

Optical Piston Temperature Measurement in an Internal Combustion Engine

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ABSTRACT

In the last ten year the mechanical power output of car engine increased significantly. This result has been possible especially through new injection systems that brought to an optimization of the combustion (direct injection, common rail) and to an improvement of the turbo charging. Moreover, these technical devices brought to a reduction of the exhaust emissions and an increasing of the engine efficiency. In particular, the specific power is increased from 34kW/litre of the 1992 to the 63kW/litre of the 2010. Furthermore, the pressure peaks into the combustion chamber and the fuel injection pressure have been increased to the aim of emission reduction and higher engine efficiency.

In this scenario, car manufacturers are following the direction of the engine downsizing that means to have the same engine power by a lower engine displacement. The downsizing has as main consequence a thermal risks specially for the hot parts of the combustion chamber (exhaust valves, spark plug body and piston) because these parts have an increased high heat load and thermal stress. These temperatures could have as main consequence to the risk for engine damage by irregular combustion due to “surface ignition” by hot spot or by deposit of the combustion chamber.

In this paper a method for optical measurement of piston temperature during the fired and unfired operation of an internal combustion engine has been developed.

An optical access to the combustion chamber is achieved by an optical element made from sapphire lens that can be located in a special spark plug or other engine parts (injectors, cylinder head). The thermal radiation of the piston observed with this optical element is guided to the detector with optical fibers. As a detector InGaAs-photodiodes are

used, which allow a detection of the infrared radiation up to 2.6 μm .

The relation between the signal intensity and piston temperature was determined outside the engine in a calibration unit: the piston was heated up to 400 °C. In the calibration unit the sensor and the piston are arranged in the same geometry as in the combustion chamber. During cool down the thermal radiation is simultaneously measured with the temperature of the piston surface, obtained from a thermocouple.

AVL uses optical sensors in spark plugs to investigate combustion phenomena in spark ignited internal combustion engines. In a recent application the measurement of valve temperatures has been demonstrated using these sensors.

In this paper the possibility to measure piston temperatures with this measurement system is investigated. For this purpose following tasks have been performed:

- The measurement range was extended from 400° down to 200° by selecting appropriate optical materials and detectors.
- A calibration unit was developed to determine the relation between radiation signal and piston temperature.
- The piston temperature was measured for different pistons in a single cylinder research engine

INTRODUCTION

The new European emission standards Euro 6, valid from September 2014, fix strong limits to the engine emission (CO, HC, NOx, PM, CO₂). The ultimate EU target is to reach an average CO₂ emission (as measured according to Commission Directive 93/116/EC) of 120 g/km for all new

passenger cars by 2012. This new European CO2 legislation requires massive technology efforts.

In the last two years a fast development is concerning the downsizing of the gasoline engine for their low emission capacity and high power density through the direct injection (with stratified charge) and the turbo-charging. The downsizing ensures high engine efficiency but implies high thermal load which could bring to thermal risks and stress for many engine components.

The optical method for temperature measurement of hot parts in the combustion chamber is an innovative method and it is becoming successfully used because it is possible to detect different engine hot components in continuous and fast movement (piston, valves, turbine) and it does not need any contact with the measured surface because it works with the thermal radiation emitted from the hot surfaces that has the speed of light ($3 \cdot 10^8 \text{ m} \cdot \text{sec}^{-1}$). Furthermore, applying this method it is possible to analyse the surface radiation and so its surface temperature without temperature gradient.

In this activity, the optical access to the combustion chamber was achieved by an optical element “AVL Visioknock lens” made from sapphire lens that can be located in a special spark plug or other engine parts (injectors, cylinder head) as shown in [figure 1](#) and [figure 2](#).

In this paper, we are interested to detect the hot surface radiant energy (IR, Infra Red wavelength) as shown in [figure 3](#). The IR piston spark plug detects the intensity of radiation “I” emitted from the hot piston surface and it is measured by a special photodiode that converts “I” into a voltage signal that can be related with the piston surface temperature as we describe in the following calibration procedure.

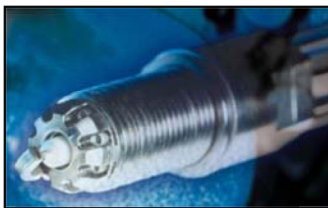


Figure 1. Visioknock spark plug

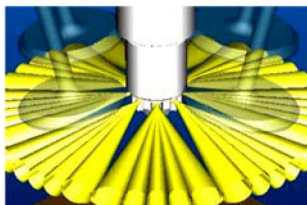


Figure 2. Visioknock spark plug

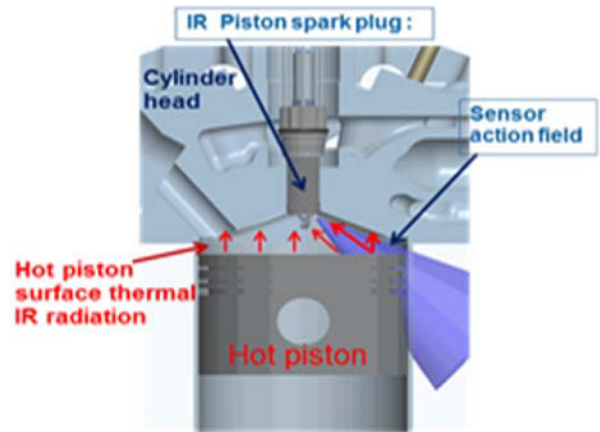


Figure 3. Piston visioknock spark plug

The body of the whole activity represented in this paper can be summarized as follow:

- Measurement system and its calibration by experimental tests on a heated piston (Calibration phase): We defined the measurement chain in all its components. We calibrate it by and external calibration unit composed with the required piston an a special box for the heating.
- Experimental tests on a laboratory engine (Signal interpretation): We did several test on a single research gasoline engine by acquiring the interested optical piston signal and estimating and post processing it for a correct signal interpretation.
- Signal analysis by experimental tests (Signal as function of piston position): To understand and evaluate correctly which part of the measured part comes from the piston radiation intensity we did investigation using special endoscope in the combustion chamber.
- Temperature Measurement tests (Piston signal): Once evaluated the correct piston signal we defined the measurement procedure. Afterwards we applied and tested our measurement system in different engine tests.
- Results validation: We evaluated the consistency of the results for reliable conclusions and future development.

CALIBRATION AND MEASUREMENT SYSTEM

[Figure 4](#) shows the optic piston temperature measurement equipment consisting of :

- **Optical sensor** (sapphire lens inserted into a special spark plug or a sensor) that captures the infrared intensity of radiation emitted from the piston surface into the combustion chamber during its movement from BDC to TDC.

- **Optical fiber** (fused silica) that connects and transports the piston infrared radiation captured from the optical sensor to a special photodiode.
- **Detector** (Infrared (IR) photodiode in VISIOFEM hardware) that absorbs the infrared intensity of radiation and converts it to an output voltage signal.
- **Crank angle encoder** that reads the engine crank angle during the measurement to know the piston position.
- **Indicating system** (VISIOFEM-INDIMODUL-INDICOM): hardware and software for data acquisition and post processing.

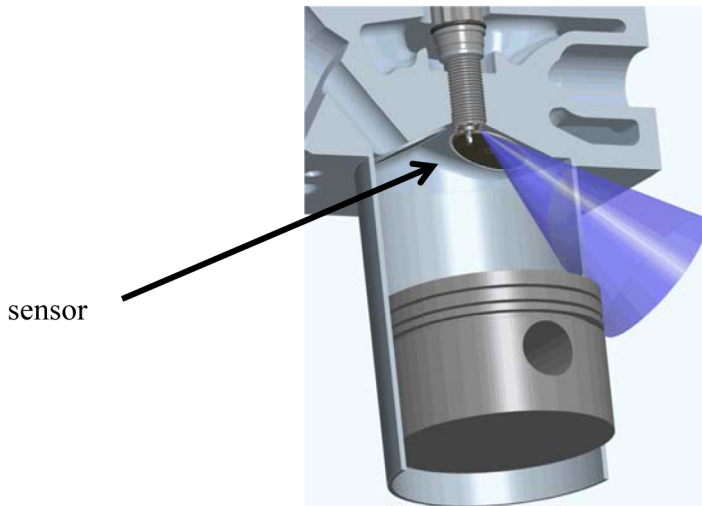


Figure 4. Optical sensor

The optical front element is a sapphire prismatic lens located into the combustion chamber and it is directly exposed to the exhaust gases at high temperature (above 2000°C). Sapphire is infusible and it has a transmission coefficient 85% at piston IR wavelength. The prismatic lens geometry is necessary to deviate the sensor action field, to detect better the piston surface thermal radiation and to reduce the influences and noises of other hot parts.

Our sensor, detects the intensity of radiation and converts it into a voltage signal that has to be related with the surface temperature by the calibration curve, function of the sensor and piston properties. We considered two different piston surfaces conditions: new and sooted (after many hours of engine operation by depositing of burned combustion residues).

Piston surface can be considered as a gray body and its surface emissivity is taken care of by calibrating sooted as well as clean pistons. With this model, the piston surface intensity of radiation is function of the temperature $I(T)$:

$$I = \frac{dQ}{dt \cdot d\omega} [W \cdot sr^{-1}] \quad \text{and it is proportional to the integral of}$$

the product of the *spectral density of radiation* of the gray body $L_{\lambda,g}(\lambda, T)$ and the spectral sensitivity of the photodiode $S_{\lambda,Ph}$ for the wavelength λ [7] :

$$I(T) \rightarrow \int_0^{\infty} L_{\lambda,g}(\lambda, T) S_{\lambda,Ph}(\lambda) d\lambda \quad (1)$$

The relation between the signal-intensity and the temperature [7] can be described from a fit-curve (2) simple function of temperature and three constants c , n , T° that we'll determine during calibration. The possibility to use these three constants is an empirical result of several test and there is no physical meaning for n , c or T° . We'll use this simple expression to generate a calibration function. The photodiode receives and converts the intensity of radiation into a voltage output determining the required calibration fit curve volt (T).

$$I(T) = c(T - T_0) \quad (2)$$

We need to determinate these three constants for every piston surface (signal intensity depends from temperature surface properties and optical sensor) that means to associate for each different piston surface temperature T (from 180 °C till 350°C) its respective value in radiant intensity signal. The piston calibration is defined as the methodology, instrumentation and proceedings of this task.

We reproduced in laboratory the same sensor the same sensor and piston relative position that we had in the combustion chamber. We heated it uniformly till its possible maximum temperature in the engine (approx.360 °C) then we left it to cool down slowly by natural convection from 360°C till 180°C in an aluminum box to have an uniform piston temperature. We measured the piston temperature surface by K-type thermocouple opportunely fixed on it. During the piston cooling we measured and acquired simultaneously the piston intensity radiation (by the optical sensor) and the piston surface temperature (by thermocouple) The INDICOM software, calculates for each piston calibration the three constants c , n , and T° , give us the required "piston calibration curve" for our piston temperature measurement on the test bed.

For the different sensor applications on new and used engine we tested always the same piston in two different surface conditions.

1. "New" (clean) piston surface.
2. "Sooted" piston surface (with impure carbon particles resulting from the incomplete combustion of HC)

Sensor piston calibration procedure sequence is composed of three steps shown in [figure 5](#):



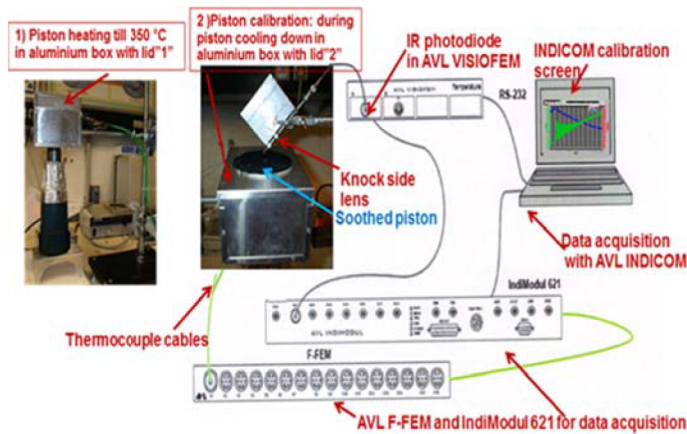


Figure 5. Optical sensor calibration.

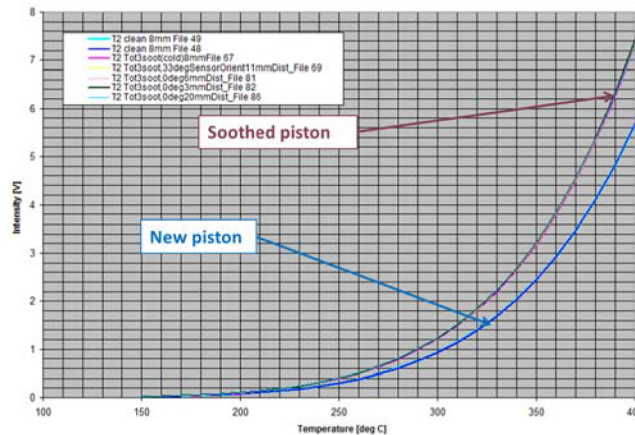


Figure 6. Piston calibration curve.

1. Piston heating till 350 °C with an hot air gun in aluminum box and sensor positioning.
2. Piston cooling down till 180°C in aluminum box and data acquisition.
3. Data processing by INDICOM to obtain the piston calibration curve.

At the end of the calibration procedure we have the data processing by INDICOM to obtain the new and sooted piston calibration curve (Fit curve by c, n, T° determination) as shown in [figure 6](#): $I(T) = 2551,5(T + 10)^{6,413}$.

ENGINE MEASUREMENT AND SIGNAL INTERPRETATION

In this paragraph we describe the experimental test on an single cylinder spark ignited research engine, 500 cm³, four strokes, four valves. We used two optical sensors: a side view sensor (located between the intake valves) and a spark plug sensor (located into the park plug). Both are installed into the cylinder head together with a pressure transducer as described

in [figure 7](#). T pressure transducer is installed between the intake and exhaust valves to detect the engine indicating pressure.

The engine was installed on a test bed controlled by AVL PUMA software. It can work in fired and motored operation in all its interested conditions. PUMA controls the engine and acquires the engine main data: torque, temperature, speed (rpm), IP (Indicated Pressure) and IMEP (Indicated Mean Effective Pressure), $\lambda = a/a_{st}$, time injection, time ignition, engine temperature, intake (air) temperature and pressure, exhaust gas temperature. We used AVL INDICOM as main software to acquire and post process our measurement data derived from the engine and from VISIOFEM for the optical sensor signal.

The tests revealed that it's not possible to use the complete optical sensor signal during the engine four strokes because of the combustion interference and other engine components influences. We describe how to detect and purify the piston

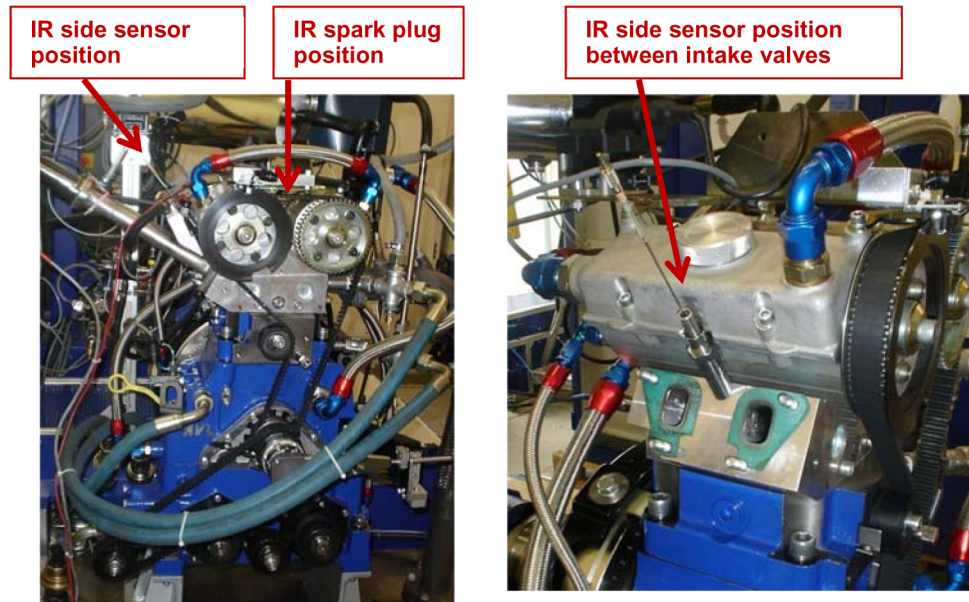


Figure 7. AVL single cylinder research engine, sensor position.

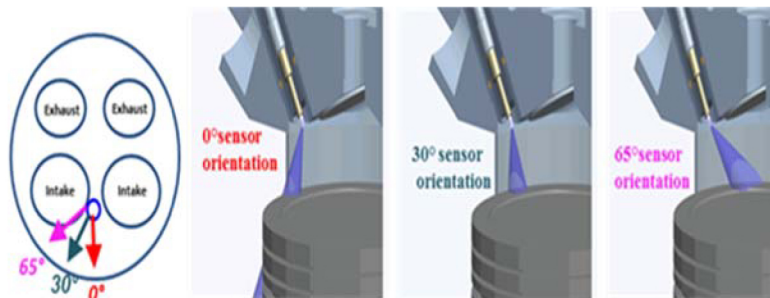


Figure 8. Visioknock side sensor.

signal to be able to use it for the optical piston temperature measurement.

The side view sensor is fixed between intake valves as showed before and in figure 7. Due to detect the radiating intensity for different part of the piston we'll use three different orientation of the side sensor into the combustion chamber as showed in fig. 8.

- 0 deg side view sensor orientation
- 30 deg side view sensor orientation
- 60 deg side view sensor orientation

The spark plug sensor has 8 IR lens. In our measurements we used only two lens but in different sensor orientations as described in figure 9. These two lens were connected, through special infrared optical fiber, to two different photodiodes (Photodiode Long Wavelength Type) with different sensitivity. We'll call by now these two channels (lens + photodiode) simply channel 5 (Ch.5) and channel 7 (Ch.7).

We describe now the steps to obtain the piston signal and its temperature measurement from our IR sensors:

1. We run the engine to the desired load and speed (rpm) for our measurement, checking the indicating pressure (no knocking), output power, torque, engine water/oil temperature, λ and waiting some seconds for the stabilization of them.
2. We operate an "offset shutter" on the two photodiode in VisioFem (a measurement of photodiode's zero by braking the transmission between optical fiber and photodiode) then we start the measurement by acquiring and recording with INDICOM the intensity signal detected from the sensor and measured with the photodiodes. Contemporary we switch off the ignition and injection (called: "Cut Off") for few seconds (approx 100 engine cycles) motoring the engine with test bed. In this way we have measured data of fired cycles (with combustion) and the subsequent motored cycles (without combustion).