

Investigations on Deposit Formation in the Holes of Diesel Injector Nozzles

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ABSTRACT

Current developments in fuels and emissions regulations are resulting in an increasingly severe operating environment for diesel fuel injection systems. The formation of deposits within the holes or on the outside of the injector nozzle can affect the overall system performance. The rate of deposit formation is affected by a number of parameters, including operating conditions and fuel composition. For the work reported here an accelerated test procedure was developed to evaluate the relative importance of some of these parameters in a high pressure common rail fuel injection system. The resulting methodology produced measurable deposits in a custom made injector nozzle on a single cylinder engine. The results indicate that fuels containing 30%v/v and 100% Fatty Acid Methyl Ester (FAME), that does not meet EN 14214 produced more deposit than an EN590 petroleum diesel fuel. Overall, the addition of zinc to the fuel had the biggest effect on deposit formation and resulted in a 12.2% decrease in Indicated Mean Effective Pressure (IMEP). The effects of zinc were unexpectedly reduced when it was added to fuel containing 30%v/v biodiesel. Reducing the common-rail pressure with 30%v/v biodiesel (no added zinc) increased the loss in IMEP. Raising the air and fuel temperatures by 40°C and 30°C respectively showed no bigger loss in IMEP. The results indicate that deposit formation may continue after engine shut down.

INTRODUCTION

Significant pressure exists to improve the fuel economy and CO₂ emissions of passenger cars, often reinforced by legislative demands directed towards strict emissions and fuel economy limits. The common rail fuel injection system plays a central role in

achieving these requirements through more accurate and more frequent injections per cycle at higher fuel rail pressures. As a result, the overall system design including the nozzle is evolving rapidly to optimize spray quality and control. The latest injector designs balance these parameters to optimise performance while maintaining durability even under the most demanding operating conditions.

The formation and the removal of deposits in any location in an engine was described by Lepperhoff and Houben [1]. A mechanism for the formation of deposits in injector nozzles was described by Caprotti [2] and is shown in Figure 1. The resulting deposits have the potential to restrict the hydraulic flow in the nozzle holes, thereby reducing maximum flow rate and engine power. Such deposits can also affect the fuel spray quality, resulting in increased fuel consumption and emissions [3, 4].

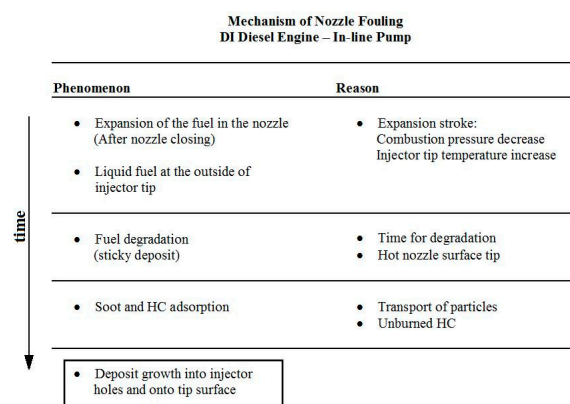


Figure 1 Mechanism of Deposit Formation [2]

Previous publications have identified three main influences on injector deposits: nozzle geometry, fuel composition and temperature [5]. The geometry of the nozzle design as an influence was identified by Argueyrolles et al. [6]. Streamlining reduces the turbulence and cavitation in the fuel, which may have the effect of reducing the ability of the fuel to remove deposits from the nozzle. Modern nozzles are designed to minimise energy losses due to cavitation, raising the possibility that deposits may form more easily with this design.

At the same time, Fatty Acid Methyl Ester (FAME) is rapidly becoming more widely used as a fuel component in compression ignition engines. Some publications show that FAME can cause increased nozzle hole deposits [7]. The influence of 5%v/v biodiesel was investigated by [8] and the influence of 10%v/v biodiesel was instigated by [9, 10, 11]. Overall, the effect of biodiesel remains unclear.

Small concentrations (1-3ppm) of zinc have long been recognised as a major influence on injector coking [12, 13, 14]. A number of other publications have discussed the role of zinc, either as a catalyst or as a deposit component [9, 14]. Pick up of zinc is possibly aggravated by use of aged or acidic biodiesel or through use of acidic lubricity additives [12], although such additives are becoming increasingly rare. An industry standard engine test exists for evaluation of nozzle coking tendency using 3 ppm zinc to promote deposit formation [15]. The relationship of this test procedure to real world driving is discussed in [10].

A critical temperature of 300°C is mentioned as raising the amount of injector coking by thermal condensation and cracking reactions, see [16].

MAIN SECTION

EXPERIMENTAL APPROACH AND TEST METHODOLOGY

SINGLE CYLINDER ENGINE TEST

A test methodology was required that produced measurable and repeatable deposits within a reasonable test duration. The mechanism outlined in Figure 1 shows that deposits are affected by the combustion process, including the compression and expansion of combustion gasses through the nozzle holes. These gasses contain combustion products and soot, as well as volatilized crankcase lubricant and additives, which contain zinc and phosphorous. As a result, a fired engine test is unavoidable.

A single-cylinder engine, based on the Ricardo Hydra experimental engine design was built. The engine head and piston were taken from a commercially available 4-cylinder 2.0 litre high speed turbocharged automotive diesel engine equipped with a common rail injection system. The engine cylinder bore and stroke were both 86mm and the piston was of the bowl-in-piston design. An adaptor plate was used to

convert the 4-cylinder head so that only cylinder no. 1 was operational.

An external supercharger air system was designed and installed. A screw-compressor driven by a variable speed electrical motor was used to pressurise the air which was cooled using a heat exchanger. As a result, the temperature and pressure of the air in the engine manifold could be independently controlled. The exhaust back pressure was set with a fixed exhaust gas throttle before all engine tests and no Exhaust Gas Recirculation (EGR) was used for any of the tests.

The instantaneous in-cylinder pressure was measured using a piezo-electric quartz pressure transducer, which was installed via a glow plug adaptor. The air-manifold pressure, in-cylinder pressure and exhaust pressure were recorded every 0.2 Crank Angle Degrees (CAD), timed by an optical shaft encoder driven from the engine crankshaft. Engine speed, torque, air inlet- and exhaust-temperature were recorded. Fuel consumption was measured with an AVL gravimetric fuel balance. Engine Brake Mean Effective Pressure (BMEP) was obtained from measurements of the torque reaction on the engine brake, monitored by means of a load cell. Indicated Mean Effective Pressure (IMEP) was instantaneously calculated from the in-cylinder pressure. Specially written data acquisition and analysis software allowed heat release analysis to be performed continuously while the testing was in progress.

The control system for the fuel injection system allowed free control of all injection parameters. The fuel injection system was based on a modern common-rail design with a servo-hydraulic injector containing a non production nozzle. The nozzle had 7 holes and was of a μ -sac design with a high discharge coefficient (Cd) value likely to produce minimal or no cavitation. This tended to accelerate the rate of deposit formation relative to production equipment, while maintaining the same overall trends. A new injector having a new nozzle set was fitted to the engine prior to each test. All injectors were run-in to give their optimum performance at the start of each test.

Prior to starting the engine, electrical heaters were used to warm the crankcase lubricant and coolant for approximately 20 minutes. The engine was then started and the engine speed was increased accompanied by increasing load. A load sweep was performed at a constant air temperature of 55°C. For this load sweep, the injection duration was increased stepwise until the operating point was reached. A full set of measurements was taken at each point. The last point of the load sweep was the high load point of the test cycle. This point was used as reference point / nominal point for any drop in IMEP. This point is represented in the subsequent plots as a solid marker. After the load sweep, the main test cycle started and the air temperature was further increased to 70°C (30°C for Test No. 3). At the end of the test cycle the same load sweep was performed but with a stepwise decrease in the injection duration. This was done to allow any drop in IMEP to be measured over multiple

load points. In the subsequent plots this is again represented by the solid marker, whilst the continuous lines represent the measurements made throughout each test day.

The main engine load cycle consisted of cycling the load for 10 minutes at high load followed by 10 minutes at very low load - almost engine motoring condition. These high and low load conditions were defined by a fixed injection pulse duration. At the low load motoring condition, only a small quantity of fuel was injected, at common rail pressure 400bar and 300µsec injection duration. This was done to maintain diesel fuel in the nozzle holes, to encourage the build up of further deposits. During the test cycle the high load and low load injection durations were kept constant, so that any deposits in the holes of the injector could be observed as a drop in IMEP and BMEP and thereby a reduction in engine power output. The test cycle was repeated on two consecutive days with a shut down period over night.

Further details of the test matrix, including the engine operating conditions, are shown in Table 1. During the tests the fuel temperature was normally set to 60°C and the air temperature was set to 70°C. Test No. 2 was performed with a constant load instead of cycling load. Test No. 3 was run at 35°C fuel temperature and 30°C air temperature to ascertain the effects of temperature, while Test No 4 was performed to define the effects of injection pressure. The engine speed was always constant at 2800 RPM and the boost pressure was constant at 1.98 bar.

Table 1 Engine test matrix and engine operating details

Test No.	Fuel Comp.	Load Cycle	Fuel Temp. [°C]	Air Temp. [°C]	Fuel Press. [bar]
1	30%v/v FAME (B30)	Cyclical	60	70	700
2	B30	Constant	60	70	700
3	B30	Cyclical	35	30	700
4	B30	Cyclical	60	70	1100
5	B0 (RF06)	Cyclical	60	70	700
6	100% FAME (B100)	Cyclical	60	70	700
7	B0 +3 ppm Zn	Cyclical	60	70	700
8	B30+3 ppm Zn	Cyclical	60	70	700

TEST FUELS

As previously discussed, some of the fuel variables likely to affect deposit formation are zinc and biodiesel concentration. Reference diesel (B0 / RF06) was used as the base fuel, this fuel was chosen since it did not contain any biodiesel or performance additives. The principal characteristics of this fuel are detailed in Table A-1 and A-3 in the appendix and confirm that it contains low levels of zinc and other elements.

The biodiesel used was based on transesterified used vegetable cooking oil. The batch used for this work did not meet the EN14214 standard for pure FAME, as shown in Table A-2. Elemental analysis is provided in Table A-3. The sodium content is relatively high in the bio-fuel, which is probably due to the use of sodium hydroxide as a catalyst during the transesterification process. Engine tests were performed with both the pure biodiesel (B100) and a blend (B30) of 30%v/v biodiesel with 70%v/v of the RF06 reference diesel fuel.

A number of tests were performed with 3 ppm of zinc added to the fuel. This was achieved with the addition of zinc neodecanoate. The zinc compound was added to the RF06 reference fuel for test No. 7 and to the B30 blend for test No. 8.

RESULTS

INFLUENCE OF TEST CYCLE

Several preliminary tests were performed to optimize and validate the engine test conditions. This test sequence was performed using B30 fuel, which caused measurable deposits.

Tests No. 1 and 2 were performed to define the effects of cyclical versus constant load conditions. In Test 1, the engine was operated at the test conditions described in Table 1, which gave a nominal starting IMEP of ca. 13.4bar. Test No. 2 was conducted with steady state load instead of the cycling load. The remaining conditions of the two tests were identical.

The results are plotted in Figure 2 as a function of test duration. A decrease in IMEP is observed with both test conditions. The cyclically varying test produced a larger decrease in IMEP (4.1%) than the constant load test (2.88%). It is likely that the low load portion of the cyclical load test maintains a small amount of fuel in the nozzle holes, to encourage the build up of further deposits. All subsequent tests were performed with varying load.