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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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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-hour 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 stabilised 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, CO₂) only changed slightly.

Keywords: Deposits, Particulate matter, Gasoline direct injection, Spray characteristics.

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 with a downsizing strategy has become a trend for the automotive industry due to its ability to reduce CO₂ 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-hour 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 *et 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-hour 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 understandings gained in this study can be used to guide the design of new GDI injection systems which have resistance towards deposit formation.

2. Methodology and Experimental setup

2.1 Methodology

In this study, the experimentation was divided into two main parts: the engine deposit accumulation experiments and the spray characterization experiments. The aim of the engine deposit accumulation test was to create deposits on the injector while engine performance and emissions were measured. The formation and effects of the injector deposit were evaluated through the observation of engine performance, fuel injector pulse width and emissions measurements at three different fuel injection pressures (50, 100 and 150 bar). In addition injector flow rates, penetration lengths and droplet sizes

of the representative injector spray were measured off-site before and after the deposit accumulation tests.

The condition of the injector prior to installation in the engine was called the “clean injector” state. The “clean injector” was installed on the spray rig to measure its flow rate and spray penetration lengths of all jets. This created the reference for the spray characterization tests. The deposit accumulation tests were carried out on a dynamometer mounted test engine (see engine specifications in Table 1). Eight “clean injectors” were marked and installed on the engine. The deposit accumulation tests consisted of 6 cold starts (at approximately 20 °C) followed by steady state engine operation for 30 hours. The ECU controlled cold start running process was shown in Figure 1. The whole process lasted for approximated 60 seconds. In the first 9 seconds, the engine speed overshot and stabilized at 1400 rpm for 20 seconds. After that, the engine speed reduced to 800 rpm in 10 seconds. The speed then stayed at 800 rpm (idle mode) until the engine shut down at the end of the 60-second running. The 30-hour steady state running was conducted at an engine speed of 2000 rpm, a load of 5 bar BMEP and at 150bar fuel injection pressure. These operation conditions were chosen because Xu *et al.* [14] summarized in their review that most researchers used low engine speeds (1500-2000 rpm) and medium engine loads (maximum load for engine used in this study was 10 bar) in order to form deposit quickly on the injector tip. During the 30 hours of running, the lambda of the engine was kept at 1 and the fully warmed up coolant temperature was 95°C. The injection pulse width was monitored (engine speed and load were maintained) for the whole running process. It

increased and then stabilized at the end of the 30 hours test. After stabilization, it was considered that the injectors had reached a run-in condition where deposit formation and removal rates were in equilibrium, according to the injector plugging kinetic model proposed by Aradi *et al.* [22]. The injection duration increased while maintaining a constant fuel injection quantity due to a reduction in effective flow rate through the fuel injectors. A representative injector was then taken out of the engine and the flow rate and the spray penetration length measurement were carried out on the same injector after the engine operation (considered as a “fouled injector” state). Comparisons between the “clean injector” and the “fouled injector” were made and the effects of the injector deposit were analysed.

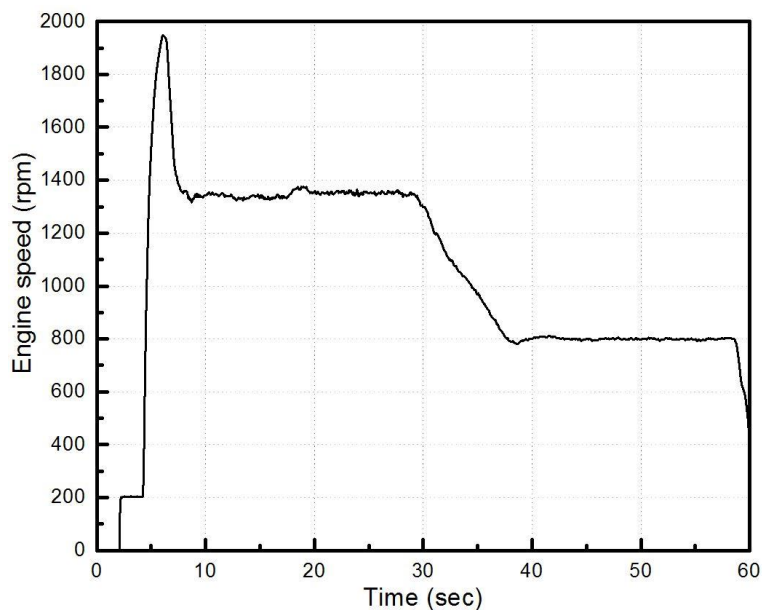


Figure 1: Engine speed versus time for cold start running

2.2 High speed imaging and laser optical techniques for spray characterization

In order to estimate the effects of the injector deposit on the spray characteristics, high speed imaging and Phase Doppler Particle analysis (PDPA) tests were carried out at atmospheric conditions of 1 bar using a single component gasoline-surrogate

reference fuel (isooctane). It was injected under an injection pressure of 150 bar and at three pulse widths of 0.38 ms, 1.5 ms and 1.65 ms.

The injector and the nomenclature of the spray jets

The injector used in this study is a 6-hole GDI injector. The layout of the spray jets is shown in Figure 2. It had 3 sets of symmetric jets named jet 1 to jet 6. The symmetric jets had the same spray inclination angle relative to the injector axis.

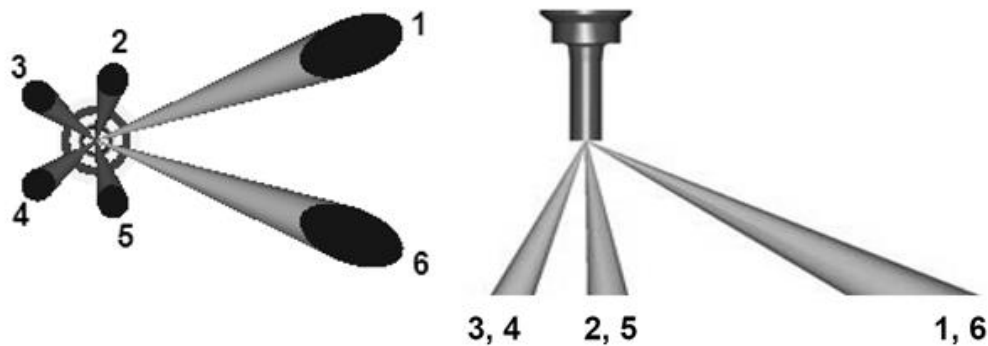


Figure 2: Nomenclature of the spray jets.

High speed imaging for spray penetration length

The spray penetration length was the essential parameter describing the macroscopic characteristics of the spray. In order to measure the spray penetration length, MATLAB code was created to process the images recorded by the high speed camera. Figure 3 a and b show the original image and the MATLAB processed image used for analysis. The MATLAB code drew reference lines along the spray axes and measured penetration lengths of the 6 jets. Thus, the visual penetration length was measured by identifying the grayscale change along this reference line. The actual penetration length could then be calculated according to the inclination angle of the spray, as shown in Figure 3 c. The pixel/length ratio was measured and calculated before the

test so that the penetration length could be transferred from pixel to physical length. In order to avoid shot-to-shot variation, 10 groups of images were recorded for 10 injections at each test point. The averaged penetration length was used in further analysis.

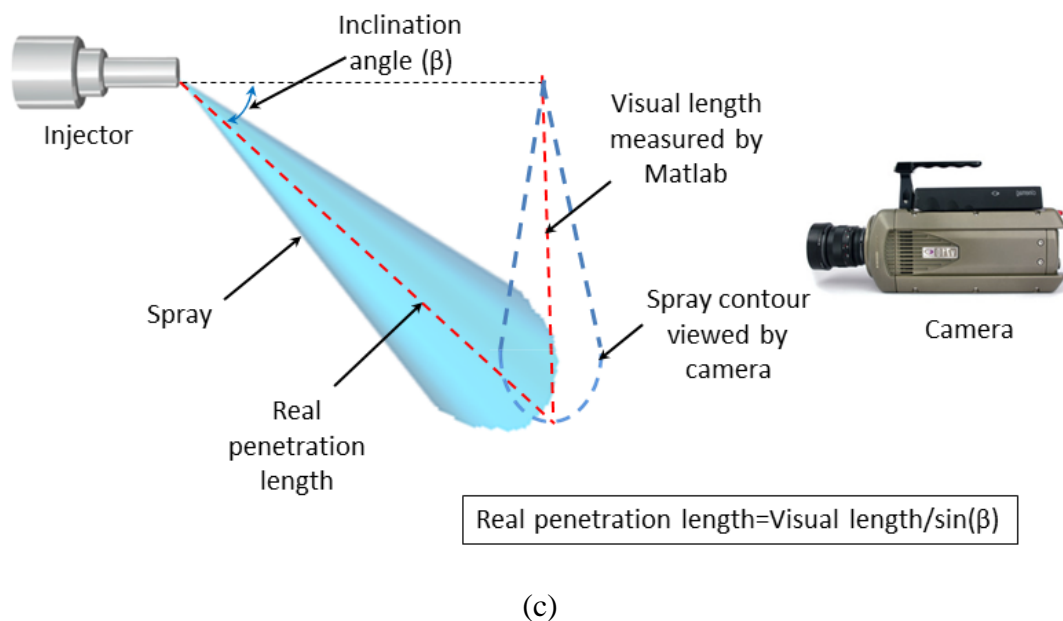
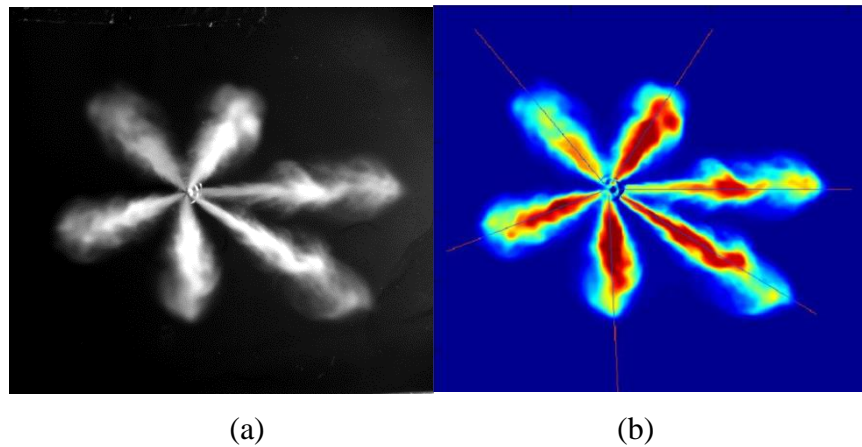


Figure 3: High speed imaging data processing (a) original image (b) processed image (c) transformation from visual length from real length.

Laser optical techniques (PDPA) for droplet size measurement

The droplet sizes of different spray jets were measured using a PDPA system. The schematic of the PDPA system used in this work is shown in Figure 4. The entire PDPA system, including the transmitting optics and the detectors, were fixed on a 3D

traverse system allowing the measuring point to moved 3 dimensionally within an accuracy of 0.01 mm. The droplet sizes of the ‘clean injector’ and the ‘fouled injector’ were compared and the effects were analysed.

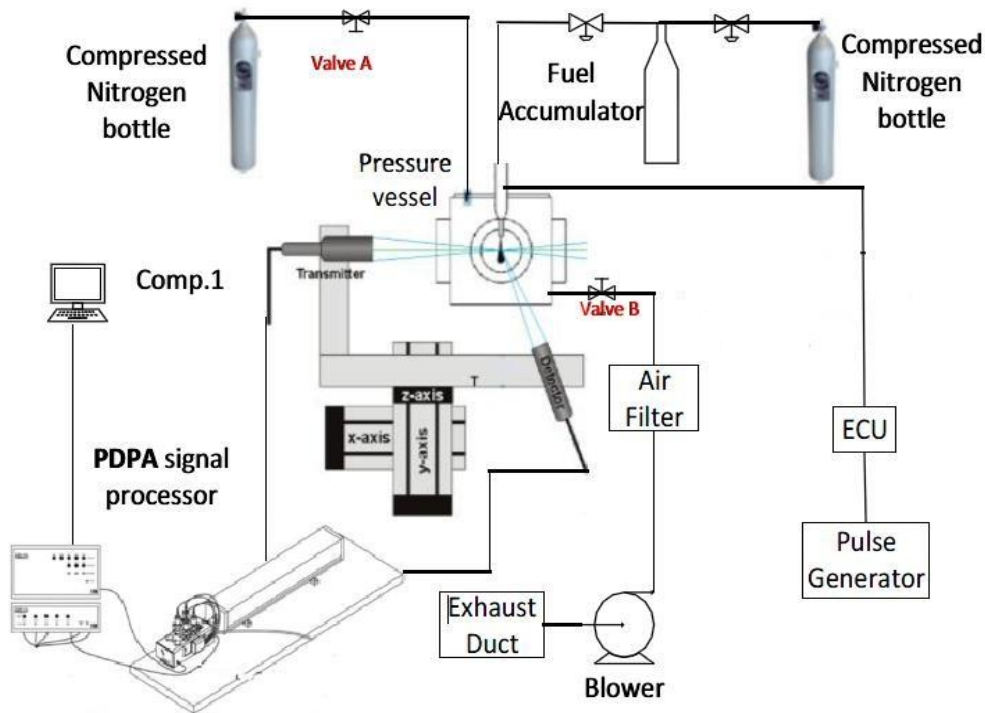


Figure 4: PDPA system in this test.

2.3 Fuel and emissions measurement

The fuel used in the deposit accumulation test was standard EN228 gasoline (see Table 2 for fuel specifications). The exhaust gas was sampled via a heated line at 190 °C to avoid the condensation of gaseous emissions by a Horiba Mexa-7100 DEGR gas analyser. CO and CO₂ emissions were measured by the method of non-dispersive infrared (NDIR), HC by a flame ionization detector (FID) and NO_x were quantified by a chemiluminescence detector (CLD). PM emissions were recorded by a real time aerosol electrical mobility spectrometer (Cambustion DMS 500). A heated sampling line and primary dilution ratio at the point of sampling were used to avoid condensation and a secondary variable dilution ratio to assure optimal particulate

concentration levels according to the specifications of the equipment. The samples were taken from the tailpipe of the engine upstream the three way catalytic (TWC) converter in order to avoid any influence of the catalyst in the exhaust emissions.

Table 1. Engine specifications

Engine	Jaguar Non-production variant
Displacement volume (l)	5
Bore/stroke (mm)	92.5/93
Compression ratio	11.5:1
Peak power (kW)	276 @ 6500rpm
Peak torque (Nm)	495 @ 3500rpm

Table 2. Gasoline properties

Fuel properties	Standard gasoline (PR4915) ULG95/E5
Liquid density (kg/m ³)	752.6
T90 (°C)	156.5
RON/MON	95.4/85.3
Paraffins (% vol)	46.2
Olefins+dienes (% vol)	3.3
Aromatics (% vol)	34.8
Oxygenates (% vol)	8
C/H/O ratio	84.7/13.1/2.2
Sulphur (ppm)	<10

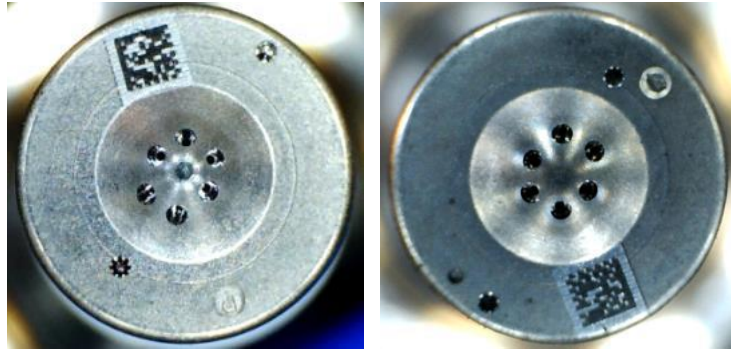
3. Results and discussion

3.1 Deposit formation

Figure 5 a-d shows images of the external part of the injector after being removed from the engine at different stages of the deposit accumulation. A boroscope was used to visualize the ‘in-situ’ external status of the injector (i.e. in the combustion chamber) after the deposit accumulation test (Figure 5 e). In the case of the clean injector (Figure 5 a), the tip is clean and the injector holes are fully visible. After 2 cold starts some black deposits were formed on the injector tip, while after 6 cold starts a

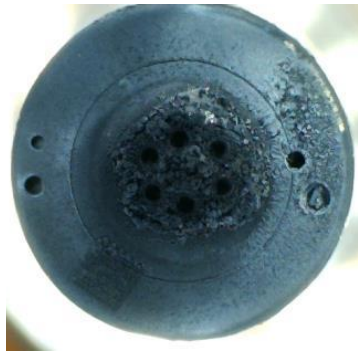
noticeably larger area of the injector tip surface was covered by deposits, showing the effect of the cold start in the creation of external deposits. Figure 5 d and Figure 5 e show the injector after the 6 cold starts and 30 hours of deposit accumulation test. The injector tip was totally covered by deposits created mainly during the steady-state engine operation. Visually the sizes of the holes were much smaller compared to its clean status, as shown in Figure 5 a.

In order to gain a deeper understanding of the deposit accumulation, this injector was split and magnified scan electron microscope (SEM) images (Figure 6) were taken to identify the location of the deposit accumulation inside the nozzle. It can be seen that on the internal parts, the needle seat and the injector hole, very little deposit could be seen. However, on the external counterbore, large quantities of deposit were present. Combining the observation derived from 'in-situ' and 'off-site' deposit visualization techniques, it could be concluded that at this stage of the injector fouling, the deposit mainly accumulated on the counterbore and in the outer parts of the injector holes (injector tip). In the other work conducted by the authors' group [5], detailed Scanning Electron Microscopy with Energy Dispersive X-Ray Spectroscopy (SEM-EDS) was conducted in order to understand the components of injector deposits. The EDS analysis showed that the deposits in different locations of the injector consist of different levels of typical fuel and lubricant elements, such as C, O, Na, Mg, Si, P, S, K, Ca, Mg and Zn. Four dominating elements (C, S, Ca and O) were identified for the injector.



(a)

(b)



(c)



(d)



(e)

Figure 5: Deposit formation process on the injector tip (a) clean injector, (b) injector after 2 cold starts, (c) injector after 6 cold starts, (d) injector after 30 hours deposit accumulation tests, (e) 'in-situ' injector status

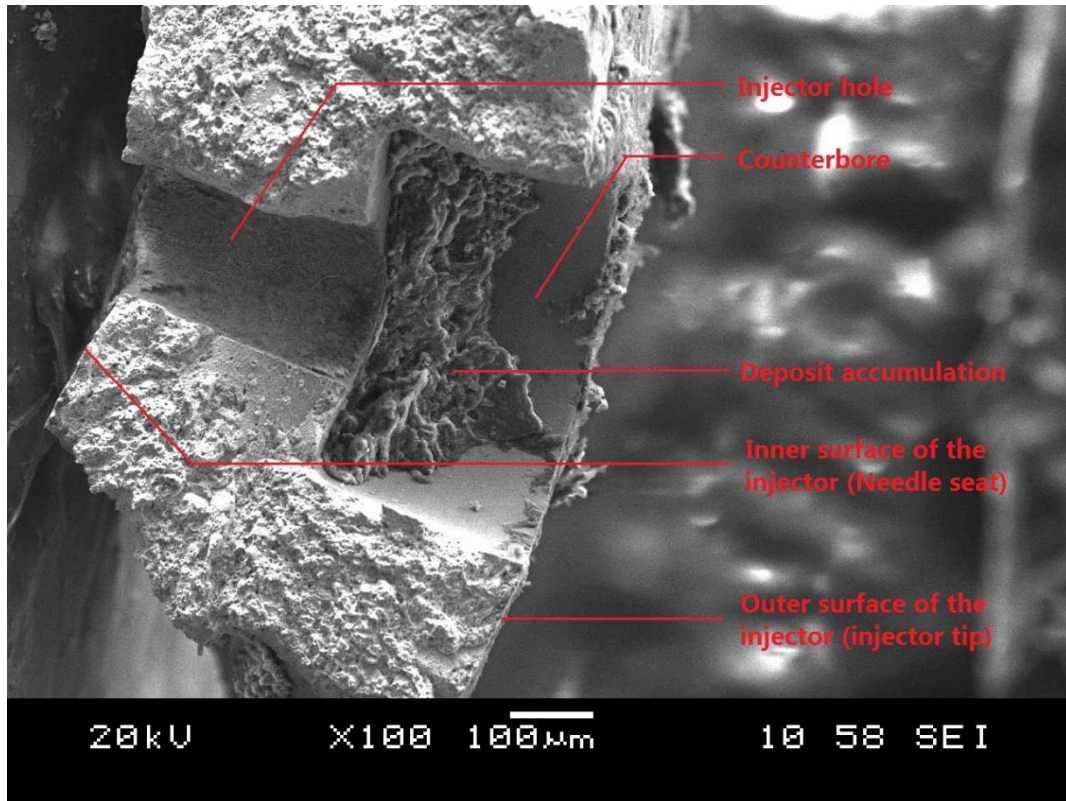


Figure 6: SEM image for deposit formation in the injector nozzle

3.2 Effect of deposits on the injector pulse width and flow rate

Figure 7 a shows the measured injection pulse width for cylinder 1 of the engine during the deposit accumulation steady state operation (2000 rpm, 5 bar BMEP and 150 bar injection pressure). It can be seen that the injection duration slowly increased on each day of the test (over a total of 7 days for the 30 hour test). This increase could be due to either a loss in fuel efficiency (a higher quantity of fuel therefore being needed to maintain the same engine performance) or a reduction of the injector flow rate because of the accumulation of deposits which would require compensating with a longer injection duration to deliver the same quantity of fuel, or the combination of both effects. In the last 4 hours of this 30-hour test (day 7), the pulse width stabilized at around 1.60 ms. It is considered that the injectors had reached a run-in condition where deposit formation and removal rates were in equilibrium. Figure 7 b presents

the percentage of pulse width increase in all 8 cylinders. The pulse widths of the injectors in all 8 cylinders increased by a similar amount, between 1.4% and 1.5%, meaning that they all had a similar level of fouling. Thus, it is reasonable to analyse only one representative injector. In later parts of this paper, optical diagnostics, including flow rate measurement, high speed spray imaging and PDPA measurement, were conducted on the injector from engine cylinder 1.

In order to confirm that the increase of injection duration (shown in Figure 7) was caused by a reduction of the injector flow rate, the “off-site” (i.e. an injector flow test rig) injector (cylinder 1 injector) flow rate under different injection pressures and pulse widths for a constant number of injection (500) were measured using isooctane. Figure 8 shows the injected mass for the clean status (before deposit accumulation tests) and the fouled status (after deposit accumulation test) of this injector for 500 pulses at a pulse width of 1.5 ms. Reduction of the flow rate was observed at three injection pressures because of the presence of deposits on the chosen injector created during the deposit accumulation process. When the injection pressure is low (i.e. 50 bar) or injection pulse width is short (i.e. 0.38 ms), the flow rate loss becomes more obvious (see Table 3). Overall, the flow rate for the injector is reduced after the deposit accumulation test by 2-8% depending on pulse width setting and injection pressure.

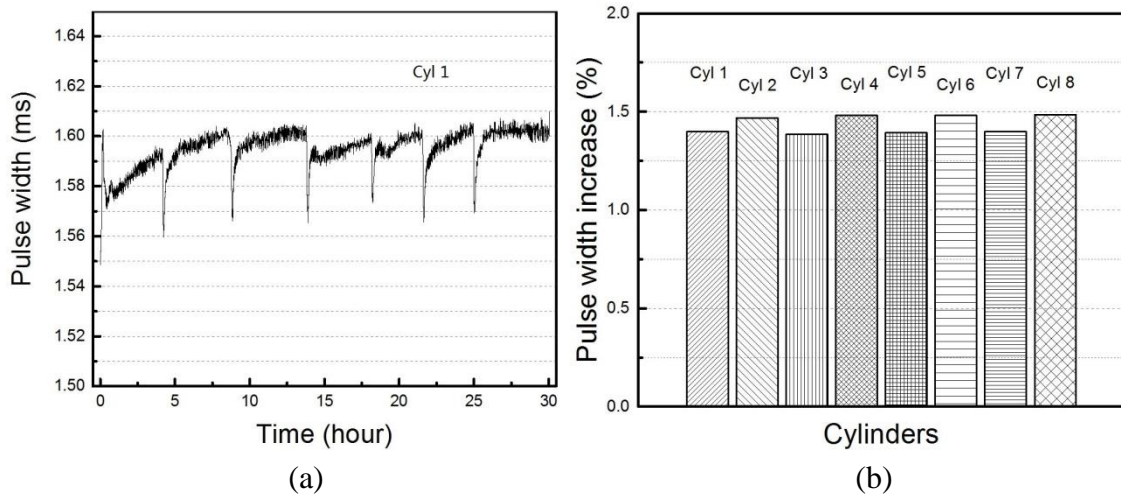


Figure 7: Pulse width changes (a) Pulse width of injector placed in cylinder 1 over 30-hour test (b) Percentage of pulse width increase in 8 cylinders after 30-hour test.

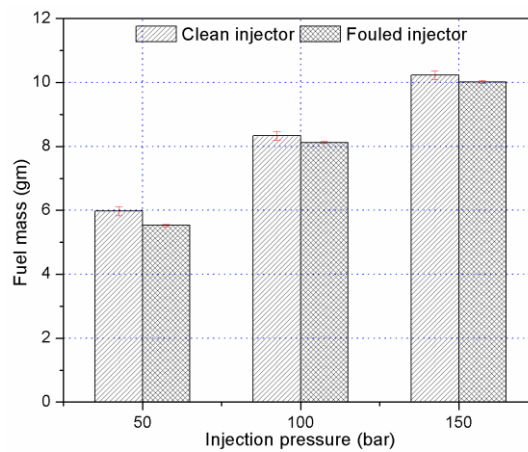


Figure 8: Flow rate for the injector tested on the spray rig under different injection pressures (1.5 ms pulse width, 500 injections)

Table 3. Flow rate loss of the injector at different injection pressures and different pulse widths for constant number of injections

Injection pressure (bar)	Pulse width (ms)	Flow rate loss (%)
150	0.38	8.4
	1.5	2.04
	1.65	2.21
100	1.5	2.5
50	1.5	7.4

3.3 Spray morphology: Spray cone angle and penetration length

Spray morphology, typically quantified by spray angle and penetration length, is one of the most relevant features which controls local in-cylinder mixture and emissions formation being especially influential in the regions near the cylinder wall (wall wetting region). It is hypothesised that the accumulation of deposits in the injector differ depending on the injector hole, thus the deposit induced differences in spray morphology should be studied for all injector jets. This means that even though the differences between the injector pulse width and injector flow rate for ‘clean’ and ‘fouled’ injector were small, the spray morphology parameters for the different jets could be very different and therefore produce large differences in local in-cylinder mixture conditions and subsequently, emission formation.

Figure 9 shows the chronological images of the spray from 0.39 ms after the start of injection (ASOI) to 1.94 ms ASOI for the 6 jets of the injector previously analysed. On the first images, there is no spray due to the injection delay, although, with the evolution of the jets, some clear differences in the spray pattern could be observed between the ‘clean’ and the ‘fouled’ injectors. In comparison to the ‘clean’ injector, the spray cone angle of the ‘fouled’ injector is smaller due to deposit accumulation on the injector tip. This phenomenon affects the in-cylinder mixture formation and will eventually affect the gaseous emissions and PM emissions.

Another visual difference observed for the ‘fouled’ injector was the presence of jets with divergent tips (i.e. for the symmetric jets one of the tips is much longer than the other in the late stage of the injection duration). In order to quantify the change of the

penetration length from jet to jet for the ‘clean’ and ‘fouled’ injectors, statistical analysis of the spray penetration length before and after the deposit accumulation tests have been carried out (see Figure 7 for 150 bar injection pressure and 1.5ms injection duration). For the ‘clean’ injector, its symmetric jets had nearly the same penetration lengths as shown in Figure 10 a. However, for the ‘fouled’ injector some of the symmetric jets, for example jet 6, has a penetration length longer than jet 1 at the later stage of the injection (Figure 10 b). This comparison also reveals that the penetration lengths of all the jets increased after the deposit accumulation tests. Detailed comparison of the percentage of the penetration length increase of the 6 jets at different injector status and injection pulse widths is given in Table 4. Generally, the increment of the penetration length after the deposit accumulation test is around 10-15%, but the magnitude (10-20%) and jet to jet variability increased for the shortest injection pulse width. Overall the penetration length percentage increase of jet 6 was the largest, while the percentage increase of jets 1 and 4 were the shortest. This confirmed a variation of the injector tip deposit build-up on different nozzle holes.

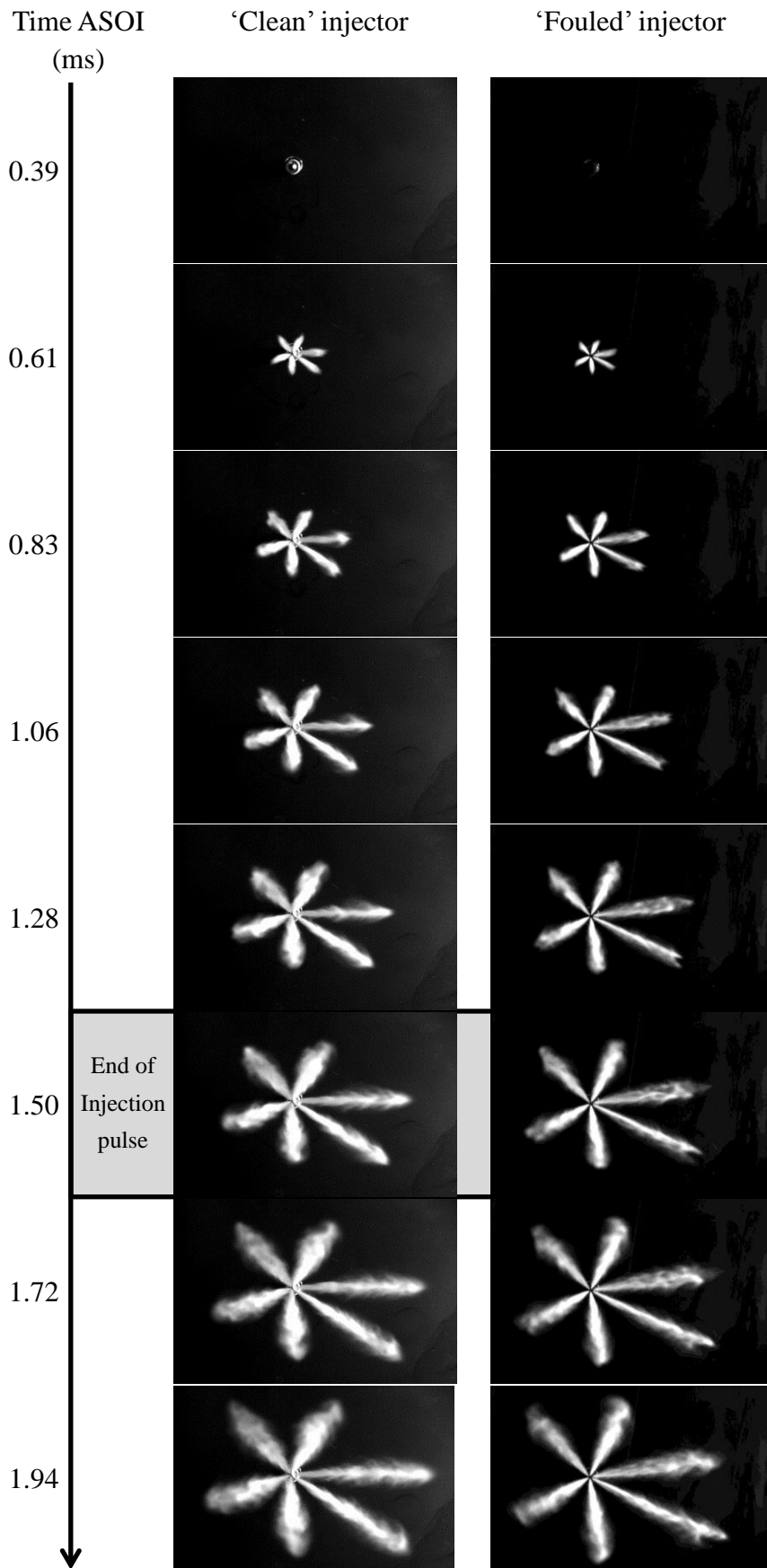


Figure 9: Chronological images of the spray at injection pressure of 150 bar and injection pulse width of 1.5 ms.

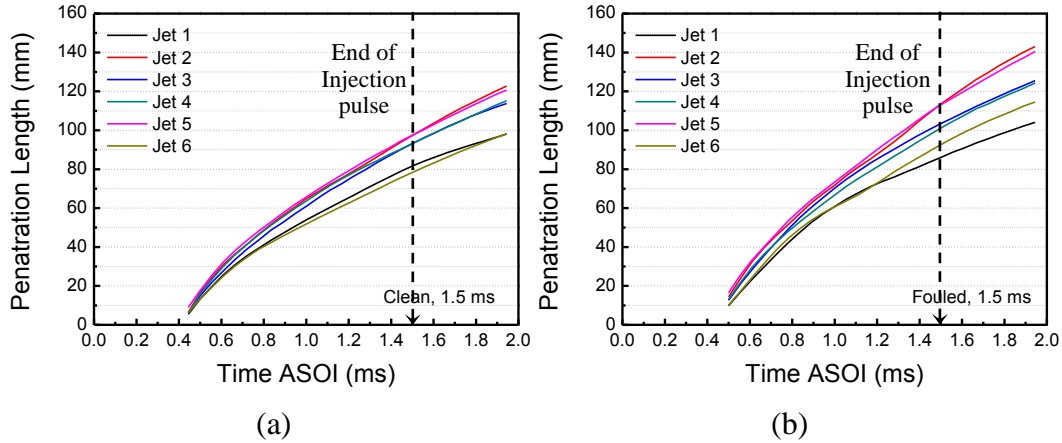


Figure 10: Penetration lengths of 6 jets at an injection duration of 1.5ms (a) Clean injector (b) Fouled injector.

Table 4: Percentage of penetration length increased after deposit accumulation test

Percentage of length increased (%)	Jet1	Jet2	Jet3	Jet4	Jet5	Jet6
1.65 ms	7.99	13.11	12.58	11.28	14.93	14.99
1.5 ms	6.11	16.51	10.35	7.93	16.38	16.59
0.38 ms	13.82	13.90	19.97	10.07	13.81	19.74

3.5 Effect of injector tip deposit on the droplet size

From Figure 10, it can be seen that when the injector is clean the symmetric jets had the same penetration length. However, after the injector was fouled, jet 6 had a much longer penetration length than jet 1, while the differences for the other two sets of symmetric jets were smaller. Therefore, jet 1 and jet 6 were chosen for further droplet sizes analysis after deposit accumulation tests and were compared with respect the droplet sizes corresponding to the clean injector. For the other two pairs of symmetric jets, only one jet in each pair (jet 2 and jet 3) was chosen for further analysis.

In order to understand the impacts of deposits on microscopic characteristics of the spray, PDPA measurements were conducted for the chosen jets at a distance of 60 mm from the injector tip, at an injection pressure of 150 bar and injection pulse width of 1.5 ms under atmospheric conditions. Since the experiments were carried out at such a

long distance towards the injector tip, the spray was suitably sparse for PDPA measurements to be made with very high validation rates, between 85% and 92% for all the test points in this paper. Histograms of the clean and fouled status of jet 1 and 6 sprays are compared in Figure 11. It can be seen that the droplet size distribution behaves similarly to a log-normal distribution which indicate that a statistically significantly number of droplets had been analysed. This figure gives insights into the effects of accumulated deposits on the probability distribution of droplets diameters. For both jet 1 (Figure 11 a) and jet 6 (Figure11 b), it could be seen that the numbers of large droplets (larger than 12 μm) significantly increased after the fouling tests. The average droplet size (Sauter mean diameter, SMD) at different spatial distances to the nozzle tip was calculated from the droplet size distributions. For the 'clean' injector (Figure 12 a), the average droplet sizes of all the jets were quite similar. However, after the deposit accumulation tests, the droplet sizes of the jet 1 and 6 were significantly different and larger than in the case of the clean injector. Table 5 summarizes the percentage of SMD value increased after the deposit accumulation test for jets 1 and 6 at three different injection pulses. Jet 6 has the largest droplet size variation (around 30%) in accordance with the largest variation in penetration length which suggests either a larger deposit built-up in the hole number 6 or a higher effect of the presence of deposits in the hole number 6 on spray morphology.

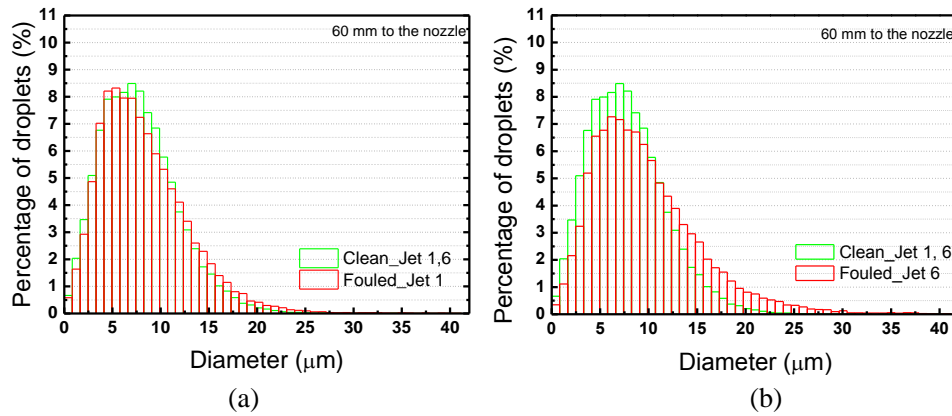


Figure 11: Histogram of the droplets at 60 mm distance to the nozzle for clean injector and fouled injector (a) Clean injector Jet 1,6 compared to Jet 1 (b) Clean injector Jet 1,6 compared to Jet 6

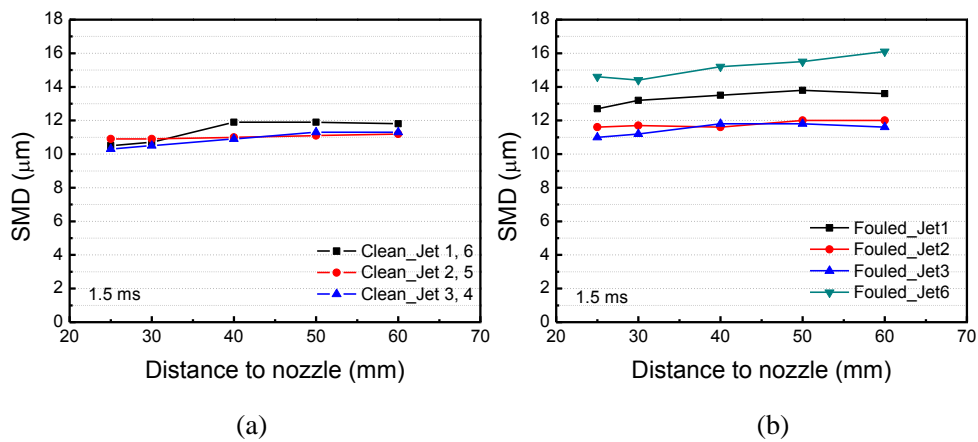


Figure 12: SMD value of the clean and fouled status (a) Clean injector (b) Fouled injector

Table 5: Change of the droplet sizes after deposit accumulation tests

Percentage of droplet size increase (%)	Jet1	Jet2	Jet3	Jet4	Jet5	Jet6
1.65 ms	16.12	8.80	-1.03			35.66
1.5 ms	17.79	6.89	5.75			33.61
0.38 ms	21.51	5.76	3.24			28.23

3.6 Effect of injector deposits on fuel consumption and emissions

The engine out (upstream three way catalyst) gaseous and particulate matter emissions were measured during the deposit accumulation process (2000 rpm, 5 bar BMEP and 150 injection pressure). Furthermore, in order to evaluate the effect of the same deposit built-up at different injector pressures, gaseous and particulate matter emissions were measured before and after the deposit accumulation test under 3

injection pressures: 50, 100 and 150 bar.

The engine brake specific fuel consumption (BSFC) is presented in Figure 13. Irrespective of the injector fuel flow rate loss observed from Figure 7, Figure 8 and Table 3, the engine fuel consumption was not significantly changed during the 30-hour running. Figure 14 shows the rate of variation of engine output gaseous emissions during the steady state deposit (after cold starts) accumulation experimental test, while Figure 15 compares the evaluation of the engine out gaseous emissions with the clean and fouled injectors at different injection pressures. It can be seen that the variation rate of CO₂ and CO emissions was almost negligible (around 1-1.5% increase with respect to the start of the test). These variations, while potentially being considered statistically negligible, were also observed in Figure 15 a and Figure 15 b. Interestingly, the NO_x emissions seemed to slightly decrease with the steady state engine operation (especially from 8 to 25 hours of operation, Figure 14). Figure 15 d also confirms a slight decrease in NO_x emissions at injection pressure of 50 and 100 bar (around 2%).

The most statistically significant effect of the deposit formation on engine output gaseous emissions occurs for unburnt HC. It can be clearly seen that HC emissions increase with the steady state engine operation and this is also confirmed when the deposit effect is evaluated at different injection pressures. Figure 15 c also shows that the decrease of the injection pressure leads to an increase of the HC emissions. It is believed that this increase is due to a worse atomization of the spray at lower injection pressures being especially noticeable for the 'fouled' injectors. The large influence of

injector pressure in injector flow rate and unburnt hydrocarbons for the fouled injectors suggests the major contribution of injector hole deposits to the increase in unburnt hydrocarbon emissions was in-cylinder mixture deterioration rather than the presence of injector tip deposits which should not be largely influenced by the injector pressure. Therefore, it is concluded that the increase of the unburnt hydrocarbon emissions was due to i) deposits in the injector hole and ii) injector tip deposits (in direct contact with the combustion chamber and outer of the injector hole).

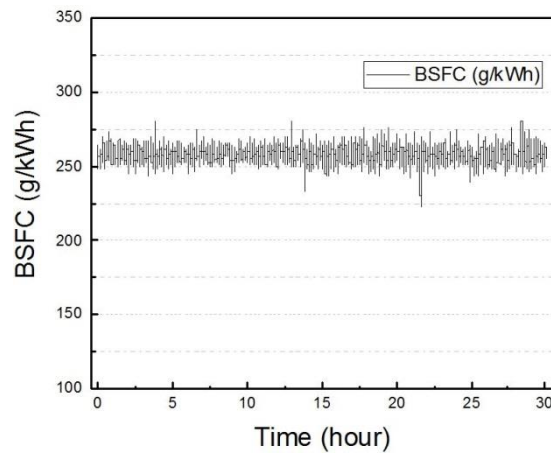


Figure 13: Engine break specific fuel consumption (BSFC) over 30-hour running

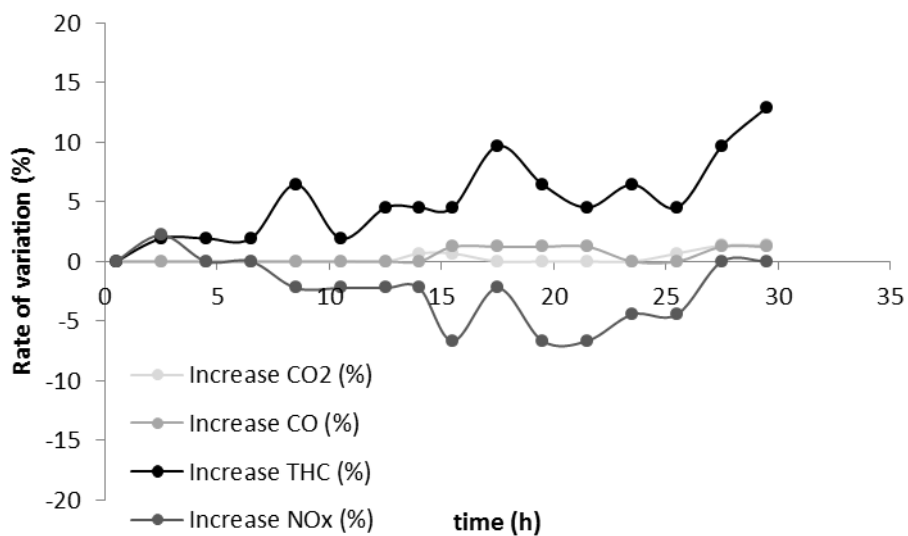


Figure 14: Variation rate of gaseous emissions during the deposit accumulation test (after cold starts)

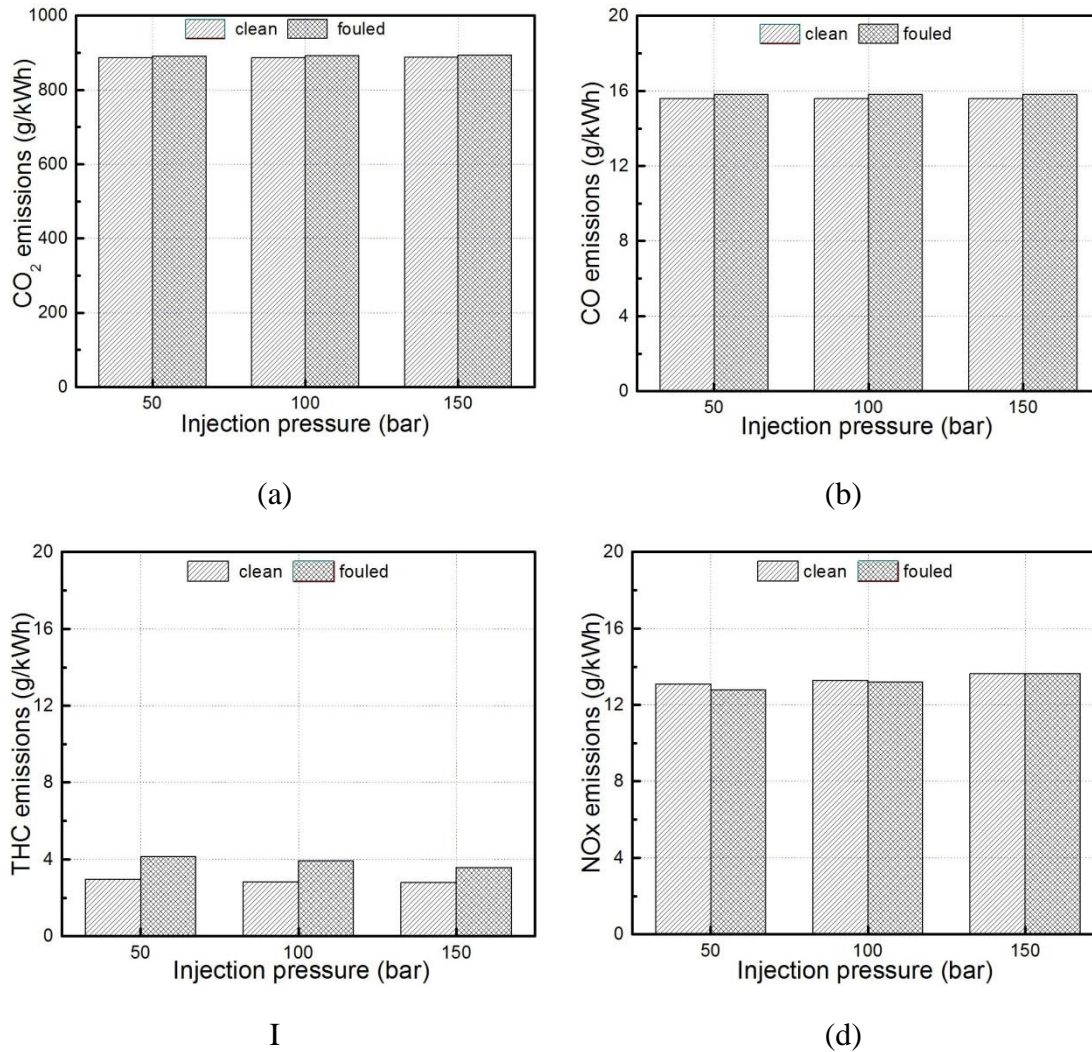


Figure 15: Gaseous emissions of the engine before and after the deposit accumulation test (a) CO₂ (b) CO (c) HC (d) NOx

The engine-out particulate size distributions in the 30 hours of deposit accumulation tests are shown in Figure 16 a. It can be seen as bimodal (nucleation and accumulation) particulate size distributions were obtained. Nucleation mode is mainly composed of droplets of hydrocarbons, while the accumulation mode is composed by both soot and adsorbed/condensed hydrocarbons on the soot agglomerates [16]. During testing, the total particle number increased, as shown in Figure 16 b. At the end of the deposit accumulation tests, the ‘fouled’ injectors produce PM emissions around 4-5 times higher than for the ‘clean’ injectors for the standard ECU settings injection pressure.

The increase in particulate emissions occurred both for the nucleation mode (according to the increase in the unburnt hydrocarbon emissions) and more dramatically for the accumulation mode. The high concentration of particulate emissions in the accumulation mode for coked injector indicated high soot formation, which was a result of diffusive combustion. Diffusive combustion could occur in the cylinder if (1) there is spray-wall impingement (caused by longer penetration length); (2) there is residual fuel absorbed by deposits formed outside the injector tip (as shown in Figure 5 e) after injection (3) there are very rich areas or big fuel drops in the cylinder after injection. Fouled injectors could potentially deteriorate PN emissions from all three aspects thus higher level of particulate emissions was seen in the accumulation mode.

Figure 17 shows the impact of different injection pressures on PM emissions. The effect of injection pressure on particulate size distributions was small when the injectors were 'clean' (no statistically significant effect on accumulation mode but an increase in nucleation mode according to the increase in unburnt hydrocarbon emissions), as shown in Figure 17 a b and c. However, in the case of the 'fouled' injectors, a decrease in the injection pressure increased the nucleation mode and dramatically increased the accumulation mode. As in the case of unburnt hydrocarbon emissions, the effect of injection pressure on particulate matter formation for the 'fouled' injectors identified the large contribution of counterbore deposits to particulate matter through the modification of the spray in addition to the contribution of injector tip deposits which promote diffusive combustion and the formation of

particulate matter (mainly in the accumulation mode). The partial contributions of i) internal deposits and ii) tip deposits will vary depending on the engine operating conditions. There were some cases (defined by injection timing, injection pressure, fuel quantity, etc.) in which the modification of fuel spray characteristics due to the accumulation of internal deposits would not be critical for in-cylinder mixture and emissions formation and the effect of injector tip deposits would be more important on particulate formation (e.g. diffusive combustion of the fuel attached on the injector tip deposit).

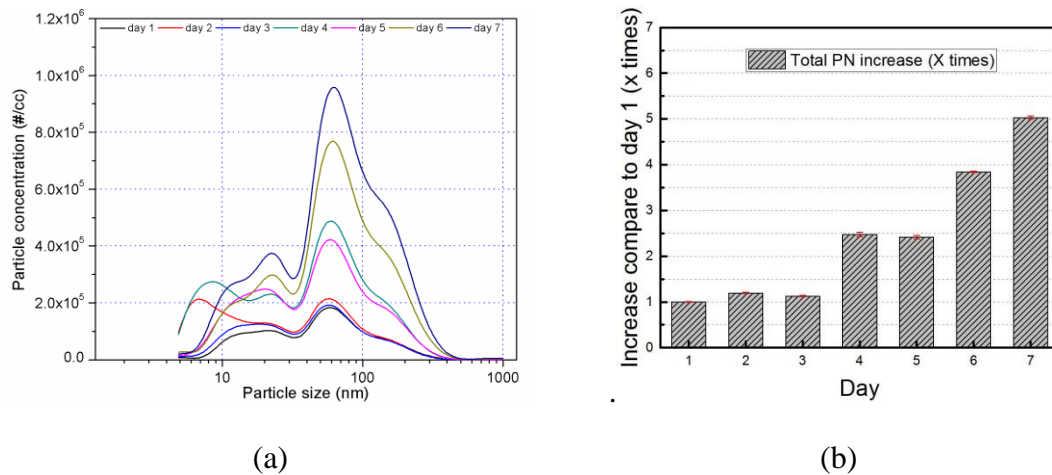


Figure 16: PM emissions of the engine during the deposit accumulation test (a) particulate size distribution (b) total PN increase.

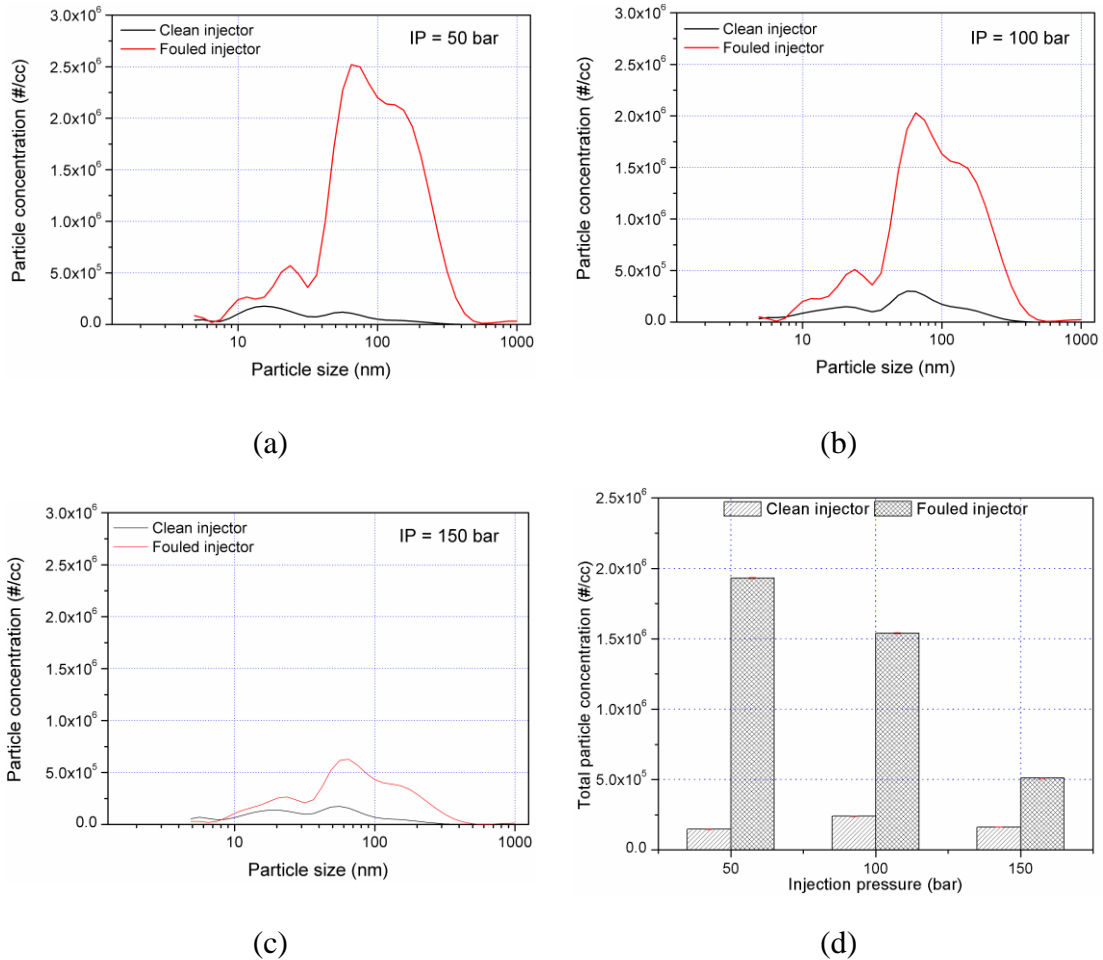


Figure 17: PM emissions of the engine before and after the deposit accumulation test for different injection pressure (a) 50bar (b) 100 bar (c) 150 bar (d) total PN

4. Conclusions

This work has presented an experimental investigation on the effects of injector deposits on the spray characteristics, engine performance and exhaust emissions. A set of deposit accumulation tests, which included 6 cold starts and a 30-hour steady state running, were carried out in a GDI engine on multiple injectors. After formation of deposits, a representative injector was taken out and examined by SEM in order to understand the amount and location of the deposit. Spray characteristics of this fouled injector were compared to its clean status. Combined with the analysis on the change of engine emissions, this paper highlighted the interaction between the deposit, the

spray and the emissions at an early stage of injector fouling. The following conclusions were drawn from this work:

1. The deposit accumulation process created deposits not only on the injector tip but also inside the injector nozzle. Significant amount of deposits were observed on the counterbore while barely no deposit was observed on the deeper part of the nozzle (i.e. nozzle hole).
2. After the deposit accumulation tests, the in-cylinder pulse width data indicated that comparable deposits were formed on all the injectors. Overall, the injector fuel flow rate reduced by 2% and the fuel consumption of the engine was not affected.
3. The impacts of deposits on spray characteristics varied from hole to hole on a given injector. After deposit accumulation tests, penetration lengths of the 6 jet increased in the range of 6% to 20%. For average droplet sizes, the maximum increase was about 36%.
4. At this early stage of injector fouling, unburnt hydrocarbon emissions increases about 30% during the steady state engine operation while other gaseous emissions (e.g. CO, NO_x, CO₂) only changed slightly.
5. The most significant consequence of injector fouling during engine operation was found to be the increase in particulate matter (maximum 5 times increase of PN), particularly in the soot carbonaceous accumulation mode. Compared to an injection pressure of 50 bar and 100 bar, the PN emissions of the fouled injector at injection pressure of 150 bar were significantly lower.

Furthermore, from this research, it could be deduced that the counterbore design and lower pressure injection are undesirable features for the GDI engine injection system. The former led to deposit accumulation and the latter led to higher PN emissions. Thus, in order to mitigate the impacts of injector deposits, the injection system of a GDI engine should have the following features: straight injector nozzle hole rather than stepped hole (to avoid deposit build-up on the counterbore), temperature control at the injector tip (to avoid the temperature reaching T90) and high pressure injection (providing better atomization and ability to flush deposits away). More investigation is needed to confirm the capability of these features.

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