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Investigation of injector coking effects on spray characteristic and engine performance in gasoline direct injection engines

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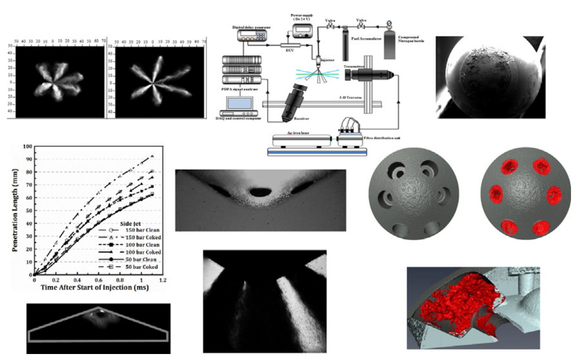
HIGHLIGHTS

- Injector tip deposits effects on spray characteristics and atomization were examined.
- Injector tip deposits effects on mass flow rate reduction were investigated.
- Injector tip deposits impacts on diffusion flame formation were examined.

GRAPHICAL ABSTRACT



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ABSTRACT

Spray and droplet characteristics of a coked injector were compared to those of a clean injector at the atmospheric conditions and investigated using high-speed imaging and a Phase Doppler Particle Analyzer (PDPA). Scanning Electron Microscope (SEM) and X-ray 3D microtomography images were analysed to understand the physical characteristics of injector nozzle deposits. Furthermore, Energy Dispersive X-Ray Spectroscopy (EDS) was utilized to obtain the elemental composition of the deposit. A single cylinder optical gasoline direct injection (GDI) engine was used to compare diffusion flames for each injector. In this study, the location and topography of the deposits demonstrated that they extensively formed in the external holes of the injector, and reduced in size and quantity through the internal holes. Elemental analysis of the deposits exhibited that carbon (C) and oxygen (O) were the predominant elemental components through both the internal and external holes of the injector. The coked injector exhibited higher penetration lengths, smaller plume angles, larger spray cone angles, higher mean droplet velocity and larger droplet size as compared to the clean injector. Images of the optical engine indicated strong diffusion flames around the coked injector tip. In-cylinder pressure measurements indicated that the coked injector produced lower in-cylinder pressures, implying lower combustion stability

Abbreviations: ASOI, after start of injection; ATDC, after top dead centre; BTDC, before top dead centre; CAD, crank angle degree; COV, Coefficient of Variation; DCA, deposit control additives; ECU, engine control unit; EMOP, exhaust maximum opening position; ETBE, ethyl tertiary butyl ether; EDS, energy dispersive X-ray spectroscopy; GDI, gasoline direct injection; HC, hydrocarbon; IMEP, indicated mean effective pressure; ST, seat; OS, outer surface; IMOP, intake maximum opening position; MFB, mass fraction burned; PDPA, phase Doppler particle analyser; PM, particulate matter; PN, particulate number; SEM, scanning electron microscopy; SOC, start of combustion; SOI, start of injection; TDC, top dead centre; SMD, Sauter mean diameter; ULG, unleaded gasoline; HRR, heat release rate; EH, external hole; IH, internal hole; BL, ball

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compared with the clean injector. This work was carried out to obtain a comprehensive study of injector coking effects on spray behaviour and engine performance.

1. Introduction

Injector coking is a common phenomenon observed in fuel injection apparatus, and occurs when chemically degraded components of the fuel and combustion products adhere to the internal surfaces of an injector [1]. Injectors are highly sensitive to the formation of small amounts of deposits in the critical regions where the fuel is metered and atomized due to the small passage of the fuel nozzle. These deposits once formed, reduce the flow rate delivered for the injection pulse width. Additionally, it also distorts the injection of the fuel spray, hence influencing its shape and penetration length [2]. This has an adverse effect on both the mixture formation and the combustion processes inside the combustion chamber. At the same time, the average size of the atomized fuel droplet increases which slows down the process of mixture formation. Furthermore, the formation of deposits on the inner surface of the injector including the needle valve and needle valve seat [3] due to the deterioration of the residual fuel is manifested in two aspects. First, the reduction of the actual sac volume and subsequently the flow rate will be altered for the same injection conditions. Second, the needle valve needs to be lifted higher to allow the fuel to be supplied at the beginning of the injection, which results in a fuel injection starting delay; and thus the needle valve falls a shorter distance to cut off the fuel supply, which leads to the advance ending of fuel injection [4]. Consequently, the injector needle motion resistance will be increased and the temporal and qualitative course of opening and closing of the electromagnetic injector against the set controlling impulse will be changed [5]. As a result, all the aforementioned phenomena can lead to a reduction in engine efficiency and its performance whilst the exhaust emissions and fuel consumption tend to increase.

Nozzle tip temperature was considered one of the key parameters affecting the formation of deposits on the injection nozzles. A much more pronounced reduction of mass flow rate due to the build-up of the deposits has been observed when the tip temperature exceeds 150 °C [6]. The thermal condensation and cracking reaction kinetics of gasoline fuel had been shown to accelerate the rate of deposition in the nozzle when temperatures reach over 150 °C. However, this acceleration in deposit formation occurred within a certain temperature range and upon exceeding a particular high temperature, it altered based on the fuel and deposit composition, the injector deposits more or less ceased forming and the already formed deposits were self-cleaned [5]. Furthermore, Kinoshita et al. [6] delineated the relation between the injector tip temperature and T90 distillation temperature of the fuel on the formation of GDI injector deposits. They demonstrated that as long as the injector temperature is kept below the T90 of the fuel, the residual fuel will stay in a liquid state, which facilitates the washing process and removal of the deposit precursors by the next fuel injection event. By contrast, when the temperature at 90% volume distillation is lower than the injector tip temperature the deposit formation rate increases due to liquid fuel evaporation, which would cause the deposit precursors to agglomerate and adhere strongly to the nozzle wall [6,7]. EGR and charge air-cooling as engine design key parameters will influence the nozzle coking due to their direct influence on the in-cylinder gas temperature and hence the temperature of the component exposed to combustion chamber gases such as the injector tip [2,8–10]. Carbon deposits formation at higher temperature is occurred via two routes; either through the presence of the elemental carbon and hydrogen generated from the hydrocarbon decomposition process; or through the formation of larger poly-nuclear aromatic hydrocarbons (PAHs) from the polymerization or condensation of hydrocarbon species, which consequently will nucleate and grow to become carbonaceous deposits [11].

Many researchers have utilized a Scanning Electron Microscope (SEM) to investigate the internal and the external deposits of GDI injectors [3,6,10,12,13]. Song et al. [4] investigated the deposit formation of the orifice holes of the coked injectors using SEM photographs. They concluded that the deposits on the external surface seemed loose and easy to be removed as deposits on the protrusion of injector tip. Meanwhile, there are thick deposits inside the holes, where the deposits at internal aperture distribute axially and tended to increase in density along one side of the hole. Whilst the deposits at external aperture were radially distributed. Furthermore, Dearn et al. [3] investigated the distribution of deposits inside the GDI injector tip by employing a method of mechanically cracking the injector. They studied the composition and location of injector deposits through five areas across the injector tip. Their study revealed that different levels of deposits were formed over the injector, and the deposits in different locations consisted of different levels of typical fuels and lubricant elements. Their elemental analysis results indicated that the dominant elemental deposit compositions are C, O, S and Ca, of which S and Ca decreased, but C increased as the deposit locations became closer to the combustion chamber.

Attar et al. [14] utilized high speed imaging to investigate the direct influence of the tip coking on spray structures of a multi-hole injector. They revealed that the tip coking can increase plume penetration length and reduce plume angle. Moreover, the effects of the injector coking on the spray characteristics were not similar for each plume produced from each hole of the injector. Additionally, Yiqiang et al. [15] and Lindgren et al [16] studied the effect of GDI engine injector coking on spray characteristics. They showed that the coked injector had a poorer atomization as well as a significantly smaller spray angle and longer penetration distance compared to that of a clean injector. Recently, several studies regarding the injector deposits showed a longer penetration length associated with the coked injector in comparison to the clean injector [17–19]. Song et al. [4] found that the coking effect decreased the actual aperture of the GDI injector and thus reduced the spray penetration distance and particle size while increased the spray cone angle, so it would seem that deposits affect the spray from different injectors in different ways.

Deposit formation had been linked to subsequent increases in engine emissions. Joedicke et al. [20] used a special fuel designed to accelerate the deposit formation process. They observed, after 55 h dirty-up test that the fuel rate losses were approximately 23.5%, accompanied with 20%, 93% and 2.45% increase of HC, CO emissions and fuel consumption respectively. Wang et al. [21] investigated the performance of a single cylinder spray guided DISI engine under three different injectors, one clean and two fouled injectors. They demonstrated that fouled injector consistently produced higher emissions and the maximum difference was observed at highest engine load of 8.5 bar IMEP, where fouled injector produced 58% higher PN emissions and 200% higher PM emissions.

The injector deposits formation could be minimized in several ways including: (1) using detergents [22,23], (2) enhancing the injector design by using a coating with lower thermal conductivity to that of the injector body to reduce the injector tip temperature and consequently, the deposit formation [24], and (3) using high fuel injection pressure as an efficient way to minimize the injector deposits formation [25].

The current study presents a comprehensive examination of coked and clean injectors' spray structures and provides a quantification of their characteristics. This includes plume penetration lengths and angles (relative angle and cone angle), droplet size and droplet velocity