

Linking the Physical Manifestation and Performance Effects of Injector Nozzle Deposits in Modern Diesel Engines

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ABSTRACT

The formation of deposits within injector nozzle holes of common-rail injection fuel systems fitted to modern diesel cars can reduce and disrupt the flow of fuel into the combustion chamber. This disruption in fuel flow results in reduced or less efficient combustion and lower power output. Hence there is sustained interest across the automotive industry in studying these deposits, with the ultimate aim of controlling them.

In this study, we describe the use of Scanning Electron Microscopy (SEM) imaging to characterise fuel injector hole deposits at intervals throughout an adaptation of the CEC Direct Injection Common Rail Diesel Engine Nozzle Coking Test, CEC F-98-08 (DW10B test)[1].

In addition, a similar adaptation of a previously published Shell vehicle test method [2] was employed to analyse fuel injector hole deposits from a fleet of Euro 5 vehicles. During both studies, deposits were compared after fouling and after subsequent cleaning using a novel fuel borne detergent.

In all cases, the use of fuel borne detergents quickly recovered >75% of power lost during the fouling stage of the tests. SEM images showed that the removal of deposits within the injector nozzle holes was key to the recovery of power and that deposits on the injector nozzle exterior could be misleading in predicting the performance of fuel injectors.

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INTRODUCTION

The formation of deposits within the nozzle holes of modern direct-injection diesel engines can reduce the quantity and disrupt the spray pattern of fuel injected into the combustion chamber. The reduced or less efficient combustion that results gives lower power and increased fuel consumption and emissions [3, 4, 5]; therefore studying the formation, removal and control of these deposits is of great interest.

Prior studies in this field [6, 7, 8, 9, 10] have shown that the speed and load of a given drive cycle (i.e. an individual's driving style), fuel composition (presence of trace elements, such as zinc), and the inherent sensitivity of the engine design can affect the formation of such deposits.

Modern diesel engines are designed to deliver on a set of competing parameters: high power density, low fuel consumption, reduced Noise, Vibration and Harshness (NVH) and whilst being required to conform to stringent emissions standards. The evolution of the modern diesel

engine to meet these design parameters has seen the adoption of engine downsizing and increasingly complex exhaust after treatment as well as an over-riding need for precision control of combustion.

More recent fuel injection equipment (FIE) innovations to address precision control of combustion include increasingly high pressure common rail systems with multiple injection events to deliver precise control and metering of injected fuel quantity. High hydraulic efficiency fuel injector nozzles featuring an increased number of smaller diameter tapered and honed nozzle holes have also been adopted.

Potential side-effect of these trends, which could increase susceptibility to injector nozzle fouling are high pressure common rail systems thermally stressing re-circulated fuel, and reduced cavitation-cleaning of deposits in high hydraulic efficiency injector nozzles.

Further deployment of FIE using increasing common rail pressures and high hydraulic efficiency injector nozzles to comply with emerging emissions regulations (Euro 6 & Tier 2 bin 5) and the need

to comply with these emissions standards throughout the useful lifespan of the vehicle [11][12] could mean that fouling of fuel injector holes continues to be a relevant issue in future vehicles.

The objective of the program outlined in this paper was to gain insight into the physical manifestation of injector nozzle hole deposits and their response to fuels and additives and link this to their effects on performance. Techniques employed were purposely non-destructive so that analysed injectors could be refitted to the engines enabling series measurements to be made. Physical manifestation of the deposits was evaluated using Scanning Electron Microscopy (SEM) imaging and in some samples, Energy-Dispersive X-ray spectroscopy (EDX) techniques. Initial measurements were made in an adaptation of the industry standard DW10B engine fouling test [1] and then compared to deposits formed *in vehicle* during chassis dynamometer testing in a range of modern (Euro 5) vehicles. Performance effects of deposits were measured by evaluating steady state engine power output.

In this study, only deposits on the injector nozzle body and inside the injector nozzle hole are considered; deposits formed on surfaces internal to the injector (Internal Diesel Injector Deposits - IDID's) are not implicated in this mode of testing and were therefore outside the scope of this study.

STUDYING FUEL INJECTOR HOLE DEPOSITS IN A COMMON RAIL DIRECT INJECTION TEST ENGINE

The CEC Direct Injection Common Rail Diesel Engine Nozzle Coking Test, CEC F-98-08 (DW10B test) [1] is the industry standard test for evaluating fuel and additive effects on injector nozzle coking (fouling) in European diesel passenger cars with Direct Injection (DI) engines. The test uses a Euro 4 PSA DW10B 2.0L, Common-Rail, 4 cylinder, turbo-charged engine and relies on the following key factors to increase its baseline sensitivity to the formation of injector nozzle deposits:

- It is fitted with non-standard, prototype injectors designed to be sensitive to deposit formation. These feature tapered and honed nozzle holes that reduce cavitation cleaning [13], and are of a valve covered orifice design, which can allow hot exhaust gas to be drawn into the nozzle hole after an injection event.
- It requires zinc to be added to the reference fuel (at 1 mg/kg) to accelerate deposit formation rates to emulate substantial mileages that would not be practical in engine test scenarios.
- It features a cycle dominated by high load running to accelerate deposit formation.

A DW10B test engine running an adaptation of the CEC F-98-08 method was used to evaluate the physical manifestation of injector nozzle deposits in conjunction with their effect on engine power. The injectors were removed for SEM imaging periodically through the test.

Experimental

Test Engine

The test engine set up used was as per the CEC F-98-08 (DW10B) test [1]:

Table 1. Particulars of DW10B engine used in the CEC F-98-08 test

Engine code	DW10BTED4
Donor Vehicle	Peugeot 407 2.0 HDi 16v
Chassis number series	21010347
Displacement/layout	1998 cc / I4
Output	100kW at 4000 r/min
Peak torque	320Nm at 2000 r/min
EMS	Continental/Siemens
Injection system	Common rail, 1600 Bar peak pressure, piezo actuated injectors, 6 hole nozzles
Emissions	Normally certified to Euro 4; vehicle uses Exhaust Gas Recirculation (EGR) and Diesel Particulate Filter (DPF)

Test fluids

A 16 hour break-in run of a new injector set was carried out as per the CEC F-98-08 testing procedure; fuel was CEC DF-79-07 (Batch 6) without any additives or FAME.

For the dirty-up phase, an EN590 compliant, refinery sourced zero sulphur diesel (ZSD) was selected instead of the CEC Reference DF-79-07 fuel for testing to represent real world fuels. The B0 base fuel was blended with 7% of EN14214 certified Rapeseed Methyl Ester (RME) to represent the use of bio-fuels worldwide. As per CEC F-98-08, 1 mg/kg zinc (neodecanoate counter-ion) was added. Concentrations of zinc were confirmed by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES).

The clean-up fuel was identical to the dirty up fuel, but with the addition of a novel fuel-borne detergent.

In a variation from the established CEC method, an alternative lubricant, with an increased concentration of anti-wear additives was used to enhance engine durability.

Table 2. Particulars of the test fuels for DW10B engine tests

Fuel	Base Fuel	Target Zn Concentration (mg/kg)	Measured Zn Concentration (mg/kg)	Novel Detergent Package
Run-in	CEC DF-79-07 (Batch 6)	0	0	
Dirty-Up	B7 (ZSD + 7%v/v RME)	1.00	0.80	
Clean-Up		1.00	1.00-1.02	x

Test Cycle

The speed/load cycle employed throughout the engine test was as per CEC F-98-08. Please see the [appendix](#) for details.

Cold soaks were omitted from the test cycle, except where the engine was stopped to allow for injector removal and imaging by SEM.

Test Procedure

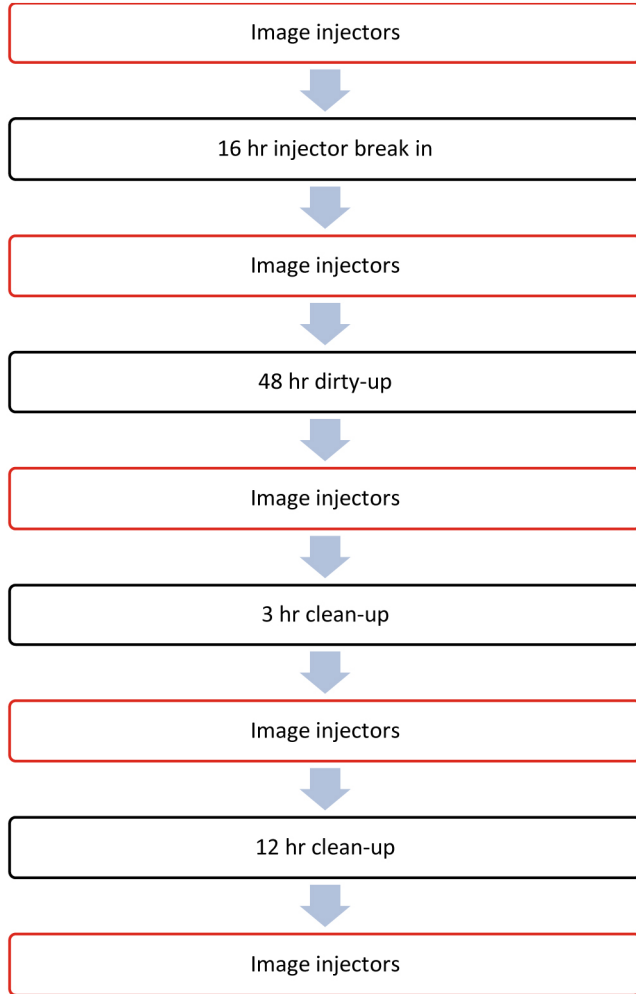


Figure 1. Test protocol for studying fuel injector hole deposits in a common rail direct injection test engine.

Analysis of Fuel Injector Hole Deposits

Fuel injectors were removed from the engine, while taking care not to damage any deposits on the injector tip, before preparation for SEM (via backscattered electron imaging), which was performed under variable pressure at 20 kV. EDX spectra data were also collected to gain information on the elemental content of the deposit layer; however the EDX data were corrupted and hence is not discussed. Further details on the SEM analysis can be found in the [appendix](#).

Results of Study of Fuel Injector Hole Deposits in a Common Rail Direct Injection Test Engine

Maximum Power Measurements

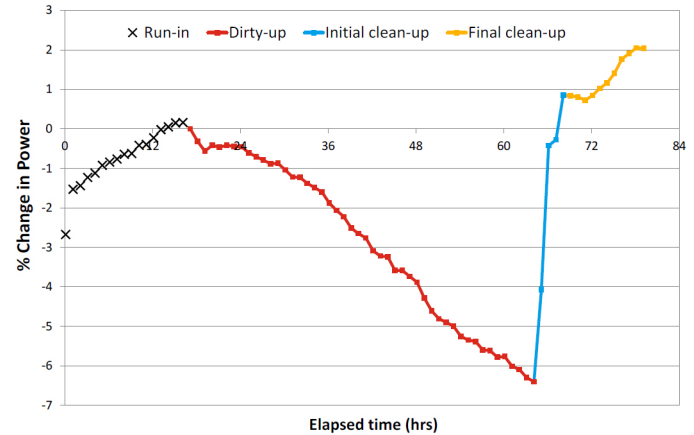


Figure 2. Percent change in power output during dirty-up and clean-up; note that the >100% power recovery is in line with the upward trend exhibited by the engine during the run-in.

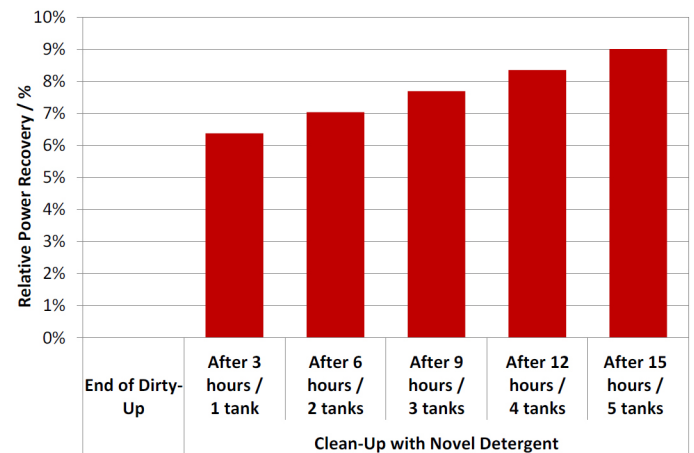


Figure 3. Relative power output of the test engine through the clean-up phase.

SEM Images of Injector Nozzle Holes Throughout Test

Back Scattered Electron Images

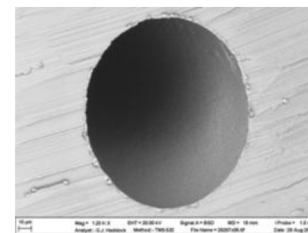


Figure 4. Clean Injector Hole (Prior to test commencement). Manufacturing marks on the outer surface and a smooth finish in the hole are evident

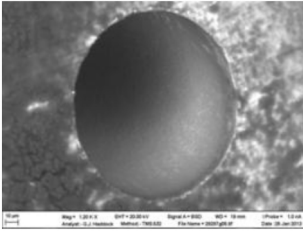


Figure 5. Bedded in Injector (16 hours bedding in, as per CEC F-98-08) A substantial deposit layer has formed on the outer surface but only light deposits are evident in the hole

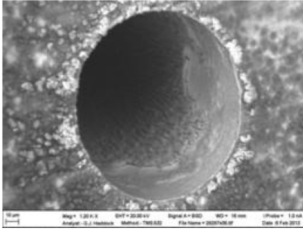


Figure 6. End of Dirty-Up. Deposits on the outer surface have increased and a thick deposit layer has formed in the hole

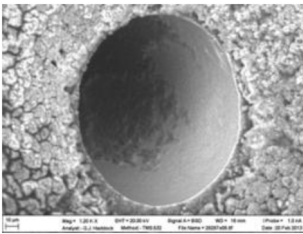


Figure 7. After 3 hours Clean-Up (66 litres - 1 tank). Deposits continue to accumulate on the outer surface and the deposits inside the hole are substantially reduced.

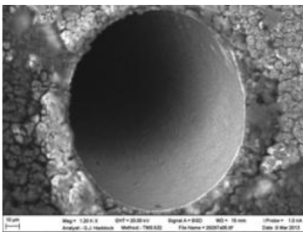


Figure 8. End of Clean-Up. Deposits continue to accumulate on the outer surface but have been completely removed from the nozzle hole.

Summary of bench engine study

Injector nozzle hole deposits have been studied in an adaptation of the industry standard CEC F-98-08 DW10B test with the aim of understanding the physical manifestation and performance effects of the deposits during formation and removal using a market realistic refinery sourced fuel containing FAME (B7).

The study of injector deposits through SEM imaging has visually linked the severity of deposits within the injector hole with the magnitude of power loss and recovery. Deposits outside of the nozzle hole increased with engine run time and were not linked to power loss or recovery as they do not affect delivery of fuel into the combustion

chamber. N.B. The rough surface morphology of deposits outside the injector hole lead to an increase in charging, giving their bright appearance in the SEMs, and is not indicative of the depth of deposits.

The mechanism for the effect of visible nozzle hole deposits on engine power is proposed to be a reduction in hydraulic efficiency of the nozzle hole. This is partly caused by the deposit layer reducing nozzle hole cross sectional area and partly from the visibly irregular deposit topography which will increase frictional flow loss; effectively reducing the flow capacity of the nozzle. Because the injected fuel quantity is metered on a time (not volume) basis, reduced nozzle flow capacity will reduce the amount of fuel passing through the injector into the cylinder available for combustion. Irregular deposits could also disrupt the fuel spray formation and atomisation, leading to reduced combustion efficiency or thermodynamic efficiency, resulting in increased emissions and reduced fuel efficiency and power.

Running the engine on the same zinc dosed dirty up fuel containing a novel detergent additive was proven to remove the deposits which were detectable through SEM and through recovery of lost power. The deposits were removed gradually as a function of time and/or fuel used. After 3 hours / 1 tank full of fuel equivalent, most of the power lost had been regained and the thickness, rather than the area of the deposit layer had been substantially reduced. This suggests that the deposit removal process is better described as delamination than edge erosion.

STUDYING FUEL INJECTOR HOLE DEPOSITS IN A FLEET OF EURO 5 VEHICLES

Experimental

Vehicle Selection

Vehicles were chosen for this study, based on the following criteria:

- Euro 5 emissions compliant - therefore all are fitted with modern common rail engines and DPFs;
- Represent 5 of the most popular European marques with read across to other vehicle types through common engine platforms;
- Represent a range of vehicle segments.

Table 3. Comparison of vehicles used in this study

Vehicle	OEM	Engine Capacity	Compression ratio	Output	Vehicle Segment
1	A	2.0L	16.5:1	170 PS	D
2	B	1.6L	16.5:1	105 PS	D
3	C	1.5L	15.2:1	110 PS	J - SUV
4	D	1.3L	16.8:1	95 PS	C
5	E	1.6L	16.0:1	115 PS	M - MPV

Test Fluids

CEC Reference RF-79-07 (batch 7) fuel was used throughout the Chassis Dynamometer (CD) testing. This fuel was selected to future-proof the results obtained; though the fuel used in the previously described static engine test was representative of a “real world”, refinery sourced fuel, by definition it is not a perpetuated fuel composition and will vary in time due to changes in refinery feedstock and market conditions. The CEC Reference RF-79-07 fuel composition will remain relatively constant driven by the requirement to adhere to the fuel's specification and this in turn will allow comparison of this work with future studies. Furthermore RF-79-07 has the relevance of being specified in the industry standard CEC F-98-08 nozzle fouling test.

A novel fuel-borne detergent (same chemistry and concentration as per the engine test discussed earlier) was added to the clean-up fuel, as well as the stabilisation/run-in fuel.

1 mg/kg zinc (neodecanoate counter-ion) was added to the dirty-up and clean-up fuels as specified in the CEC test. Concentrations of zinc were confirmed by ICP-AES.

Table 4. Particulars of the test fuels for chassis dynamometer test

Fuel	Base Fuel	Target Zn Concentration (mg/kg)	Measured Zinc Concentration (mg/kg)	Novel Detergent Package
Stabilisation	CEC DF-79-07 (Batch 7)	0	0	x
Dirty-Up		1.00	0.85-0.95	
Clean-Up		1.00	0.95	x

Tank Fill Intervals

As the CEC F-98-08 test clean up phase results were plotted at intervals relevant to the tank capacity of the donor vehicle a comparison of the fuel consumption and tank capacity of the CD test fleet was completed to show if a similar data interval was applicable for the data obtained - see [Table 5](#).

Table 5. Comparison of fuel tank capacity and fuel consumption

Vehicle	OEM	Tank Capacity (l)	Fuel Consumption (l/hr – in this test)	Fuel Consumed in 4 hrs (l)
1	A	65	16.1	64.6
2	B	70	12.6	50.6
3	C	55	12.5	50.0
4	D	56	10.0	39.8
5	E	70	12.6	50.3
Mean		63.2	12.8	51.1

The fill levels at which drivers refill their fuel tanks vary, but [Table 5](#) shows that for this test cycle and fleet, the 4 hour interval used to present data as “a tank fill” is appropriate as the average data show that a 5 hour interval would exceed the fleet average tank capacity.

Test Cycle

Vehicle testing was completed on a CD using a minor modification of a previously published [2] test cycle. The method combines high fouling operating conditions with pro-fouling fuels to give measureable and repeatable fouling and clean-up evaluation within a 36 hour test. The legitimacy of test methods designed to simulate injector nozzle fouling occurring in the field are often challenged due to their tendency to operate at loads (severity) exceeding those normally experienced in the field, e.g. the aforementioned CEC DW10B test, [1]. The Shell method maintains a representation of real world driving by incorporating >50% duration of the test drive cycle at typical motorway road loads.

Contextualisation of Test Cycle Severity

Equivalent uphill gradients for the test method conditions are given to contextualize test severity.

Table 6. Test cycle condition split and equivalent fleet average gradients of test conditions

Stage	Percentage time spent at condition	Equivalent gradient for fleet average (°)
Maximum Accelerator Pedal Position (APP) for power measurement	1.1	6.4
Road load	50	0
80% load	47	4.7
Coast down & Transients between conditions	1.9	Various negative and positive



Figure 9. Illustration of gradient equivalent to 80% load condition for fleet average.

The illustration in [Figure 9](#) shows that the gradient equivalent to load the ‘fleet average vehicle’ up to 80% at the defined road speeds would not be overly severe and could be encountered and