Investigating the impact of copper leaching on combustion characteristics and particulate emissions in HPCR diesel engines.

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Abstract

A helicoidally shaped copper duct was installed along the fuel line just before the high pressure pump. The impact of fuel contamination from this copper duct on combustion and emission characteristics of a Direct Injection High Pressure Common Rail (DI HPCR) diesel engine was investigated. The copper duct constitutes the core of a fuel conditioning device, powered from the battery. A single cylinder Ricardo Hydra research engine with the cylinder head, piston assembly and crankshaft from a production 2.2 L DI diesel engine was used in the investigation. Combustion characteristics were analysed via post-processing pressure measurements, while an AVL Smoke Meter was used to monitor particulate emissions. A diesel fuel with a copper content of less than 0.2ppm was used. Inductively coupled plasma mass spectrometry (ICP-MS) analysis of the fuel showed copper leaching into the fuel, with 1 ppm Cu being found in the fuel after flowing through the helicoidally shaped duct. Recirculation of fuel to the tank led to an increase of Cu concentration in the fuel. A pilot plus main strategy was used to achieve a target Brake Mean Effect Pressure (BMEP) typical of medium load. Soot reduction in the range of 7-14% was measured when the device was connected to the fuel line, compared to the baseline. The initiation and early development of combustion was also investigated using

an unstirred, quiescent combustion chamber with optical access, and the results corroborate findings from the engine work.

Introduction

Recent predictions of the demise of the automotive internal combustion engine (ICE) have been greatly exaggerated, as hybrids are a key part of the long-term transport plan. Mild hybrids with clean ICEs are forecast to be popular in small and medium sized cars, while heavier commuter and heavy-duty long haul vehicles will still be reliant on diesel. The recent Bosch breakthrough offers an opportunity for aggressive emission reductions (i.e. 5 times below the legal limit). Regulations will continue to restrict further the exhaust emissions, with particular attention paid to new pollutants and particulate emissions. It is likely that particulates will be limited using new number and size-based metrics with thresholds as low as 10nm or less. Greater emphasis will also be given to pollutant emissions studies based on real-driving conditions, in contrast to defined test procedures. Though particulate filters are effective when employed to trap particulate matter in the exhaust gas stream, their use comes at the cost of increased backpressure and consequent decrease in engine efficiency and fuel economy. Additional decreases in fuel economy arise due to filter regeneration events [1]. Moreover, while engine calibration over the Worldwide harmonized Light vehicles Test Cycle (WLTC) allows for the limits to be met, real driving emission, cold start and performance subsistence over the entire vehicle life constitute a real challenge. These challenges have recently been faced also by the modern gasoline direct injection engines [2,3]. Researchers' efforts have been focusing on reducing formation of particulate matter via improving combustion chamber design, fuel injection strategies, combustion modes, and new fuels. Considerable numbers of diesel vehicles, including registered agricultural, construction vehicles and other off-road applications such as boats, currently in use are well behind with regards to Euro standards compliance. Retrofitting of particulate filters is challenging due to high soot emission levels causing premature failure of these after-treatment devices [4]. To meet the stringent emissions legislation governing air pollutants released into the atmosphere requires the addition of new technology to older systems aiming at needs to either prevent or reduce the formation of particulate matter to levels that are manageable for the filtration systems.

Fuel nanoparticles added to the diesel fuel can have positive effect on engine behaviour; in particular, an interesting route to achieve lower particulate emission is the use of metallic additives. The presence of particles in the fuel can also be due to the interaction between fuel and Fuel Injection Equipment (FIE). Fuel contamination with particles greater than 4μm can have important consequences on FIE lifetime [5]. The catalytic activity of metallic-based fuel additives has been investigated widely [6,7]. In their comprehensive review of the effect of metal nanoparticles on combustion, Saxena et al. [8] provided a pathway to maximise the potential of metal nanoparticles in fuels. Keskin et al. [9] found that fuel properties such as pour point, cloud point, and viscosity change with addition of metallic based additives. Typically, mechanical mixing of nanoparticle or the so called sol-gel method are used to prepare the nanometal mixture [10,11], although the cost of nanopowder can be expensive. Suspensions of sonicated metal nanoparticles require addition of surfactants to achieve stable and homogeneous mixtures [11]. Soluble additives such as ferrocene and iron pentacarbonyl can also be used [12-14]. In the study proposed by Keskin et al. [15,18] the addition of 8 -16 μMol L^{-1} of metal-based additive resulted in a decrease in fuel consumption up to 4%, and smoke opacity up to 30%. The addition of Fe_3O_4 nanoparticles in very low concentration is reported to have a considerable effect on diesel engine characteristics [14]. Addition of copper oxide to diesel fuel using the sol-gel method is reported to lead to a marginal increase in performance, but a rather significant decrease in pollutants emitted by a single cylinder diesel engine. Work by Lenin et al. found that manganese showed an even stronger influence on emission reduction [9]. The metallic additive is seen to enhance the combustion process and shorten the ignition delay. A reduction of 7% in specific fuel consumption was also revealed when using fuels with sonicated metal nanoparticles (Al, Fe, B) [10]. A flame sustained over a longer period was noticed. In 2016, Gumus et al. [16] reported that the use of copper nanoparticles in diesel increases the ignition probability and has a positive effect on reducing brake specific fuel consumption and noxious emissions. Similarly, Tyagi et al. observed enhanced ignition probability of the diesel fuel with the addition of nanoparticles [17]. They suggested further investigation on the effect of copper and aluminium nanoparticle size as the metal nanoparticles are surface reactive and surface area can be of importance. The mechanisms governing the working principle and the development of a suitable theoretical model are still debated. Metallic catalyst reacts firstly with water producing hydroxyl radicals and enhancing soot oxidation; then, with carbon atoms in the soot lowering the oxidation temperature [18]. Additives are generally nanosized as more stable than microscale suspensions and require a lower activation energy [19]. The effect of addition of iron, cerium or copper, in combination with the Diesel Particulate Filter (DPF) has been studied in [20-21]. The analysis has demonstrated that the presence of DPF determines: always an increase of benzene and 1,3-butadiene (both carcinogenic); always a reduction of carcinogenic PAH; an increase of PCDD/F if the fuel is added with copper (usually between 10 and 50 μg/g) but only in presence of significant amounts of chlorine.

Several works in the literature have also analysed the effect of fuel on copper corrosion [22–27]. Corrosion behaviour of aluminium, copper and stainless steel in diesel was investigated by Fazal et al. [26] showing that the exposed metal surfaces are indeed susceptible to corrosion. Biodiesel was found to be more corrosive than diesel, with copper being the least resistant forming comparatively more corrosion products than other metals [23–25]. A corrosion rate of 23μm/year was reported for copper exposed to biodiesel [23]. Albeit the effect of copper leaching on fuel properties has been quantified [24-26], its impact on emissions and combustion characteristic has not.

In this work, a new fuel conditioner device (from here on referred to as "device"), constituted by an helicoidal copper duct surrounded by electromagnetic coils and installed just before the high pressure pump, was tested and its effect assessed on the combustion characteristics and particulate emissions of a modern DI HPCR diesel engine. Several devices, the majority of which are based on the application of a magnetic field along the fuel supply line, have been proposed in the past to improve fuel economy and reduce emissions. Some of these devices underwent through a thorough assessment carried out by the Environmental Protection Agency (EPA) [28,29]. At the end of the experimental campaign, conducted during the ’80, it was demonstrated that, with either road or dynamometer testing, such devices failed to improve vehicle fuel economy or reduce emissions. However, it must be emphasized here that the tested devices were designed to be installed on (pre-eighties) gasoline engines with the goal to reduce carbon monoxide, unburned hydrocarbons and nitrogen oxides emission levels; given the inherent low soot emission propensity of these engines, Particulate Matter (PM) measurements were therefore not carried out.

The engine testing reported in this work suggests that, when the device is used, leaching of metals in the fuel takes place; these fuel borne catalysts have then a role in enhancing soot oxidation lowering particulate emissions. Leaching of additives into the fuel is potentially an interesting addition mechanism which could allow for ions, or subnanometric particles, to be released at the point of need.

EXPERIMENTAL SETUP

Single cylinder DI diesel engine

The investigation has been carried out on a single cylinder Ricardo Hydra, with the cylinder head, piston assembly and crankshaft from a production 2.2 L DI diesel engine. The swept volume was stated as 550 cc, bore 86 mm, and stroke 94.6 mm (four valves per cylinder; 2 intake and 2 exhaust). The compression ratio (CR) was measured as 15:1. Diesel was supplied to the HPCR fuel injection system by a Bosch high pressure pump rated to 2000 bar. The 8-hole piezo-electric injector was centrally mounted. The engine was kept at test temperature by circulating “coolant” through the block and head. Heaters were used to directly increase the coolant and oil temperature. A 3 kW immersion heater from Watlow Industries was used to regulate the coolant fluid, and two Eltron Chromalox sump mounted heaters were used for the oil. The additional heat input from these heaters was necessary since the single cylinder engine does not produce sufficient heat to achieve typical warm operating conditions. A Carter M3 series cooling tower was used rather than a radiator for heat rejection. An 80 L plenum placed before the intake was used to provide a reservoir of constant temperature and pressure intake air. A reference fuel with Cetane Index 54.7 was used throughout these tests. Pressure transducers and thermocouples were used to monitor operation.

Cylinder pressure was measured using a Kistler 6125B quartz pressure sensor rated to 250 bar peak pressure. An optical shaft encoder with half degree crank angle resolution output (1440 pulses per engine cycle) was used as trigger for LabVIEW data acquisition system, through which many system variables are measured and stored every half crank angle step. The encoder top dead centre (TDC) marker was set to coincide with piston TDC in the cylinder. To ensure accurate TDC position, an AVL 402 dynamic probe was used. Accurate measurement was required since small errors in TDC measurement can result in large calculation errors in IMEP. The shaft encoder was set to within 0.5 °CA compared to TDC measured using the capacitance probe. Other measurements such as air, coolant, exhaust, fuel, and oil temperatures were recorded on the time based National Instruments Data Acquisition hardware and Labview software. A dedicated software was used to communicate with the engine’s ECU. The software provided control of various injection parameters such as injection quantity, number of injections, injection timing (and therefore separation) and rail pressure. Up to six injections per cycle were possible on this system but two were the maximum used in this study (one pilot injection followed by a main injection).

The test conditions chosen reflect low-speed, medium load conditions. The engine was run initially at the desired test speed, by which time both engine speed and fuel rail pressure had stabilised to their respective set point values. The fuel injection was then enabled, and injection quantities and timings were held constant. The dynamometer was used to maintain the set point engine speed throughout the test. The use of a single cylinder research facility with dynamometer control allows detailed analysis of combustion events by eliminating variables such as engine speed and cylinder to cylinder variations/interactions, a technique previously applied by McGhee et al. [30,31] and MacMillan et al. [32]. Complete control over injection parameters was possible throughout the investigation. An AVL Smoke Meter was used to measure the soot concentration (in mg/m^3) emitted by the DI diesel engine used in the present investigation. The variable sampling volume and the thermal exhaust conditioning ensure an extremely high reproducibility. The instrument can be used not only on large engines but also on light duty engines independent of their generation. The instrument has a high measurement resolution (10μg/m^3) and low detection limit (20 μg/m^3).

The conditioning device was installed in the fuel line just before the high pressure pump. Two sets of test conditions were investigated: with device powered (WDP conditions) and with device not powered (WDNP conditions).

Quiescent combustion chamber

The initiation and early development of combustion that occurs before the effect on cylinder pressure is measureable is of interest here for the two sets of test conditions: WDP and WDNP. The study of combustion initiation by glow plug was carried out using an unstirred, quiescent Constant-Volume Combustion Chamber (CVCC). This has optical access through a quartz window giving a view normal to the plate in which the injector and glow plug were mounted. The spacing between the injector and glow plug was the same as in the single cylinder engine.

The internal volume of the CVCC is roughly cylindrical with a height of 190mm and a bore of 100mm. The experimental facility is shown schematically in Figure 1. The same design of HPCR fuel injection system and fuel injector were used as employed on the engine. The injector was piezo-electric with 8 nozzle holes, the same design as used in the single cylinder engine. The holes have a diameter of 120μm. The volume of the CVCC is large compared to the clearance volume of the engine cylinder, being CVCC used here only to examine the initial development of combustion which takes place at constant pressure. The rationale is to investigate whether the device has an impact on initiation and early development of combustion. Prior to fuel injection, air in the CVCC is quiescent. Whilst this would not usually reproduce in-cylinder conditions, at the low engine speeds, associated with idling, turbulence levels are low, and motion in the vicinity of the glow plug just prior to the start of combustion is dictated by the momentum of the fuel sprays, entrainment, and mixing.

Pressure inside CVCC and internal tip temperature of glow plug and injection parameters such as injection separation, timing, and number of injections were controlled and recorded using National Instruments USB-6351 X Series Data Acquisition hardware and Labview software. Rail pressure was monitored by a pressure sensor on the fuel rail. A pressure control valve was utilized to adjust pressure in the high pressure fuel pump by means of PID control.

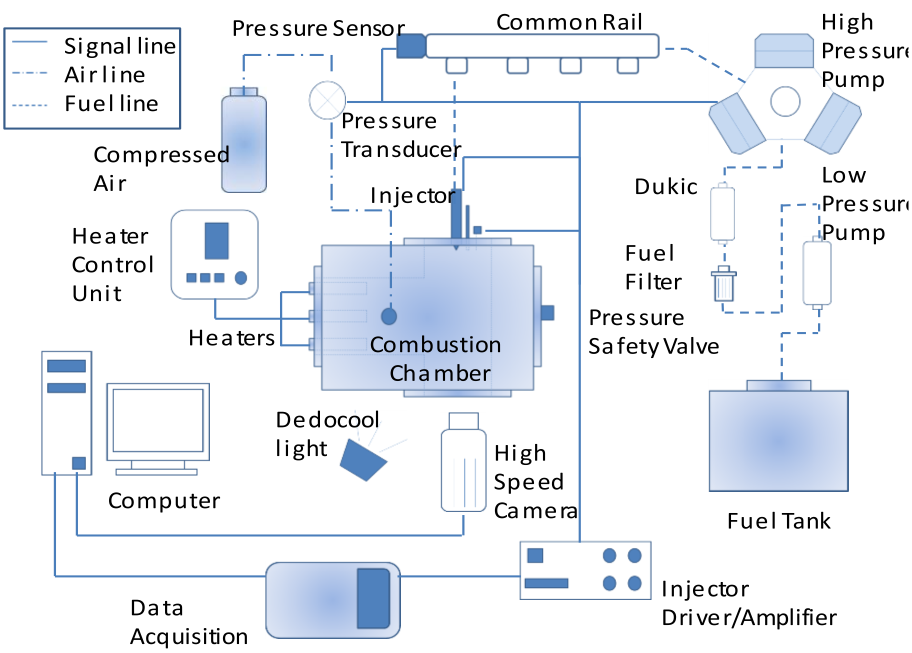


Figure 1 - Schematic representation of the CVCC test rig architecture

High-speed video recordings were made of the fuel sprays penetrating the chamber and, if initiation was successful, of the first appearance and growth of luminous emissions in one or both sprays adjacent to the glow plug. The camera used was a Phantom V12.1 CMOS high-speed camera capable of 6,242 frames per second at a maximum resolution of 1280x800 pixels. The settings of focal length, aperture and exposure time were respectively 105mm, f/3.5 and 100 μs. One Dedocool tungsten light was used to illuminate the fuel sprays. A fixed fuel injection strategy of single pilot and main was used throughout the set of experiments. The first luminous emissions have been taken to indicate the start and sites of combustion, as suggested in [33]. The subsequent growth of the luminous area has been taken to indicate successful ignition.

Inductively coupled plasma mass spectrometry (ICP-MS)

Copper detection was carried out using ICP-OES (Inductively coupled plasma - optical emission spectrometry) PerkinElmer Optima 3300 DV with autosampler AS90 Plus and controlled with Perkin Elmer Winlab software. ICP operational conditions occurred with Cross-flow GemTip nebuliser, Ryton Scott type spray chamber; details are in Table 1.

Table 1 - Operational conditions of ICP-OES

Plasma flow	15 L/min
Aux flow	0.5 L/min
Neb flow	0.8 L/min
RF Power	1300W
Pump	1.0 ml/min
Wavelength measured	Cu 324.752, Cu 327.393

Calibration standards were prepared from single element standard solutions (Romil PrimAg) diluted with 4% HNO_3 prepared from 68% nitric acid (Fisher PrimarPlus). All solutions were prepared using Milli-Q ultrapure water (18.2 MΩ cm^{-1}).

In order to trace metals in the samples, ICP technique has been used. The composition of metals in water diluted samples is determined using plasma and spectrometer; the sample is conducted by a peristaltic pump through a nebulizer into a spray chamber that produced aerosol; the latter is lead into an argon plasma which is generated at the end of a quartz torch by a cooled induction coil, through which a high frequency alternate current flows. Consequently an alternate magnetic field is induced which accelerated electrons into a circular trajectory and, due to collision between the argon atoms and the electrons, ionization occurs, giving rise to a stable plasma (6000-7000 K). Due to the thermic energy taken up by the electrons, they reach a higher "excited" state. When the electrons drop back to ground level, energy is liberated as photons. Each element has an own characteristic emission spectrum that is measured with a spectrometer, so the light intensity on the wavelength is measured and, with the calibration, converted into a concentration.

Heat release analysis of combustion

The rate of release of the fuel's chemical energy through the engine combustion process is commonly referred as heat release rate (HRR). In this work, the calculations mostly follow the approach suggested in Heywood [34]. The experimentally acquired in-cylinder pressure data was used to provide the heat release rate. As described in [34] the in-cylinder pressure changes with crank angle as a result of cylinder volume change, combustion of fuel, heat transfer to the chamber walls, flow into and out of crevice regions, and leakage; where the first two of these effects are the most relevant. Heat release analysis provides an insight of the combustion phenomenon inside the engine cylinder. By analysing cumulative and heat release rate the combustion phasing, the burning rate, and the degree of completeness of combustion can be quantified and compared. Heat release rates were determined from cylinder pressure data using [34]:

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dp}{d\theta}$$

The four stages typically recognisable in a compression ignition engine are ignition delay, premixed combustion, mixing-controlled combustion and late combustion; each stage can usually be identified on the HRR curve [34]. In this work, the ignition delay is defined as the time between the start of injection (SOI) and the start of combustion (SOC). In this work, SOC has been defined as the point after SOI at which the rate of heat release is equal to 2J/º. During the ignition delay stage, part of the injected fuel vaporises and mixes with air; as SOC occurs, the premixed combustion stage begins. During the premixed stage, the air/fuel mixture close to stoichiometric proportion that has formed throughout the ignition delay period burns. After this stage, the heat release and burn rate are dictated by fuel vaporisation and mixing rates; this stage of the combustion is known as mixed controlled phase. The last stage is a late combustion phase characterised by low rates of heat release.

Results and discussion

1. Single Cylinder DI Engine Tests

An initial dataset was collected as baseline for comparison with the device not connected in the fuel line (WO conditions). A pilot injection of 2mg fuel was followed by a main injection of 10mg fuel. The engine was run at a constant engine speed of 1000rpm. Once a steady state was reached, measurements were taken recording torque, brake mean effective pressure (BMEP), and exhaust soot concentration. A summary of the results is given in Table2. Average value (AVG) and Standard Deviation (STD) were calculated over 15 soot measurements, while heat release rate was calculated on average of 200 pressure traces acquired.

Table 2 - Test operating condition and measurements of torque, BMEP and soot with the device not connected along the fuel line (WO conditions). Total fuel injected 12mg/str. AVG stands for average and STD for standard deviation.

pilot		main		AVG Torque	AVG BMEP	AVG Soot	STD Soot
ºATDC	mg	ºATDC	mg	Nm	bar	mg/m^3	mg/m^3
-12	2	-4	10	24.7	5.7	2.19	0.22

When the device was powered for the first time (WDP conditions), an increase in torque and BMEP was noticed, together with a 10% decrease in the average soot concentration measured using the AVL smoke meter. A summary of the results is given in Table 3.

Table 3 - Test operating condition and measurements of torque, BMEP and soot with the device connected and powered along the fuel line (WDP conditions). Total fuel injected 12mg/str. AVG stands for average and STD for standard deviation.

pilot		main		AVG Torque	AVG BMEP	AVG Soot	STD Soot
ºATDC	mg	ºATDC	mg	Nm	bar	mg/m^3	mg/m^3
-12	2	-4	10	26.3	6.0	1.98	0.18

In Figure 2, the heat release rate and the cumulative heat release of the two test conditions from Table 2 and Table 3 are compared. Combustion characteristics and heat release were investigated to understand the reasons behind the measured soot reduction. In all the tests, fuel starts to combust shortly after fuel from main injection enters the combustion chamber, with a measured ignition delay of 5.5CA degrees. For both cases (WDP and WO conditions) the ignition delay was the same. This suggests that physical/chemical delay and fuel/air mixture preparation before ignition is not the reason for the difference in soot concentration measured in the exhaust stream. A greater heat release is observed during the premixed combustion, and overall during the entire combustion process when the device is powered (WDP conditions).

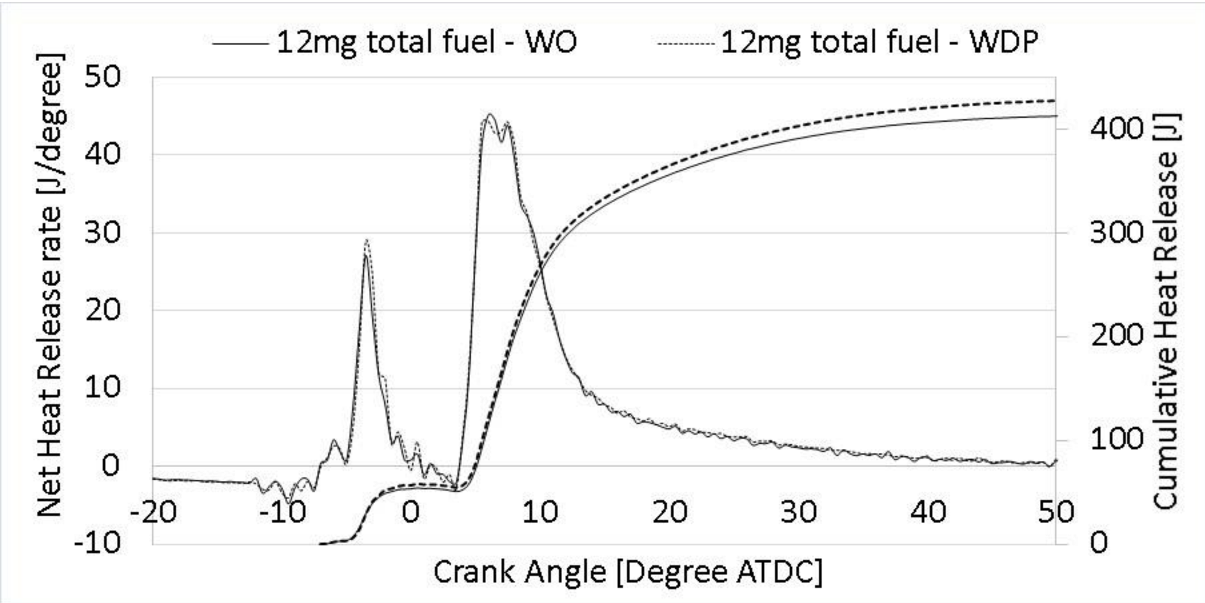


Figure 2 - Comparison of the heat release rate and the cumulative value. WO and WDP. Injection strategy pilot plus main 12mg of fuel injected per cycle. Day 1

It was then decided to reduce the fuel quantity in the main injection with the aim to match the torque and BMEP given in Table 2. Pilot injection quantity was kept constant at 2mg per stroke while 9.25mg of fuel was injected at 4 degrees before top dead centre (BTDC). As summarised in Table 4, this also resulted in a soot concentrations that were 25% lower than the value reported in Table 2.

Table 4 - Test matrix and measurements of torque, BMEP and soot with the device connected and powered along the fuel line (WDP conditions). Total fuel injected 11.25mg/str. AVG stands for average and STD for standard deviation.

pilot		main		AVG Torque	AVG BMEP	AVG Soot	STD Soot
ºATDC	mg	ºATDC	mg	Nm	bar	mg/m3	mg/m^3
-12	2	-4	9.25	24.4	5.6	1.63	0.095

The cumulative heat release, and the rate of heat release for the reduced fuelling with the device in WDP conditions is compared to the 12mg total fuel case in WO conditions. Results are summarised in Figure 3. Despite there being less fuel injected, a higher spike in HRR and cumulative heat release is noticeable in the premixed phase of combustion. Overall, however, the cumulative heat released by combustion is slightly lower for the 11.25mg, WDP conditions.

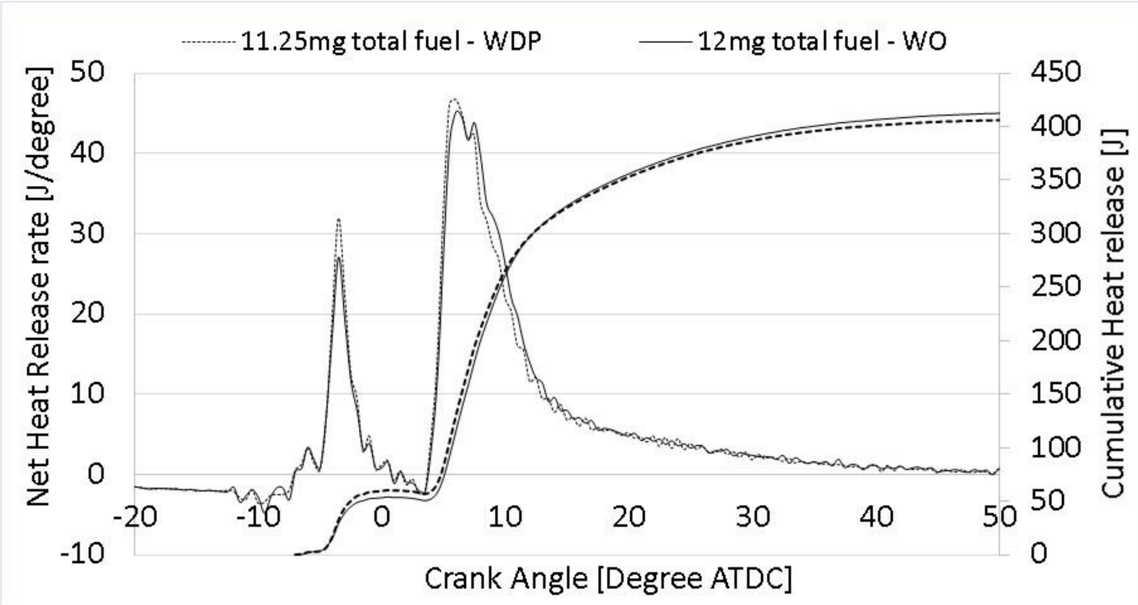


Figure 3 - Comparison of the heat release rate and the cumulative value. 12mg of fuel injected per cycle WO, and 11.25mg of fuel injected per cycle in WDP conditions. Injection strategy: pilot plus main, 12mg of fuel injected per cycle.

The findings described above were generally true for all test conditions in day one. Four more days of engine testing were carried out to corroborate the findings of the first day of testing. The device was left in the fuel line but electrically disconnected (WDNP conditions). The fuel tank and fuel line were not flushed, and the fuel filter was not replaced. The fuel tank was not refilled during the first day of engine testing. Day 2 started with roughly half a tank of fuel from the previous day, and was refilled towards the middle of the day. On the subsequent days of engine testing, the fuel tank was regularly refilled throughout the day. On each day of testing the same test point was repeated several times without powering the connected device (WDNP conditions), and then again with the device powered (WDP conditions). Over 200 tests and soot measurements were carried out in this period.

An overall decrease in the amount of soot emitted was noticed over the five days of testing, as shown in Figure 4. In detail, a gradual decrease in the soot emission was noticed even when the device was not powered (WDNP conditions) from 2.19mg/m^3 (day 1), to 1.61

mg/m^3 (day 2), and to 1.25 mg/m^3 (day 4). Moreover, as shown in Figure 4, each day of testing when the device is powered a further 8-14% reduction in soot emission was observed. Details of the results are reported in Table 5.

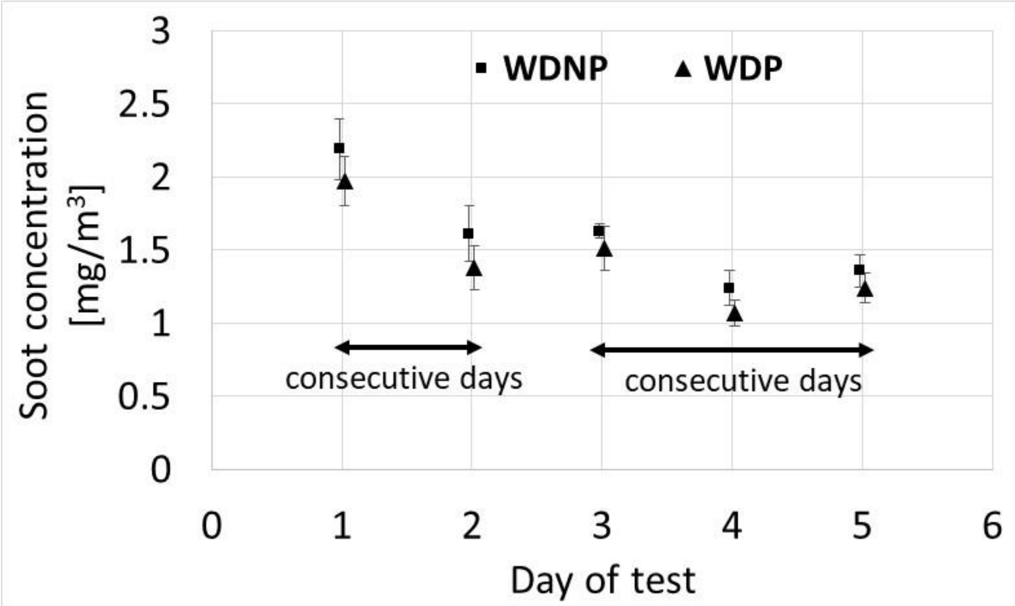


Figure 4 - Comparison of the average soot concentration collected over five days of testing in WDNP and WDP conditions; over 200 tests and soot measurements were carried out in this period. Injection strategy: pilot plus main injections, 12mg of fuel injected per cycle.

Table 5 - Comparison of soot concentration results collected over five days of testing; over 200 tests and soot measurements were carried out in this period. AVG stands for average and STD for standard deviation.

		With device not powered (WDNP conditions)		**With device powered (WDP conditions)**	
	Soot reduction [%]	Average Soot conc. [mg/m^3]	STD of Soot conc. [mg/m^3]	Average Soot conc. [mg/m^3]	STD of Soot conc. [mg/m^3]
1st day	9.64	2.19	0.22	1.98	0.18
2nd day	14.04	1.61	0.19	1.39	0.15
3rd day	7.36	1.63	0.05	1.51	0.15
4th day	13.92	1.25	0.12	1.08	0.09
5th day	9.14	1.36	0.11	1.24	0.10

On each day of engine testing, a reduction of soot emissions is significant and measurable. After the first day of testing the gains on work output and heat release between powering (WDP condition) and not powering (WDNP condition) the device cases become less apparent. BMEP varied in the range 5.6-5.9 bar and a clear trend was not identified. Comparison of cumulative and rate of heat release are given in Figure 5, suggesting that the catalyst in the fuel promotes soot oxidation rather than affecting chemical or physical ignition delay.

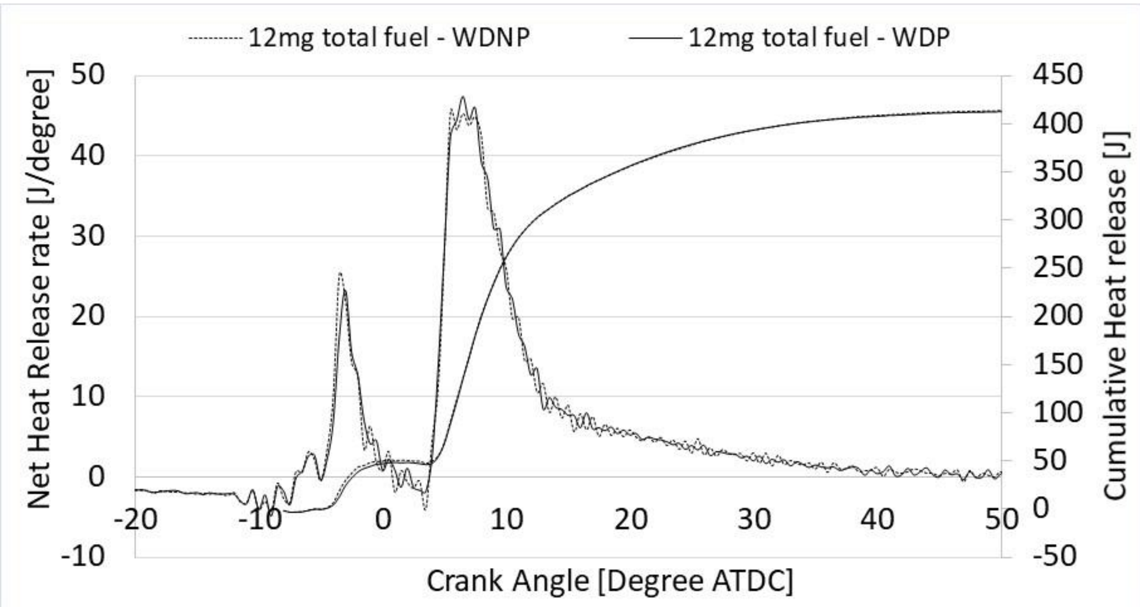


Figure 5 - Comparison of cumulative heat release and heat release rate. Test 61 run in WDNP conditions and test 92 in WDP conditions. Injection strategy: pilot plus main injections, 12mg of fuel injected per cycle.

A higher BMEP target of 7.6bar was also investigated. The amount of fuel injected per cycle was increased to 15mg with the device always hydraulically connected. A pilot plus main injection strategy was employed; pilot quantity was kept constant at 2mg/str while the main injection quantity was increased to 13mg/str. The average soot emissions are given in Table 6 and Table 7. These results are included in Figure 6. In this test, reduction in soot emissions of 7%, from an average value of 1.84 mg/m^3 to average value of 1.71 mg/m^3 was observed when the device was powered (WDP conditions). Interestingly the soot concentration is always lower than tests when the device is not powered (WDNP conditions) as shown in Figure 6.

Table 6 - Test matrix and measurements of torque, BMEP and soot. Total fuel injected 15 mg/str. WDNP.

pilot		main		AVG Torque	AVG BMEP	AVG Soot	STD Soot
[ºATDC]	[mg]	[ºATDC]	[mg]	[Nm]	[bar]	[mg/m^3]	[mg/m^3]
-12	2	-4	13	33.7	7.7	1.84	0.15

Table 7 - Test matrix and measurements of torque, BMEP and soot. WDP. Total fuel injected 15mg/str.

pilot		main		AVG Torque	AVG BMEP	AVG Soot	STD Soot
[ºATDC]	[mg]	[ºATDC]	[mg]	[Nm]	[bar]	[mg/m^3]	[mg/m^3]
-12	2	-4	13	33.5	7.6	1.71	0.14

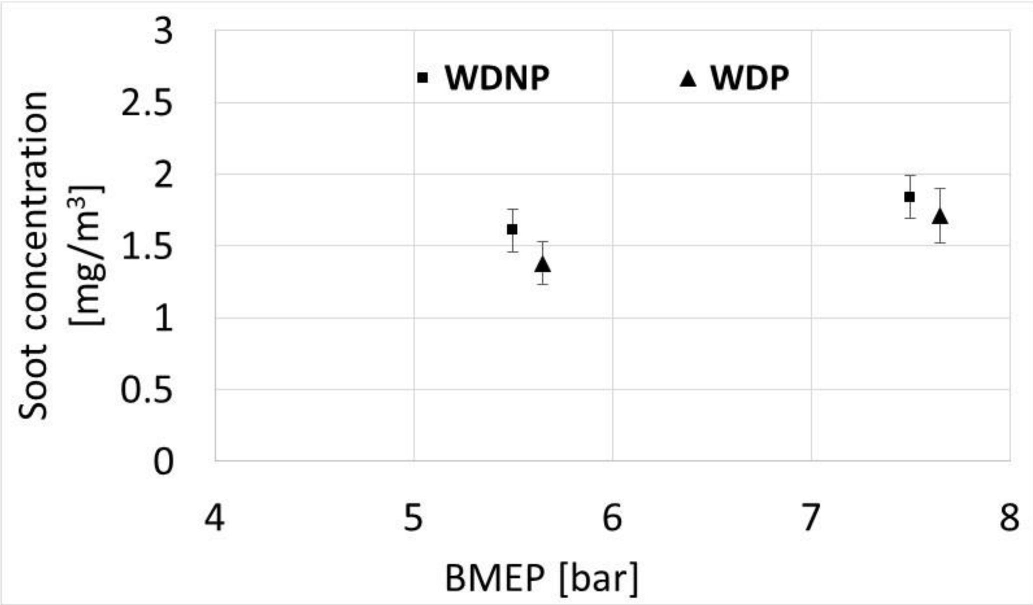


Figure 6 - Comparison of the average soot concentration collected in WDNP and WDP conditions at two BMEP target values. Injection strategy: pilot plus main injections.

The hypothesis proposed here to explain the measured reduction in soot emission is linked to leaching of metals into the fuel. The device is constituted by a 190mm long copper pipe containing a helicoidally shaped copper duct and therefore a large copper surface area is in contact with the fuel. Authors had previous experience of copper contamination of the fuel, when a copper heat exchanger was used during cold start testing, impacting on engine performance. Fuel contamination due to metal contact has been extensively studied [22], with presence of copper ions determined by ICP [26]. Metallic additives are well known in the literature as catalysts for the combustion process and for promoting oxidation of carbon nanoparticles during combustion [6,11,16,17]. Literature review covering the state of the art in fuel additives has suggested that additives are typically added to a fuel in form of nanoparticle powder; these nanoparticles are then dispersed in the base fuel and remain in suspension. Leaching releases metals in sub-nanometric aggregates or even ions rather than as nanoparticles so increasing the contact surface area.

In the present study, a fuel flow meter installed before the HP fuel pump measured a fuel flow rate of 30kg/h. At the operating condition tested, only 1.44kg/h is delivered to the injector while the remainder is discharged from the pump to return to the fuel tank. Therefore if leaching occurs the fuel borne metallic catalysts are partially recirculated into the fuel tank. This might explain the sharp reduction in soot emission starting from day 2 even when the device was not powered (WDNP conditions), as the fuel tank was not refilled during the first day of engine testing. Day 2 started with roughly half a tank of fuel from the previous day, and was refilled towards the middle of the day. On the subsequent days of engine testing the fuel tank was regularly refilled throughout the day. Fuel-borne catalyst concentration build-up can potentially explain the steeper decrease in soot emission in the first two days of testing.

Effect of tank top up with fresh fuel was investigated by plotting cumulative heat release calculation of consecutive tests.

Figure 7shows the effect of fuel tank refill on the cumulative heat release. According to our hypothesis, restoring the fuel level in the tank to its maximum, using fresh diesel, dilutes the concentration of metals leached from the device. After a short period of time, a noticeable drop in cumulative heat release was measured. Adding new fuel to the tank seems to have a detrimental impact on the cumulative heat release, as it decreases shortly after tanks is topped up.

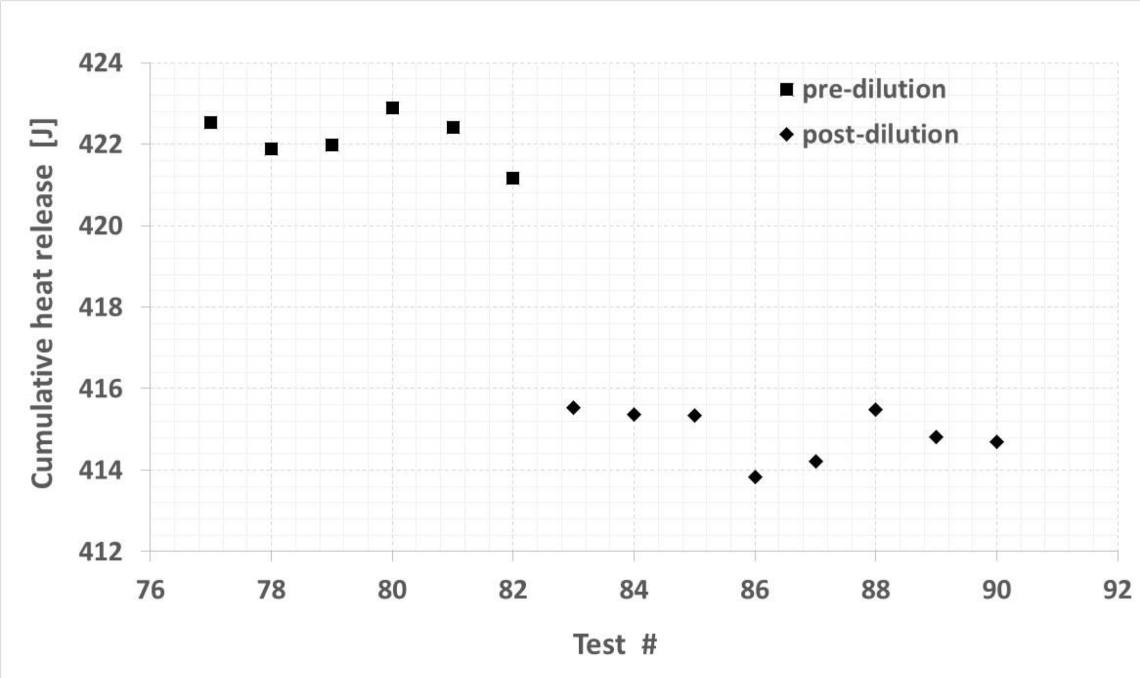


Figure 7 - Effect of fuel tank top up on cumulative heat release in WDP conditions.

A 20ml fuel sample was collected towards the end of the last day of testing. ICP analysis showed presence of copper in the diesel fuel. Results were compared to the baseline diesel fuel (0,2ppm Cu); the analysis of the fuel collected directly from the injector of the single cylinder engine showed an increase in copper concentration from 0.2mg/L to 1mg/L when the device is connected in the fuel line (see Table 8).

However, it was not clear if the metal in the fuel can be associated with wear of the fuel injection system or rather released by the device. Therefore, a dedicated test rig was used to assess whether the device is capable to release metals in the fuel. The test rig does not have other possible sources of metal contamination and is constituted mainly by the device and a high-density polyethylene (HDPE) tank. ICP analysis of fuel recirculated for 180 minutes shows concentrations of copper in diesel with a cumulative concentration measured going up to 4.6mg/L with recirculating fuel. Metallic additives in diesel fuel are effective in reducing particulate emission by enhancing soot nanoparticles oxidation as is widely reported in the literature.

Table 8 - Copper concentration in diesel fuel measured using inductively coupled plasma - optical emission spectrometry

Sample analysed	Concentration [mg/l]	STD [mg/l]
Baseline – Diesel	0.2	0.1
Samples from fuel injector	1	0.1
Diesel fuel recirculated to tank taken after 120minutes	3.7	0.1
Diesel fuel recirculated to tank taken after 180minutes	4.6	0.5

Although the mechanism of leaching is not the focus of this paper, the ICP measurement provided in Table 8 corroborate the hypothesis on the mechanism of soot reduction noticeable from measurements taken in this work, i.e., metal contamination of the fuel act as soot oxidation catalyst. Leaching is a well-known process that involves dissolution of solids into a liquid. It is a natural process but can also be implemented by an industrial process. Albeit the leaching rates of metals can be rather low, the hypothesis proposed here is that the utilisation of the magnetic field generated by the device leads to higher leaching rates of metals into the fuel. This can potentially be an interesting way to add combustion catalysts to a fuel; the additive can be released in sub-nanometric aggregates, even as single atoms or ions, rather than as nanoparticles, and this might enhance its catalytic effectiveness.

What is still unclear is the size distribution of the copper nanoparticles in the dispersion and whether this is stable over time. Further work will also need to focus on evaluating the rate of copper deposition into the diesel fuel and its dependence on fuel flow rate and surface temperature.

Initiation and early development of combustion

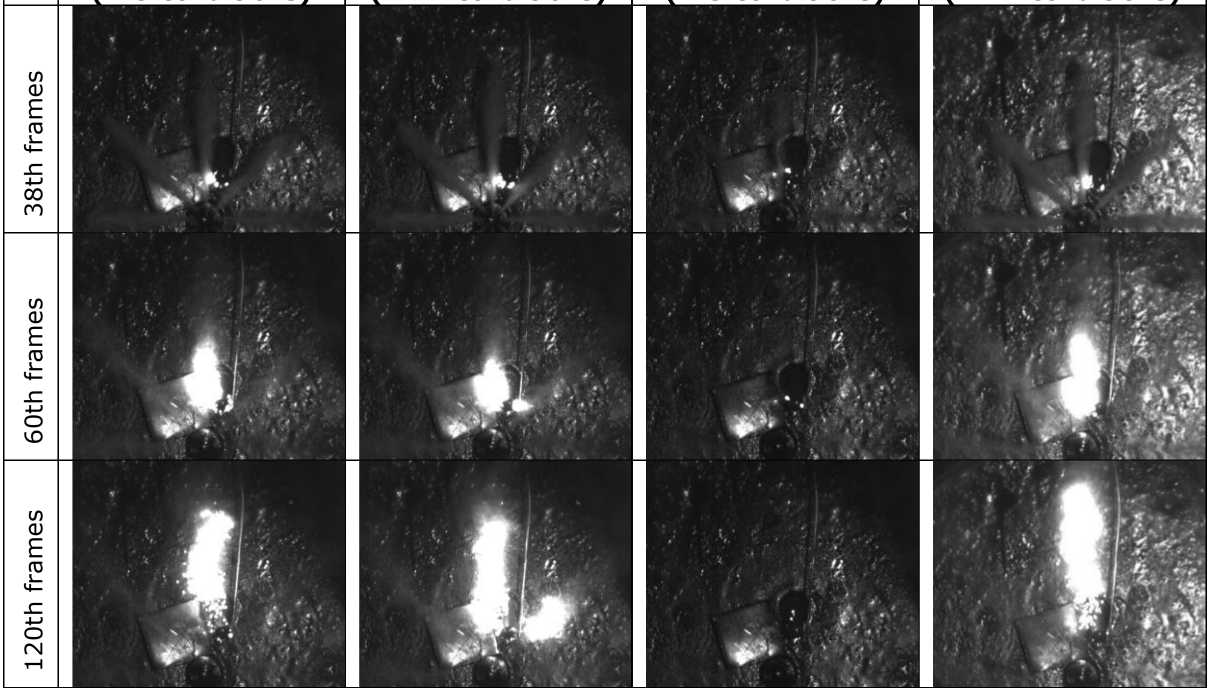
Details of the initiation and early development of combustion in a firing engine cylinder are difficult to unravel from cylinder pressure measurements because of the small heat release involved. Commonly, optical techniques are employed which require either engine modifications to provide optical access to the combustion system or, as here, the use of a quiescent optical vessel. Optical studies of the initiation of combustion aided by a glow plug have been reported in several publications [35-38]. These have shown that the site of initiation is in the vicinity of the glow plug surface, and combustion spreads into one or both sprays nearest to the glow plug before the remaining sprays ignite.

In complementary studies McGhee [30] and Li et al [33] investigated a range of factors which influence the early stage of diesel spray combustion in a quiescent optical vessel and showed that glow plug temperature and number of pilot injections have the strongest impact on initiation of combustion. The investigations presented in this section were undertaken to clarify the effect of the device on the successful initiation and development of combustion. Of particular interest is its effect on ignition delay and occurrence of a successful initiation.

The site of the initial luminous emissions associated with the first high temperature reactions has been identified~~,~~ with the device powered (WDP) and without the device (WO). A modified version of the test rig used in [33] was employed, including the device installed before the HP pump so that optical analysis of combustion initiation and early development could be carried out. The pilot plus main injection strategies that mimics the engine testing was used. An example of a sequence of images illustrating the successful initiation of combustion is given in Figure 8.

Ignition delay is not affected by the presence of the device, but it is more likely to achieve a sustainable combustion when the device is powered.

	In-cylinder pressure 30bar & glowplug on		In-cylinder pressure 28bar& glowplug on	
	Test 4 Glow plug on **(WO conditions)**	Test 5 Glow plug on **(WDP conditions)**	Test 6 Glow plug on **(WO conditions)**	Test 7 Glow plug on **(WDP conditions)**



	Device not powered. At an in-cylinder pressure of 30bar combustion initiation occurred. Only one of the fuel plumes close to the glow plug ignites	In-cylinder pressure of 30bar; combustion initiation occurred. When the device is powered the two fuel plumes close to the glow plug ignite	Device not powered. Misfire recorded. When pressure is lowered to 28bar, it was more likely for combustion initiation to fail.	Despite the lower in-cylinder pressure of 28bar, when the device is powered combustion of the fuel did occur.

Figure 8 - Comparison between high speed photography images of combustion initiation in a quiescent constant volume optical vessel equipped with HPCR DI fuel injection system and a glow plug in WDP and WO conditions.

The images in Figure 8 show the initial luminous emissions associated with the first high temperature reactions occurs at the same time (the 38th frame, whether the device is powered or not). Test 4 and test 5 in Figure 8 show that the first spots of luminous emissions appear close to the glow plug tip at the edge of the fuel spray after the start of the main injection. This local initiation triggers a rapid expansion of the enflamed volume, principally in the downstream direction of spray penetration. There were no significant differences in the way a successful initiation was achieved, although subsequent development took place in a different fashion with test 6 showing combustion of both adjacent sprays when the device is powered (test 5). When lowering the chamber pressure to 28 bar (test 6 and 7) initiation failed when the device was not installed (WO). In contrast, when the device was powered initiation was always successful. This ties rather well with the finding from Gumus et al. stating that the use of copper nanoparticles in diesel increases the ignition probability [16].

Conclusions

Soot measurements were taken from a single cylinder DI Diesel engine equipped with a Euro V high pressure common rail fuel injection system and a fuel conditioner device constituted by a helicoidally shaped copper duct embedded within electromagnetic coils. Inductively coupled plasma optical emission spectrometry revealed that copper contamination of the fuel occurred when the device was powered. Fuel collected directly from the injector of the single cylinder engine showed an increase in copper concentration from 0.2mg/L to 1mg/L. A bespoke test rig with fuel recirculating through device showed a copper concentration equal to 4.6mg/l after 180 minutes, significantly higher than the initial concentration, equal to 0.2mg/L; indicating that the device can release copper into the fuel.

The engine testing investigation showed that a 7-14% reduction in soot emissions is achieved when the device was connected. The combustion analysis and soot emission measurements suggest that the presence of metals from the helicoidally shaped copper duct into diesel fuel is responsible for the soot reduction and the combustion enhancement measured in this work.

High speed photography of combustion initiation in a quiescent constant volume optical vessel equipped with HPCR DI fuel injection system showed that the ignition probability is enhanced when device is used.

The catalytic effect of the leached metals in the fuel is thought to be the responsible for the soot reduction mechanism. This is potentially an interesting mechanism for the release of fuel borne catalyst at the point of need. However, further investigation is necessary to quantify the rate of leaching as function of operating conditions, the soot reduction as function of catalyst concentration and the stability of fuel borne catalyst in suspension.

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