

Laser-Induced Phosphorescence and the Impact of Phosphor Coating Thickness on Crank-Angle Resolved Cylinder Wall Temperatures

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ABSTRACT

In order to further improve the energy conversion efficiency in reciprocating engines, detailed knowledge about the involved processes is required. One major loss source in internal combustion engines is heat loss through the cylinder walls. In order to increase the understanding of heat transfer processes and to validate and generate new heat transfer correlation models it is desirable, or even necessary, to have crank-angle resolved data on in-cylinder wall temperature.

Laser-Induced Phosphorescence has proved to be a useful tool for surface thermometry also in such harsh environments as running engines. However, the ceramic structure of most phosphor coatings might introduce an error, due to its thermal insulation properties, when being exposed to rapidly changing temperatures. In this article the measurement technique is evaluated concerning the impact from the thickness of the phosphorescent layer on the measured temperature. Experiments with different layer thicknesses are performed both during motored and fired operation of a HCCI engine. The results reveal a need for caution when applying the technique for in-cylinder measurements.

INTRODUCTION

Increasing fuel prices and more stringent legislation on emissions of greenhouse gases, such as CO₂, have driven the requirement for engines with higher efficiency. The upper limit has been pushed forward and is now approaching 60% indicated thermal efficiency (ITE) [1, 2]. In order to reach 60% ITE and beyond, all losses in combustion engines need to be considered. Heat loss through the cylinder walls is one major source of losses in internal combustion engines [3]. To gain knowledge about the heat transfer processes it is crucial to have information about the boundary conditions, including the wall temperature. In-cylinder wall temperature studies have previously been performed by e.g. Woschni et al [4] and Chang et al [5].

Homogeneous Charge Compression Ignition (HCCI) is a combustion process that can be described as a hybrid between the Spark Ignition (SI) and Compression Ignition (CI) engines. During the last decade the HCCI concept has been more intensively studied due to its higher efficiency at lower loads, compared to SI engines, and having lower emission of nitrogen oxides and soot than the CI engines [6, 7]. There are, however, drawbacks such as difficulty of controlling the combustion phasing and the heat release rate which is

globally high and thus resulting in high pressure rise rates. The pressure rise rate can, to some extent, be reduced by for example using diluted mixtures of air or recirculated exhaust gas.

Besides giving structural stresses and high noise, the high pressure rise rates also have an effect on the heat transfer to cylinder walls [8]. Similar observations have also been made for partially premixed combustion engines where high pressure rise rates lead to strong pressure oscillations and increased heat losses [9]. The thermal boundary layer (TBL) is a layer of fluids that to some extent insulates the cylinder walls from the high temperature of the burned gas during combustion, figure below. With high pressure rise rates and the resulting severe pressure oscillations, the TBL can be reduced or even broken exposing the relatively cooler cylinder walls to the hot gas and thus the heat transfer increases.

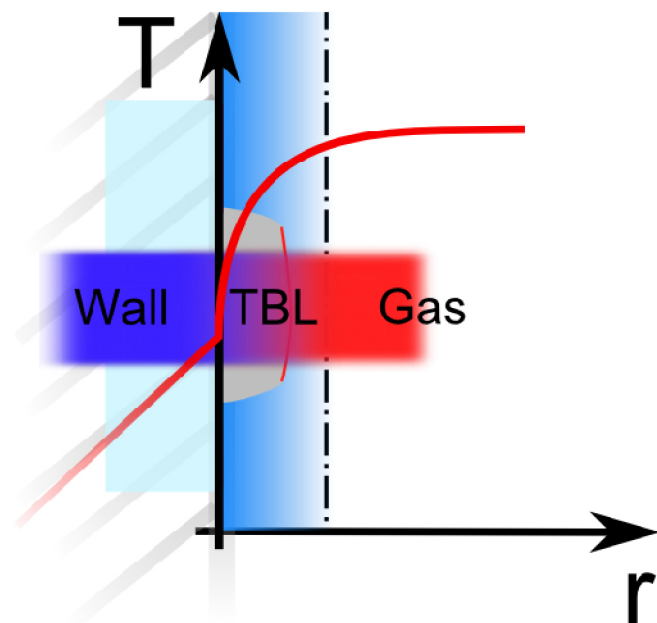


Figure 1. Schematic temperature gradient in a combustion engine showing the TBL near the chamber surface as well as a phosphor dot on top of the surface.

Understanding of the behavior of the TBL will aid the development of all combustion systems with high pressure rise rates. For understanding which variables and to what extent they will affect the TBL, the temperature within and near the TBL is of high interest. In recent experiments Laser-Induced Phosphorescence combined with other optical techniques, such as Filtered Rayleigh Scattering or Coherent Anti-Stokes Raman Spectroscopy proved its potential to measure temperature transients near and on surfaces [10, 11].

During the past years the technique of using LIP for thermometry has been proven to be an alternative to

thermocouples and infrared pyrometry for surface temperature probing. The phosphor technique is believed to be non-intrusive and capable of remote probing while still offering high spatial and temporal resolution with good accuracy [12, 13, 14].

Cylinder wall temperature measurements have previous been studied at Lund University, for instance by Särner et al [15] and Wilhelmsson et al [16]. In both cases the aim was to measure the temperature on the valves and the cylinder head. Särner and Wilhelmsson showed that the phosphor technique was capable of providing crank-angle resolved temperature data.

The aim of this paper is to evaluate the LIP technique with respect to different phosphor layer thicknesses. When applying LIP for surface thermometry it is common practice to apply what is considered a “thin” layer of phosphor material to the surface of interest. Ideally, the measured temperature should reflect the temperature of the coated surface. However, one should keep in mind that the active elements are often embedded in a ceramic host material. As familiar, ceramics are used as thermal barrier coatings (TBC) in for example gas turbines [17, 18]. Although the TBC coatings are significantly thicker compared to what is found in LIP thermometry, it is relevant to ask if the thermal insulating properties of the ceramic host material influence the measured temperatures. This is especially important in extreme environments such as in a reciprocating engine where the temperature gradients across the surfaces/in-cylinder gas interface are severe and subject to rapid oscillations during operation.

EXPERIMENTAL SETUP

ENGINE

The engine used in this experiment was a 2 liter port injected in-line 4 cylinder Toyota engine that was running in single cylinder operation and in HCCI mode. The combustion chamber was in the shape of a disc, i.e. no bowl in the piston.

Figure 2 shows a picture of the engine used in the experiments, whereas table 1 presents some vital engine parameters.

The engine was equipped with a piston extension (Bowditch) and a metal piston. The location of the phosphor dot was chosen to be on the inside of a quartz liner right below the combustion chamber ceiling, covering the full squish height of 3 mm (see fig. 3). This position enabled optical access throughout the whole cycle without being restricted to a certain range of Crank-Angle Degrees (CADs). The width of the phosphor dot was chosen wide enough (ca. 7 mm) to account for vibrations during engine operation and to assure laser illumination at all times.

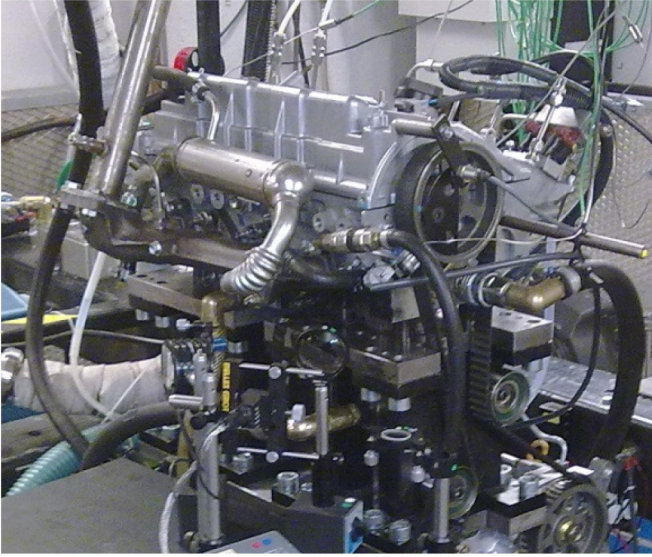


Figure 2. The Toyota engine with piston extension and a quartz liner.

Table 1. Geometric properties of the Toyota engine.

Displacement volume	499 cc
Stroke	94 mm
Bore	82.2 mm
Compression ratio	11.2:1
Number of Valves	4

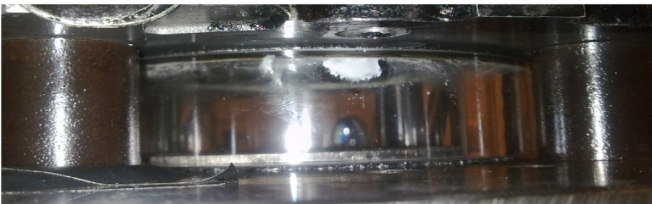


Figure 3. Outside view of the phosphor dot below the cylinder ceiling, sprayed onto the quartz ring's inner side surface.

The fuel used in this work was PRF 50, i.e. Primary Reference Fuel consisting of 50% iso-octane and 50% n-heptane. The engine was controlled by a LabView computer program, developed in-house. The engine control software also triggered the laser in order to timely adjust laser pulses to desired CADs. During combustion the inlet air was heated to around 120-125 °C with a manually controlled Leister heater to ensure HCCI combustion. The gas temperatures are calculated from recorded pressure traces by taking an average over 100 cycles and then use the ideal gas law to calculate the gas temperature for a given CAD.

$$\frac{p \cdot V}{T} = \text{const.} \Rightarrow T_{\text{CAD}} = T_{\text{ivc}} \cdot \frac{p_{\text{CAD}} \cdot V_{\text{CAD}}}{p_{\text{ivc}} \cdot V_{\text{ivc}}} \quad (1)$$

In equation (1) (p_{ivc} , V_{ivc} , T_{ivc}) are variables for pressure, volume and temperature after inlet valve closing whereas (p_{CAD} , V_{CAD} , T_{CAD}) are corresponding variables at any given CAD during the cycle. Equation (2) was used to estimate the uncertainty for T_{CAD} from the errors of all input parameters in (1):

$$\Delta T_{\text{CAD}} = T_{\text{CAD}} \cdot \left(\frac{\Delta p_{\text{CAD}}}{p_{\text{CAD}}} + \frac{\Delta p_{\text{ivc}}}{p_{\text{ivc}}} + \frac{\Delta V_{\text{CAD}}}{V_{\text{CAD}}} + \frac{\Delta V_{\text{ivc}}}{V_{\text{ivc}}} \right) \quad (2)$$

ΔT_{CAD} was therewith estimated to be below 5 °C before TDC, then reaches up to 60 °C around TDC and decreases to 10 °C after TDC.

However, the ideal gas law approximation estimates the mean gas temperature and does not take the spatial temperature profile seen, in figure 1, into account. It also implies a number of limitations: It considers changes of states to happen instantaneously and thus energy transfer with the environment can only be taken into account as a subsequent process. Particle interactions are neglected such that it applies best for small molecules with a long mean free path (high temperature, low pressure). Moreover it does not hold for thermodynamically open systems, which means that it applies only when the inlet and outlet valves are closed, i.e. from -149 CAD ATDC to 129 CAD ATDC (ATDC = After Top Dead Center).

LASER-INDUCED PHOSPHORESCENCE

By utilizing the well known phosphorescence from thermographic phosphors, temperatures can be measured remotely and non-intrusively with high accuracy in the range between cryogenic temperatures up to 1700 °C [19,20]. An appropriate phosphor is applied on the surface area of investigation using an appropriate non-fluorescent binder, e.g. HPC [14]. The surface is then irradiated with pulsed UV laser radiation for excitation of the phosphor material. The resulting emission intensity will decay exponentially according to

$$I = I_0 \cdot e^{-\frac{t}{\tau}} \quad (3)$$

where I_0 is the initial emission intensity, t is time and τ is the lifetime of the phosphorescence, i.e. the time after which the intensity has decreased to $1/e$ of the initial emission I_0 [12]. The phosphorescence time-decay depends on the temperature of the thermographic phosphor. Temperature can thus be