

Investigation of Combustion Robustness in Catalyst Heating Operation on a Spray Guided DISI Engine, Part II - Measurements of Spray Development, Combustion Imaging and Emissions

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ABSTRACT

In-cylinder spray imaging by Mie scattering has been taken with frame rates up to 27,000 fps, along with high speed video photography of chemiluminescence and soot thermal radiation. Spectroscopic measurements have confirmed the presence of OH*, CH* and C2* emissions lines, and their magnitude relative compared to soot radiation. Filtering for CH* has been used with both the high speed video and a Photo-Multiplier Tube (PMT). The PMT signals have been found to correlate with the rate of heat release derived from in-cylinder pressure measurements. A high power photographic strobe has been used to illuminate the fuel spray. Images show that the fuel spray can strike the ground strap of the spark plug, break up, and a fuel cloud then drifts over and under the strap through the spark plug gap. Tests have conducted at two different spark plug orientations using a single spark strategy. The images show interaction of a fuel jet with the earth electrode, stretching of the arc, variable location for the start of combustion and significant cycle-by-cycle variations with the same operating point leading to normal combustion, slow combustion and misfiring cycles. The high speed photography confirms that liquid droplets exist in the spark plug gap at the 10 o'clock spark plug orientation but not at the 2 o'clock spark plug orientation.

INTRODUCTION

Gasoline Direct Injection engines are seen as a possible engine technology that will reduce carbon dioxide emissions,

increase fuel economy and increase specific power output of spark ignition engines.

One particular stage that is key to meeting current emissions legislations is the catalyst heating stage. It is reported that up to 80% of Unburnt Hydrocarbon (UHCs) emitted during the Federal Test Procedure (FTP) are emitted during the cold start [1,2]. This is due to the catalyst not being lit. A retarded ignition strategy is used to increase the exhaust temperature, hence increasing the heat flow to the exhaust while causing a reduction in UHCs [2,3]. A twin injection strategy is then implemented in order to increase the combustion stability. This strategy has been shown to increase the exhaust temperature while maintaining stable combustion [1,4,5].

Robust combustion in this operation mode is essential, i.e., misfire free operation must be ensured on production engines with manufacturing tolerances. Combustion initialisation is found to be sensitive to spark plug protrusion, spark plug orientation, injector orientation and the timing of the 2nd injection in relation to the spark. There is a desire to understand the mechanisms by which the combustion robustness is reduced as geometric changes are made to the combustion system. Therefore, it was decided to research the issue further by using an engine that was deliberately set up to induce a misfire by increasing the spark plug protrusion relative to the production value.

Spark plug orientation, injector orientation, timing of the 2nd injection in relation to the spark and the spark strategy are all

shown to significantly alter the misfiring trends during the catalyst warm-up period [4,6].

Various mechanisms have been presented for the cause of misfiring cycles, both during the warm-up and also during normal engine operation. Fuel preparation is believed to be the major cause of engine misfire, especially when a DISI engine is operating in a stratified mode. There must be an ignitable mixture in the spark plug gap at the time of the spark [7]. CFD modeling shows the air-to-fuel ratio (AFR) in the spark plug gap will depend on the timing of the 2nd injection and also the spark plug orientation [4].

Depending on the timing of the 2nd injection and the spark plug orientation it is possible that liquid fuel could pass through the spark plug gap at the time of the spark. This liquid fuel could act as a heat sink, removing energy from the kernel and hence extinguishing it. The same could happen to the spark as well [4]. However, High Tension (HT) measurements presented in [6] show that the behavior of the arc is similar for both firing and misfiring cycles.

There could well be a high velocity air jet in the spark plug gap induced by the 2nd injection. Depending on the timing of the 2nd injection and the spark plug orientation HT measurement indicate that the arc is being stretched [6]. CFD modeling shows that the spark plug gap gas velocity can be extremely high [4]. If a spark or a kernel was to be formed then they could be stretched by the air flow and hence extinguished.

Work has been conducted at a single injection stratified operating point [8,9,10]. Spark plug orientation has been investigated and depending on the orientation, the spark has been shown to stretch, re-strike and extinguish and then re-strike. Infrequent misfiring cycles were presented, showing a flame kernel to develop and then extinguish. This supports the theory presented by [4]. Similar work has shown that the intense flow created by the spray-induced charge stretches and extinguishes the spark [11].

The reported work focuses on characterizing the differences between the firing and misfiring cycles using two optical techniques: High speed photography and a Photo-Multiplier Tube

EXPERIMENTAL HARDWARE AND SET UP

The engine used in these experiments is a Single cylinder research engine [12] which has a combustion system similar to the 5L Jaguar V8 engine [13]. Both engines have the spark plug and the injector mounted centrally in the combustion chamber. A 6 nozzle multi hole injector is used with an injection pressure of up to 150 bar. Two jets were directed

towards either side of the spark plug while the remaining four jets were directed down towards the piston. The J type spark plug was supplied by NGK.

DATA ACQUISITION (DAQ)

Cylinder pressure was measured on the Single Cylinder using a water cooled Kistler 6041A pressure transducer coupled to a charge amplifier. The cylinder pressure was recorded at a speed of once per crank angle using a National Instruments PCI-M10-16E-1 card. Steady state temperatures and pressures, such as manifold absolute pressure and fuel temperature, were recorded at a speed of once a cycle using a National Instruments PCI-6024E. One hundred cycles of engine data were recorded.

CHEMILUMINESCENCE

During combustion, radicals are formed such as CH, OH and C₂. These radicals can exist in an excited state for a short period of time before they decay down to a lower energy level. This can lead to the emissions of a photon, this process is known as chemiluminescence [14]. The wavelength of the photon emitted is dependent on the species of the radical as shown in Table 1.

Table 1. Wavelength of photon emitted as an excited radical decays to a lower energy state [15]

Radical	Wavelength [nm]	Bandwidth [nm]
CH	430	5
OH	308	10
C ₂	516	3

These photons can then be collected using an optical device such as a Photo Multiplier Tube.

PHOTO MULTIPLIER TUBE (PMT)

A photomultiplier tube, shown in Figure 1, is a vacuum tube consisting of an input window, a photocathode, focusing electrode, a series of electron multipliers and an anode usually sealed into an evacuated glass tube [16].

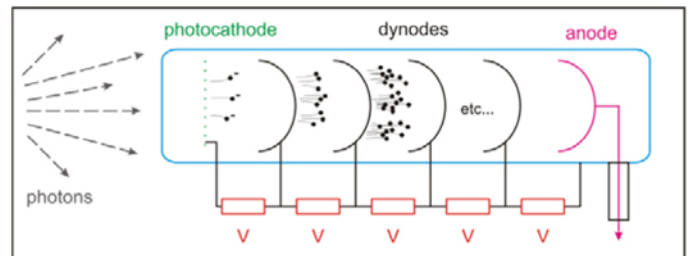


Figure 1. Schematic showing the working of a PMT

The photon emitted by chemiluminescence passes through the input window where it excites electrons in the photocathode. These photoelectrons are then accelerated, by means of a high voltage, towards the dynodes (electron multipliers) by a pair of focusing electrodes. When the photoelectrons strike the dynodes they are multiplied by means of secondary electron emissions. The electrons emitted from the last dynode are then collected onto the anode where they are passed through a resistor leading to an output voltage. A more detailed explanation of the working of a PMT, including explanation of the electron emissions, can be found in [16].

A Hamamatsu R595 PMT with a 55 mm f/2 focusing lens was used to collect photons. The bias voltage was set to 500V. A Comar 430 nm interference filter was located on the front of the PMT so that only photons corresponding to the CH radical were collected. The output of the PMT was recorded at a rate of once per crank angle. 100 cycles of engine data were recorded.

The PMT was installed according to the schematic shown in Figure 2. A dichroic mirror was installed so that there was the option of doing simultaneous high speed videos of combustion while also recording the output of the PMT.

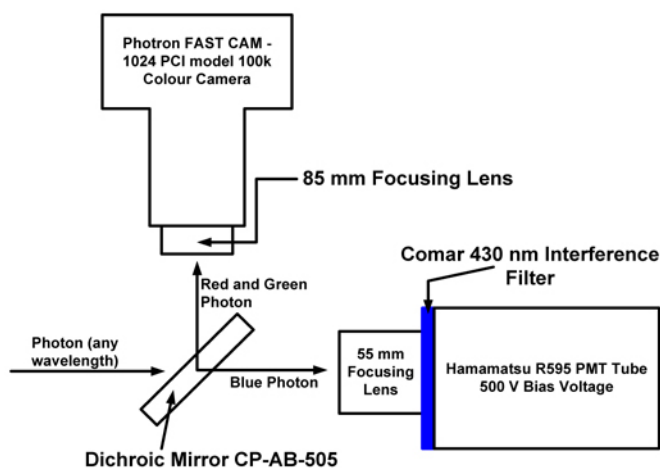


Figure 2. Schematic of the PMT Tube and the High Speed Camera

The dichroic mirror transmits light in the blue region and reflects light in the red and the green region, and the transmittance of the dichroic mirror is shown in Figure 3. This set up would allow the 430 nm photons to reach the detector of the PMT while light from the glowing soot would be imaged using the high speed camera. However, it is not possible to visualize the spray, the spark and combustion on the high speed camera while simultaneously using the PMT. The spark spectrum, Figure 4, shows that the majority of the light from the spark would be transmitted through the dichroic mirror and hence would not appear on the camera

detector. The light source needed for illuminating the spray would also be transmitted through the dichroic mirror and due to its rather wide bandwidth could not be filtered out and hence would be detected on the PMT.

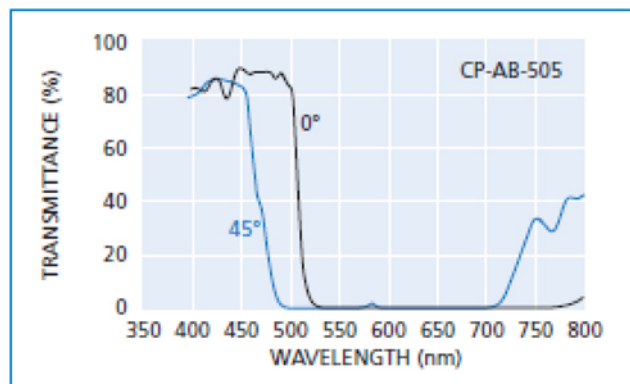


Figure 3. Transmittance of the dichroic mirror

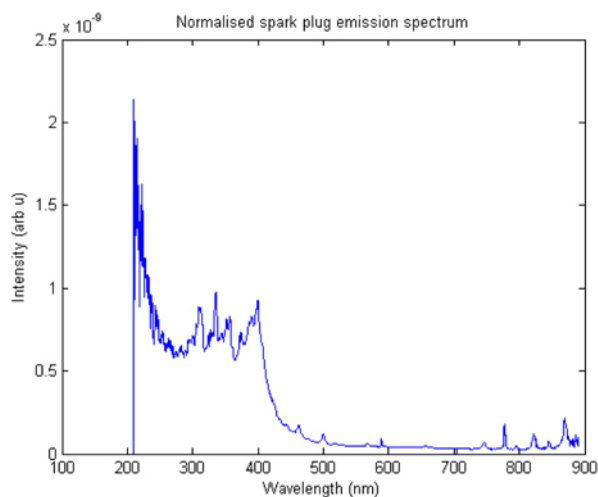


Figure 4. Spark Emission Spectrum

HIGH SPEED PHOTOGRAPHY

High speed photography was conducted in order to visualize the spark, the 2nd injection and combustion. The camera set up is shown in Figure 2, except that the dichroic mirror was replaced by a standard mirror.

A Photron FASTCAM-1024 PCI colour camera was used with an 85 mm focusing lens. Two different light sources were investigated for illuminating the spray; first a 100W halogen lamp and second a photographic studio strobe.

Table 2. High Speed Photography Camera Set Up

Light Source	Studio Strobe	100W Halogen Lamp
Resolution	512*256	512*256
Frame Rate	6000	6000
Lens	85 mm f(2)	50 mm f(2)
Aperture	f(8)	f(2)
Image Rate	1 in 16 cycles	Every Cycle

The power of the studio strobe is much higher than the halogen lamp, hence it enables a lot more light into the engine cylinder. This then means that the lens aperture can be reduced and as a result a better depth of field is achieved leading to a much sharper image. However, the disadvantage of the studio strobe is that takes 1s to recharge so that images can only be taken every 17th cycle; an image taken using the studio strobe is shown in [Figure 5](#).

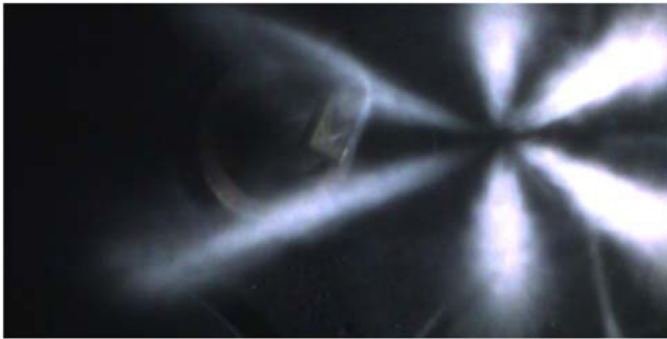


Figure 5. Image taken using the studio strobe, inlet valves located at the bottom of the image

The lower power 100W halogen lamp operates continuously so an image can be taken every cycle. However, the aperture is fully open leading to a less sharp image compared to the studio strobe, this is shown in [Figure 6](#).



Figure 6. Image taken using the halogen lamp, inlet valves located at the bottom of the image

The purpose of using the high speed camera is to determine if there are any differences in the spray, the spark and combustion between the two cycles. Hence, it is imperative to record as high a quality image as possible. It does not matter if the cycles recorded are not consecutive, hence the studio strobe will be used as the light source.

ENGINE OPERATING POINT

A twin injection, retarded ignition strategy is used with the option of using either a single or a twin spark strategy.

The 1st injection occurs during the intake stroke where approximately 70% of the fuel is injected to give a well mixed but lean background mixture in the cylinder.

The 2nd injection occurs close to ignition and causes a locally rich mixture to be present in the spark plug gap at the time of ignition, while the overall air to fuel ratio in the cylinder is slightly lean.

A typical pressure trace for this operating condition is shown in [Figure 7](#). The timing of the 1st injection is fixed at 290 CAD bTDC as shown in [Figure 7](#). The end of the 2nd injection is fixed at 0.2 CAD aIGN.

The dwell time associated with this sparking strategy is fixed at 4.5ms for the single spark.

The data is presented at the 2 and the 10 o'clock spark plug orientation as defined in [Figure 8](#).

Table 3. Catalyst Warm-up Operating Point

Engine Speed	1350 [RPM]
Manifold Pressure	770 [mbara]
Start of 1 st Injection	290 [CAD bTDC]
1 st Injection Duration	1.1 [ms]
End Of 2 nd Injection	0.2 CAD after Ignition
2 nd Injection Duration	0.5 [ms]
Ignition Timing	-7.8 [CAD bTDC]
λ	1.05
Fuel Pressure	150 [bar]
I VO	33.5 [CAD aTDC]
I VC	241.5 [CAD aTDC]
E VO	200 [CAD bTDC]
E VC	50 [CAD aTDC]

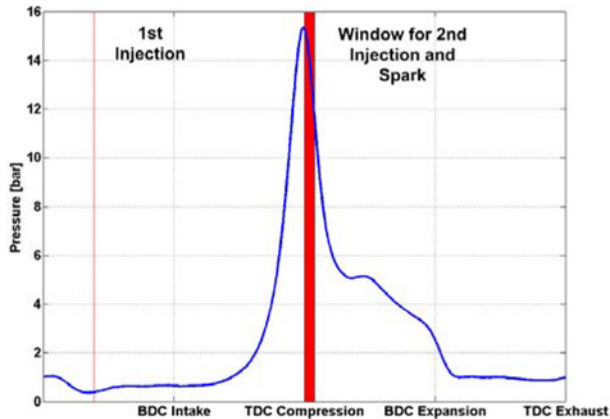


Figure 7. Typical catalyst warm-up pressure trace

The in-cylinder pressure, PMT output and steady state temperatures and pressures were all logged.

PMT output will be presented for: a firing cycle, a misfiring cycle and a slow burning cycle at a spark plug orientation of 10 o'clock. These PMT traces will then be analysed and plotted against gross mean effective pressure. High speed images will be presented for both a firing and a misfiring cycle at both a 2 o'clock and 10 o'clock spark plug orientation.

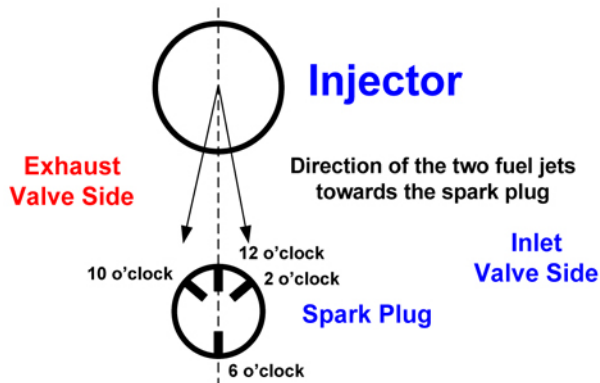


Figure 8. Spark Plug ground strap orientation, as viewed from above

RESULTS AND DISCUSSIONS

PHOTOMULTIPLIER TUBE RESULTS

The PMT data will be presented for a 10 o'clock spark plug orientation, a single spark strategy and with the 2nd injection ending at 0.2 CAD aIGN. Previous work has already been conducted to look at the effect of spark plug orientation and injection timing on the misfiring trends during the catalyst heating mode. The purpose of the PMT is to determine whether light emitted from combustion is proportional to heat

release and also if there is any combustion during the misfiring cycles.

Cylinder pressure trace can be converted into net heat release rate using an analysis based on the 1st law of thermodynamics as shown in [17]. The heat release analysis computes how much heat would have to be added to the cylinder contents, in order to produce the observed pressure variations. The usual assumption is to have a single zone; this implies that the products and the reactants are fully mixed.

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma-1} P \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dP}{d\theta}$$

[1]

Q_n – Net Heat Release

P – Cylinder Pressure

V – Cylinder Volume

γ – Ratio of specific heats

θ – Engine crank angle

This analysis has been applied and the results of this as well as the output of the PMT is shown for a firing cycle in Figure 9. The output of the PMT is then integrated with respect to crank angle and plotted against GMEP as shown for all cycles in Figure 10. The maximum PMT output is then found and the location at which this maximum occurs is then plotted against GMEP for all cycles as shown in Figure 11.

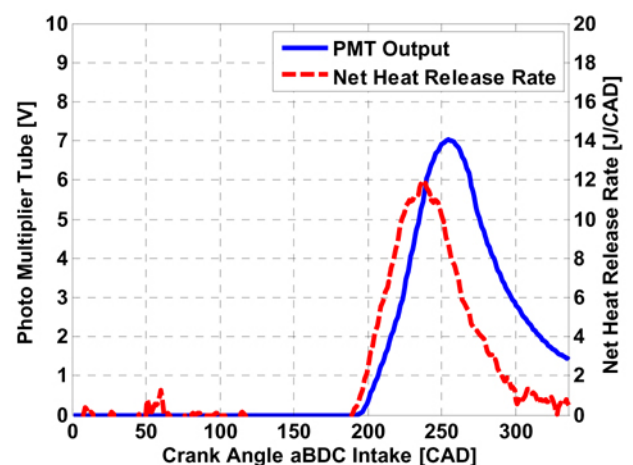


Figure 9. Net heat release rate and the PMT signal for a firing cycle