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DETECTION OF COMBUSTION CHAMBER DEPOSITS IN DIESEL ENGINES THROUGH CYLINDER PRESSURE AND EXHAUST TEMPERATURE MEASUREMENTS

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ABSTRACT

This paper describes experimental research aimed at developing techniques for monitoring the growth of combustion chamber deposits in diesel engines using data obtained from cylinder pressure and exhaust temperature measurements.

A naturally aspirated single cylinder research engine was operated alternately between low load "coking" conditions (2.5 bar BMEP) and higher load "decoking" conditions (5.5 bar BMEP) intended to promote the formation and removal, respectively of combustion chamber deposits.

The polytropic exponent of compression was observed to increase during coking runs and decrease during decoking runs. The peak heat release rate was observed to decrease during coking runs and increase during decoking runs. The peak cycle value of the first derivative of the exhaust thermocouple signal decreased during coking runs but exhibited no clear trend during decoking runs.

Conventional exhaust temperature measurements showed no consistent trend during coking runs but the exhaust temperature decreased during decoking runs.

INTRODUCTION

The accumulation of hard carbon deposits in diesel engine combustion chambers (often referred to as "coking") can lead to serious problems. Morehouse *et al.* [1] describe a mechanism for exhaust valve failures due to deposits which in some cases led to the destruction of the engine itself. The presence of hard glazed deposits between the sealing surfaces of the valve and cylinder head prevented heat transfer from the valve to the head. Eventually breaches in the valve seat sealing provided passages for hot combustion gases to flow through and the resulting localized heating cracked and destroyed the valves.

Acute coking problems have been experienced with some multiple diesel generator set installations. In one particular case, this was found to be related to frequent operation where electrical loads slightly exceeded the output of a single diesel generator. This made it necessary to bring a second diesel generator on line. Under these conditions, each diesel engine was operating at a low load (relative to its rated output) for extended periods and the growth of deposits appeared to be exacerbated [1].

A "decoking" procedure was eventually adopted in which each diesel engine was periodically run a maximum load to burn off the deposits. This procedure compromises the ability of a generator installation to meet varying electrical load requirements so it is desirable to minimize the frequency and duration of these decoking runs.

The study described in this paper was undertaken to develop methods of detecting the growth of deposits during engine operation. If "coking monitoring" was possible, decoking procedures could be carried out only as needed (i.e. as condition-based maintenance rather than as routine maintenance).

BACKGROUND

Deposit Sensing Through Cylinder Pressure Measurements

Recent improvements in the durability of cylinder pressure sensors have made it possible to achieve continuous online monitoring of cylinder pressure in large diesel engines. This is most practical for engines equipped with cylinder indicating valves where an existing passage can be used to expose the sensor to in-cylinder pressure. (Note: Indicating valves are manual valves connected to the inside of the cylinder via a passage in the cylinder head. They are intended to allow the periodic use of manual pressure indicating test equipment and are typically found on large bore engines). Such pressure monitoring systems would normally be fitted to facilitate Indicated Mean Effective Pressure (IMEP) measurements and load balancing between cylinders. However, it would also be possible to monitor deposit growth if deposit thickness could be correlated with a thermodynamic process or property that could be derived from cylinder pressure data.

It was anticipated that such a correlation would exist because the heat loss through the combustion chamber walls should affect the processes within the cylinder. For example, the real compression stroke is polytropic and not isentropic (adiabatic reversible) as the ideal cycle supposes. How close the evolution is to adiabatic should reflect how well the walls are insulated. This should vary with the deposit thickness.

Polytropic Exponent – Since the compression and expansion processes are non-adiabatic and dependent on heat loss in the cycle, they will follow different paths on the indicator diagram when the amount of heat transfer varies. This means that an actual variation in the quantity of heat losses would generate a deflection in the $P-V$ curve and could possibly be quantified. Both the compression and expansion processes in the $P-V$ diagram for the diesel engine cycle can be represented by Equation 1 [2], the form of which can be derived from the first law of thermodynamics when the evolution is isentropic ($n = k$)

$$PV^n = \text{cst} \tag{1}$$

Equation (1) is used to represent the processes in the $P-V$ diagram but it can also be used to represent the processes in the logarithmic $P-V$ diagram which should give straight lines of slope

$$\ln P = n \ln V \tag{2}$$

In the present study, the engine speed and load were held constant. In real-world diesel monitoring situations, it would also be necessary to account for variations in the polytropic exponent due to variations in engine speed and load. This might be achieved by mapping "normal" polytropic exponent values versus speed and load with a clean engine and comparing current values with these stored reference values.

Heat Release Profile: Using the $P-V$ diagram, it is possible to monitor the heat transfer process that occurs in the engine and to look at the influence of deposit accumulation on this process. The cylinder pressure was therefore used to analyze the variation of heat transfer to the walls. It is possible to write the first law of thermodynamics only as a function of pressure and volume and therefore use the cycle characteristics to find the heat release to the cylinder walls [3].

The first law energy equation for a closed system where the potential and kinetic energy variations are considered negligible [2] is written as:

$$\delta Q = \delta W + \mathrm{d}U \tag{3}$$

The heat transfer term in Equation (3) corresponds to the net heat transfer which is the difference between the heat produced by the combustion reaction, Equation (5) [4] and the heat loss to the cylinder walls

$$_1Q_2 = Q_{net} = Q_{gross} - Q_{wall} \tag{4}$$

$$\dot{Q}_{gross} = \dot{m}_f LHV \tag{5}$$

To analyze the heat release rate, Equation (3) was written only as a function of the pressure and the volume. If the net work produced is replaced by the area within the curve of the $P-V$ diagram and the internal energy is written as a function of temperature when the gas is considered ideal, then Equation (3), once derived with respect to the engine crank angle (CA) can be written as Equation (6).

$$\frac{\mathrm{d}Q_{net}}{\mathrm{d}\theta} = P\frac{\mathrm{d}V}{\mathrm{d}\theta} + m\,c_V\frac{\mathrm{d}T}{\mathrm{d}\theta} \tag{6}$$

The ideal gas law can also be derived with respect to the CA (Equation 7).

$$P\frac{\mathrm{d}V}{\mathrm{d}\theta} + V\frac{\mathrm{d}P}{\mathrm{d}\theta} = RT\frac{\mathrm{d}m}{\mathrm{d}\theta} + Rm\frac{\mathrm{d}T}{\mathrm{d}\theta} \tag{7}$$

To express the first law as only a function of pressure and volume, the $\mathrm{d}T/\mathrm{d}\theta$ term of Equation (7) was first isolated and then substituted in Equation (6) to generate Equation (8).

$$\frac{\mathrm{d}Q_{net}}{\mathrm{d}\theta} = P\frac{\mathrm{d}V}{\mathrm{d}\theta} + \frac{c_V}{R}\left(P\frac{\mathrm{d}V}{\mathrm{d}\theta} + V\frac{\mathrm{d}P}{\mathrm{d}\theta} - \frac{PV}{m}\frac{\mathrm{d}m}{\mathrm{d}\theta}\right) \tag{8}$$

If no mass variations, $\frac{\mathrm{d}m}{\mathrm{d}\theta} = 0$, are considered in the combustion chamber for one cycle, i.e., no mass loss around the piston skirt and the added mass during the injection is neglected, Equation (9) can be generated.

$$\frac{\mathrm{d}Q_{net}}{\mathrm{d}\theta} = P\frac{\mathrm{d}V}{\mathrm{d}\theta} + \frac{c_V}{R}\left(P\frac{\mathrm{d}V}{\mathrm{d}\theta} + V\frac{\mathrm{d}P}{\mathrm{d}\theta}\right) \tag{9}$$

Since deposit accumulation causes a variation of the heat transfer through the cylinder walls, Equation (10) is used to analyze such a variation using only the pressure and the volume of the cycle [5]:

$$\frac{\mathrm{d}Q_{net}}{\mathrm{d}\theta} = \frac{\mathrm{d}Q_{gross}}{\mathrm{d}\theta} - \frac{\mathrm{d}Q_{wall}}{\mathrm{d}\theta} = P\frac{\mathrm{d}V}{\mathrm{d}\theta}\left(1 + \frac{c_V}{R}\right) + V\frac{\mathrm{d}P}{\mathrm{d}\theta}\left(\frac{c_V}{R}\right) \tag{10}$$

To calculate the heat release rate for an entire cycle (720 deg) using Equation (10), the constant volume specific heat capacity is required. In this project, the C_V of air, calculated using the properties of the ambient air at the time of the tests was used in the equation for the intake and the compression processes. For the expansion and exhaust processes, the constant volume specific heat capacity of the combustion products was used.

Deposit Sensing Through Exhaust Temperature Measurements

Changes in heat loss through the combustion chamber walls due to deposits should also affect the exhaust temperature. However, it was anticipated that these modest effects would be difficult to discern from conventional exhaust temperature measurements using durable (but slow responding) exhaust thermocouples. Such measurements do not provide a good reflection of actual temperature of the gas leaving the cylinder. This may be understood by considering the transient behaviour of the exhaust temperature within an engine cycle.

Figure 1 (adapted from Ref [6]) shows the real time behaviour of the exhaust port temperature of a diesel engine during a single cycle as measured by a very fast response (and very fragile) 6.7 μm diameter platinum wire resistance thermometer. The peak exhaust temperature occurs when the exhaust valve first opens and the burned gases in the cylinder (which are still under pressure) flow rapidly past the valve and through the exhaust port. This is known as the "blowdown" portion of the exhaust stroke and the temperature of this portion of the exhaust gas contains the best information about conditions within the cylinder prior to the exhaust valve opening. Displacement flow then occurs as the piston rises and the exhaust gas remaining in the cylinder (which is now at about the same pressure as the exhaust manifold) is pumped out.

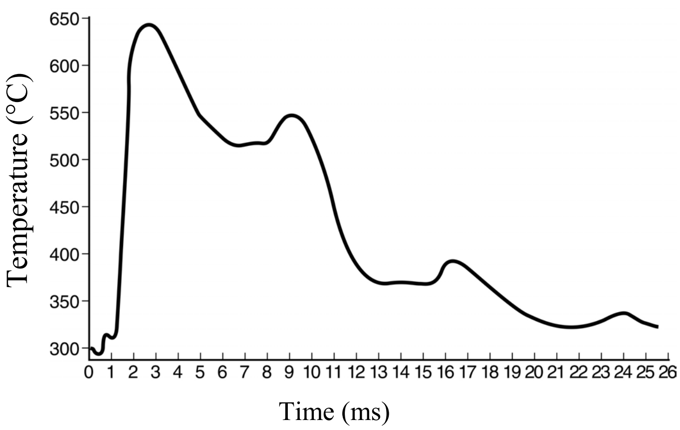


Figure 1: Transient Gas Temperature in a Diesel Engine Exhaust Port (Adapted from Benson [6])

During the remainder of the cycle, the exhaust cools (at rates determined by the surface temperatures of the exhaust port and manifold walls) and the temperature sensed by the thermocouple is no longer representative of in-cylinder processes. The cooling process dominates the time-averaged signal obtained from conventional thermocouple measurements because the blowdown process occurs in less than 90° of the crankshaft rotation (1/8 of the 4-stroke engine cycle).

The equilibrium temperature of a relatively large thermocouple is similar to the time-averaged temperature of the exhaust [7]. The peak cyclic temperature is more representative of the temperature in the cylinder when the exhaust valve first opens. Capturing this peak value directly would require a fine wire thermocouple or resistance thermometer that was too fragile to survive for very long in a diesel exhaust application.

However, even a relatively large thermocouple produces a small signal fluctuation when exposed to large transient temperature excursions. Over fifty years ago, Shepard and Warshawsky [8] showed how this signal fluctuation could be used to reconstruct the actual gas temperature that the thermocouple had been exposed to. Shepard and Warshawsky's technique required prior knowledge of the velocity of the gas. Later researchers overcame this limitation by making simultaneous measurements using two or more thermocouples (or resistance thermometers) of different sizes. Examples of this approach applied to piston engine exhaust gas measurements include the work of Benson [6], Mollenhauer [9], Kee *et al*. [10] and Kar *et al*. [11].

In the present study it was hypothesized that the gradual buildup of combustion chamber deposits could be detected by monitoring relative changes or trends in the peak cyclic exhaust temperature. This would not require an accurate reconstruction of the transient exhaust temperature during each cycle. It would only be necessary to produce a signal that was proportional to the peak value. Furthermore, this signal could be obtained by averaging many engine cycles (thereby improving the signal-to-noise rate). The resulting signal (i.e., the averaged signal for a batch of cycles) could be sampled infrequently since significant changes in deposit buildup typically take hours.

It should be noted that for the laboratory engine tests used in the present study, operating parameters such as speed, load, ambient temperature and intake air temperature were essentially constant. This would not be true for real world diesel monitoring. Thus, it would be more difficult to isolate changes in exhaust temperature due to deposits from changes due to variations in these and other parameters.

The basic equation for determining the instantaneous gas temperature (T_g) from the wire temperature of a thermocouple (T_w) is:

$$T_g = T_w + \tau \frac{\mathrm{d}T_w}{\mathrm{d}t} \tag{11}$$

The time constant of the thermocouple (τ) varies substantially within each engine cycle because the gas velocity changes as the cycle progresses from blowdown to displacement flow to the stagnant period when the exhaust valve is closed with no flow [11].

In the present case, only one part of the cycle (the part producing the peak temperature) was of interest. For this purpose, the assumption of a single value for the time constant (although not strictly true) may be adequate. The fluctuations of the wire temperature (T_w) of a relatively large thermocouple will be very small compared with the fluctuation in gas temperature (T_g) so T_w will contribute little to the cyclic waveform shape.

Thus the cyclic temperature waveform (as depicted in Figure 1) is obtained primarily from the first derivative of T_w that is, by differentiating the thermocouple signal. Furthermore, the peak value of $\frac{\mathrm{d}T_w}{\mathrm{d}t}$ for each cycle should reflect changes in the peak cyclic exhaust temperature. Based upon these considerations, the peak first derivative value of the thermocouple signal was selected as a candidate parameter for deposit detection.

It should be noted that Equation (11) was intended for bare wire thermocouples. The practical application of exhaust thermocouple probes in diesel engines requires that the thermocouple wire be protected by a sheath of corrosion resistant material. As shown by Chuang [12], sheathed thermocouples have a much more complex response to transient temperatures than bare wire thermocouples. Despite these limitations, the simple first derivative analysis was applied to sheathed thermocouple measurements in the present study as it was anticipated that it could be adequate for trend analysis capabilities that were being sought.

EXPERIMENTAL DETAILS

Test Engine. The test engine was a Ricardo Hydra single cylinder research engine configured as a Direct Injection diesel. The engine had a displacement of 0.45 L and was naturally aspirated. The nominal compression ratio was 20:1. It was equipped with a pump and line type fuel injection system with a 4-hole injector.

This engine was equipped with a cylinder head passage to enable a piezoelectric pressure transducer (Kistler 6121) to be installed with its tip nearly flush with the combustion chamber wall. In an earlier study [13], a deposit sampling probe was developed that replaced the pressure transducer during deposit buildup tests. This probe was removed and weighed periodically and the increase in weight (due to deposit accumulation on the tip) was used as an approximate indication of the overall deposit accumulation trends for the combustion chamber. During the present study, the cylinder pressure transducer was installed at all times and a Kistler type 5010 charge amplifier was used.

The exhaust temperature was measured using an inconel sheathed, grounded junction K-type thermocouple mounted near the cylinder head exhaust port. The main probe diameter was 6.35 mm but this design used a taper at the tip (to a minimum diameter of 1.5 mm) to improve its response. A production version of this thermocouple is used for exhaust temperature monitoring in general aviation piston engines. The thermocouple was connected to a purpose-built signal conditioning circuit. The thermocouple signal and the cylinder pressure signal were recorded every crank angle degree with a Nicolet Model PRO20 12 bit digital storage oscilloscope that was clocked by the engine's 360 pulse/revolution COM optical crankshaft encoder.

Each engine test run consisted of a half hour warm-up period followed by 8 hours of continuous operation. The engine was operated at either a low load (2.5 bar BMEP) to encourage the growth of deposits or a higher load (5.5 bar BMEP) to encourage the removal of deposits. The low load (coking) and high load (decoking) runs were carried out on alternate days and an engine speed of 1800 rpm was used in both cases.

Data sets consisting of 250 engine cycles were collected at 0.5 hr intervals. The data points shown in the upcoming figures were mean values for each data set.

RESULTS AND DISCUSSION

Data obtained earlier in this program had revealed the overall deposit accumulation behaviour of this engine, as shown in Figure 2 [14]. It can be seen that the deposit growth is asymptotic, with most of the increase occurring within the first 8 hours of operation. This observation is consistent with those of other deposit studies in the scientific literature [15]. The data shown was obtained using a removable deposit probe. This technique made it necessary to stop the engine frequently to remove and inspect the probe, and was not, therefore, suitable for the extended run times to be used in the current study.

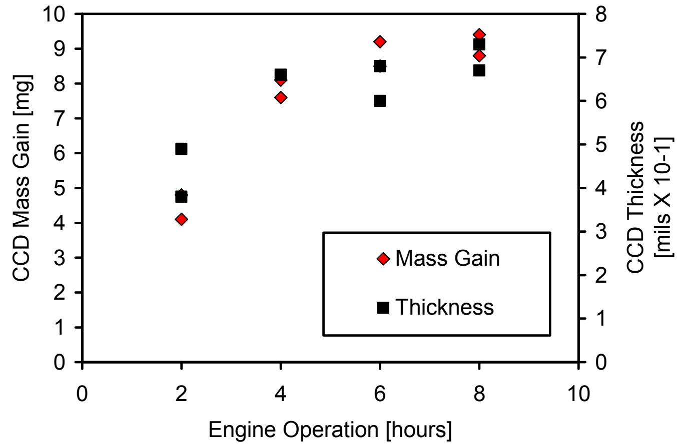


Figure 2: Combustion Chamber Deposit (CCD) Growth Trends for the Ricardo Hydra Measured with a Removable Probe (Adapted from Ref. [12])

Figure 3 compares the trends for the signals during three low load coking runs. This series of tests was carried out after disassembly and physical decoking of the engine. However, the engine was not completely clean at the beginning of run 1 because it was preceded by an initial run attempt during which a fuel pump failure occurred. Note that a high load decoking run was carried out after each of these coking runs.

The polytropic exponent of compression exhibited the expected trend during the second and third coking runs. As shown in Figure 3, the value increased over the 8 hour run period. During the first run the polytropic exponent value fell between the second and third hour of the test but rose during the remainder of the run period.

The values obtained during the third run were significantly higher than those of the preceding runs. The reason for this behaviour is not known. The possibility was considered that unintentional coking had taken place during the preceding decoking run (i.e., the polytropic exponent value was greater because there was actually more deposit build up) but this trend was not seen in the other parameters for the run.

The trend observed for the peak heat release rate was a decline during the coking runs with the majority of the reduction occurring during the initial 1-2 hours. This trend was contrary to initial expectations as it was suspected that insulating the combustion chamber with deposits would (by reduced heat loss during combustion) lead to higher measured heat release values. Closer inspection of the cylinder pressure data revealed that a reduction in the ignition delay period was likely responsible for this behaviour.

Since less fuel had been injected before ignition took place, a smaller portion of the fuel participated in the rapid heat release associated with premixed combustion. The presence of insulating deposits is believed to have reduced the ignition delay period by providing higher temperatures during injection thereby accelerating droplet vaporization and auto ignition. It should be noted that this behaviour may be characteristic of the engine and injection equipment used in the study and might not be representative of other engines.

The peak first derivative value of the thermocouple temperature (intended to reflect the peak cyclic exhaust temperature) showed a declining trend for all three coking runs.

This was unexpected, as it had been suspected that the insulating effects of the deposits would retain more heat in the cylinder and lead to higher temperatures when the exhaust valve opened.

Like the heat release results, trends in the peak cycle exhaust temperature may have been influenced primarily by the impact of the deposits on the combustion process. Earlier heat release phasing particularly during the very late stages of combustion could have been responsible for lower cylinder gas temperatures at the time of exhaust valve opening. However, it was impossible to confirm or eliminate the existence of such an effect from the heat release data acquired in this study.

The trend seen for the peak cyclic value of the first derivative of the thermocouple temperature was largely absent from the conventional measurement of exhaust temperature. A modest declining trend was observed for coking run 2 which was the test that also produced the greatest reduction in the thermocouple derivative value. Given the normal variations in exhaust temperature encountered with diesel engines in service, it would probably be difficult to identify coking trends based upon conventional (time averaged) exhaust temperature alone.

The signal trends during the decoking runs are shown in Figure 4. Based upon the results for coking discussed earlier, the decoking process would be expected to show the opposite trends, i.e., the polytropic exponent of compression should decline while the peak heat release value and the thermocouple derivative value should rise. Instead, the trends for all of the signals were inconsistent.

The polytropic exponent value declined as anticipated during the first and third decoking runs. However, it rose (and began at a higher level) during the second decoking run. This run was terminated early due to a fuel line leak and the fuel injection characteristics may have been abnormal while the run was in progress.

The peak heat release rate rose as anticipated during the first and third decoking runs. During the second run, the behaviour was unusual as the heat release rate rose relatively abruptly but later fell.

The thermocouple peak first derivative of the thermocouple temperature signals exhibited no clear trend during any of the decoking runs. This was surprising given the strong response of this signal to coking shown earlier in Figure 3. On the other hand the conventional exhaust temperature measurement (which had exhibited relatively little response during coking) showed an overall decline during the decoking runs.

The Ricardo Hydra research engine was not turbocharged like the high output diesel generator engines the research was intended for. Thus, operation at higher load resulted in less excess air and more in-cylinder soot formation. Note that the "high load" condition (5.5 bar BMEP) was very low by the standards of turbodiesels. This load limit was imposed to avoid excessive smoke levels from the naturally aspirated Hydra. Thus the apparatus used in this study did not provide a good representation of the in-cylinder conditions experienced in the generator engine decoking procedures described in Ref. [1].

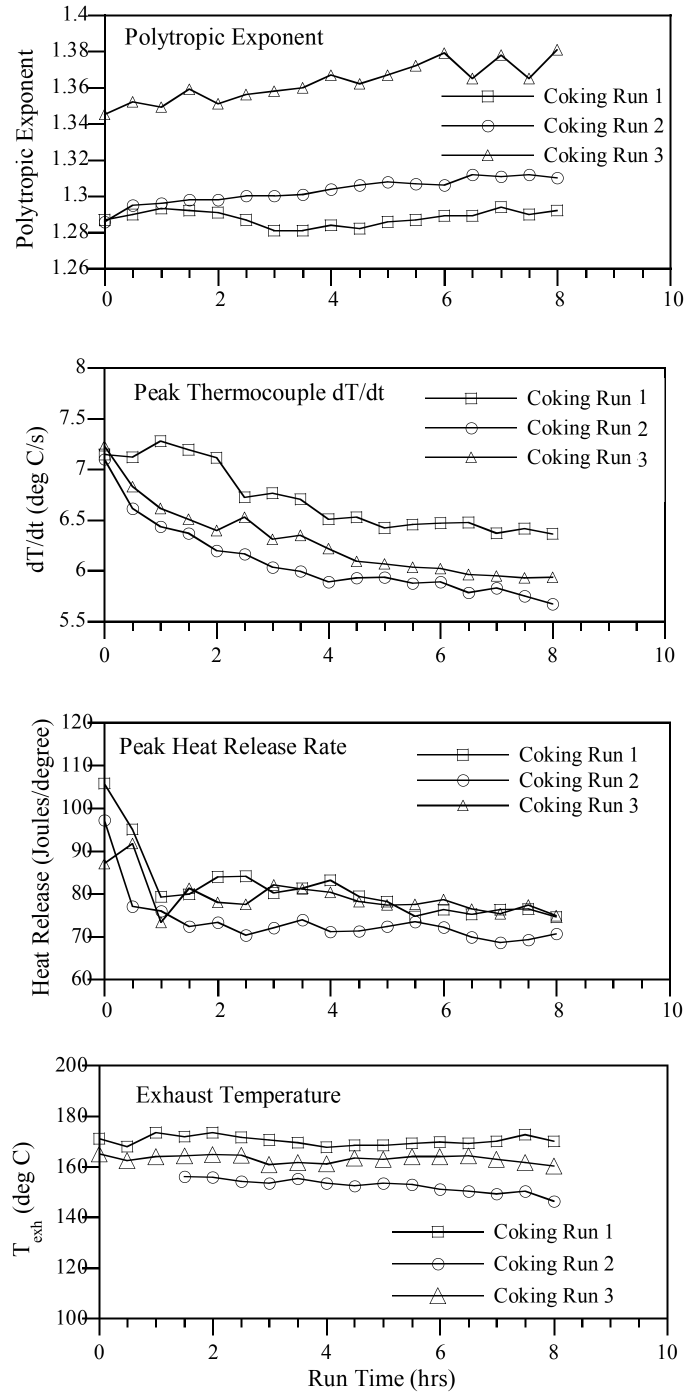


Figure 3: Signal Trends During Single Cylinder Engine Coking Runs (1800 rpm, 2.5 bar BMEP)

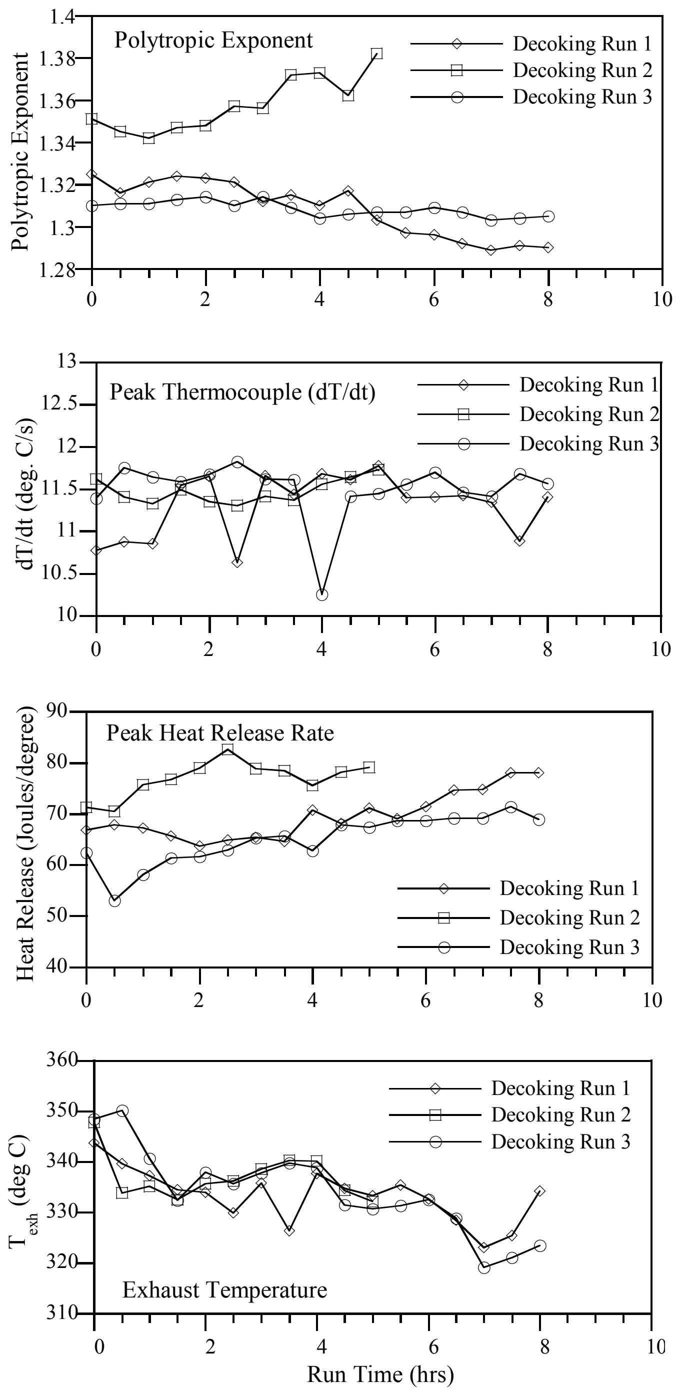
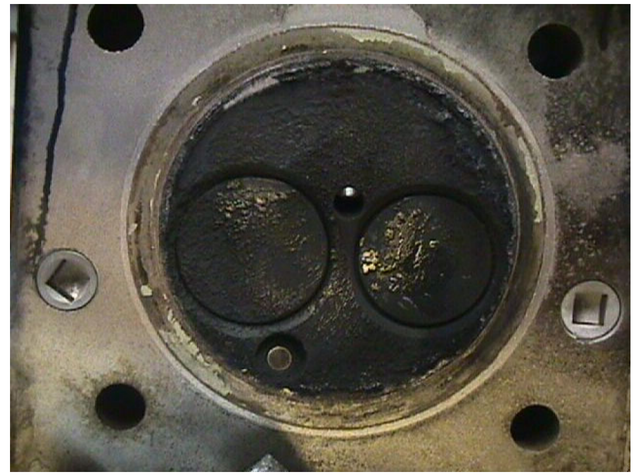


Figure 4: Signal Trends During Single Cylinder Engine Decoking Runs (1800 rpm, 5.5 bar BMEP)

Further evidence of the inadequacy of the decoking procedure on the Hydra is shown in Figure 5. These photographs were taken when the engine was disassembled following a decoking run. Heavy deposits were present on the cylinder head and piston surfaces indicated that the decoking operation was not achieving the desired effect in these experiments.



Cylinder Head

Piston

Figure 5: Engine Deposits Remaining After Decoking

CONCLUSIONS

A naturally aspirated single cylinder research engine was operated alternately between low load "coking" conditions (2.5 bar BMEP) and higher load "decoking" conditions (5.5 bar BMEP) intended to promote the formation and removal respectively of combustion chamber deposits. From these tests, the polytropic exponent of compression and peak heat release rate (obtained from cylinder pressure measurements) were compared with the peak cyclic value of first derivative of an exhaust thermocouple signal (which was intended to reflect peak cyclic exhaust temperature values) and conventional exhaust temperature measurements. The following conclusions were drawn:

1. During the majority of the tests, the polytropic exponent of compression was observed to increase during coking runs and decrease during decoking runs. This was attributed to reductions in heat losses during compression when deposits were present.

2. The peak heat release rate was observed to decrease during coking runs and increase during decoking runs. This was attributed to reductions in ignition delays believed to be due to higher in-cylinder temperature (due to deposit insulating effects) during early injection.

3. The peak cycle value of the first derivative of the exhaust thermocouple signal showed a consistent and marked decrease during coking runs. It is proposed that this was related to changes in the heat release pattern but this cannot be shown conclusively. However, this parameter exhibited no clear trend during decoking runs.

4. Conventional exhaust temperature measurements showed no consistent trend during coking runs but the exhaust temperature decreased during decoking runs. The reason for the decrease is unknown at this time.

5. This study was carried out using a naturally aspirated diesel engine operating at relatively low BMEP levels. Since the results were likely influenced by the engine type and operating conditions, they may not be representative of the behaviour of high BMEP turbocharged diesels.

ACKNOWLEDGMENTS

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