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# An Optical Characterization of the Effect of High-Pressure Hydrodynamic Cavitation on Diesel

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## Abstract

Most modern high-pressure common rail diesel fuel injection systems employ an internal pressure equalization system in order to provide the force necessary to support needle lift, enabling precise control of the injected fuel mass. This results in the return of a substantial proportion of the high-pressure diesel back to the fuel tank. The diesel fuel flow occurring in the injector spill passages is expected to be a cavitating flow, which is known to promote fuel ageing. The cavitation of diesel promotes nano-particle formation through induced pyrolysis and oxidation, which may result in deposit formation in the vehicle fuel system.

A purpose-built high-pressure cavitation flow rig has been employed to investigate the stability of unadditised crude-oil derived diesel and a paraffin-blend model diesel, which were subjected to continuous hydrodynamic cavitation flow across a single-hole research diesel nozzle. Continuous in-situ spectral optical extinction (405 nm) has been employed to identify, determine and measure variations in fuel composition as a function of the cavitation duration.

The results of two high-pressure diesel cavitation experiments are reported. The first dealt with the effect of injection pressure on the rate of induced variation in chemical composition of diesel, and concluded that faster degradation of the fuel occurred at higher pressure.

The second experiment involved an investigation into the variation in composition occurring in diesel fuel and the paraffin-blend model diesel, subjected to cavitating flow over a longer duration. Observed differences suggest that the high-pressure cavitation resulted in hydrodynamic sono-chemical destruction of aromatics in the diesel, which is believed to lead to carbonaceous nano-particle formation.

## Introduction

Modern passenger car diesel engines employ common rail fuel injection equipment (FIE) that typically operates at pressures in the range of 1,600 bar to 2,500 bar. The diesel fuel is supplied to a high-pressure pump, which provides it at high pressure to a common rail (pressure accumulator), which is connected to the fuel injectors. The FIE original equipment manufacturers (OEMs) have developed different strategies for metering the diesel fuel flow. Some manufacturers meter the fuel at the inlet of the pump, while others meter the fuel at the outlet, often utilizing a spill return mechanism. However, there is a tendency for convergence on inlet metering for energy saving purposes. Both methods of metering create the opportunity for cavitation to occur during compression, across the piston supply valves, and in the spill return.

The injectors are activated through magnetic solenoid or piezo-electric actuation. The supply of diesel fuel to the engine through the injectors relies on the establishment of an imbalance of fuel pressures inside the diesel injector body through a spill path created by the lift of the actuator pin. The actuation of the spill port results in a pressure difference between the fluid pressure at the base of the injector (adjacent to the needle) and the fluid pressure above the needle, which induces the needle lift. The use of an injector spill mechanism means that a significant fraction of the high-pressure diesel fuel supplied to the injectors is returned to the tank at low pressure.

It is suggested that the fuel flow across the cylinder supply valves and spill ports in the pump, and the spill ports in the injectors is a cavitating flow, which may result in significant fuel degradation and ageing [1 – 4]. Indeed, cavitating fuel flows in diesel FIE may be responsible for deposit/sediment formation in the injectors, leading to modified nozzle spray structure, spray atomization, poor fuel-air mixing in the engine, needle stick and eventual injector failure [1, 5 – 7].

This consideration has led to a systematic investigation into the effect of sustained high-pressure cavitation on diesel. Two cavitation recirculation flow rigs have been designed and manufactured, one of which was described in Lockett and Jeshani [8]. The experimental rig described in this paper is based on a similar design, using a high-pressure diesel pump.

This paper reports the results of an investigation into the effect of long-term hydrodynamic cavitation on diesel, using optical diagnostics. Variations in the composition of the fuel samples during cavitation were identified using in-situ spectral optical extinction measurements. Diesel samples obtained from the cavitation rig at discrete intervals were subjected to measurements of spectral absorbance.

## Experimental

### *Experimental Setup*

### *High-Pressure Continuous Cavitation Flow Rig*

A high-pressure, continuous flow rig similar to the rig described by Lockett and Jeshani [8] was designed to allow continuously recirculating flow of diesel through a permanently open injector nozzle into a receiving cylinder. A schematic of the rig is presented in Figure 1.

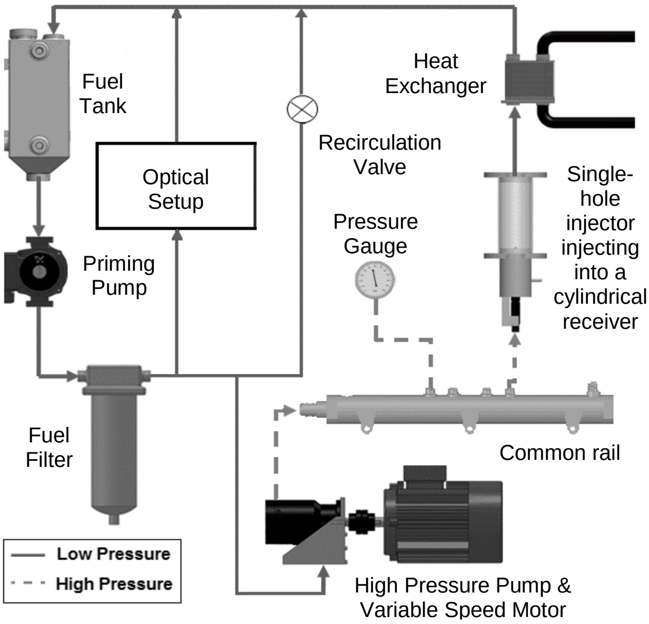

Figure 1. Schematic of the high pressure diesel cavitation flow rig.

A primer pump was used to supply diesel from a fuel tank to a high-pressure common rail fuel injection pump through a 5μm fuel filter at 1.3 bar. The high-pressure pump was shaft-driven by a 7kW variable speed electric motor, which enabled it to maintain the diesel in a common rail pressure accumulator at pressures of up to 1,700 bar. The diesel fuel pressure in the common rail was measured using a conventional pressure gauge connected to one of the four common rail outlet ports. A second outlet port was employed to supply high-pressure diesel to an axially located single-hole injector nozzle, which injected the diesel continuously into a receiving cylinder at ambient pressure.

The diesel pump compression energy released into the receiver during injection was converted to internal energy, resulting in large fuel temperatures in the receiver. Consequently, a temperature control system was installed in order to maintain the temperature of the diesel in the recirculation flow rig at a safe, steady-state value. The temperature control system was comprised of a thermocouple, a temperature controller and a counter-flow shell-and-tube heat exchanger. The thermocouple was located near the suction port of the high pressure stage of the high-pressure pump. The rate of cooling water passing through the heat exchanger was controlled using a solenoid valve. The cooled diesel was then returned to the tank.

### *Nozzle Description*

The injector nozzle employed in this study was an axially located, axisymmetric, single-hole mini-sac nozzle produced for research purposes. The nozzle hole had a diameter of 0.213 mm with a 20 % hone, such that the flow rate through the nozzle was 0.3 l/min at 100 bar ($C_d \sim 0.8$), and approximately 1.2 l/min at 1,650 bar. Figure 2 presents a schematic drawing of the nozzle. The injector needle was removed from the assembly to allow a continuous flow of diesel through the nozzle.

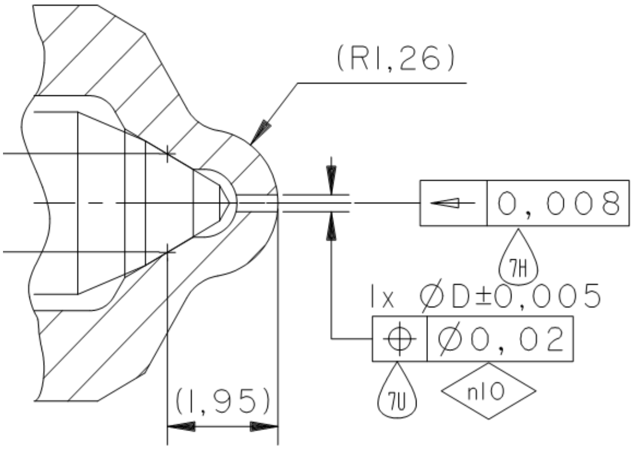

Figure 2. Drawing of the 0.213 mm single-hole injector nozzle.

### *Optical Extinction Measurement System*

The optical system employed in these experiments was a simplification of the conventional spectral extinction and scattering approach, which is usually used to determine real and imaginary refractive indices, and scattering and extinction coefficients. The intention was the deployment of a simple system that was capable of identifying a variation in composition of the diesel sample as it was subjected to recirculating cavitation flow in the rig.

The optical extinction of a light source traversing a medium occurs through optical absorption and scattering, which is specified by the Beer-Lambert-Bouguer law

$$I_t(x) = I_0 e^{-\alpha x} \qquad (1)$$

where $I_0$, $x$ and $I_t(x)$ are the spectral flux of light incident on an absorptive sample, the distance the light travels through the sample and the spectral flux after travelling distance $x$. $\alpha$ is the spectral extinction coefficient and is comprised of the scattering coefficient $\alpha_{sc}$ and the absorption coefficient $\alpha_{abs}$, such that $\alpha = \alpha_{sc} + \alpha_{abs}$.

The optical extinction system consisted of a 20 mW cw, 405nm (World Star Tech.) diode laser radiating towards an optically accessible cell, containing flowing diesel sample. Approximately 10 % of the laser light was reflected from a ND0.03 filter (45$^{o}$ angle-of-incidence) onto a Laserpoint reference laser power meter. The remaining 90 % of the laser light was transmitted through the fused silica glass windows and the diesel sample in the optically accessible cell to a Laserpoint transmission laser power detector. The diode laser, ND filter, optical cell and laser power meter assembly is shown in Figure 3.

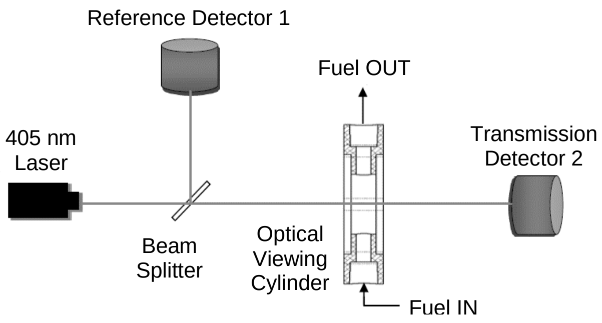

Figure 3. The optical extinction measurement system.

The optically accessible cell was supplied with a small flow of diesel being circulated in the flow rig, via a hose connected near the suction port of the high-pressure pump. The optical cell consisted of a short stainless steel cylinder 20 mm wide, 80 mm diameter with a wall thickness of 30 mm. The cylinder was fitted with 6 mm thick, 50 mm diameter fused silica windows, such that the diesel flowed through a 10 mm wide, 40 mm diameter space, before flowing upwards into the return hose, and back to the fuel tank.

The optical arrangement and calibration employed for the laser extinction measurement system was similar to that employed by Lockett and Jeshani [8], with the removal of the final mirror, and the location of the transmission laser power meter along the axis of the laser path.

### *UV-Visible Spectrophotometer*

The ultraviolet-visible spectrophotometer (UV-1800 Shimadzu) was employed to obtain the spectral absorbances of the discrete diesel samples at 405 nm.  It was capable of determining absorbance from zero to 4.  Measurements were obtained in the zero to 2.7 absorbance range in order to ensure a proportional response to variation in concentration.

## Experimental Methodology

### *Recirculation Flow Results in the High-Pressure Cavitation Rig*

Two cavitation experiments were conducted. The first experiment exposed diesel samples to 40 hours of cavitation with rail pressures of 550 bar, 1,100 bar and 1,650 bar respectively.  The second experiment exposed diesel and the paraffin blend model diesel to cavitation for 130 hours and 104 hours respectively, with a common rail pressure of 1,650 bar.  Table 1 below summarizes the test conditions.

**Table 1: Cavitation Flow Test Conditions**

| Fuel | Rail Pressure (bar) | Test duration (hours) | Control temperature ($^{o}$C) |
|---|---|---|---|
| Diesel | 550 | 40 @ 10 per day | 55.0 |
| Diesel | 1,100 | 40 @ 10 per day | 55.0 |
| Diesel | 1,650 | 40 @ 10 per day | 55.0 |
| Diesel | 1,650 | 130 @ 10 per day | 55.0 |
| Paraffin-blend model diesel | 1,650 | 104 @ 8 per day | 55.0 |

The high-pressure cavitation flow rig was flushed twice using fresh charges of the test fuel, prior to each cavitation test. Each flushing procedure involved filling the system using the feed pump, which ensured the removal of air cavities. This was followed by circulation of the fuel for an hour at low pressures (200 – 250 bar) using the high-pressure pump. The two flush cycles reduced the contamination from previous test cycles to approximately 1 %.

The rig was filled with a 3.4 – 3.6 L charge of fresh test diesel. The filling procedure was undertaken a day before the commencement of the cavitation tests. On the first test day the fuel was circulated using the low-pressure pump for 2 minutes. During this low pressure recirculation period, a 10 ml (30 ml for pressure dependence tests) sample was drawn off from the filter drain valve, providing a reference sample for later spectrophotometric analysis. The laser power meters were then calibrated and the laser was turned on to begin the in-situ laser extinction measurements.

The diesel pre-compression temperature control was set to 55°C. This was followed by the high-pressure pump being turned on, and the rail pressure raised to the test pressure by adjusting the speed of the electric motor. The diesel was circulated in the rig at this pressure for 10 h (8 h for paraffin blend model diesel) each day.

Each of the pressure dependence tests involved 10 h of circulation per day for four days. The prolonged cavitation tests (1,650 bar rail pressure) were conducted for 13 days. However, the daily testing duration varied for the two fuels; in the case of conventional diesel the daily testing duration was 10 h, whereas for the paraffin-blend model diesel it was 8 h. The 13 days of testing included four days during which the testing was not conducted, such that the distribution of consecutive testing days was four, five and four days respectively, with two day gaps after each consecutive testing period.

During the cavitation flow tests, the laser power meters sampled the reference and transmitted laser power with a sampling rate of 1 Hz. The computer control software computed 30 second averages of the discrete reference and transmitted laser power. At the end of the daily cavitation test periods, the electric motor and pump were stopped, and the diesel charge allowed to cool down to ambient temperature.

Diesel samples were collected at regular intervals during the tests. The volume of the rig required a different sampling methodology to be followed for the two cavitation experiments. During the pressure dependence tests, three 30 ml diesel samples were drained from the rig each test day, corresponding to start (0 h mark), middle (5 h mark) and end (10 h mark) phases of daily tests. During the prolonged cavitation tests, two 10 ml samples were taken each day over the 13 days of testing, at the beginning of the day before pressurizing the rig and at the end of 10 h (8 h) after the high-pressure pump was stopped.

### *Optical Extinction Measurements*

The in-situ laser transmission measurements were conducted as the 405 nm laser beam passed through the diesel sample flowing through the optically accessible cell. As the beam passed through the diesel sample it was subjected to internal absorption and scattering. As stated earlier, the power of the laser beam transmitted through the diesel sample is expressed by the Beer-Lambert-Bouguer law for optical extinction

$$I_t(x) = I_0 e^{-\alpha x} \qquad (1)$$

where $I_0$ is the laser power incident on the diesel sample, $I_t(x)$ is the transmitted laser power at point $x$ in the sample after travelling a distance $x$ through the sample.

The laser power incident on the diesel samples $I_0$ has to pass through the reference beam filter, followed by the fused silica window into the optical cell, that is $I_0 = t_f t_{fs} I_{laser}$, where $t_f$, $t_{fs}$ and $I_{laser}$ are the transmission coefficient through the OD0.03 ND filter, the transmission coefficient through the fused silica window and the 405 nm diode laser power, respectively.

$I_0$ can also be expressed in terms of the laser power reflected from the ND filter onto the reference detector $I_{ref}$, such that $I_0 = \frac{t_{fs}(1-r_f)}{r_f} I_{ref}$, where $r_f$ is the reflectivity of the OD0.03 ND filter, being used as the beam splitter.

The laser power exiting the diesel samples $I_t$ passed through the second fused silica window before reaching the laser power detector. The laser power measured with the detector is denoted by $I_P$ and is related to the laser power leaving the diesel sample $I_t$ by $I_P = t_{fs} I_t$.

The time-dependent spectral extinction coefficient is then derived from equation (1) to be

$$\alpha(t) = \frac{\ln\frac{I_{0(t)}}{I_t(t)}}{l} = \frac{\ln\frac{t_{fs}^2\left(1-r_f\right)I_{ref}(t)}{r_f I_P(t)}}{l} \qquad (2)$$

where $l$ is the optical path length of the laser through the diesel in the optical cell.

The transmission coefficient is defined to be the fraction of light transmitted through the sample, and may be expressed as

$$T = I_t(l)/I_0 \qquad (3)$$

The values for $t_{fs}^2$ and $r_f$ were determined through a series of calibration tests described in detail by Lockett and Jeshani [8], they were found to be 0.945 ± 0.010 and 0.093 ± 0.005, respectively.

The optical extinction arrangement was calibrated before and after the experiments. During the course of the cavitation flow tests and optical extinction measurements, the fused silica windows of the optical cell were checked daily for external and internal fouling. No fouling was observed over the duration of the tests.

### *Discrete Sample Spectral Absorbance Measurements*

Discrete diesel fuel samples of 30 ml volume were drawn from the rig using a gate valve located at the base of the filter housing. The samples were obtained at zero hours (unfiltered), zero hours (filtered), 30 hours, 60 hours and 130 hours respectively, and were subjected to spectral absorbance measurements at 405 nm using the Shimadzu spectrophotometer.

## Results

### *Effect of Injection Pressure*

The transmitted laser power was normalized against the reference laser power, producing the non-dimensional normalized laser power. This is presented as a function of cavitation duration in Figure 4.

The normalized transmitted laser power was observed to decrease with cavitation time to the same minimum value for all of the three pressures measured. The rate of change of the 1,650 bar profile was observed to be larger in magnitude than the 1,100 bar profile for the first 5 hours. The rate of change of the 1,100 bar profile was observed to be larger in magnitude than that of the 550 bar profile for the first 12 hours. The 1,650, 1,100 and 550 bar profiles were observed to achieve their minimum values after approximately 23 hours, 30 hours and 40 hours respectively.

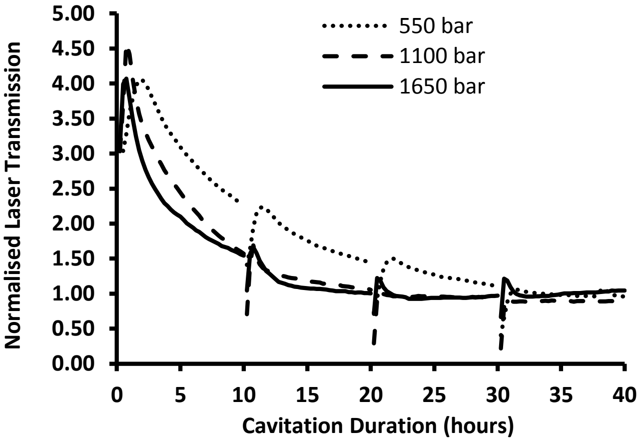

Figure 4. Non-dimensional normalized transmitted laser power as a function of cavitation duration.

The corresponding variations in the spectral extinction coefficients with cavitation duration are presented in Figure 5. It was observed that as time proceeded, the spectral extinction coefficients increased irrespective of the injection pressure. The 1,650 bar and 1,100 bar spectral extinction coefficient profiles were observed to achieve a maximum value at approximately 23 hours and 30 hours respectively, while the 550 bar profile reached the same maximum at approximately 40 hours.

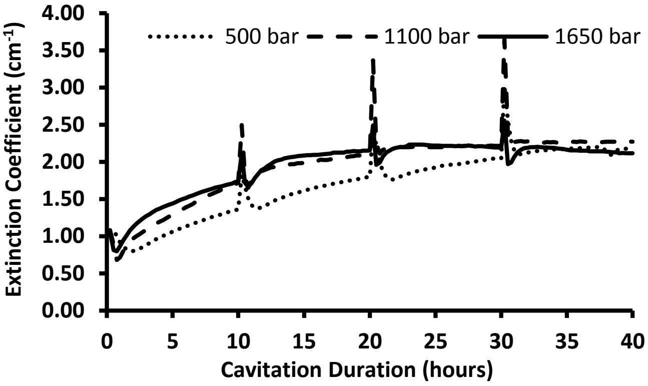

Figure 5. Variation of spectral extinction coefficient as a function of cavitation duration.

## *Long Duration Tests at 1,650 bar*

Figure 6 presents the non-dimensional normalized transmitted laser power as a function of cavitation duration for the diesel and paraffin-blend model diesel samples. The normalized transmission power profile was observed to decrease from its initial value to a minimum at approximately 23 hours, followed by an increase to a constant value at approximately 100 hours.

The transmission coefficient for the diesel began at 0.46 ± 0.01, decreasing to 0.112 ± 0.005 after 23 hours, and then increasing to a steady-state value of 0.276 ± 0.005 after approximately 100 hours of cavitation.

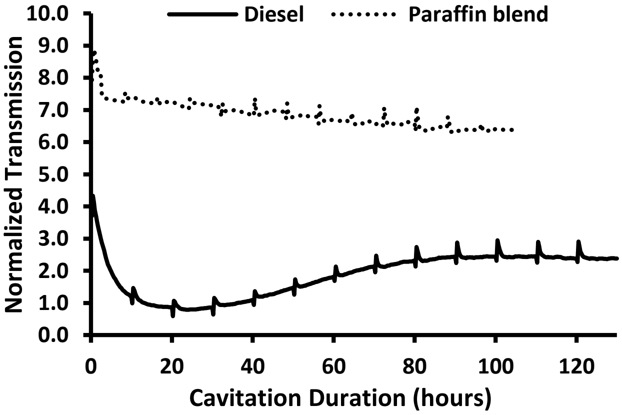

Figure 6. Non-dimensional normalized transmitted laser power as a function of cavitation duration.

The paraffin blend model diesel appeared transparent at optical wavelengths, and was observed to permit the transmission of nearly 90 % of the incident laser light at 405 nm at ambient temperature. The normalized transmitted laser power was observed to linearly decrease with cavitation time from an initial transmission coefficient of 0.80 ± 0.01 (at 55 °C operating temperature) to a final transmission factor of 0.70 ± 0.01 after 105 hours cavitation.

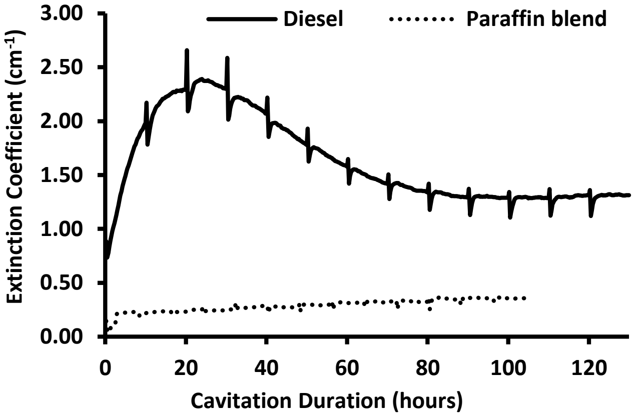

Figure 7. Variation of spectral extinction coefficient of diesel and paraffin blend model diesel with large cavitation duration.

Figure 7 presents the variation of the spectral extinction coefficients for the diesel and paraffin blend model diesel during the long duration cavitation tests. The spectral extinction coefficient for diesel was observed to increase from its initial value of 0.733 ± 0.01 cm$^{-1}$ to a maximum value of 2.39 ± 0.01 cm$^{-1}$, achieved at the 23rd hour of the cavitation period.

Following the maximum value at 23 hours, the spectral extinction coefficient decreased until it reached its minimum steady-state value of 1.21 ± 0.01 cm$^{-1}$ at the 100th hour. From the 100th to the 130th hour, the spectral extinction coefficients remained steady at approximately 1.21 ± 0.01 cm$^{-1}$.

On the other hand, the spectral extinction coefficient of the paraffin-blend model diesel fuel increases linearly with cavitation duration, beginning with an initial value of 0.218 ± 0.005 cm$^{-1}$, increasing to a final value of 0.359 ± 0.005 cm$^{-1}$ after 100 hours of cavitation. Unlike diesel, the spectral extinction coefficient of the paraffin-blend model diesel consistently increases with cavitation duration.

The spikes observable in the graphs in Figures 4 – 7 are due to the temperature dependence of the extinction coefficient and the temperature rise that occurred at the beginning of each day for each sample, and the temperature fall that occurred at the end of each day for each sample. The temperature rise at the beginning of each day was caused by the temperature of the diesel rising from ambient laboratory temperature (~ 18 °C) to the operational temperature of 55 °C. The temperature fall at the end of each day occurred when the high pressure pump and the temperature control system was turned off at the end of each day, when the diesel temperature fell from 55 °C to ambient temperature (~ 20 °C).

### *Discrete Spectral Absorbance Measurements*

The absorbances of the discretely obtained unfiltered zero hour, filtered zero hour, 30 hour, 60 hour and 130 hour cavitated diesel samples were measured at 405 nm using the uv-visible absorption spectrometer. These discrete sample absorbances as a function of cavitation duration are presented in Figure 8.

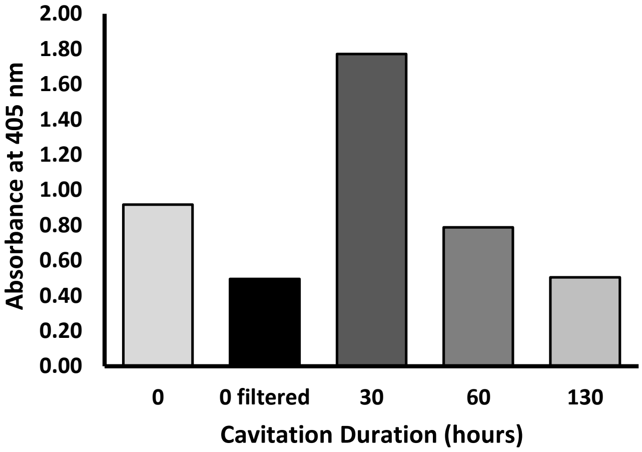

Figure 8. Spectral Absorbance of cavitated diesel samples at 405 nm as a function of cavitation duration.

The spectral absorbance of the zero hours filtered sample was observed to decrease significantly relative to that of the zero hours unfiltered sample. Subsequent measurements of the spectral absorbances of the cavitated diesel samples at 30 hours, 60 hours and 130 hours reveal a maximum absorbance attained at 30 hours followed by a progressive decrease to that of 130 hours.

The spectral absorbances obtained from the cavitated diesel samples at zero hours (filtered), 30 hours, 60 hours and 130 hours are observed to be consistent with the behavior of the time-dependent spectral extinction coefficient for the diesel. It is to be noted that the diesel is maintained at 55 $^{o}$C in the cavitation rig during the in-situ measurement of spectral extinction coefficient, while the discrete sample spectral absorbances were measured at ambient laboratory temperature (~ 20 $^{o}$C) approximately one week after the cavitation tests were completed.

## Discussion

The high pressure cavitation recirculation rig recirculated cavitated diesel samples of approximately 3.0 l volume with a volumetric flow rate of approximately 0.6 l/min at 1,650 bar. Hence the entire fluid volume was cycled through the rig every 5.0 minutes, corresponding to approximately 12 cycles/hour when the rig was operated with a rail pressure of 1,650 bar.

The variations in spectral extinction coefficients and discrete spectral absorbances for the cavitated diesel samples with cavitation duration suggest that the diesel samples were being altered chemically as a result of the hydrodynamic cavitation occurring across the single-hole nozzle and in the receiver. Extrapolating the effects of ultrasound cavitation on diesel to the effect of hydrodynamic cavitation on diesel suggests that the diesel may be subject to chemical alteration as a result of cavitation bubble collapse occurring in the receiver during flow stagnation.

Figure 5 shows that the spectral extinction coefficients of the cavitated diesel samples achieved the same maximum value for the three common rail test pressures, albeit with different time constants. This suggests that the composition of the diesel suspension obtained at the maximum spectral extinction coefficient is similar for the three test pressures.

Assuming a constant nozzle discharge coefficient for the three test pressures, the time constants of 23 hours (1,650 bar), 30 hours (1,100 bar) and 40 hours (550 bar) respectively resulted in the maximum spectral extinction coefficient being achieved after 276 cycles (1,650 bar, 0.6 l/min), 294 cycles (1,100 bar, 0.49 l/min), and 277 cycles (550 bar, 0.346 l/min) respectively. The similarity of the number of cycles necessary to achieve the maximum spectral extinction coefficients suggests that the variations in the spectral extinction coefficients for the diesel samples scale with the mass and volumetric flow rate through the rig, and appear to be independent of the common rail pressure.

It is known from ultrasound cavitation research that cavitation sono-chemistry is induced in the liquid medium during cavitation bubble collapse [2, 3], during which the temperature and pressure of the collapsing vapour bubbles rise dramatically. The similar maximum extinction coefficient achieved for the three test pressures, together with the apparent independence of the rate of fuel degradation on upstream pressure (aside from the dependence on volumetric flow rate), suggest that the mechanism responsible for the alteration of the composition of the diesel occurred in the receiver, and therefore was most likely associated with the collapse of the cavitation bubbles in the receiver. This would be consistent with the suggested mechanism for ultrasound induced sono-chemistry [1 – 4].

Figure 7 shows the variation of the spectral extinction coefficients for diesel and paraffin-blend model diesel for a cavitation duration of 130 hours and 104 hours respectively. The spectral extinction coefficient for the diesel sample was observed to increase from its initial value to a maximum after 23 hours of cavitation, followed by a decrease to a steady-state value at approximately 100 hours. In contrast, the paraffin-blend model diesel showed a linear increase in the spectral extinction coefficient over 104 hours.

Figure 8 shows the spectral absorbances of the discrete diesel samples obtained at 405 nm for zero hours (unfiltered), zero hours (filtered), 30 hour, 60 hours, and 130 hours duration respectively. The spectral absorbance of the unfiltered diesel was observed to be approximately twice that of the filtered diesel. Considering that the cavitation recirculation flow rig contained a 5 µm polypropylene filter element, a comparison of the two zero hour spectral absorbances suggests that the filter captured a large number of micron-sized particles in suspension in the unfiltered diesel prior to the cavitation tests beginning.

Crude oil derived middle distillate diesel is composed of approximately 72 % - 75 % paraffins, 22 % mono-aromatics, 2 % di-aromatics, 1 % tri-aromatics, and 1 % other species [9]. The 72 % - 75 % n-paraffins, iso-paraffins and naphthenes present in the diesel are almost transparent to 405 nm light, and would be likely to undergo a similar variation in spectral extinction coefficient as the paraffin-blend model diesel. A comparison of the spectral extinction coefficient obtained from the diesel with that obtained from the paraffin-blend model diesel therefore suggests that the difference in profile was due to chemical change induced in the aromatics present in the diesel, which were absent from the paraffin-blend model diesel.

It is well-known that ultrasonic cavitation of diesel is capable of producing pyrolysis-like sono-chemistry, leading to the formation of a carbonaceous nano-particle suspension [1 – 4]. It is believed that the high temperatures achieved during cavitation bubble collapse result in C-C and C-H bond cleavage [2], followed by molecular recombination and rearrangement to form olefins, acetylenes, and polycyclic aromatic hydrocarbons (PAHs), eventually leading to the formation of carbonaceous nano-particles. These suspensions have been observed to produce larger particles through Brownian motion agglomeration kinetics [1]. Figure 7 shows that the spectral absorbance increased from the initial value to a maximum at 23 hours, followed by a decrease to a steady-state value achieved after 100 hours. Figure 8 shows discrete sample spectral absorbances which are consistent with the spectral extinction measurements shown in Figure 7.

An assessment of the increase in spectral absorbance from 0 to 23 hours suggests that the destruction of aromatics leads to the formation of polycyclic aromatic hydrocarbons (PAHs), which in turn lead to the formation of primary carbonaceous nano-particles. It is suggested that the formation of PAHs and nano-particles led to the observed increase in the spectral and discrete sample absorbances from 0 hours to the maximum achieved after 23 hours cavitation duration.

The subsequent decrease in spectral absorbance with cavitation duration suggests that the nano-particles formed were able to agglomerate to form larger micron-sized particles which were captured by the 5 µm filter element. These filter elements have a logarithmic particle size capture profile, and are capable of capturing 98% of 1 µm size particles. The production of nano-particles and the filter capture of micron-sized particles eventually achieved a steady-state, resulting in the observed steady-state spectral absorbance after 100 hours cavitation duration.

An important aspect of the hydrodynamic cavitation degradation of the diesel and the paraffin-blend model diesel is the separate effects of cavitation and bulk fluid temperature on the rate and character of the degradation of the fuel. Lockett and Jeshani [8] have attempted to separate out the effect of bulk fluid temperature from the effect of cavitation on the rate of degradation by hydrodynamic cavitation flow. They were able to demonstrate separate effects of temperature and cavitation on a number of commercial diesel samples. However, if this experiment is representative of the flow occurring across pressure control valves in diesel injectors and diesel high-pressure pumps, then the hydrodynamic cavitation and the conversion of compression energy to fluid internal energy occur concurrently, and the fuel degradation that occurs is subject to both effects.

## Conclusion

A high-pressure recirculation flow rig utilizing a single-hole diesel injector nozzle was built to investigate the effect of hydrodynamic cavitation on diesel. A crude oil derived diesel and a paraffin-blend model diesel were investigated. In-situ continuous measurement of sample spectral absorbance was conducted at 405 nm.

A set of spectral absorbance measurements were obtained from diesel fuel samples as a function of cavitation time for cavitation produced in the rig at 550 bar, 1,100 bar and 1,650 bar rail pressure respectively. The spectral absorbances obtained were observed to increase to the same maximum value with characteristic timescales that appeared to be inversely proportional to the volume flow rate. This suggested that the chemical alteration to the composition of the diesel was independent of the rail pressure, which supports the view that the chemical alteration of the diesel occurred as a result of cavitation bubble collapse at ambient pressure in the receiver.

Diesel and paraffin-blend model diesel samples were subjected to hydrodynamic cavitation for a rail pressure of 1,650 bar for a period of 130 hours and 104 hours respectively. Continuous in-situ measurements of spectral extinction coefficient at 405 nm were obtained during the tests. Separate measurements of spectral absorbance were obtained from discrete fuel samples drawn from the rig, and provided independent confirmation of the time-dependent behavior of the diesel spectral extinction coefficient.

The spectral extinction coefficient for the diesel was observed to increase from the initial value to a maximum after 23 hours of cavitation, followed by a progressive decrease to a steady-state value achieved after 100 hours cavitation duration. In contrast, the spectral extinction coefficient obtained from the paraffin-blend model diesel increased linearly during the cavitation test.

The zero to 23 hour increase in spectral extinction coefficient suggests that the hydrodynamic cavitation of diesel led to the formation of carbonaceous nano-particles in suspension. The later decrease in spectral extinction coefficient to a steady-state value suggests that a decrease in the nano-particle concentration occurred to an equilibrium (steady-state) value. This was explained by the formation of and subsequent filter capture of micron-sized particles, formed through flow-driven nano-particle agglomeration.

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