

Deposit Control in Modern Diesel Fuel Injection Systems

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Infineum UK, Ltd.

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ABSTRACT

Modern diesel Fuel Injection Equipment (FIE) systems are susceptible to the formation of a variety of deposits. These can occur in different locations, e.g. in nozzle spray-holes and inside the injector body. The problems associated with deposits are increasing and are seen in both Passenger Car (PC) and Heavy Duty (HD) vehicles. Mechanisms responsible for the formation of these deposits are not limited to one particular type.

This paper reviews FIE deposits developed in modern PC and HD engines using a variety of bench engine testing and field trials. Euro 4/ IV and Euro 5/V engines were selected for this programme. The fuels used ranged from fossil only to distillate fuels containing up to 10% Fatty Acid Methyl Ester (FAME) and then treated with additives to overcome the formation of FIE deposits.

It was observed that engine performance was significantly impacted by the formation of deposits which may lead to increased fuel consumption, loss in power, poor driveability and failure to start.

The selection of appropriate fuel additive technology allows control of all deposit types, either by preventing their formation or restoring engine performance.

INTRODUCTION

Modern-day diesel powered vehicles are subject to increasingly stringent exhaust emission regulations, whilst at the same time having to meet end user requirements with respect to power, torque, fuel economy, good driveability and increasing levels of refinement. In addition, concerns over climate change have resulted in measures being taken to reduce CO₂ emissions from road transport. For example, in

Europe a target of 120 g/km for passenger cars will be phased in from 2012 to 2015, with punitive financial penalties for failure to meet the targets. For light commercial vehicles, the fleet average CO₂ limit will be 175 g/km, being phased in from 2014 to 2016.

Diesel powertrains have already undergone major technical advances in order to satisfy regulatory and end user requirements, and these will continue to be further developed. Advances in Common Rail (CR) FIE have included increased injection pressure, multiple injection strategies, smaller nozzle holes and high efficiency injector nozzles. These measures ensure the precise and repeatable metering of even the smallest quantities of fuel as well as providing the excellent fuel atomisation and spray characteristics necessary across all engine operating conditions to promote more complete combustion. Other recent developments have included direct-acting piezoelectric injectors, which provide improved atomisation and more accurate fuelling control resulting in reduced gaseous emissions, higher power and torque and improved fuel economy [1].

These recent technical advances in fuel injection systems require components to be smaller and lighter to ensure highly dynamic response. They need to be manufactured to very exacting tolerances and have to operate within very small clearances to minimise any leakage at the very high pressures encountered in modern systems. Therefore, it is essential that the FIE is kept free from deposits of any kind and is operated with fuel which is fit for purpose, otherwise problems of power loss, emissions non-compliance, reduced fuel economy, poor driveability and difficulty in starting are likely to be observed.

DEPOSIT FORMATION IN OLD, CURRENT AND MODERN FIE SYSTEMS

Injector spray-hole deposits have been observed for many years. Historically, these were most problematical in InDirect Injection (IDI) engines operating with pintle type injector nozzles. This resulted in the development of the CEC-023 injector deposit test based upon a Peugeot XUD9 engine intended for passenger car applications. The test defined an “acceptable” level of deposit which would allow satisfactory engine performance. This enabled the engine manufacturers and FIE companies to develop FIE systems which were specifically designed to operate with the levels of deposits which would result from operation with typical market fuels [2]. Mentioned in this reference is that ‘complete elimination of deposits is undesirable as nozzles are ‘designed’ to give optimum performance with a certain level of deposit. This is the only FIE system where complete cleanliness is considered undesirable. However, the use of this particular type of FIE design was discontinued in the late 1990’s because of its inability to meet stringent emission regulations.

Direct Injection (DI) and High Speed Direct Injection (HSDI) engines did not suffer to the same extent, but more recently the trend for smaller holes and high efficiency nozzles has resulted in many more instances of injector spray-hole deposits causing problems [3, 4, 5]. The reasons for this increase include:

1. Smaller holes which for a given deposit level will result in a proportionately larger reduction in flow area and therefore larger flow rate reduction, resulting in loss of torque and power.
2. High efficiency nozzles with honed entry to nozzle holes and/or tapered nozzle holes resulting in reduction or elimination of cavitating flow within the nozzle. The collapse of cavities in such flow regimes is known to be effective in dislodging and preventing the build up of deposits.
3. Combustion and air management trends resulting in higher nozzle tip temperatures, which promote nozzle deposits. The trend towards downsized engines will tend to exacerbate this.

The FIE systems utilised since the late 1990s, unlike those described in [reference 2](#), require no or very minor level of deposits to perform at their best, hence ensuring the lowest possible level of noxious emissions and fuel consumption. Therefore, a fuel additive solution to control deposit formation is very complex to achieve as the requirements are dependent of the FIE type. It is therefore the remit of the additive and fuel formulator to develop solutions that are applicable to such a diverse range of FIE systems. This challenging target can however be met as described in [reference \[6\]](#) where the best level of spray-hole deposit is achieved for any FIE system in the market:

I). No deposits in modern FIE systems

II). The level of deposit that the IDI system has been calibrated to [2]

Internal Injector Deposits (IID) are a relatively new phenomenon, initially reported in PC applications [7, 8], and now increasingly observed in PC and HD vehicles. Currently the problem appears to be particularly acute in HD applications in North America, and as a consequence the CRC has now formed a working group to look at this issue. In addition, there have been reports of deposits in high pressure fuel pumps causing operational problems.

FUEL ADDITIVE APPROACH

The problems described in the previous chapter are seen in a variety of countries and can occur in PC and HD type applications equipped with High Pressure Common Rail (HPCR) systems or with Electronic Unit Injectors (EUI). These problems are not specific to one fuel type as they are seen in markets that have Ultra Low Sulphur Diesel (ULSD) fuel, but also in markets where sulphur (S) level is up to 500 ppm. It would seem that the presence of Fatty Acid Methyl Ester (FAME) can significantly vary the level of deposit, sometimes more, equivalent or lower than that seen in fossil based diesel fuel. Therefore, the mix of issues is complex and is somewhat difficult to postulate mechanisms that describe all the phenomena experienced. It has been made aware to the authors that more than 20 companies around the world have reported one or more of these issues related to injector deposits.

Traditionally, injector deposits have been tackled by the use of detergent/surfactants chemistries developed in the 1980s. Through their life, such fuel additives have undergone a variety of improvements to increase their performance and cost effectiveness. However, studies carried out recently [3, 4, 6] have confirmed that these chemistries are no longer the best option to deal with a type of deposit that is chemically different from the wholly carbonaceous type deposit seen in IDI type FIE or that which is formed in a completely different area of the fuel injector [7,8].

The challenge then becomes the development of an additive solution which can deal with all these types of deposits. This would then allow any fuel used in the market place to overcome most of the issues that have recently surfaced, and this is the task that has been addressed in this paper. New diesel detergent technology has been tested in a variety of FIE system applications to understand the potential for the control of different types of injector deposit. In some of these tests, the results obtained have also been compared with conventional diesel detergents.

The testing carried out used modern engines which are fitted with the latest FIE systems. As such, the expectation is that

there should not be a large change in engine performance over the short period of time typical of the deposit test cycles described in this paper. Therefore, the effects that are observed in the testing carried out can be largely attributed to FIE deposits being formed.

Engine Testing

The testing undertaken encompassed the use of the CEC DW10 bench engine test and field trials using passenger cars fitted with CR Euro 4 engines to assess the performance regarding spray-hole deposits. HD bench engine tests were used to confirm additive performance in EUI Euro IV engines, whilst an advanced Euro V engine was used to understand the ability to prevent one particular type of internal injector deposits.

Test Fuels

In the market today there are a variety of fuel qualities. These range from fuels of different S level, to those containing different level of bio-component, typically FAME. In order to confirm the performance of the additives tested, a variety of fossil fuels and BX have been selected (X is the percentage of bio-component). Today, diesel fuel can contain bio-component. In Europe B7 is now becoming more prevalent and as the level of the bio-component will further increase in the future, most of the data were developed in European type fuels containing 10% FAME.

Zinc contamination has been used in most testing presented in this study. Metal contamination has shown to be present in field conditions. Two sources have been described, the first contamination occurs prior to fuel delivery into vehicle tanks; the other happens due to the corrosive attack of the fuel toward FIE components [5, 11]. Therefore, there is scope for metal contamination of fuel throughout its pathway from refinery to its combustion in the engine. The metal contamination, together with fuel degradation products, can accumulate within the FIE system causing deposits that can lead to increased fuel consumption, loss in power and poor drivability. A further study has been conducted to confirm this potential. Twenty five different ULSD fuel samples have been collected from service stations in the same market/country. The level of metal contamination was measured. Several metals were found to be present including Zn, Na. The level of Zn and Na measured is reported in the [table 1](#) below. In this market FAME is not yet used. The expectation is that the presence of this bio-component will further exacerbate the metal pick up potential.

Table 1. Zn and Na content of 25 ULSD market samples

Metal, ppm in ULSD		
	Zn	Na
0	13	5
up to 0.2	5	3
up to 0.4	2	2
up to 0.6	-	7
up to 0.8	1	4
up to 1.0	-	4
up to 1.2	-	-
up to 1.4	1	-
up to 1.6	-	-
up to 1.8	1	-
up to 2.0	1	-
≥ 2.0	1	-

Passenger Cars

With the plethora of fuel qualities available in the market place, there is an increasing incentive for an additive company to supply detergent technologies that work effectively across the board. The CEC F-098-08 Peugeot DW10 engine is widely recognised as the industry standard injector deposit test for Euro 5 and beyond [3, 6]. This section examines the appetite and propensity to form deposits of varying fuel types in this test with and without diesel detergents.

Infineum's experience with this test has shown that base fuels of different origin have a varying degree of propensity to foul injectors resulting in power loss. The CEC procedure prescribes the use of DF-79-07 as the reference fuel for the test with and without metal contamination, where the metal contamination is 1 ppm Zinc (Zn). It can be noted that fossil fuels which are not contaminated with metal prior to the test do not usually show the tendency to foul injectors. However, the fouling levels can be quite substantial with the level of metal contamination used in the CEC reference fuel (which is indicative of the level of Zn observed in the field).

[Figure 1](#) demonstrates the level of power loss observed when using different fuels over an extended period of time. DF-79-07 at 32 hours has developed up to 6.5% power loss; conversely a standard EN590 fossil fuel (EU 1) achieved up to 12% power loss. Additional tests were then carried out to understand what the maximum possible fouling level was for both fuels. Extending the run time to 64 h did not change the level of deposit for the CEC reference fuel, however for EU 1 fuel, the deposit level further increased by an additional 5% by 80 h.

Moreover, at the end of this test, this fuel continued to show a trend to develop further deposits. This phenomenon has also

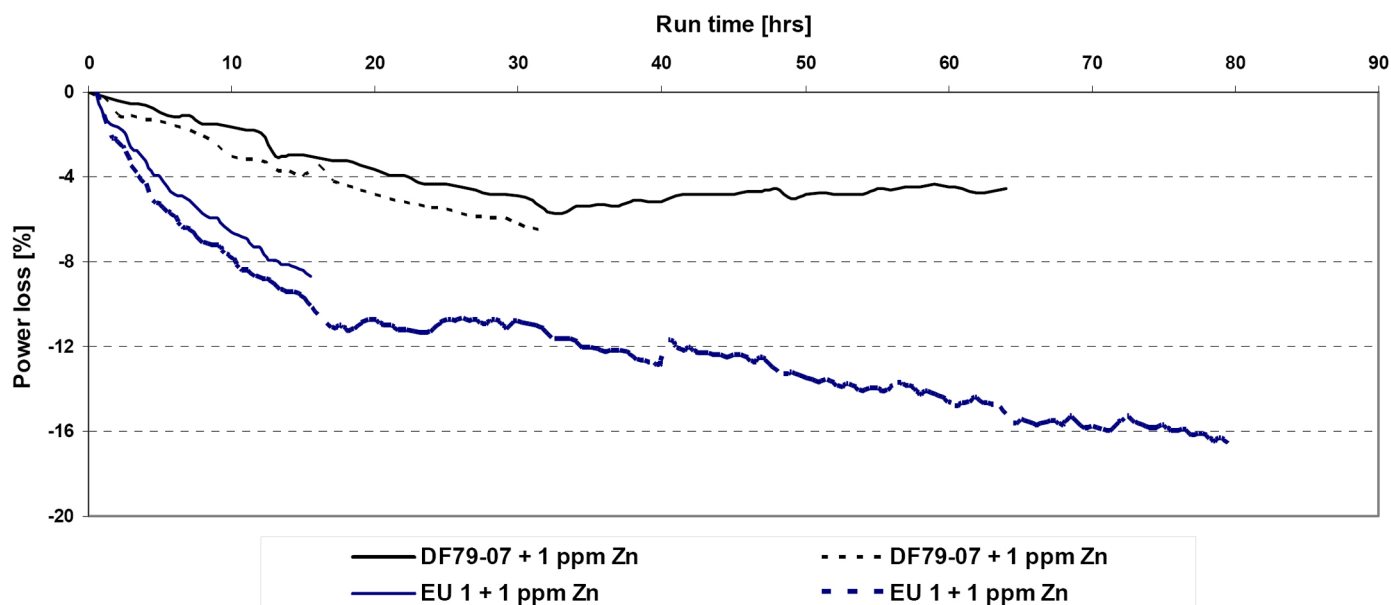


Figure 1. DW10 power loss results for B0 reference fuels with 1 ppm Zn.

been seen with other fuels from Europe and Asia Pacific in testing recently carried out. The level of fouling shown is similar to the EU 1 fuel, whilst different batches of the CEC reference fuel, tested in different DW10 engines, have only given between 4 and 6% power loss with 1 ppm Zn. These data suggest that the CEC reference fuel, if anything, is representative of market fuels which generate a low level of injector deposits. Possibly, the typical market fuel has a higher degree of fouling as also confirmed in other papers [9].

As previously mentioned, the use of FAME in the DW10 test can result in varying levels of injector fouling. Numerous papers, including that presented by the CEC working group, describe extensive studies in this area. There does not seem to be a clear and agreed position on why different biofuels in diesel generate different level of deposits. The level of possible oxidative degradation, as measured by the Rancimat test or inferred from the iodine value, and the level of impurities like mono-glycerides do not seem to correlate with the deposit formation rates observed [10]. Therefore, our work focussed on the use of test fuels containing bio-component with 1 ppm Zn in an effort to provide consistency in deposit generation. The data in [table 2](#) show that:

1. The European BX market fuels tested have a large deposit formation propensity when metal contamination occurs.
2. Using the same biofuel batch of RME, the results seen are very variable and also somewhat confusing. The RME10 alone has the highest level of injector deposit. When this test was repeated with 1 ppm Zn added, the result was better, from 15% to just below 5% power loss. This phenomenon has been seen in some studies, whilst others have reported the opposite effect [4].

3. The reference fuel and the market fuel treated with the same batch of RME at different levels of BX gave substantially different results, from just below 5% power loss to more than 8%.

4. Different batches of commercial RME give can also give different results

These data confirm that the behaviour of FAME is variable and can not be predicted as yet. Furthermore, the profile at 32 hours shows that deposit is still forming and, for some BX fuels, the downward trend is still very pronounced (not reported in this paper). The implication is that any additive treat rate that is used to control injector coking must take this into account. Therefore, any safe level selected for market use should be able to cope with fuels as severe as those shown. This is further supported by other studies where similarly high levels of deposits were reported for market fuels [9].

These types of injector deposits can be controlled with appropriate additive technology for entirely fossil and FAME containing diesel as shown in [figure 2](#). The treat rate used (as active ingredient or as a component) for the new diesel detergent is substantially lower than the typical treat rate of conventional diesel detergent used in most standard market diesel fuel. The treat rate of the new diesel detergent used to develop the data in [figure 2](#) is the same for fossil fuel and BX.

For ease of interpretation, new diesel detergent has been abbreviated to NewD and conventional diesel detergent to ConvD in all figures going forward.

Table 2. DW10 results in BX fuels with and without 1 ppm Zn.

Fuel	DF79-07	DF79-07	EU 2	EU 3	EU 4
Bio-Component [%]	10	10	7	2	5
FAME Source	RME 1	RME 1	RME 1	RME 2	RME 2
Zinc Level [ppm]	0	1	1	1	1
Power Loss at 32 hours [%]	-15.09	-4.79	-8.62	-9.4	-6.93

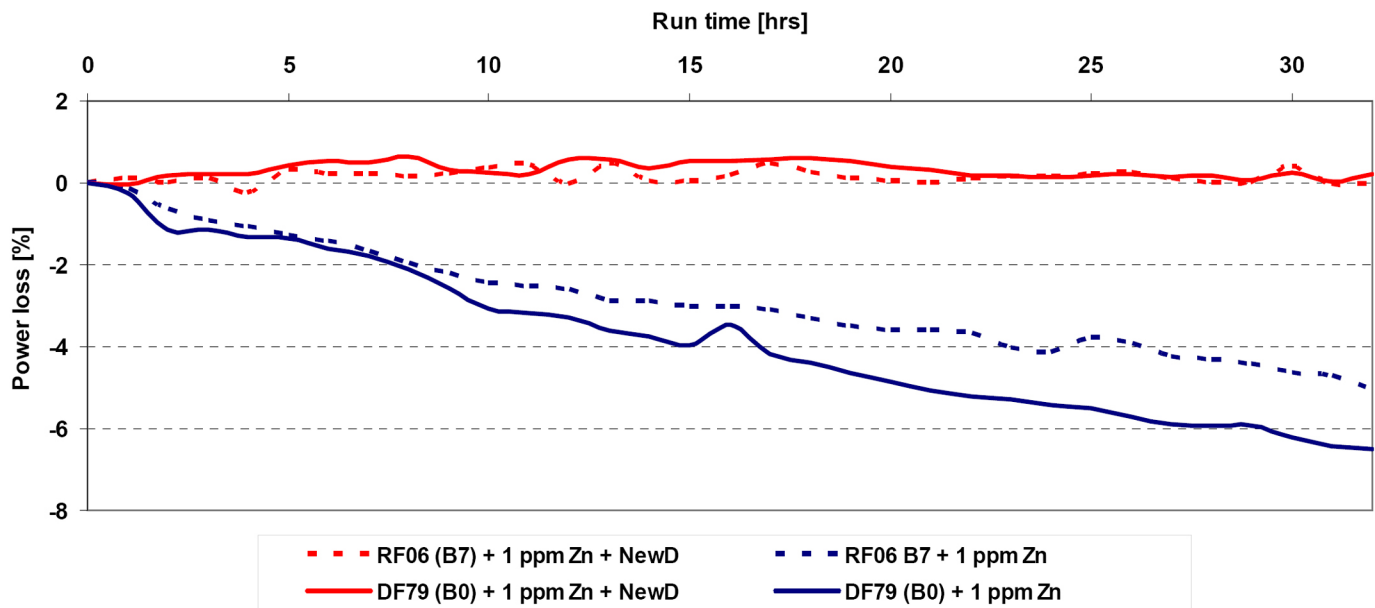


Figure 2. DW10 power loss results of base fuel with 1 ppm Zn and the same fuel treated with NewD, at a treat rate which is lower than typical treat rate of conventional detergent for most standard fuel qualities in the market place today.

With the same additive technology it is possible to achieve reliable and consistent clean up performance in this type of test. The injectors are first run on base fuel for 32h, as per the CEC test, or until a certain level of power loss has been reached. Then, the same fuel treated with additive is used to assess its cleaning ability. Typically, additive treat rates used are higher than those applied to keep the injector clean.

The ability of the new diesel detergent to remove deposits at a treat rate which is typical for top premium fuel qualities in the market place today can be seen in [figure 3](#). The power loss in this engine test is proportional to the deposit level as confirmed by the findings of the CEC 098 working group. The clean up profile suggests that the vast majority of the deposit is removed in the first hour, approximately 70%, which corresponds to 2% absolute power loss. This is generally considered by the industry to be the maximum acceptable level for modern powertrains. The rate of cleaning

reduces after the first hour and all the deposit is removed with a further 11 hours of running. The data have been obtained in a typical European B7 market fuel.

It has been observed, that by varying the relative treat rates of the new diesel detergent technology, the rate/profile of power restoration in the first few hours will differ greatly, whilst the subsequent rate of cleaning is somewhat similar regardless of the additive treat rate level, see [figure 4](#). This shows the potential that, at elevated treat rate, the new detergent can reach the industry target of less than 2% power loss well within a tank full of premium fuel (equivalent to 80% normalised power loss in [figure 3](#)).

Several papers report that conventional diesel detergents, usually long chain poly-isobutylene/polar bridge/N rich surfactants, are less effective in this environment [8]. This describes the typical chemical signature of most diesel