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RISE TIME EVALUATION OF THE HEAT FLUX MICROSENSOR (HFM) ON A HOT-AIR-GUN TEST RIG

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ABSTRACT

Investigating the heat transfer inside internal combustion engines is key in the search for higher efficiency, higher power output and lower emissions. To understand the process and to validate model predictions, heat flux measurements inside an engine have to be conducted. In previous works, we have always used a commercially available thermopile to measure the heat transfer in a hydrogen combustion engine, but its large dimensions pose concerns about the sensor's response time. Therefore, measurements have been done on a calibration rig with a hot air flow as heat source. This paper presents a comparison of the rise time of the thermopile with that of an alternative sensor developed for heat transfer measurements in gas turbines. The papers results in an increased confidence in the thermopile sensor, because its response time is at least as good as that of the alternative sensor. The results do show that the reproducibility of the test rig can be improved. Moreover, due to fluctuations in the heat flux level generated by the source, only the order of magnitude of the measured heat flux of two different experiments was comparable. Therefore, a new calibration rig will be developed to improve the reproducibility and to increase stability of the heat flux level of the heat source.

INTRODUCTION

A lot of research efforts focus on further improving the efficiency, emissions and power output of internal combustion engines (ICE) to propel (heavier) vehicles with lower fuel consumption and emissions. These three properties are all influenced by the heat transfer inside the engine, so it is crucial to understand its mechanisms. In particular, the convective and radiant heat transfer from the combustion gases to the inner cylinder walls have been the subject of many research programs since the 1950s [1]. Although there has been a lot of research, the mechanisms are still not well characterised, especially not for new combustion types (e.g. HCCI [2]) and alternative fuels (e.g. hydrogen [3, 4]). At Ghent University, we are investigating the heat transfer in hydrogen combustion engines, focusing on convection since radiation is negligible in spark ignition engines [1].

To characterise the heat transfer process inside the cylinder it is necessary to measure the transient heat flux at the gas-wall interface. In literature, the transient surface temperature of the cylinder wall is most of the time measured and a signal processing technique is used to calculate the heat flux out of it. We have in contrast always used a commercial thermopile in our [5, 6], as it has been calibrated by the manufacturer to directly convert the output voltage into heat flux.

There are two concerns regarding the use of this thermopile in an internal combustion engine because of its large outer dimensions (diameter of 8.74 mm). First, it complicates the mounting inside the engine. This is not a problem for the current test engine, but an alternative sensor will be necessary to measure the heat flux in other engines. Second, it raises doubts about the sensor's rise time, although the manufacturer claims it to be 300µs for the uncoated version. Therefore, this paper compares the rise time of the thermopile to an alternative sensor on a calibration rig.

NOMENCLATURE

Abbreviations

HFM		*heat flux microsensor*
HFS		*heat flux sensor*
RTD		*resistance temperature detector*
RTS		*resistance temperature sensing*
TFG		*thin film gauge*
TP	$J/Km^2s^{1/2}$	*thermal product*

Greek symbols

α_0	$\Omega/°C$	*temperature coefficient of TFG*
ρ	kg/m^3	*density*

Roman Symbols

h		*impulse response*
k	W/mK	*thermal conductivity*
q	W/cm^2	*heat flux*
T_0	°C	*ambient temperature*
V_0	V	*voltage over TFG at* T_0

EXPERIMENTAL METHOD

Sensors and signal processing

The reference sensor was an uncoated Vatell HFM-7 sensor, as shown in Figure 1. This sensor was used to measure the heat flux inside a hydrogen combustion engine [5, 6]. The sensor has two output signals: a heat flux signal from a thermopile (HFS-signal) and a temperature signal from an RTD (RTS-signal). For the tests on the rig, the Vatell AMP-6 amplifier was used as a current source for the RTD and as an amplifier for both output signals. The sensor was calibrated by Vatell and polynomials were given to calculate the heat flux directly out of the HFS- and RTS-signal (see HFM manual [7]).

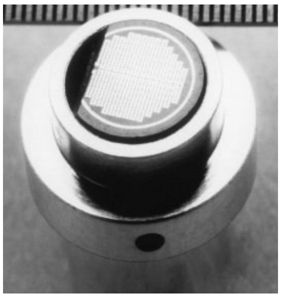

Figure 1: uncoated HFM-7 sensor

The alternative sensor was developed at the University of Oxford to measure the heat flux inside gas turbines [8]. The sensor (TFG: thin film gauge) is a thin film RTD and is used to measure the surface temperature of a substrate. The TFG can be deposited on different materials and two versions of the sensor were tested here. Two TFGs were deposited directly on a Macor substrate and one was deposited on a polyimide insulating layer (Upilex-s) which was glued to an aluminium substrate, as schematically shown in Figure 2 and Figure 3. The two TFGs on the Macor substrate were deposited in parallel with a distance of 1.2 cm in between.

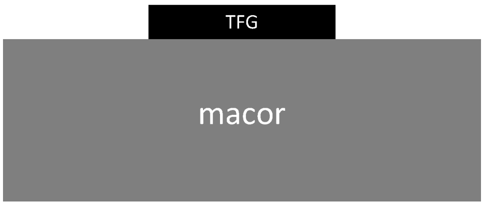

Figure 2: TFG on Macor

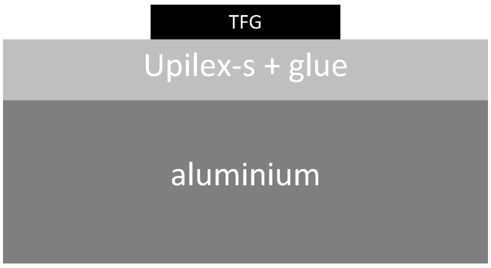

Figure 3: TFG on Upilex-s on aluminium

For the TFGs on Macor, the heat flux could be measured directly with a hardware box, simulating the one dimensional heat conduction equation of Fourier. This direct measurement was not possible for the TFG on Upilex-s because there are several layers on top of each other with different thermal properties. For this TFG, a signal processing technique is needed to convert the measured temperature trace into a heat flux trace. Here, the impulse response method developed at the University of Oxford [9] was used, which will be discussed below. This method was used for the TFGs on Macor as well to enable a comparison between the directly measured heat flux ('direct') and that calculated with the impulse response method ('impulse').

The relationship between the resistance and the temperature of the TFG is given in the following equation, with R_0 being the resistance at a temperature T_0:

$$R = R_0 \cdot [1 + \alpha_0 \cdot (T - T_0)] \tag{1}$$

A constant current was sent through the TFG to generate a change in the voltage over the sensor proportional to the change of the sensor's resistance in function of the temperature. Multiplying the equation above with the current I results in the following equation which is used to derive the temperature increase out of the measured voltage increase (V_0 is the measured voltage at T_0):

$$\Delta T = \frac{\Delta V}{\alpha_0 \cdot V_0} \tag{2}$$

The impulse response method, used to convert this temperature trace into a heat flux trace, assumes that the combination of the substrate and TFG is a linear time invariant system with the temperature being the input and the heat flux being the output as shown in Figure 4.

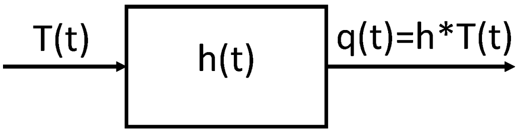

Figure 4: the heat flux is the convolution of the impulse response and the temperature

The system is characterised by its impulse response h(t) which can be used to calculate the output from the input with the convolution integral:

$$q(t) = h(t) * T(t) = \int_{-\infty}^{\infty} h(\tau) T(t - \tau) d\tau \tag{3}$$

Because discrete signals are recorded, the convolution integral is converted into a summation:

$$q[n] = \sum_{k=0}^{N-1} h[k] \cdot T[n-k] \qquad (4)$$

The impulse response has to be calculated once for each sensor according to the methods described in ref. [9]. The impulse response for the TFGs on Macor is that of a semi-infinite gauge with one layer, the impulse response of the TFG on Upilex-s is that of a semi-infinite gauge with two layers. The material property that is needed for the calculation of the impulse response of the TFGs is the thermal product (TP), being equal to $\sqrt{\rho \cdot c_p \cdot k}$, of the layers. These were determined experimentally at Oxford [8] and are given in Table 1. For the TFG on Upilex-s, the ratio of the thickness over the thermal conductivity is needed as well, being 6.10^4 m^2K/W [8].

All the signals were acquired with an oscilloscope at a sample rate of 1MHz.

Table 1: thermal products of the materials used

material	TP ($J/m^2Ks^{1/2}$)
Upilex-s + glue	485
Aluminium	22100
Macor	2050

Test rig

The experiments were conducted on the ‘hot-air-gun test rig’ at the University of Oxford. This rig consists out of two structures which are not connected to each other, as shown in Figure 5.

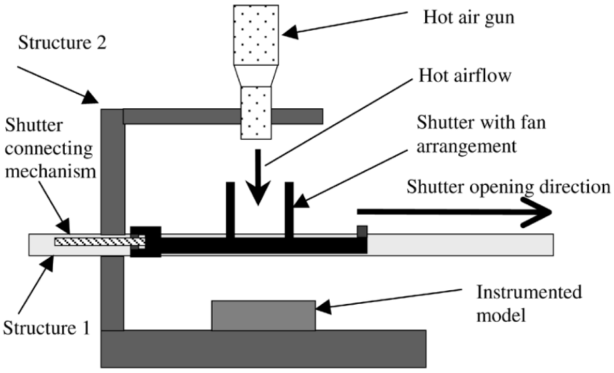

Figure 5: the hot-air-gun test rig [8]

On the first structure, a rail with a fast-opening shutter is mounted. The sensors (instrumented model on Figure 5) and hot air gun are mounted on the second structure. These structures are not connected to avoid that vibrations of the opening shutter disturb the measurements. The hot-air-gun provides an air flow with a maximum temperature of 650°C and a velocity of 22 m/s. The opening of the shutter causes a step function in the heat flux measured by the sensor at the bottom of the test rig. For each experiment, the HFM sensor was mounted next to one of the TFG sensors to compare the response time of the two sensors. Their centres were hereby aligned as shown in Figure 6.

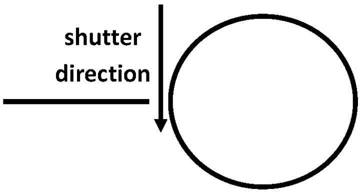

Figure 6: the alignment of the TFG (left) and HFM (right)

RESULTS AND DISCUSSION

Temperature coefficient α_0

The temperature coefficient, α_0, was determined for the three TFGs with a calibration experiment in an oven. The temperature in the oven was controlled by a reference Pt-100 sensor and varied between 30 and 90°C in 10°C intervals. After stabilisation of the oven temperature, the resistance of the TFGs was measured. The measurements for the TFG on Upilex-s are given in Figure 7. The least squares method was used to generate a linear curve through the measurement points, also shown in the graph. This curve was converted into the form of equation 1 to calculate the α_0. Therefore, T_0 was chosen to be 25°C, because this was the ambient temperature in the lab during the experiments on the hot-air-gun test rig. The calculated coefficients of all the TFGs are given in Table 2. That of the TFG on Upilex-s is lower than those of the TFGs on Macor because this sensor was thinner.

Table 2: determined α_0 of the TFGs

sensor	α_0 (Ω/°C)
TFG1 on Macor	0.0015
TFG2 on Macor	0.0016
TFG on Upilex-s	0.0011

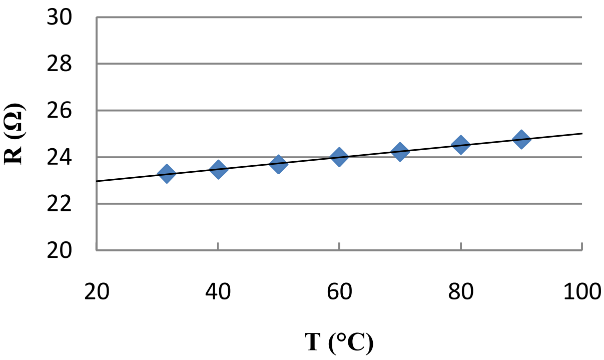

Figure 7: the resistance as function of the temperature for the TFG on Upilex-s.

HFM vs. TFGs on Macor (direct)

The directly measured heat fluxes of the HFM and TFGs on Macor are first discussed to give general findings about the experiments.

The reproducibility of the experiment was tested by repeating it several times with the HFM sensor. Five of these results are shown in Figure 8. The graph shows that all the signals coincide at zero seconds, because they were triggered at

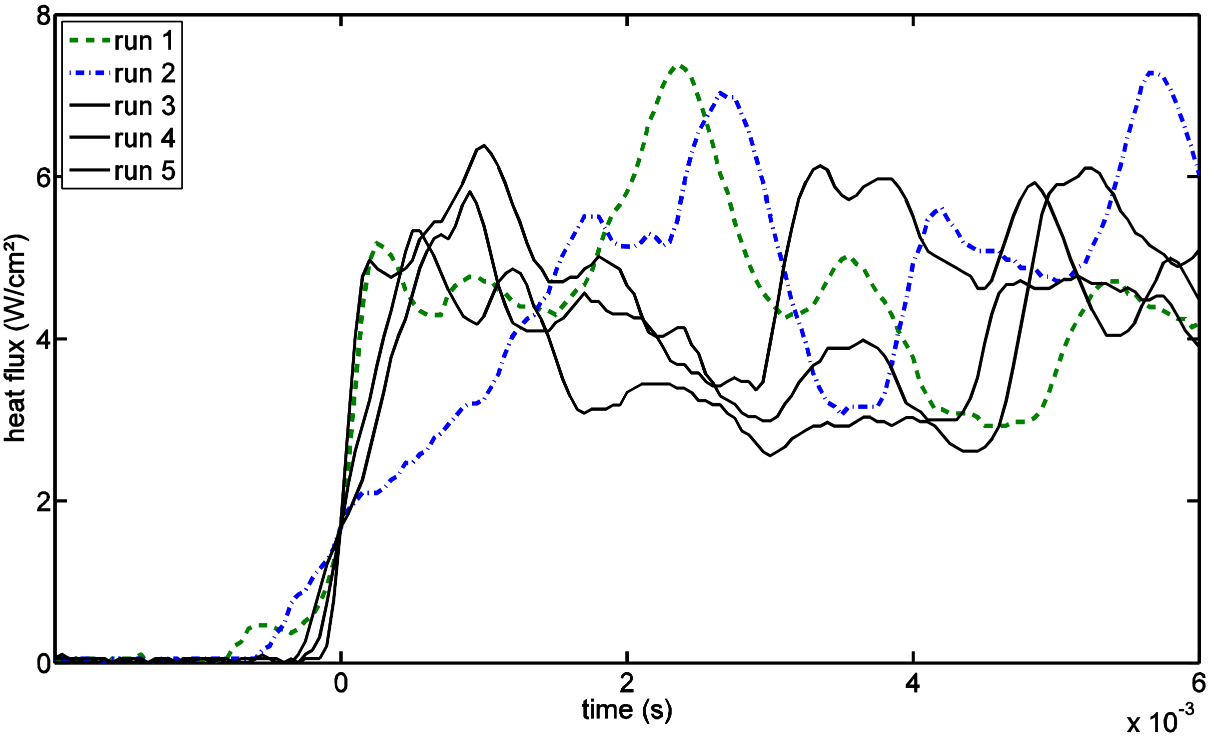

Figure 8: the heat flux produced by the hot-air-gun fluctuates between 3 and 8 W/cm², the rise time measurement is reproducible with a deviation of 40%.

a certain heat flux level. During the step generated by the opening shutter, the heat flux rises towards 5 W/cm² on average. The hot air flow out of the hot-air-gun is not very homogeneous and it generates a fluctuating heat flux between 3 and 8 W/cm² once the shutter has fully opened. The green trace in Figure 8 (run 1) demonstrates that the heat flux of the HFM sometimes rises a little bit before the steep rise generated by the opening shutter. This can be caused by an early heat flux slip at the sides of the shutter connection mechanism. Some experiments show a very slow heat flux step, e.g. the blue curve (run 2) in Figure 8, which could indicate that the sensor was not cooled down enough after the previous experiment. Due to the fluctuations in the rise time and the level of the heat flux after the generated step, it is only possible to compare the different sensors based on an average rise time and an order of magnitude of the measured heat flux. It is not possible to make a sample-by-sample comparison between two measurements with the same sensor, as demonstrated in Figure 8.

The directly measured heat fluxes by the HFM and the TFG on Macor during the same experiment are shown in Figure 9. The graph shows that the TFG measures a heat flux with the same order of magnitude as the HFM. The graph indicates that the rise time of the TFG is somewhat longer than that of the HFM. As already mentioned it is only possible to compare average rise times, so the average rise times of both sensors over 10 measurements are given in Table 3 together with their standard deviation. The standard deviation expressed as a percentage of the average is also given. The results show that the average rise time of the TFGs is between 1.6 and 2 times longer than that of the HFM. However, if the standard deviation is taken into account it cannot be concluded that the rise time of the HFM is lower. The results show that the test rig generates a step in the heat flux which is reproducible with a standard deviation of 40%.

It is not possible to compare the traces of two sensors during the same experiment either, because the fluctuations in the heat flux generated by the hot-air-gun and the fact that the sensors do not measure the heat flux at exactly the same position.

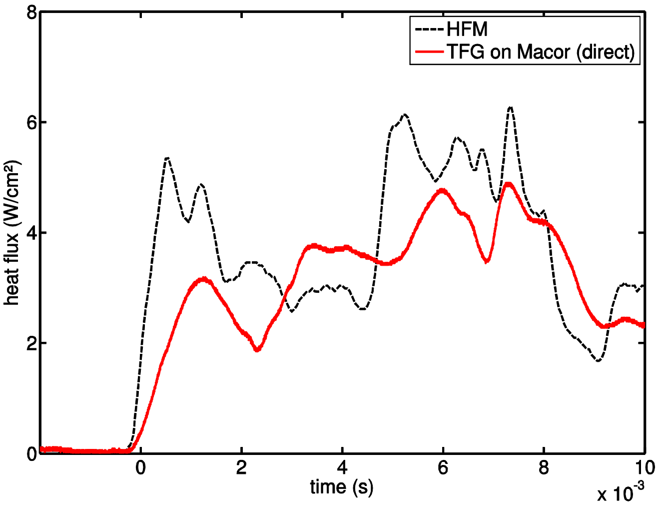

Figure 9: a comparison between the heat flux of the HFM and TFG on Macor during the same experiment

Table 3: overview of average rise times of the sensors

sensor	avg. rise time (μs)	st. dev. (μs)	% dev.
TFG1 on Macor	1281	371	29%
TFG2 on Macor	1597	690	43%
HFM	771	293	38%

Shutter speed

An estimation of the shutter speed has been determined with experiments where the heat flux of the two TFGs on Macor were measured. These two sensors were deposited parallel to each other with a distance of 1.2 cm in between. The sensors were positioned perpendicular to the shutter direction as shown in Figure 10, so the shutter speed could be estimated out of the time delay between the heat flux step of the two sensors. The HFM was positioned in between the two TFGs.

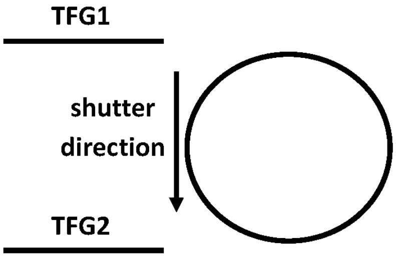

Figure 10: alignment of the two TFGs (left) and the HFM (right) for the estimation of the shutter speed

Figure 11 shows the measured heat flux traces of such an experiment. As expected, the heat flux of TFG1 started to rise first, then that of the HFM and last that of TFG2. However, the heat flux of the HFM started to rise before that of TFG1 in most of the measurements, indicating the restrictions of the test rig. During one measurement, the heat flux of TFG2 even started to rise before that of TFG1.

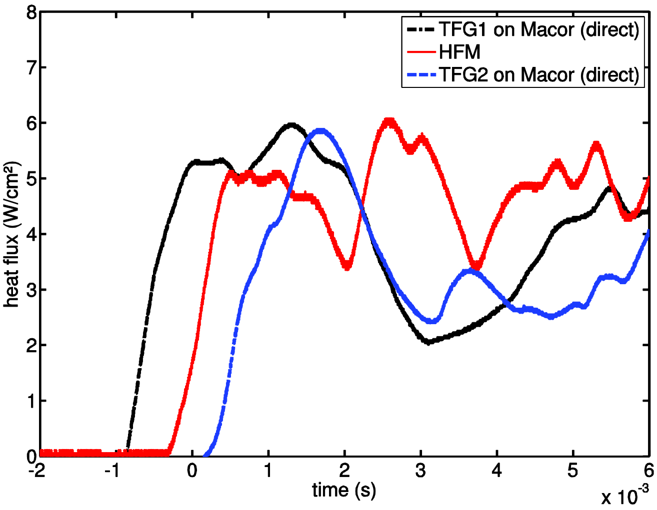

Figure 11: the time delay between the heat flux of TFG1 and TFG2 was used to estimate the shutter speed

On average, the shutter speed was 12 m/s with a standard deviation of 3.5 m/s (30%). At this average speed, the shutter needs 83 and 728 μs to fully pass over the TFG (1 mm) and the HFM (8.74 mm), respectively. Because the measured rise time of the HFM is of the same order of magnitude as that of the TFGs it is clear that the larger dimensions of the HFM do not pose restrictions on its response time. The heat flux measured by the HFM must therefore start to increase significantly from the moment that a fraction of its surface is exposed to the heat source.

Temperature traces of TFGs

In the next sections, the impulse response method will be used to convert the measured temperature traces of the TFG on Macor and Upilex-s into heat flux. Figure 12 shows a comparison between the temperature traces of the two different TFGs. These signals were filtered with a 5kHz filter to remove high frequency noise. The graph shows that the heat flux fluctuations caused by the hot-air-gun result in higher peak-to-peak swings in the temperature trace of the TFG on Upilex-s. The temperature increase in such a short time frame is higher for the TFG on Upilex-s, because the thermal product of Upilex-s is lower than that of Macor. In a longer time frame, the temperature gradient across the thin Upilex-s layer would decrease and the thermal product of the underlying Aluminium layer would become the driving factor for the temperature increase. Hence, the temperature increase of the TFG on Macor would become higher, because the thermal product of Aluminium is higher than that of Macor.

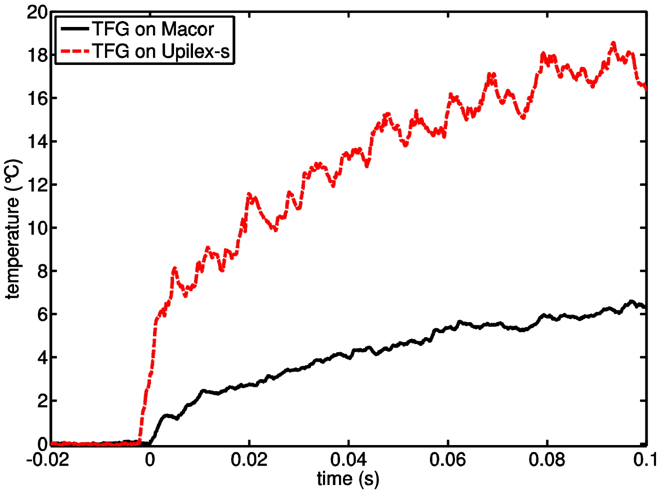

Figure 12: comparison of the temperature traces of the TFG on Macor and Upilex-s

HFM vs. TFG on Macor (impulse)

Figure 13 shows a comparison between the heat flux measured by the HFM and that calculated out of the temperature trace of the TFG on Macor. The level of the heat flux of the TFG is of the same order of magnitude as that of the HFM and that directly measured by the same TFG. The average rise time of the heat flux trace of the TFG calculated with the impulse response method is also equivalent to that of the directly measured heat flux trace. Consequently, the impulse response method can be used for the TFG on Upilex-s. The plot

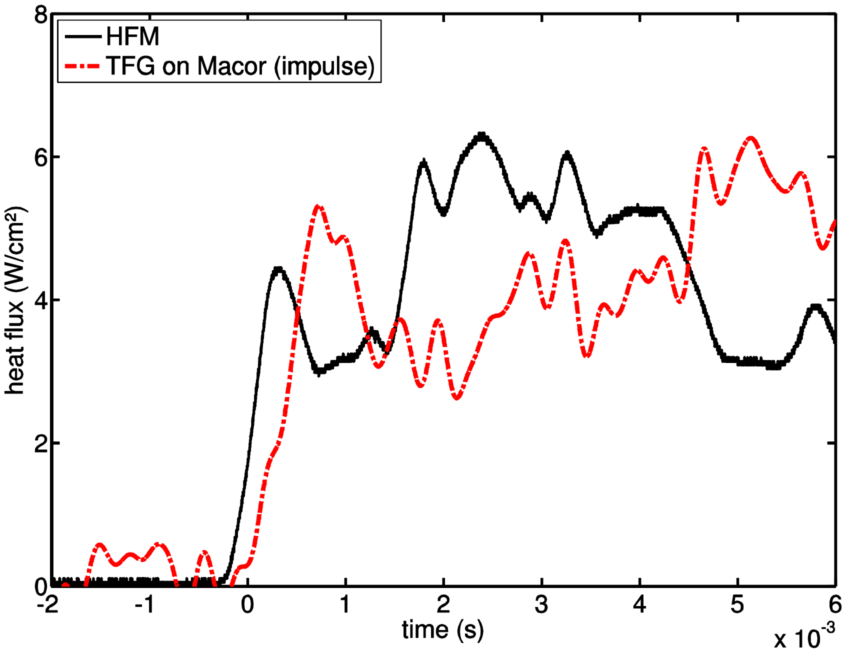

Figure 13: the impulse method results in an equivalent heat flux trace for the TFG on Macor as the direct heat flux measurement of the HFM

in Figure 13 does show some fluctuations in the heat flux which are caused by noise in the temperature trace, e.g. between -2 and 0 ms.

HFM vs. TFG on Upilex-s

Figure 14 shows the comparison between the heat flux traces of the HFM and the TFG on Upilex-s, the latter being calculated with the impulse response method. Again, an equivalent heat flux trace is obtained. However, the step in the heat flux of the TFG seems to have a time delay to that of the HFM, which must be caused by some misalignment in the positions of the sensors since it was not the case for the TFG on Macor. The heat flux of the TFG on Upilex-s contains less noise compared to that of the TFG on Macor.

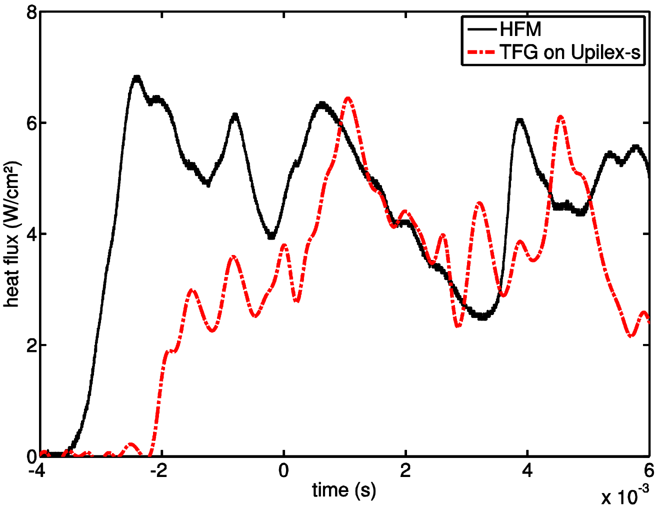

Figure 14: the heat flux trace of the TFG on Upilex-s shows a delay to that of the HFM

CONCLUSION

At Ghent University, we have always used a commercially available thermopile sensor (HFM) for the heat flux measurements in a hydrogen combustion engine. Its large dimensions have, however, always been a concern regarding the sensor's response time. Therefore, this paper has compared the rise time of the HFM to the thin film gauge (TFG) sensor developed at the University of Oxford for heat flux measurements in gas turbines. The measurements were carried out on the hot-air-gun calibration rig at the University of Oxford.

This paper has demonstrated that the rise time of the HFM is at least as good as the alternative sensor. The large dimensions of the HFM sensor do not impose restrictions on its response time. The heat flux measured by the sensor must already start before its entire surface is exposed to a heat source. Therefore, the confidence in the HFM sensor has increased and it will be further used to measure the heat flux in the test engine in the lab. The development of an alternative sensor will continue, since the HFM is too big to mount into other internal combustion engines.

The results showed some limitations of the calibration rig. First, the heat flux generated by the hot-air-gun contains significant fluctuations. Second, the calculated rise time showed a deviation of 40%. Therefore, it was only possible to compare the order of magnitude of the measured heat flux level and average rise times. A new calibration rig will be built at Ghent University, aiming at a better reproducibility and a higher, more steady heat flux level.

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