Applied Energy 220 (2018) 351–374

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Assessment of gasoline direct injector fouling effects on fuel injection, engine performance and emissions

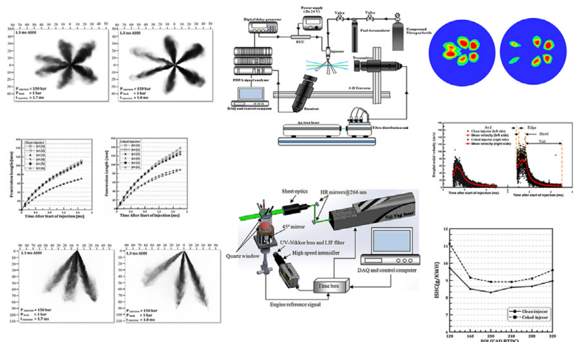
Tawfik Badawy[a], Mohammadreza Anbari Attar[a], Hongming Xu[a,b,*], Akbar Ghafourian[a]

[a] Vehicle and Engine Technology Research Centre, University of Birmingham, Birmingham B15 2TT, UK
[b] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing, China

HIGHLIGHTS

- Effects of injector tip deposits on spray dynamics and atomization were studied.
- Effects of injector tip deposits on charge inhomogeneity were investigated.
- Effects of the injector tip deposit on engine performance and emissions were investigated.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
DISI engine
Injector fouling
Mixture preparation
Combustion
Emissions

ABSTRACT

The current optical and thermal experimental tests were mainly focused on obtaining a comprehensive understanding of the effects of gasoline direct injector fouling on mass flow rates, spray characteristics, engine emissions and engine performance. A robust injector fouling cycle was employed to produce coked injectors in a multi-cylinder thermal engine. Deposit build-up in the coked injectors and fouling cycle repeatability was first examined by measurements of fuel flow rate. Macroscopic spray characteristics of the clean and the coked injectors were carried out using high-speed imaging and Planar Laser Induced Fluorescence (PLIF) of sprays footprint. Fuel droplets size and velocity were characterised with a two-dimensional Phase Doppler Particle Analyser (PDPA). It was observed that the deposit build-up inside injector nozzles and on injector tips reduced the plume cone angle while increased plume penetration length, plume separation angles, mean droplet velocity and size for the coked injector. Impact of injector fouling was further investigated by PLIF measurements of in-cylinder charge inhomogeneity and repeatability in mixture preparation. The coked injectors showed higher degree of inhomogeneity and poorer repeatability in mixture preparation. These were in agreement with combustion analysis results where the coked injectors showed lower load and lower combustion stability compared with the clean injector under same operating conditions. Significantly higher unburned hydrocarbon emissions and

Abbreviations: ASOI, after start of injection; ATDC, after top dead centre; BTDC, before top dead centre; CAD, crank angle degree; CNF, cumulative number fraction; COV, coefficient of variation; CVF, cumulative volume fraction; DCA, deposit control additives; ECU, engine control unit; EMOP, exhaust maximum opening position; ETBE, ethyl tertiary butyl ether; IMOP, intake maximum opening position; SLID, spatial light intensity distribution; EDS, energy dispersive X-ray spectroscopy; GDI, gasoline direct injection; HC, hydrocarbon; HRR, heat release rate; IVC, intake valve closing; IVO, intake vale opening; MFB, mass fraction burned; PDPA, phase doppler particle analyser; PFI, port fuel injection; PLIF, planar laser induced fluorescence; PM,, particulate matter; PN,, particulate matter number; ROI, region of interest; SEM, scanning electron microscopy; SOC, start of combustion; SOI, start of injection; TDC, top dead centre; SMD, sauter mean diameter; ULG, unleaded gasoline; WOT, wide open throttle; IMEP, indicated mean effective pressure

* Corresponding author at: University of Birmingham, Birmingham, UK.
E-mail address: h.m.xu@bham.ac.uk (H. Xu).

https://doi.org/10.1016/j.apenergy.2018.03.032
Received 16 September 2017; Received in revised form 15 March 2018; Accepted 17 March 2018
0306-2619/

particulate number concentration were also observed for the coked injectors. This work was carried out to obtain a broad picture of injector cooking effects in GDI engines.

1. Introduction

Engine deposits can form in intake system, combustion chamber and injector [1]. Once formed, deposits can often lead to changes in engine performance and emissions in both spark ignition and compression ignition engines. Effects of injector deposits are manifested in degradation of spray quality and flow reduction delivered for same injection pulse width [2]. This has an adverse effect on mixture formation and combustion reducing efficiency and engine performance [3]. Previous investigations have shown that early stages of deposit formation for most GDI injectors, did not result in significant flow reduction, but can result in substantial changes in spray angle, spray symmetry as well as droplet size and distribution [2,4]. Lindgren et al. [5] used spray visualization technique to study the spray Structure of GDI pressure swirl injector which has two parts; pre-jet (transient behaviour) and main jet (steady-state behaviour). It was observed that the pre-jet of a fouled swirl injector, was more dense and penetrated faster as compared to a clean injector. Furthermore, Yiqiang et al. [6] used Schlieren method to investigate the effect of GDI engine injector fouling on spray characteristics. They revealed that a coked injector had a poorer atomization as well as a significantly smaller spray angle and longer penetration distance compared to that of clean injector. Song et al. [7] investigated the spray characteristics of a 6-hole GDI injector under the effect of deposit formation. They reported that the reduction in the mass flow rate was 10% by testing a fouled injector had been used in a vehicle for 58,000 km in comparison to that of the clean injector. Also, they indicated that deposits formation altered significantly the spray behaviours through the nozzle holes of the GDI injector. They reported that the coking effect decreased the actual GDI injector nozzle aperture, resulting in smaller particle size and lower spray penetration length, while the spray cone angle increased, which was contradict the previous researchers' conclusions.

Joedicke et al. [8] conducted a study of fouled injectors with pulse width 8% higher than that of clean injectors at an engine speed of 1500 rpm and full load operation. They noticed at this full load point that the fouled injectors reduced the engine power by 1% and increased the brake specific fuel consumption by 2% compared to that of the clean injector. Likewise, Ding et al. [9] investigated an injector coked for 55 h under engine conditions of 3 bar BMEP and 2000 rpm. They demonstrated that fouled injector caused an increase in both the combustion duration and brake specific fuel consumption, whilst the combustion efficiency was reduced. Jiang et al. [10] examined the spray characteristics, gaseous emissions and particulate matter concentrations of a GDI engine using an injector coked for duration over 30 h with the engine running. They demonstrated that at all pulse widths and injection pressures investigated, the mass flow rate associated with the coked injector was reduced by 2–8%, in comparison to that of the clean injector. The coked injector penetration lengths increased in the range of 6–20% compared to that of the clean injector. Moreover, the average droplet size and UBHC emissions associates with the coked injector were higher than the clean injector by approximately 36% and 30% respectively. Wang et al. [11] on the other hand investigated numerically, using three-dimensional computational fluid dynamic (CFD) modelling, the effects of the deposits on the dynamics of in-nozzle flow and spray behaviour development. They concluded that the deposits through the counterbore act as an extension of the internal hole which reduced the generated turbulent kinetic energy at the nozzle exit. Consequently, this reduced the atomization process associated with the coked injector. In addition, they noticed that the coked injector yielded a longer penetration length and smaller spray cone angle.

The location of the injector and fuel plumes relative to the spark plug has been considered to be one of the important features of spray-guided combustion systems. The position of the fuel spray geometry with respect to the spark plug position must be optimized, in order to cover a wide map of operating conditions; and furthermore, to assist with the existence of an ignitable mixture around the spark plug at the point of ignition [12,13]. Consequently, any shifts from the expected spray geometry will result in significant degradation of the combustion process within different operating conditions. The deposit formation had been linked to subsequent increase in NO_x and particulate emissions, some increase in CO and HC emissions, and general decrease in vehicle's performance in terms of its driveability, acceleration and fuel economy [14,15]. The observed increase in NOx emissions was due to local regions of rich fuel combustion caused by poor injection characteristics of coked injector. Also, deposits which are porous can absorb some of the injected fuel causing uncontrolled increase of the mixture excess air coefficient and consequently resulted in higher NOx emissions particularly at lower engine speeds [3,16]. It was found that for a fouled injector with 8.5% fuel flow rate loss, there was approximately 10% higher HC emissions in the engine load range of 5.5–8.5 bar IMEP, as compared to a clean injector [17]. Also, the fouled injector with a 23.5% fuel flow rate loses led to 30% and 125% more HC and CO emissions, respectively, compared to a clean injector [8]. Particulate emissions from injector fouling were investigated and it was found that for an engine load of 8.5 bar IMEP, the clean injector had PN emissions nearly 53% and 58% of the fouled injectors, with 8.5% and 5.3% fuel flow rate loss respectively [17]. The relation between injector fouling and diffusive combustions was also investigated and it was revealed that diffusion flames resulted in higher Particulate Matter (PM) emissions [18].

Injector deposit formation was found to be strongly related to the injector tip temperature and injector position in the combustion chamber [19,20]. It was shown that the loss of fuel flow rate due to the deposit accumulation, increased sharply for tip temperatures exceeding 150 °C, peaking around 175 °C. Kinoshita et al. [21] observed that PM emissions were affected by the temperature at 90% volume distillation of the fuel as a key fuel property. They concluded that when the temperature at 90% volume distillation of the fuel was lower than the injector tip temperature, the pyrolysis process of the fuel occurred resulting in more formation of tip deposits. Two types of injector deposits have been identified: carbonaceous sediment produced during engine operation from lubricating oil and soot, and deposits forming from the gasoline ingredients such as aromatic or olefin components during hot soak periods [2,22,23]. Deposits of the latter type typically form as a thin layer of waxy residue on the injector's internal surfaces, near the injector tip and at the nozzle outlet [2,14]. Dearn et al. [24] analysed deposits for multi-hole injector using Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS). They showed that extensive deposits were formed in both internal and external injector holes and the external-hole deposits were radially distributed and collected in the shoulder while the internal aperture deposits were axially distributed and tended to increase in density along one side of the hole. Their elemental analysis results indicated that dominant deposit compositions are C, O, S and Ca, of which S and Ca decreased but C increased with the distance to the combustion chamber.

In addition, low level of deposit formation was observed when the injector tip 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 pre-cursors by the next fuel injection event [21]. Therefore, drying of the injector tip was considered an essential