

A Chemical and Morphological Study of Diesel Injector Nozzle Deposits - Insights into their Formation and Growth Mechanisms

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ABSTRACT

Modern diesel passenger car technology continues to develop rapidly in response to demanding emissions, performance, refinement, cost and fuel efficiency requirements. This has included the implementation of high pressure common rail fuel systems employing high precision injectors with complex injection strategies, higher hydraulic efficiency injector nozzles and in some cases $<100\mu\text{m}$ nozzle hole diameters. With the trend towards lower diameter diesel injector nozzle holes and reduced cleaning through cavitation with higher hydraulic efficiency nozzles, it is increasingly important to focus on understanding the mechanism of diesel injector nozzle deposit formation and growth. In this study such deposits were analysed by cross-sectioning the diesel injector along the length of the nozzle hole enabling in-depth analysis of deposit morphology and composition change from the inlet to the outlet, using state-of-the-art electron microscopy techniques. Deposits produced in the injector nozzles of the industry standard fouling test (CEC F-98-08 DW10B bench engine) were compared with those formed in a vehicle driven on a chassis dynamometer, using a drive cycle more representative of real world vehicle conditions, to explore the effects of differing drive cycles and engine technologies. Fouling in all tests was accelerated with the addition of 1ppm zinc neodecanoate, as specified in the CEC DW10B test. This in-depth characterisation revealed a complex multi-layered system of deposits inside the diesel injector nozzle. Through analysing these layers the mechanisms enabling the initial deposit formation and growth can be postulated.

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INTRODUCTION

Direct injection fuel equipment has been developed to allow greater control of engine emissions and fuel economy whilst delivering more power and refinement. As fuel injection equipment has technologically advanced, injector nozzle holes have become smaller to improve the atomisation of the diesel spray. This requires increased control of the fuel injection events and delivery of diesel to the combustion chamber. To maintain this control, it is prudent to use fuels which have been formulated to prevent deposit build up inside injector holes [1].

The industry standard CEC F-98-08 DW10B bench engine test is a controlled and reproducible method that can achieve significant fouling within hours, making it a practical technique for deposit studies. It was introduced to demonstrate and measure the detrimental effects of injector nozzle deposits on engine performance in common rail engines, specifically engine power. Such deposits restrict and disrupt the flow of fuel through the injector, preventing optimal engine operation. A great number of DW10B injector fouling tests have been reported on in both regular and scientific literature [2] [3] [4] and yet little is known about the composition and distribution of deposits forming inside the injectors. This is primarily due to the

inaccessibility of the deposits forming in the narrow nozzle holes, which can be accessed only by careful sectioning. As the diameter of injector nozzle holes continues to reduce with optimisation of modern fuel injection equipment [5], the constriction effect produced by layers of deposit formation is predicted to increase; every micron of deposit thickness will create a proportionally larger constriction on the decreasing cross-sectional area of an injector nozzle hole.

Zinc neodecanoate is added to DW10B test fuel to accelerate fouling and produce a consistent, reliable and repeatable fouling response. Similarly fouling accelerants have been applied to other test procedures designed to be more representative of real world conditions in terms of vehicles and drive cycle, thus providing alternative testing platforms with which to rate deposit formation and control characteristics of fuels and additives. Additionally, fouling tests across a range of vehicles have shown the potential for injector nozzle deposits to detrimentally effect BSFC in chassis dynamometer tests [6] [7].

Previous examination of sectioned minisac type diesel injectors indicated that deposits range in composition, depending on the temperature at which the deposit formed [8]. In analysis of a

cross-sectioned diesel injector from a medium-duty truck engine, Tang *et al.* showed the deposit composition changed through the cross-section; in particular zinc appeared to be concentrated close to the metal surface of the nozzle and the deposit became more carbonaceous away from the metal interface as it grew thicker [9]. Variation in chemical composition through the deposit indicates that the deposit may form an initiation layer followed by a thicker secondary layer on top, in a growth mechanism which might not be uniform across the length of the injector nozzle.

Building on these previous insights, in the present study diesel injectors were sectioned and analysed to explore the reasons for non-uniform chemistries and morphologies along the injector, allowing for deposit formation and growth mechanisms to be postulated. Improved understanding of these mechanisms enhances the robustness of deposit formation theories and highlights key factors which are instrumental to deposit formation and growth. This study also allowed comparison between the deposits formed in the CEC DW10B test, and chassis dynamometer testing using a lower duty test cycle and a vehicle containing “in market” Fuel Injection Equipment (FIE) technologies, with no modifications to the engine to accommodate its operation on a test bench.

EXPERIMENTAL

Sources of Injectors

Three sets of diesel injectors run under different test conditions were used for this study:

The first set of injectors were sourced from a completed 32 hour DW10B dirty up (DU) engine test, using CEC B0 reference fuel containing 1mg/kg zinc (from neodecanoate) and Valve Covered Orifice (VCO) type injectors, as specified in the CEC F-98-08 test method.

Sets of injectors from an unmodified European specification Euro 5 diesel vehicle, featuring minisac nozzles, were obtained for this study. This vehicle was driven on a chassis dynamometer (CD) following a test procedure designed to evaluate fouling in vehicles [6]. The test cycle employed on the CD was developed to be more representative of driving conditions found in real vehicle operation than that specified in the DW10B engine test. Such additional tests are important as they demonstrate the full capabilities of deposit control additive options, increasing the confidence that an additive package will work across a range of conditions. The vehicle was subjected to two different tests; firstly a “dirty-up” (DU) test using CEC B0 reference fuel blended to contain 1mg/kg zinc from neodecanoate. Secondly, replacement injectors were installed and a “keep-clean” (KC) test was performed, using CEC B0 reference fuel containing the same zinc component and a diesel deposit control additive formulated at a concentration designed to prevent major deposit build up. From this point onwards injectors from each test will be labelled according to the abbreviations detailed in [Table 1](#).

In both the DW10B DU and the CD DU tests substantial power losses ($\geq 5\%$) attributed to injector nozzle fouling were observed, whilst the CD KC vehicle lost very little power. [Figure 1](#)

demonstrates the change in power across each test. Breaks in the power curves produced during CD testing are points where the diesel particulate filter regenerated, an additional complication of testing a modern car from the market. Data generated during actual regeneration has been omitted.

Table 1. Description of the tests that injectors had undergone for this study

Abbreviated injector name	Test	Fuel
DW10B DU	CEC DW10B dirty up test	CEC B0 + zinc
CD DU	CD dirty up test	CEC B0 + zinc
CD KC	CD keep clean test run with deposit control additive	CEC B0 + zinc + deposit control additive

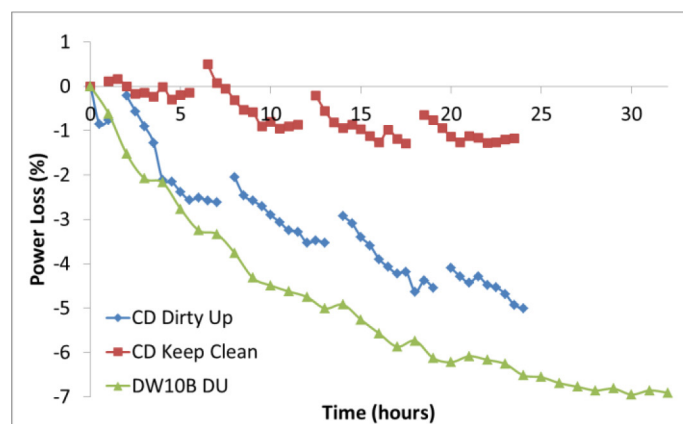


Figure 1. Power loss associated with injector fouling from each test.

Sectioning of Injectors

Injectors were removed from each engine after testing and carefully cross-sectioned to expose the extent of deposit formation in the nozzle hole, needle seat and sac areas. Sectioning was performed without cutting fluid to minimize disturbance to the deposits inside the injector nozzles. Where possible residual cutting swarf was removed with compressed air. Some residual fragments of steel remained and can be observed in the images.

Analysis Methods

Scanning Electron Microscopy (SEM) was used to image the cross-sectioned injector nozzles. For this work an FEI Quanta 650F Field Emission Gun SEM (FEG-SEM) was used, equipped with a secondary electron detector and operated at 10kV and 20kV. Features in the region of 0.5 μ m - 50mm are usually studied using this method. By combining SEM with Energy Dispersive X-Ray Spectroscopy (EDS), site specific chemical analysis can be obtained for regions of interest. This is a powerful technique allowing most elements and their location at the sample surface to be identified. With the introduction of new state of the art detectors it is now possible to identify elements with atomic numbers as low as carbon, which is necessary for this work. The EDS presented here was carried out using a Bruker XFlash@6 with Quantax 800

EDS data cannot be quantified absolutely in these types of samples due to the roughness of the surfaces being studied. However, it is possible to collect and process maps in a semi-quantitative manner to show relative trends in compositional variation and location of particular elements on the sample. The EDS maps produced have a colour assigned to each element and the intensity of the colour is an indication of the relative composition. The depth of sample from which X-rays are generated is dependent on the incident energy of the electron beam which is controlled by the operating voltage. If a higher operating voltage is used the electrons have more energy and so penetrate further. The emitted x-rays therefore originate from much deeper in the sample, not just the surface; when a lower operating voltage is used the chemical composition nearer to the surface of the sample is probed. This needs to be taken into consideration when investigating injectors because of the multilayer structure of the steel and deposition layers. There is also a trade-off between the depth being measured chemically and the element being studied - if the incident energy is too low, although more of the top layer of deposit may be being probed, only information about low atomic number elements will be obtained. In this research, to balance these two opposing requirements accelerating voltages of 10 and 20kV were used for all data.

RESULTS

Overview of Sectioned Injectors

Once sectioned an exposed nozzle hole of each injector was examined along its entire length (Figure 2). As expected, noticeable fouling was observed along the injector nozzle holes taken from the engines run on pro-fouling fuel and which experienced power loss (DW10B DU and CD DU tests). A clear deposit severity gradient was apparent along the nozzle holes, as deposit thickness varied from sub-micron size close to the inlet to more severe, $>10\text{ }\mu\text{m}$ thick, deposits at the outlet. This coincided with a general transition in morphology from a mostly smooth layer of deposit at the injector nozzle hole inlet to a rough deposit at the outlet. The exception to this was at the sac/inlet interface, where some thicker, moderately rough deposits were observed. Considering the full length of the nozzle hole, it can be seen that the deposit build up was less regular in the CD DU injector than in the DW10B DU injector.

Other than a few small flakes of material, mostly steel from the sectioning of the injector, there was no visible deposit in the area of the needle seat of the DW10B injector, with the original machining marks clearly visible (Figure 3a). Figure 3b however highlights a further issue, that of deposit build up in the minisac in real vehicles. These deposits encroached on the nozzle hole inlet, which would be unexpected in the DW10B due to its use of VCO nozzles.

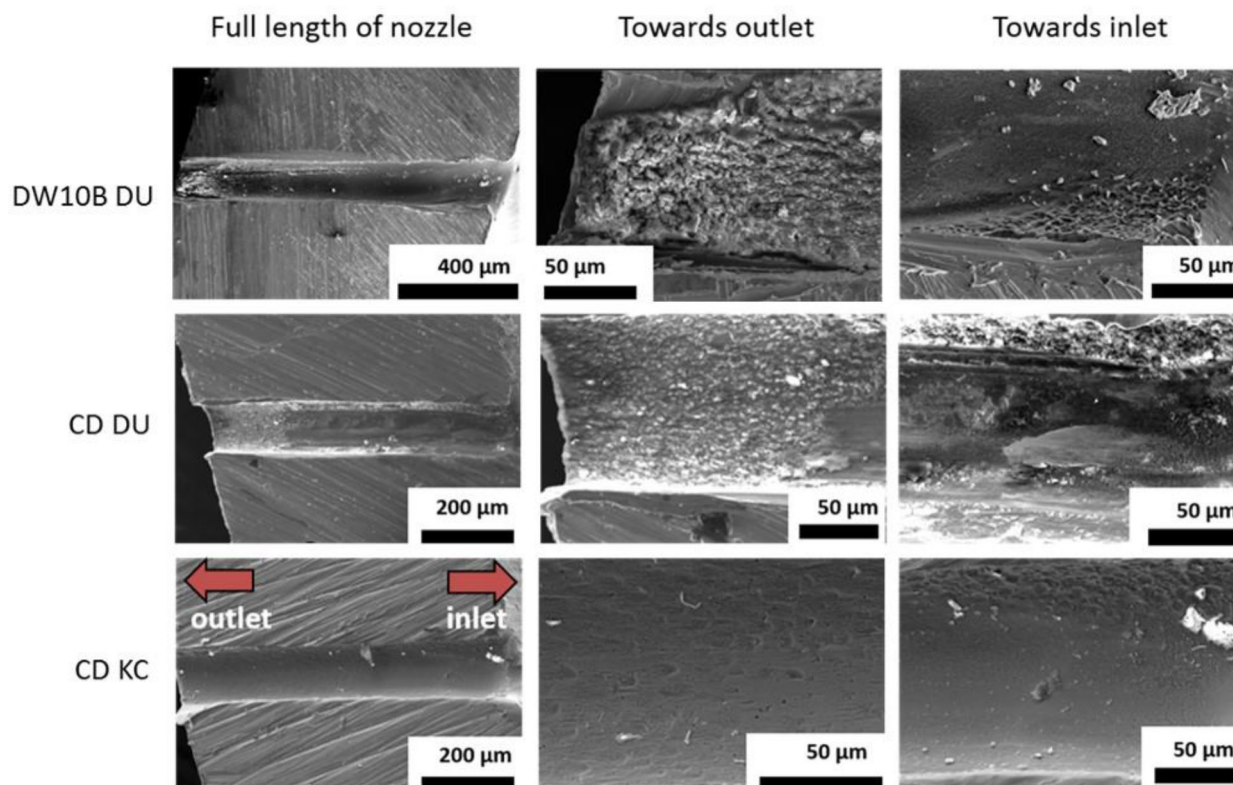


Figure 2. SEM overview of deposit formation across a diesel injector nozzle hole from each test.