

Calibration of a TFG Sensor for Heat Flux Measurements in a S.I. Engine

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ABSTRACT

In the development of internal combustion engines, measurements of the heat transfer to the cylinder walls play an important role. These measurements are necessary to provide data for building a model of the heat transfer, which can be used to further develop simulation tools for engine optimization. This research will focus on the Thin Film Gauge (TFG) heat flux sensor. This sensor consists of a platinum RTD (Resistance Temperature Detector) on an insulating Macor® (ceramic) substrate. The sensor has a high frequency response (up to 100 kHz) and is small and robust. These properties make the TFG sensor adequate for measurements in the combustion chamber of an internal combustion engine. To use this sensor, its thermal properties - namely the temperature sensitivity coefficient and the thermal product - must be correctly calibrated. First, different calibration setups with a different temperature range are used to calibrate the temperature sensitivity coefficient of the TFG sensor. These results will be analyzed and discussed. Second, the DED (Double Electrical Discharge) calibration setup for the thermal product is extensively discussed.

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INTRODUCTION

An important factor in the research of internal combustion engines (ICE) is to fully understand the mechanisms involving the heat transfer in the engine. The heat transfer from the combustion gases to the inner cylinder walls has large effects in terms of efficiency, emissions and power output of an ICE. Given the increased importance of thermal management of the engine, more accurate heat transfer models are needed to improve model predictions. This calls for accurate measurements of the heat transfer inside ICEs.

Previous research [1] has shown that due to different flow conditions and the combustion process a large spatial variation in heat flux exists. Measuring this spatial variation is far from straightforward. Extensive research [2] has been performed on different kinds of sensors that are potentially suitable. This research showed that the Thin Film Gauge had the most potential for use in an ICE. They are small, sturdy and cheap to manufacture. This allows instrumentation on all of the combustion chamber surfaces with a high spatial resolution. They have already been used with success in turbo machinery [3]. Accurate heat transfer measurements conducted with TFG sensors imply proper calibration.

The TFG sensor measures the temperature of the wall and thus first of all requires a steady state temperature calibration, to determine the temperature sensitivity coefficient. Signal processing is necessary to derive the heat flux perpendicular to the wall from the measured wall temperature.

The temperature sensitivity coefficient of the RTD needs to be calibrated in the temperature range that is expected at the wall of the combustion chamber (of the order of 250 °C) [2]. The temperature sensitivity coefficient can be calibrated using an oven or a fluid bath. Each setup has its limitations. The calibration of the temperature sensitivity coefficient is usually done in a waterbath [4]. This calibration technique is however very limited in temperature range as local boiling of the water has to be prevented. In literature no comparison has been made between different calibration methods and few details are given about the maximum temperature of the RTD calibration. Two alternative calibration methods: an oil bath [3, 5] and an oven calibration method [6] will be included. A comparative study is executed and improvements are proposed.

The signal processing of the TFG sensor signals (converting instantaneous temperature to heat flux) requires a thermal property of the sensor, namely the thermal product of the substrate. The transient heat flux is directly proportional to the thermal product [3]. Several

authors mention that the thermal product of the substrate of a TFG sensors needs to be calibrated [3, 4, 5, 6, 7, 8]. This is due to the TFG sensor construction according to [3, 7]. This will be tested in the paper.

For the calibration of the thermal product different setups exist but it has not been a widely studied subject even though it is essential for accurate transient heat transfer measurements. Only a few authors did calibrate the thermal product for their heat flux sensor. The basic concept of calibrating the thermal product is to expose the sensor surface to a known heat flux (which is mostly determined using a reference calorimeter) and record the sensor response.

Different methods exist in literature to impose a step in heat flux. The heat source can be of a radiative, convective or conductive nature. A fourth alternative method uses an electrical discharge to simulate a step in heat flux. This setup has different advantages over the other methods which will be discussed in the paper. The DED (Double Electrical Discharge) setup [3, 7, 8] is used by several authors in literature to calibrate this thermal property but no details about the influence of the operating settings are included in the discussion. Therefore a detailed study of the DED setup is performed which includes the argumentation of the used process parameters settings and the influence of them on the thermal product value.

The present work addresses the calibration of the required thermal properties of a Thin Film Gauge sensor. First the construction will be explained and an introduction to the signal processing methods to derive the heat flux will be given, to indicate the need for calibration. In the second part the methods for temperature sensitivity coefficient calibration methods will be discussed and analyzed. A third part will focus on the experimental results and analysis of the DED measurements.

THIN FILM GAUGE (TFG) SENSOR

Construction

The Transport Technology research group of the department of Flow, Heat and Combustion Mechanics has been working on ICE heat transfer since 2008. The work included a detailed comparison of different heat transfer sensors on a calibration rig and CFR (cooperative fuel research) engine and ICE heat transfer modelling.

The TFG sensor used for heat transfer measurements in the CFR engine was constructed at the Osney Thermo-Fluid laboratory of the University of Oxford. Different types of TFG sensor were developed for heat flux measurements. The thermistor type sensor uses a platinum resistor as RTD (Resistance Temperature Detector) to determine the wall temperature. Two different construction methods exist of which sketches are given in [Figure 1](#). The first method consists of depositing the TFG sensor onto a ceramic substrate (usually Macor®). Alternatively, the TFG can be deposited onto an insulating layer, which can be glued to a metallic surface. The first type is called a single-layer sensor and the second type is called a double-layer sensor. Thin film heat flux sensors are better to assure a one-dimensional heat flux in comparison to other heat flux sensors e.g. the eroding ribbon sensor. This is a thermocouple-based heat flux sensor previously used in engine heat transfer studies [9, 10]. The

substrate of the surface thermocouple consists of two different materials from which the thermocouple is created by using an abrasive paper or scratching technique to form the thermocouple junction. This construction method inherently introduces two-dimensional effects [11].



Figure 1. The two types of a TFG sensor: one directly painted on a ceramic (Macor®) substrate and one deposited on a resistance layer (Kapton®) that can be glued on any kind of surface.

The research in this paper will focus on the single-layer construction of the TFG sensor. The thermal coefficient calibration is identical for both types. The thermal product calibration shows some subtle differences between the two types. This will be discussed further below.

The sensitivity of an RTD thin film sensor in comparison with a comparable thin film thermocouple sensor is 100 times greater [3]. The sensitivity of the RTD can be enhanced by operating the RTD at a higher mean film voltage level. The platinum on the single-layer sensor is painted and then sintered at elevated temperatures. The resulting thickness of the platinum film is between 0,1 and 1 μm [3]. This low thermal mass ensures a high frequency response in the order of 100 kHz [4]. This is needed to capture the high frequency components in the heat flux (especially during e.g. knocking combustion).

Operation

Platinum is a favorable material for use as an RTD because of its stability in oxidizing atmospheres. Calibration data demonstrates that a linear fit is valid in the calibration temperature range. The linear relationship between the resistance of the RTD and temperature is given in [Equation \(1\)](#).

$$R = R_0[1 + \alpha_0(T - T_0)] \quad (1)$$

α_0 is the coefficient which expresses the temperature sensitivity of the resistance, being a property to be calibrated. Index 0 refers to a reference temperature. For operation, a constant current (I_0) is put through the RTDs, resulting in [Equation \(2\)](#).

$$\frac{\Delta V}{V_0} = \alpha_0 \Delta T \quad (2)$$

The sensitivity of the RTD is directly proportional to V_0 (and thus I_0), the magnitude of which is limited by the heat dissipation (ohmic heating) that occurs in the RTD by the current flowing through. This could result in a temperature offset which is undesirable. The optimum current I_0 is chosen after performing a calibration test (see [Figure 9](#)).

The RTD is used to determine the wall temperature of a combustion chamber surface. This temperature is then used as a boundary condition to solve the one dimensional heat conduction [Equation \(3\)](#).

$$\frac{\partial^2 T(x, t)}{\partial x^2} = \frac{\rho c}{k} \frac{\partial T(x, t)}{\partial t} \quad (3)$$

Where $T(x, t)$ is the temperature of the substrate at a given depth x and time t and k is the thermal conductivity, ρ is the density and c is the specific heat.

A widely used signal processing method is the Fourier-method. The measured wall temperature trace is transformed into an analytic expression using a Fourier analysis, the resulting expression is given in [Equation \(4\)](#) [12, 13]. B , K_n , and G_n are the numerical coefficients of the Fourier analysis and ω is the natural frequency of the signal.

$$T_w = B + \sum_{n=1}^{\infty} K_n \cos(n\omega t) + G_n \sin(n\omega t) \quad (4)$$

A second boundary condition is necessary to solve [Equation \(3\)](#). A preferred option is to assume a zero heat flux when the gas temperature (derived out of the pressure signal using the ideal gas law) is equal to the measured wall temperature [14]. This can be used to calculate the steady part of the heat flux. Using [Equation \(5\)](#) the heat flux at the gas-wall interface can be calculated (defined as positive if the heat flux is directed from the gas to the wall). It can be seen that the calculated transient heat flux ([Equation \(6\)](#)) is directly proportional to the thermal product ($TP = \sqrt{\rho c k}$).

$$q = \frac{Q}{A} = -k \frac{dT}{dx} \quad (5)$$

$$q_{trans} = \sqrt{\rho c k} \sqrt{\frac{n\omega}{2}} \sum_{n=1}^{\infty} \left[(K_n + G_n) \cos(n\omega t) + (-K_n + G_n) \sin(n\omega t) \right] \quad (6)$$

It is clear that an accurate value for the thermal product is necessary for reliable heat flux measurements. The two properties to be properly calibrated are thus the temperature sensitivity of the RTD and the thermal product of the substrate. These calibrations will be discussed in detail in the following section.

CALIBRATION OF TFG SENSOR

Temperature Sensitivity

The RTDs of the single-layer TFG sensor are painted by hand. This causes variability in the thickness of the RTDs. Therefore each RTD should be calibrated separately.

The α_0 of the RTDs can be calibrated in a fluid bath (water or oil) or an oven. The wall temperature in internal combustion engines is expected to go up to 250 °C which implies that the temperature sensitivity coefficient should be calibrated in this temperature range. In [4] a water bath is used. The maximum temperature (80 °C) is

limited by local boiling of the fluid at the location of the heating elements which would cause an inhomogeneous temperature field. Higher temperatures can be reached using an oven [2, 6]. In [2] values of α_0 seem to be inconsistent when using an oven calibration. This was explained by the natural convection which occurs in the oven as well as due to the presence of a thicker thermal boundary layer in comparison with a fluid. In [5] the use of thermal oil is suggested as a useful alternative to increase the maximum temperature during calibration. If oil is used no electrical insulation of the RTDs is necessary since the oil itself is electrically insulating.

This section will compare the temperature sensitivity coefficient determined using three calibration methods: 1) waterbath [4], 2) oil bath [3, 5] and 3) oven calibration method [6].

The measurements are performed using one RTD on a Macor® substrate. The sensor used for these calibrations is shown in [Figure 2](#). The sensor consist of three RTDs. The gold leads are used to connect the RTDs with the signal wires coming out of the back of the bolt. This is a prototype single-layer TFG sensor especially made for a CFR (Cooperative Fuel Research) engine which has special mounting holes for this TFG-equipped bolt.



Figure 2. Photo of the single-layer TFG sensor used for temperature sensitivity calibrations

The linearity of [Equation \(1\)](#) is checked for the higher temperature range obtained with the oil and oven calibration and a comparison between the temperature sensitivity coefficients is performed.

To counter the natural convection problem occurring in the oven calibration a device was designed, which is shown in [Figure 3](#). The single-layer TFG bolt is clamped between two blocks of metal. The RTDs are pressed against a copper block. To ensure electrical insulation a layer of Kapton® was put between the copper block and the TFG bolt. The steady state temperature in the copper block is homogeneous (measured with a K-type thermocouple shown in [Figure 3](#)) and eliminates natural convection. The oil used in the fluid bath is Therminol ® 66 heat transfer oil which has a maximum working temperature of 345 °C.

The temperature range during the oven and oil bath calibration is roughly double that of the water bath calibration, see [Figure 4](#). This is a significant improvement in comparison with the maximum temperature of 80 °C of the water bath calibration. The oil bath maximum temperature was limited due to the heating element. A higher power heating element will be used in future research for higher temperature calibrations. For the oven calibration the protection