1.0 to 2.5 ms were selected with 250 injections executed for each case. The injected fuel mass was measured using a balance with an accu-

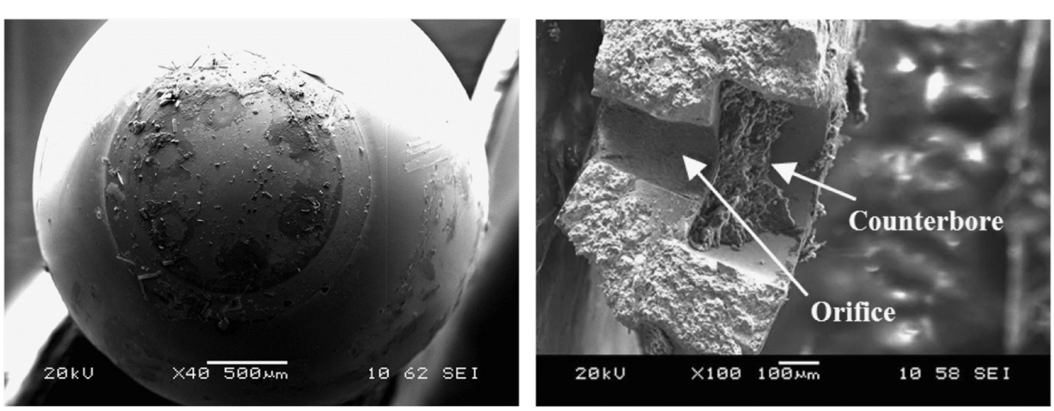

Fig. 1. SEM picture of a typical coked Bosch injector (a) deposit on ball pin; (b) deposit inside nozzle and counter bore [11].