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In-cylinder Surface Thermometry using Laser Induced Phosphorescence

(New Measurements and comparisons of Alternative Approaches)

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Key Words: Heat transfer, surface temperature, HCCI, laser induced phosphorescence (LIP)

ABSTRACT

Surface temperature in internal combustion engines is of high interest when studying heat losses. Two approaches for retrieving the surface temperatures are thermocouples and Laser Induced Phosphorescence, LIP. This study aims to analyze LIP as a technique for measuring surface temperature in internal combustion engines. The motivation for this study is the need for accurate surface temperatures which can be used by predictive models and increase knowledge about heat transfer.

In this work LIP measurements have been carried out in two optical engines. In the first engine a thermographic phosphor was applied on top of a metal piston. The second engine was fitted with a quartz liner which was coated with phosphor material. Several coating thicknesses have been tested and the LIP temperature was extracted from both opposing sides of the phosphor. Both engines were run in HCCI mode with reference fuels and electrically heated air.

In a previous publication, the authors showed that a layer of phosphor can show different temperatures i.e. a higher temperature on the side facing the cylinder gas than on the side facing the wall. In this study it is shown which thickness is needed to accurately present the temperature for typical engine combustion. With an increasing thickness of the phosphor material, the surface gets gradually insulated and the phosphor temperature reading becomes inaccurate.

LIP measurements from a quartz ring and a metal piston have been compared and the temperature increase during combustion is similar although the heat conductivity of quartz is 40-200 times smaller than the metal piston. Measurements with thermocouples often show a lower temperature increase than what is seen in the LIP results. The difference in heat conductivity between the phosphor coating and the underlying surface is of importance for understanding what temperature is actually measured.

INTRODUCTION

Every year around 60 million cars are produced worldwide [1] and each of them has an internal combustion engine. Concerns about carbon dioxide levels and decreasing supply of fuel are motivation for studying and improving the efficiency of internal combustion engines. Homogenous Charge Compression Ignition, HCCI, is a concept that has shown promising thermodynamic efficiency [2] but experiences problems with the load range and combustion efficiency [3]. There are other newer combustion concepts that together with HCCI can be summarized under Low Temperature Combustion, LTC [4-6]. More recent LTC concepts, for instance Partially Premixed Combustion (PPC), usually have a similar high thermodynamic efficiency as HCCI but with improved combustion efficiency and increased load range, thus providing the potential for very high brake efficiency [7]. For further increases in brake efficiency, the understanding of heat transfer processes is crucial. What signifies LTC concepts with high thermodynamic efficiency is the high combustion rate, which makes HCCI suitable for investigations of heat transfer processes in LTC engines.

One way to achieve high thermal efficiency is to control the combustion phasing to a few Crank Angle Degrees, CAD, after Top Dead Center, TDC [8]. With high-octane, fast burning fuel this combustion phasing can lead to high pressure rise rates, especially at higher loads [9]. High pressure rise rates can lead to increased heat transfer and thus a lower thermal efficiency. One way to study the heat transfer is to measure the surface temperature during combustion.

Surface temperature studies in internal combustion engines have been performed for many decades using fast response thermocouples [10-12]. Within the last few decades an alternative concept for remote temperature sensing has been introduced to engine research, known as Laser Induced Phosphorescence, LIP [13]. A phosphorescent material is applied onto the surface of interest, for example the piston bowl. As the material is excited by laser radiation, it subsequentially emits temperature dependent phosphorescent light. Phosphorescence intensity for most thermographic phosphors decreases exponentially in time, showing shorter decay times at elevated temperatures.

The LIP technique needs optical access for excitation and signal collection as well as a phosphor coating on the surface to be measured. Optical components used for windows are often made of Quartz or Sapphire as most phosphors require excitation wavelengths in the UV region. Quartz as a low-cost solution is more frequently used, but has the drawback of not matching the thermal properties of metals very well. Also, when applying a phosphor to a surface, by spray coating, a binding agent is needed in order to make the phosphor adhere. In these experiments a water-based binding material containing 2 % Magnesium Aluminum Silicate was used. Thermal conductivities of different materials have been summarized in table 1.

Table 1: Thermal conductivities of different materials.

Material	Thermal conductivity [W / (m K)]
Quartz	1
Sapphire	40
Binder	0.1
Steel	40
Iron	70
Aluminum	200

Temperature measurements with thermocouples on a moving engine parts such as the piston surface are rather complex since the piston is moving and the electrical signal needs to be retrieved. The wiring can be routed from the thermocouple via the connecting rod to a telemetry linkage [11,12].

The aim of this work is to provide an improved understanding of the LIP surface temperature measurements by investigating the influence of two different LIP implementations and to compare these with other reported surface temperature measurements. In a previous publication, the authors showed that a layer of phosphor can show different temperatures i.e. a higher temperature on the side facing the cylinder gas than on the side facing the wall [14].The temperature swing of the phosphor material from compression via combustion to expansion was studied as well as the temperatures on the wall-side and gas-side of the phosphor coating.

EXPERIMENTAL SETUP

The surface temperature measurements have been conducted on one heavy-duty engine and one light-duty engine. Both of the engines were only using one cylinder and both were modified for optical access. The heavy-duty engine was a converted Scania D12 single-cylinder diesel engine with one of the exhaust valves removed to provide optical access to the combustion chamber through the exhaust port. The light-duty engine was a Toyota four-cylinder diesel engine, modified to operate on one cylinder only and fitted with a quartz liner and piston extension of Bowditch design [13]. The fuel systems on both engines were changed from direct-injection to port fuel injection, PFI, and the engines were run in HCCI mode. More data on the experimental engines is presented in Table 2.

Table 2 Data on the two engines used in this study.

Engine	Light-duty	Heavy-duty
Cylinder volume, [lit]	0.5	2
Bore, [mm]	82	127
Stroke, [mm]	92	154
Speed, [rpm]	1200	1200
Load (IMEPg), [bar]	2-3	5-6
Injection system	PFI	PFI
Optical access	Horizontal through quartz liner	Vertical through exhaust port
Compression ratio, [-]	11	13
Fuel	PRF50	PRF100
Inlet pressure, [bar]	1	1.3–1.5
Inlet temperature, [K]	390	320
Piston geometry	Flat/pancake	Bowl

For this work, two different thermographic phosphors have been chosen, Cadmium tungstate ($CdWO_4$) and Lanthanum oxy-sulfide (La_2O_2S:Eu) with 2% Eu dopant concentration. These phosphors exhibit a decay time which is sensitive to temperature in between 300 and 600

K, see figure 1. $CdWO_4$ requires UV excitation at 266 nm, whereas La_2O_2S:Eu can be suitably excited by 355 nm. Both wavelengths have been supplied by a 10 Hz pulsed Nd:YAG laser with a 5 ns pulse duration, operating at its 3rd or 4th harmonic.

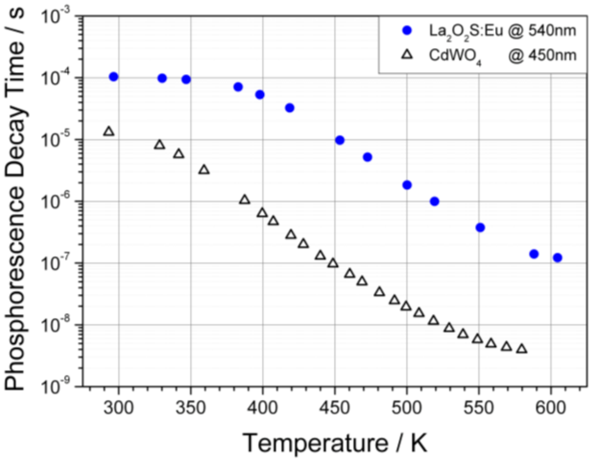

Figure 1: Phosphorescence lifetime for $CdWO_4$ and La_2O_2S:Eu as a function of temperature.

In the first experiment crank-angle resolved piston temperature measurements were performed in the SCANIA D12 heavy-duty research engine. The engine was run in HCCI mode at three different loads. Engine load was varied by controlling the fuel injection duration and the inlet air pressure. Temperatures from the piston bowl and the squish area have been monitored simultaneously using LIP after applying two spots of $CdWO_4$ onto the piston surface. The global gas temperature inside the combustion chamber was extracted from the cylinder pressure trace. An illustration of the experimental setup is shown in figure 2.

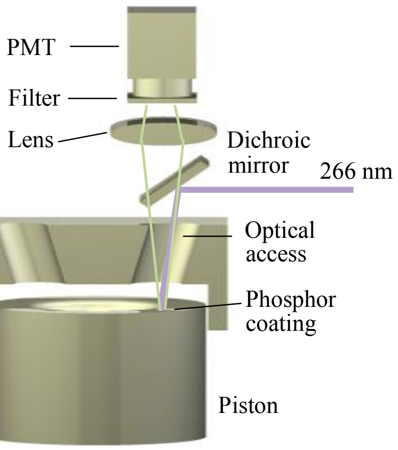

Figure 2: Experimental setup for piston surface temperature measurements in a heavy duty engine.

Laser light at 266 nm is directed through the quartz window in one of the exhaust ports to illuminate the phosphor coating on top of the piston. A lens behind the laser mirror was used to image phosphorescence signals onto two photomultiplier tubes (PMTs). Spectral bandpass filters, centered at 450nm (±20 nm) were placed in front of the detectors to eliminate spurious laser radiation and to spectrally isolate the phosphorescence emission.

The second experiment was performed in the light duty Toyota engine that has been fitted with a quartz liner for optical access to the upper part of the combustion chamber. La_2O_2S:Eu coatings of different layer thicknesses have been applied in consecutive experiments on the uppermost part of the quartz liner. The experimental setup is displayed in figure 3.

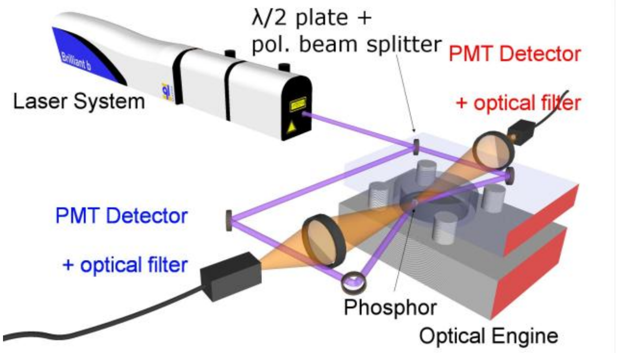

Figure 3: Experimental setup for two-face phosphor temperature determination in an optical engine.

The quartz liner allowed phosphor excitation and collection from two opposing sides of the coating, i.e. the chamber wall side (blue) and the gas side (red). Hence, the laser beam path was split into two using a λ/2-plate in combination with a polarizing beam splitter. Irises were used to limit the area on the phosphor coating over which the temperature dependent phosphorescence was extracted. Two lenses (f_1 = +100 mm, f_2 = +200 mm, $d_{1,2}$ = 50 mm) imaged the phosphorescence on two PMT detectors which were connected to a 350 MHz oscilloscope. Interference filters were placed in front of the detectors. These filters were fit to isolate the phosphorescence wavelength from spurious laser- and background radiation; a 450 nm bandpass filter was chosen for $CdWO_4$ and a 540 nm bandpass filter for La_2O_2S:Eu respectively.

Due to very short absorption lengths of UV light in ceramic materials (such as the phosphor's host material), two separate temperature readings can be obtained from the phosphor, i.e. one from each side of the substrate. In principle, although the excitation light is heavily absorbed, the generated red-shifted phosphorescence could to some extent leak trough the substrate and thus introduce cross-talk. To quantify this effect, the beam path has been blocked either way before each experiment. The amount of signal that leaked through the phosphor into the opposite detector was in the order of 20% or less.

RESULTS

Heavy duty results

The engine has been run at 6 bar Gross Indicated Mean Effective Pressure, IMEPg, in HCCI mode. The calculated cylinder gas temperature peaks below 1600 K at 10 CAD ATDC, see figure 4. The temperature of the phosphor material also peaks at 10 CAD ATDC at a temperature of 500 K, see figure 5, case 1. The difference between the maximum and the minimum phosphor temperature is 40 K in the range -30 to 30 CAD ATDC which is similar to what Husberg et al. [11] have previously shown.

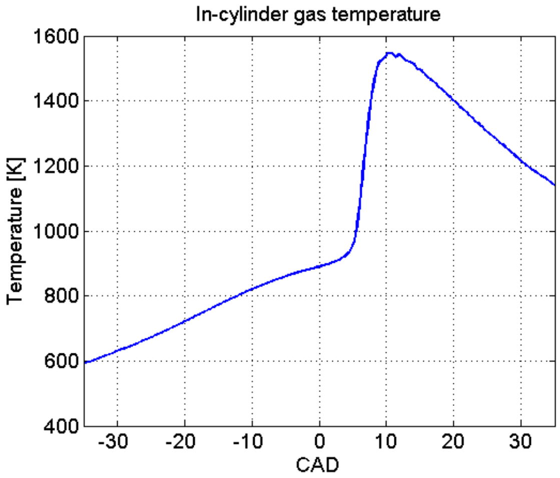

Figure 4. Gas temperature during HCCI combustion at 6 bar IMEPg in the heavy duty engine.

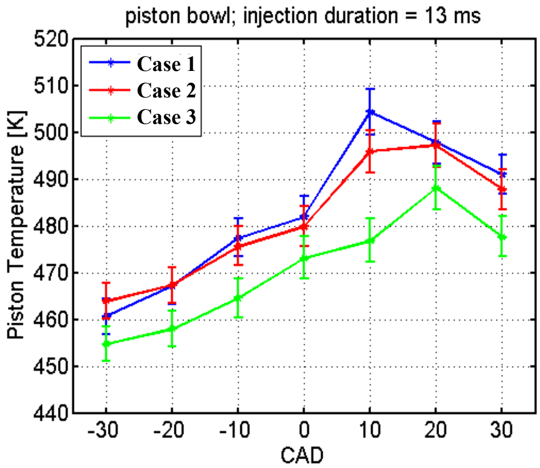

Figure 5. Temperature of phosphor material during HCCI combustion and 6 bar IMEPg. The different series have been run with different intake pressures i.e. lower intake pressure give lower surface temperature. Error bars denote the standard deviation of 100 consecutive engine cycles.

Light duty results

The light duty engine has been run at low load (2-3 bar IMEPg) in HCCI mode. At 3 bar IMEPg the cylinder gas temperature peaks just above 1600 K at 5 CAD ATDC, see figure 6. The temperature of the phosphor is higher in the light duty experiments than in the heavy duty experiments, see figure 7.

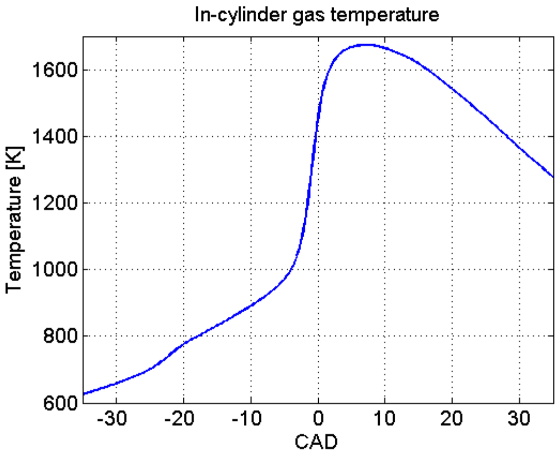

Figure 6. Gas temperature during HCCI combustion at 3 bar IMEPg in light duty engine. The range in CAD has been shortened to -30 to 30 for comparison to the heavy duty case.

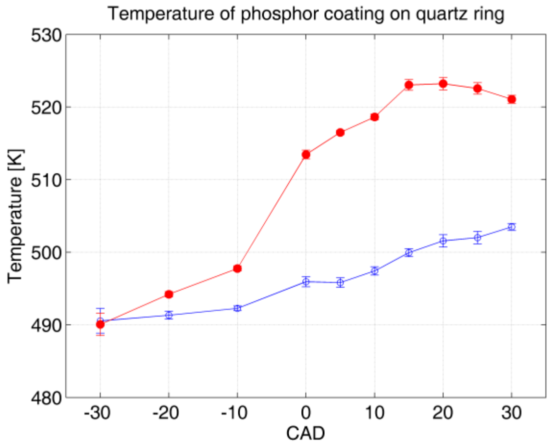

Figure 7. Temperature of phosphor material during HCCI combustion at 3 bar IMEPg. The red data is the readings from the gas side and the blue data is from the chamber wall side. The thickness of the phosphor has been measured to 70 µm.

A thinner layer of phosphor coating was tested for minimizing the difference in temperature between the two sides of the phosphor coating. Due to restrictions in pressure rise rate for the optical engine the amount of fuel injected was lowered compared to the previous results. The lower amount of fuel resulted in a load of 2 bar IMEPg and the gas temperature, see figure 8, peaked at 1500 K at 5 CAD ATDC. In figure 9 the temperature of the phosphor coating is shown and the difference between the wall side and the gas side is 5 K at the most. The thickness of the phosphor coating was measured to 20 µm which proved to drastically reduce the insulating effect of the surface as seen in figure 7.

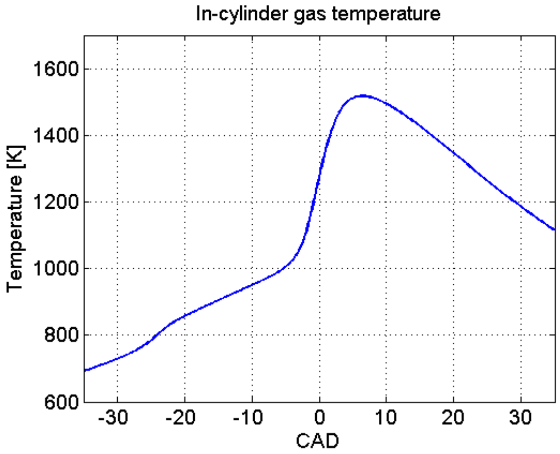

Figure 8. Gas temperature during HCCI combustion at 2 bar IMEPg in light duty engine.

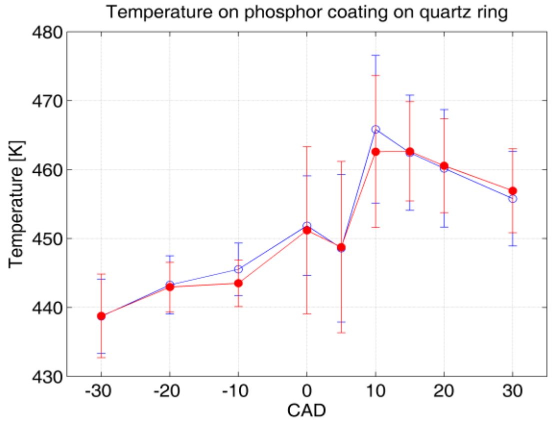

Figure 9. Temperature of phosphor material during HCCI combustion at 2 bar IMEPg. The red data is from the gas side and the blue data is from the chamber wall side. The thickness of the phosphor was measured to 20 µm.

DISCUSSION

Temperature swing

The temperature swing from -30 to 30 CAD ATDC was 25-40 K in the both light-duty experiments as well as the heavy-duty experiment which is similar to the results of Husberg et al [11]. The expectation was to see a clear difference between the surface temperature of the steel piston and the quartz ring since steel has a thermal conductivity 40 times higher than quartz (see table 1). Other surface temperature measurements in HCCI engines with thermocouples [12,16] only show a temperature swing of 5-10 K when measured on metal surfaces.

Fujimoto et al. [17] has made engine simulations using materials with different thermal conductivity in the surface material of the cylinder head with the thermal properties varying from aluminum to 0.001 times the value of aluminum, see table 1. Fujimotos simulations with aluminum showed a temperature swing, between -30 to +30 CAD ATDC, of approximately 5 K. Fujimoto also simulated a material with a thermal conductivity 0.01 times the value of aluminum which gave a temperature swing of approximately 50 K. Compared to temperature measurements conducted with thermocouples [12,16] and the simulation work [17] the heavy-duty results seem to be overstated. The cause of this could be a too thick phosphor coating which insulated the piston surface resulting in temperature readings giving information about the phosphor temperature but not the piston surface.

Temperature difference between wall-side and gas-side of the phosphor coating

In the light-duty experiments the temperature of the phosphor coating was measured from both the wall-side and the gas-side. The measurements were possible since the coating was applied on a quartz surface. In the first experiment the phosphor coating was measured to 70 µm which gave a temperature difference between the wall-side and the gas-side of the phosphor of 40 K. In the second light-duty experiment a 20 µm phosphor coating was applied to the quartz surface. The temperature difference between the wall-side and the gas-side was 5 K at the most which was within the margin of error. The insulating effect of the phosphor coating seems to have been decreased to an acceptable level due to thinner coating.

The temperature measurements on the light-duty engine were performed on a quartz surface. Iron, steel and aluminum, which are common materials in combustion engines, have a higher thermal conductivity and will transport heat faster than quartz. With a surface material with higher thermal conductivity it is possible that there would be an insulating effect to take into account even with a phosphor coating of 20 µm.

CONCLUSIONS

Surface temperature measurements were performed on both a light duty and a heavy duty engine using Laser Induced Phosphorescence. In the heavy duty engine experiments the phosphor coating was applied on a metal piston and the phosphorescence signal was extracted through an exhaust port. The temperature readings seemed overstated compared to measurements conducted with thermocouples and simulation which could be the result of a too thick coating. The binding material used for applying the phosphor material has a thermal conductivity 400 times smaller than the steel in the piston.

The thickness of the phosphor coating on a quartz surface was varied in experiment conducted on a light duty engine running in HCCI combustion. A phosphor coating of 70 µm insulated the surface of interest and gave temperature data that did not correlate with the surface temperature. A phosphor coating of 20 µm in thickness gave negligible errors but with faster and higher transients, i.e. higher load and higher thermal conductivity of the surface material, the thickness of the phosphor coating would possibly need to be reduced. More advanced coating techniques like chemical vapor deposition, RF magnetron sputtering and sol-gel-deposition allow to produce phosphor layers thinner than 1 μm and should be considered in future engine research.

The thermal conductivity of the binding material is close to ceramic materials. Therefore, the technique where the temperature of the phosphor coating is measured from both sides can also be used to study how insulating materials affect the combustion and the heat transfer.

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NOMENCLATURE

ATDC:	After Top Dead Center
CAD:	Crank Angle Degree
HCCI:	Homogenous Charge Compression Ignition
IMEPg:	Gross Indicated Mean Effective Pressure
LIP:	Laser Induced Phosphorescence
LTC:	Low Temperature Combustion
PFI:	Port Fuel Injection
PMT:	Photomultiplier tube
PPC:	Partially Premixed Combustion
UV:	Ultraviolet

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