

In-Cylinder Wall Temperature Influence on Unburned Hydrocarbon Emissions During Transitional Period in an Optical Engine Using a Laser-Induced Phosphorescence Technique

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ABSTRACT

Emissions of Unburned Hydrocarbons (UHC) from diesel engines are a particular concern during the starting process, when after-treatment devices are typically below optimal operating temperatures. Drivability in the subsequent warm-up phase is also impaired by large cyclic fluctuations in mean effective pressure (MEP). This paper discusses in-cylinder wall temperature influence on unburned hydrocarbon emissions and combustion stability during the starting and warm-up process in an optical engine. A laser-induced phosphorescence technique is used for quantitative measurements of in-cylinder wall temperatures just prior to start of injection (SOI), which are correlated to engine out UHC emission mole fractions and combustion phasing during starting sequences over a range of charge densities, at a fixed fueling rate.

Squish zone cylinder wall temperature shows significant influence on engine out UHC emissions during the warm-up process. Higher surface temperatures correlate with lower levels of engine-out UHC. Moreover, the UHC emissions are more sensitive to wall temperatures at higher charge densities. Engine-out UHC is less sensitive to bowl surface temperatures, which are observed to quickly attain values nearly 100°C greater than those measured in the squish zone. Increasing charge density reduces the time required to attain steady temperatures, but has little effect on the final surface steady state temperature. Misfire and incomplete combustion occurs more often at low bowl temperature. However, high bowl temperatures are observed to assist residual fuel evaporation, advance combustion phasing and reduce the probability of misfires.

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INTRODUCTION

Diesel engines are attractive due to their high thermal efficiencies, although meeting ever more stringent emissions regulations remains challenging. Of concern are emissions of unburned hydrocarbons (UHC), which are typically generated in elevated quantities during the starting process when after-treatment devices are below operating temperatures. Varying boundary conditions during starting may result in unstable combustion or high emissions. Emissions during starting are difficult to predict as ambient conditions vary by locale or season. Incomplete combustion and misfiring cycles can cause blue or white smoke, indicating high UHC emissions [1, 2, 3]. The phenomenon is difficult to investigate due to the complex nature of the transient process.

Auto-ignition has classically been considered to be a function of charge temperature, mixture density, induction duration, and mixture composition [4, 5, 6]. Each of these factors can have great impact on combustion phasing and emission. By influencing mixture composition through fuel wall film evaporation rates, and charge temperature by forming the boundary conditions for convective heat losses, surface temperatures can have a strong, if indirect effect on auto-ignition.

Laser induced phosphorescence is an accurate, high resolution, and non-intrusive means of temperature measurement based on temperature-dependent fluorescence lifetimes of rare earth elements [2]. Temperatures in a range from cryogenic up to 1700 °C can be determined by the use of

different phosphors. The technique has been used for wall temperature measurement in both internal combustion and turbine engines [7, 8, 9].

In this work, cylinder wall temperature and engine -out UHC emissions are measured during warm-up sequences in an optical engine over a range of charge densities. Laser induced phosphorescence is used for in-cylinder surface temperature measurement while simultaneous cycle-resolved engine-out UHC measurements are made. The temperature measurements are made at two locations on windows mounted in the piston bowl and in the squish zone region. The effect of thermal boundary conditions on cycle-to-cycle variation can thus be investigated during the starting process of an optical engine, providing insight to their effect on combustion phasing and engine UHC emission. Although the wall temperatures are measured in an engine having non-metallic parts (quartz windows), trends observed in the optical engine are believed to qualitatively represent those of metallic engines. Similar engines have been shown to closely match the near-TDC thermodynamic conditions and emissions of a metal engine [15].

EXPERIMENTAL SETUP

Laser Induced Phosphorescence

Laser induced phosphorescence is a temperature measurement technique based on the detection of phosphorescence from thermo-graphic phosphors. In the experiments, the phosphor $\text{La}_2\text{O}_2\text{S:Eu}$ was used. Excited by a pulsed UV laser, the resulting phosphorescence is observed, the emission intensity of which decays exponentially according to the following relation:

$$I = I_0 \cdot e^{-\frac{t}{\tau}} \quad (1)$$

where I_0 is initial emission intensity, t is time, and τ is the time constant of the phosphorescence decay [7]. The time constant is temperature-dependent and is a property of the laser-excited thermo-graphic phosphor. By measuring the decay rate of the emission intensity, the surface temperature can therefore be determined. Measurement error using this technique has been reported to be less than 1% [10]. Typical phosphorescent emission curves are shown in figure 2, illustrating that decay rates increase with higher temperature.

The emission processes of phosphor $\text{La}_2\text{O}_2\text{S:Eu}$ are caused by energy transitions within the Eu^{3+} atom. Transitions from $^5\text{D}_2$, $^5\text{D}_1$, and $^5\text{D}_0$ states result in emission at 512 nm, 538 nm, and 624 nm wavelengths that are highly sensitive to temperature [11].

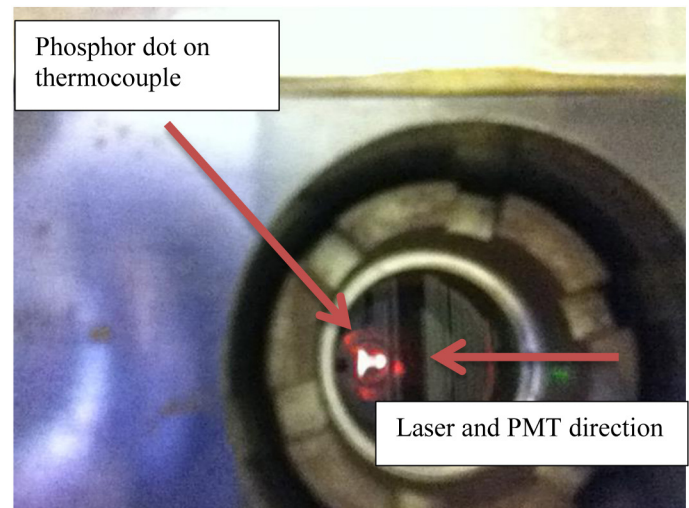


Figure 1. Inside view of phosphor calibration set up

The 538nm emission line was chosen for observation in the experiments due to its high temperature sensitivity in the 100 °C to 300 °C range. A photo-multiplier tube (PMT) (Hamamatsu model H10721) was used to detect the phosphorescence emission. A band-pass filter with 540 nm center wavelength and full width half maximum of 10 nm was placed in front of the PMT to minimize interference from the other bands. In addition, a quartz glass lens (focal length = +100mm) was used to focus the phosphorescence onto the PMT. Prior to the engine experiments, the phosphor was calibrated under controlled temperature conditions. A K-type thermocouple's junction was coated with a mixture of phosphor and HPC binder, and located in a chamber having similar geometry to the engine cylinder, as shown in figure 1. The entire thermally insulated chamber was heated to the desired feedback-controlled set point temperature by an electric resistance heater (2000W). The third harmonic of an Nd:YAG laser (Spectra-Physics INDI-HG-10S) was used to provide a 7 ns-long pulsed, 8 mm diameter beam of 355 nm wavelength, which directed at the thermocouple bead, served as the UV excitation source for the phosphor. The laser was introduced to the calibration chamber through a quartz window mounted in its side. For both calibration and experiment, the phosphorescence following laser excitation was observed from the same window which was used to introduce the excitation laser beam to the calibration chamber and cylinder, using a long pass filter to avoid introducing laser output into the PMT. The PMT gain was set to 0.5V for all experiments. The PMT current output signal was conditioned with a hardware low-pass filter before being terminated with a 100 Ω load resistor. A 1 GHz recording oscilloscope (Agilent MSO8104A) was used to sample the signal voltage across the load resistor. Time constants were then fit to the measured phosphorescence emission. Calibration was performed in the range of temperatures

between 375 and 525 K. Figure 3 shows the resulting calibration curve of time constant versus temperature. Each data point on the graph is an average of 10 measurements. The standard deviation is less than 2%.

During engine experiments the repetition rate of the laser was maintained at 10 Hz. The laser energy was kept at 200 μ J for all experiments, an energy level deemed sufficiently low such that laser heating of the wall can be neglected.

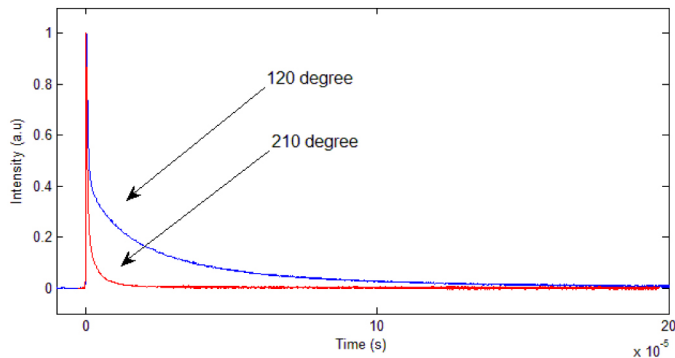


Figure 2. Phosphorescent emission intensity (538 nm) following a UV laser pulse at 120 °C and 210 °C

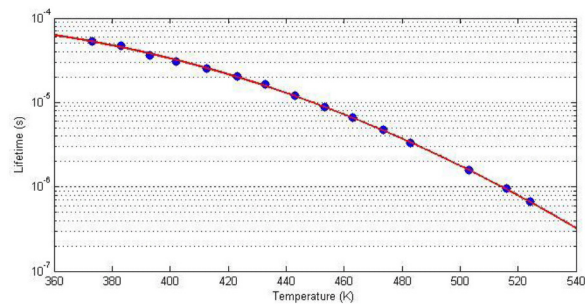


Figure 3. Phosphorescence time constant vs. temperature for La₂O₂S:Eu at 538 nm wavelength.

The phosphor was applied on two quartz windows. Non-fluorescent ZYP HPC binder and ZYP LK binder were mixed in 1:1 (vol/vol) proportions. Phosphor and binder were then mixed at a ratio of 0.2:1, (vol/vol) and then painted onto the clear quartz windows. The phosphor-painted windows were dried for 12 hours prior to being cured at a temperature of 150 °C [12].

Engine Operation Procedure

A single-cylinder, direct-injection optical research engine (AVL 5402) was used in these experiments. The specifications of the engine are shown in [table 1](#). [Table 2](#) shows injector specifications.

Table 1. Engine specifications

Number of cylinders	1
Cycle	4-stroke
Displacement	510 cm ³
Bore	85 mm
Stroke	90 mm
Connecting rod length	148 mm
Compression ratio	15:1
Bowl diameter	40 mm
Bowl depth	14.5
Number of intake vale	2
Number of exhaust vale	2
Intake vale opening/closing	330°/-152° CAD ATDC
Exhaust vale opening/closing	145°/-355°CAD ATDC
Injection system	Bosch common rail
Swirl Ratio	2.0 to 4.5
Fuel	n-heptane

Table 2. Injector specifications

DI injector type	Continental-Piezo
Design	VCO-Nozzle
Number of holes	7
Hole diameter	0.115m
Angle of fuel-jet axis(inclusive)	142°