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Effect of fuel injector deposit on spray characteristics, gaseous emissions and particulate matter in a gasoline direct injection engine

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HIGHLIGHTS

- Fouling tests on the GDI engine lead to similar flow rate losses for all injectors.
- Deposits accumulation on the injector counterbore and tip were identified by SEM.
- Deposit leads to increases in penetration length and mean droplet size.
- The impacts of deposit on spray performance vary from hole to hole.
- PM and HC emissions significantly deteriorate even at this early stage of fouling.

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ABSTRACT

For modern gasoline direct injection (GDI) engines, injector deposit is a concern because it can cause changes to the spray characteristics and lead to deterioration in fuel economy and exhaust emissions. In this study, in order to examine the link between spray variation and engine emissions deterioration due to injector deposit accumulation, 8 new injectors were installed on a GDI engine and run through a deposit accumulation process which included 6 cold starts and a 30-h steady state engine test at a speed of 2000 rpm and load of 5 bar break mean effective pressure (BMEP). One representative injector was examined before and after the deposit accumulation tests in order to understand the impact of deposit on the spray. Results showed that, at the end of the deposit accumulation test, the pulse width of the injectors stabilized at a level which was about 1.5% higher than at the start and the fuel consumption remained almost identical. High magnification and borescope imaging indicated that a significant amount of deposit had formed on the outer surface of the injector tip. However, Scan Electronic Microscope (SEM) imaging of the injector hole showed that, at this level of fouling, some deposit was present on the counterbore, while the nozzle hole was nearly completely unaffected. The deposit on the counterbore caused a 2.21% drop of the injector fuel flow rate at 150 bar injection pressure. Penetration lengths and mean droplet sizes of all jets increased significantly. As for the impacts of the varied spray characteristics on the engine emissions, unburnt hydrocarbons (HC) and particulate matter (PM) emissions significantly increased while other gaseous emissions (e.g. CO, NO_x, CO_2) only changed slightly.

1. Introduction

The adoption of the gasoline direct injection (GDI) concept has become increasingly widespread since the late 1990s [1–4]. There are several advantages of the GDI system over port fuel injection (PFI) systems. In GDI engines, fuel is injected and vaporized directly inside the engine cylinder rather than intake manifold as in case of PFI and the cooling effect of the fuel spray therefore increases the volumetric efficiency of the engine. Moreover, because the fuel is injected at moderately high injection pressure in GDI systems, the dramatically improved atomization results in better response during cold start and load change. In recent years, the use of GDI in turbocharged engines, especially those associated

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with a downsizing strategy has become a trend for the automotive industry due to its ability to reduce CO_2 emissions significantly.

Despite these advantages, the GDI system has its own challenges. Compared with its predecessor, the PFI system, GDI injectors operate in a much harsher environment because their mounting location is in the high pressure, high temperature combustion chamber rather than in the intake manifold. The injector can therefore suffer from the accumulation of deposits on the injector tip and in the nozzle holes [5]. A relatively small amount of deposit can change the carefully designed injector fuel flow rate [6–10], spray pattern [11–13], atomization characteristics [12,13] and the interaction with the in-cylinder flow [12]. And the changes of the spray may result in worsened emissions [14–17,21], increased fuel consumption [6,18,19,21] and misfire of the engine [1,18,19]. Thus, the GDI injector deposit formation problem attracts notable attention among automotive researchers.

The deposit formation mechanism is relatively complicated and unsettled. Kinoshita et al. [7] proposed a deposit formation mechanism which highlighted the importance of deposit precursors. They suggested that the 90% distillation temperature (known as the T90) of the fuel was an important parameter affecting the status of deposit precursors. When the injector temperature is lower than T90, the deposit precursors were in the liquid state and could be easily washed away by the fuel flow. When the injector temperature was higher than T90, the deposit precursors adhered strongly to the injector wall and therefore the tendency of injector deposit formation was increased. This mechanism developed by Kinoshita et al. provided guidelines for controlling injector deposit formation. However, some disputes remained since some other researchers reported that increasing nozzle temperature above T90 did not always promote injector deposit formation [8,20].

The effect of injector tip deposit on spray characteristics, engine performance and engine emissions were extensively addressed in literature [11–14,21]. Lindgren et al. [11] compared sprays of a clean injector and a fouled injector under simulated engine conditions in a chamber using spray visualization. They found that, in general, the spray of the fouled injectors tended to have longer spray penetration length and larger mean droplet diameter. Wang et al. [12] conducted experimental tests on a clean injector and a fouled injector to measure the effects of deposit on spray characteristics in the open air. The data collect was also used to calibrate a single cylinder engine Computational Fluid Dynamics (CFD) model. The effect of injector deposits on in-cylinder air/fuel mixture development was then estimated using the model. They concluded that the fouled injector had a longer penetration length and a deformed spray pattern in the open air. From the engine simulation results, they suggested that injector deposit led to more fuel impingement on the piston and cylinder walls as well as lower overall equivalence ratio during late injection events. The distorted spray pattern led to higher fuel stratification levels of the coked injector compared to those of the clean injector. The causes for the spray characteristics change brought by deposits were explored by Wang et al. [13] using a detailed 3-D injector flow simulations. These 3-D coked nozzle models were created using high resolution X-ray microtomography data. They concluded that the deposits inside the counterbore restricted air recirculation and entrainment. This led to the lower exiting turbulent kinetic energy of the spray from a coked injector and contributed to the higher mean droplet size. Due to the higher exit velocity and smaller spray cone angle, longer spray penetration length was observed. It was also not surprising that engine performance and emissions would deteriorate due to the change of spray characteristics after formation of injector deposits. Joedicke et al. [21] performed an accelerated deposit accumulation test at 19 bar BMEP and 1500 rpm engine speed on a side mounted GDI injection system equipped engine. It was concluded that after the 55-h deposit accumulation test the fuel injectors had lost 23.5% of their nominal flow rate, the fuel consumption rate increased by 2.45% and HC and CO emissions increased by 20% and 93%, respectively. Wang et al. [17] conducted PM and PN emissions measurement on two coked injectors and a new injector in a single cylinder DISI spray guided engine. The impact of engine operating condition, fuel (gasoline and ethanol) and injection system (different injectors) on emissions were examined in this study. The authors found that, regardless of the operating conditions (load from 3.5 to 8.5 bar), coked injectors consistently produced higher PN emissions compared to clean injectors. The maximum difference was found at an engine load of 8.5 bar, where the PN emissions of the two coked injectors were 53% and 58% higher than the clean injector. It was also reported that, the PM emissions from ethanol combustion were less affected by the injection system than in the case of gasoline. In a review, Xu el al. [14] summarized recent developments in research of injector tip deposit. They suggested that the mechanism and effects of injector tip deposit accumulation were still not fully appreciated. More work had to be carried out to gain understanding on the subject and in order to mitigate the impact of injector deposit formation. It was also recommended that optical diagnostics, including high speed imaging and PDPA, were useful in providing knowledge of spray formation quality.

The mitigation methods for GDI injector tip deposit have been widely explored in literature [7–10,22–25]. There were mainly three ways to mitigate injector deposits: detergents, injector designs and engine designs. Detergents could disperse deposit precursors and clean metal surfaces. Studies showed that some of the detergents could efficiently remove injector tip deposit [9,10,22]. Injector tip deposit formation could be mitigated by reducing injector tip temperature since the deposit formation is closely related to injector tip temperature [7,8,18,22,23]. Thus by adding insulating material on the injector to reduce heat transfer from engine cylinder [24] or using coating to conduct heat away [25], the temperature of the injector could be reduced. Some engine design features had impacts on injector deposit formation. Bacho et al. [23] studied the impacts of GDI injector mounting location on injector performance. It was observed that centrally mounted injectors tended to experience larger flow rate loss (7.2% versus 2%) compared to side mounted injectors. They also pointed out that increasing injection pressure was an efficient way of reducing deposit formation.

In conclusion, extensive studies have been carried out on the topic of injector tip deposit accumulation due to its importance to advanced GDI engines. These studies cover a wide range of areas, including the mechanism of deposit formation, the impact of fuel on deposit formation, the effect of deposit formation on the spray, the mitigation methods of deposit formation and the effect of deposit formation on the engine performance and emissions. However, to the best of the authors' knowledge, few publications have revealed the link between the change of spray characteristics and the change of engine emissions potentially brought about by injector deposit accumulation. In this work, a set of fouling tests which consisted of 6 cold starts followed by a 30-h steady state operation were conducted on a V8 GDI engine. During the fouling tests, engine operation and emissions data were recorded. The spray characteristics of one representative injector were studied before and after the fouling tests in order to understand the impact of deposits on the fuel spray. The combination of changes to the fuel spray and engine emissions then allowed the authors to gain deeper understanding of the following aspects: (i) where the injector deposits were formed at this early stage of fouling, (ii) how formed deposits would affect the spray characteristics (microscopic and macroscopic), (iii) the effects on engine performance and emissions caused by the deposits and (iv) in which operating conditions (e.g. injection pressure) those effects are most relevant. The under-