A FAST-RESPONSE TOTAL TEMPERATURE PROBE FOR TURBOMACHINERY

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ABSTRACT

The measurement of the time-resolved total temperature is a crucial task for the experimental investigation of loss mechanisms in turbomachinery. This is due to the fact that a sole measurement of the time-resolved total pressure loss can be misleading as no distinction can be made between the total pressure variations caused by the unsteadiness of the machine and the ones caused by viscous losses. Classical thermocouples are limited in their frequency response. Therefore, a new fast-response total temperature probe has been developed by the Institute of Aircraft Propulsion Systems and Berns Engineers. The novel design of the probe allows an improved spatial resolution compared to existing approaches for fast-response total temperature probes. The sensitive measuring surface is below one square millimeter. The present paper provides an insight into the design of the probe and the manufacturing process. Furthermore, the data reduction and calibration methods are explained and an estimation of the measurement uncertainty is given. Basic tests validating the design of the probe and showing the ability of the probe to be used in turbomachines are depicted.

NOMENCLATURE

a	layer thickness (m)
c	specific heat capacity (J/(kgK))
d	diameter (m)
f	frequency (Hz)
g	impulse response function
h	heat transfer coefficient (W/(m²K))
k	thermal conductivity (W/(mK))
l	length (m)
$\dot{q}_{cond}$	specific conductive heat flux (W/m²)
$\dot{q}_{conv}$	specific convective heat flux (W/m²)
$\dot{q}_{el}$	specific electrical heat flux (W/m²)
$\dot{q}_{rad}$	specific radiation heat flux (W/m²)
ρ	density (kg/m³)
t	time (s)
T_t	total temperature (K)
T_W	wall Temperature (K)

INTRODUCTION

The analysis of loss mechanisms in turbomachines has been forced by many researchers. However, these analyses often rely on the sole measurement of the total pressure loss in the machines under investigation. Mansour *et al.* (2012) showed that this approach holds the potential of misinterpretation. The authors proved that the correct experimental assessment of the loss production in turbomachines requires the measurement of the unsteady entropy production. Entropy cannot be measured directly, but is only feasible with both, the measurement of the time-resolved total pressure, and the time-resolved total temperature. While the first is a task, which can be conducted with existing measurement techniques, up to date no commercialized measurement technique exists for the latter.

Some approaches for the development of fast-response total temperature probes have been made by research facilities over the past decades (e.g., Ng and Epstein (1983), Buttsworth and Jones (1998)). Mansour *et al.* (2008) introduced a fast-response entropy probe, which measures the unsteady total pressure and unsteady total temperature, simultaneously. The total temperature part of the probe consists of two meander shaped thin-films operated at different overheat temperatures, similar to the probe developed by Buttsworth and Jones (1998). The application of the entropy probe is presented by Mansour *et al.* (2012) and Jenny *et al.* (2012).

The new probe of the Institute of Aircraft Propulsion Systems and Berns Engineers (Weigel (2014), Rose *et al.* (2010)) is also based on the thin-film approach introduced by Buttsworth and Jones (1998). However, only one thin-film is used for the new probe in order to reduce its spatial dimensions. To be able to compute the total temperature from the data recordings, two consecutive measurements at two different overheat temperatures are necessary at each measurement point. Consequently, the probe can only resolve periodic flow phenomena as the stochastic total temperature fluctuations differ between the two measurements. However, this is sufficient as the main flow phenomena in turbomachines are of periodic nature. The development proceedings of the fast-response total temperature probe are described by Weigel (2014).

PROBE DESIGN AND MANUFACTURING

The fast-response total temperature probe consists of a meander shaped platinum thin-film with a size of 345 µm x 400 µm and a thickness of $a_{Pt} = 125\,nm$. It is manufactured directly on a polyimide layer. The thickness of the polyimide layer is $a_{PI} = 20\,\mu m$. The platinum thin-film on top of the polyimide layer is then glued onto a cylindrical quartz rod with a diameter of d=1 mm by means of an epoxy resin with a thickness of $a_{Epoxy} > 60\,\mu m$. This layer thickness ensures that the thermal penetration depth of total temperature fluctuations down to a frequency of 500 Hz does not exceed the combined layer thickness of the two topmost layers. The polyimide and the epoxy resin are used as materials because they are both good insulators. This increases the dynamic response of the probe. The epoxy resin is a two component adhesive and does not contain solvent. This is necessary to prevent inclusions. The electrical connectivity towards the probe support is realized by a gold layer with a thickness of $a_{Au} = 0.5\,\mu m$.

The final manufacturing process of the fast-response total temperature probe is performed at Fraunhofer IBMT in St. Ingbert. A lithography mask has been designed and manufactured for the fabrication of the platinum thin-film. The base for the lithography process is a silicon wafer, which can hold 78 thin-films. The wafer is coated with the polyimide layer on which the platinum thin-films are then produced by means of the lithography process. In a final step the gold layer for the electrical connectivity towards the probe support is added. A wafer-saw is used to separate the individual sensor elements. They can then be removed from the silicon wafer. To avoid cracks in the meander structure of the thin-film, the sensor elements are bent in a tubed shape prior to the application on the quartz rod. The sensor elements are therefore heated to 588K, which allows the sensor elements to be bent to their final shape.

The quartz glass rods are immersed in the epoxy resin about ten times in order to produce the required layer thickness of at least $60\,\mu m$. The glass rod is spun after each immersion to ensure an uniform distribution of the epoxy resin. The layer thickness is constantly checked. When the required layer thickness is reached, the pre-bent sensor elements are glued on the glass rod by means of the epoxy resin.

The quartz glass rod with the applied sensor element is then used for the final assembly with the probe support. It consists of an aluminum shell with a PEEK inlay and connectors. The gold layer of the sensor element is connected to gold wires with a conductive adhesive. The glass rod is then assembled with the PEEK inlay of the probe support. Finally, the gold wires are electrically bonded to the connectors.

A quality check of every probe is performed to prove the functionality. Therefore, the probe is immersed to a variety of temperatures up to the design temperature limit of $150°C$ in steps of $20\,K$. The electrical resistance is measured continuously in order to check the correct functionality of the probe at every temperature. However, before every use of the probes in real test environments, they are newly calibrated. The probes are not sensitive to transport damage. An infant mortality of about 10% exists, though, which is addressed to the complex manufacturing process.

In order to use the fast-response total temperature probe inside turbomachinery rigs, a probe holder with a length of $l = 1\,m$ and a diameter of $d = 10\,mm$ has been constructed. It provides the connection to the probe support on one end and a Lemo ERA.1E.304.CLL connector on the other end. With the probe holder, the total temperature probe can be traversed inside turbomachinery rigs.

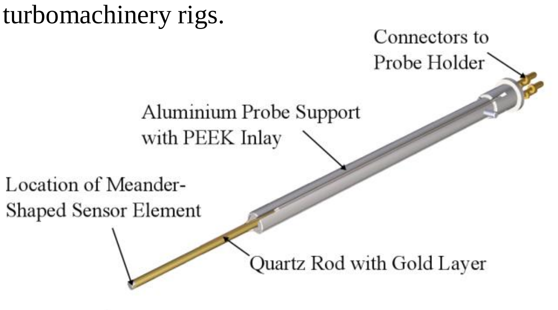

Figure 1 The fast-response total temperature probe applied to the probe support

OPERATING PRINCIPLE

Due to the single thin-film design of the fast-response total temperature probe, it is operated at two different overheat temperatures at each measurement point. The probe is fed with two different supply currents in order to achieve these overheat temperatures. The voltage drop across the sensor element needs to be measured with a high sampling rate at each point. By means of the known constant current and the measured voltage drop, the electrical resistance of the sensor element can be computed at each sample point. This electrical resistance is then transformed into the wall or surface temperature T_W of the probe with the aid of a temperature-resistance calibration. Two equations for the one-dimensional convective heat transfer can be written for both points:

$$\begin{aligned} \dot{q}_{conv1} &= h_1(T_t - T_{W1}) \\ \dot{q}_{conv2} &= h_2(T_t - T_{W2}) \end{aligned} \qquad (1)$$

The sensor element is adjusted into the main flow direction for the measurement. Hence, it can be assumed that the sensor element is located at the stagnation point at the surface of the cylindrical quartz rod. Thus, the total temperature can be used in Eqn. (1) as the convective heat transfer is only dependent on the local heat transfer coefficient and the temperature difference between the wall temperature and the flow total temperature. It is independent of the flow Reynolds number and the Mach number (c.f., Buttsworth and Jones (1998)). Literature studies on the heat transfer around cylinders also support this assumption. Nakamura and Igarashi (2004) or Bose, Wang, and Saedi (2012) show, that the Nusselt number is constant in a range of about $\pm 30°$ around the stagnation point of a cylinder for low Reynolds numbers. The probe can therefore be considered to be unsusceptible to a broad range of incidence angles and probe adjustment errors since the meander shaped thin-film covers only $\pm 17°$ around the stagnation point. Furthermore, no heat flux correction in circumferential direction of the quartz rod needs to be applied.

The total temperature can be computed by a combination of the equations of Eqn. (1) with the assumption of a constant heat transfer coefficient $h_1 = h_2$ for both measurements as the probe is exposed to the same periodic flow at the same location in space. With this, the relation for the total temperature is:

$$T_t = \frac{T_{w1}\dot{q}_{conv2} - T_{w2}\dot{q}_{conv1}}{\dot{q}_{conv2} - \dot{q}_{conv1}} \qquad (2)$$

The convective heat flux density can be calculated by means of an energy balance, balancing the electrical heat flux put into the probe with the convective heat flux, the conductive heat flux into the probe and the radiation heat flux. The latter is small compared to the convective and conductive heat flux and is neglected in the following. The electrical heat flux put into the probe is directly known from the constant supply current and the measured voltage drop. The conductive heat flux into the probe is determined by the impulse response technique developed by Doorly and Oldfield (1987) and Oldfield (2008). This method transforms the recorded wall temperatures into the conductive heat flux with the aid of a transfer function g(t). For this, the probe is assumed to act as a linear and time invariant system. The transfer function represents the response of the wall temperature to a step in the wall heat flux. The conductive heat flux can be computed with the convolution integral

$$\begin{aligned} \dot{q}_{cond}(t) &= g(t) * T_w(t) \\ &= \int_{-\infty}^{\infty} g(\tau) T_w(t-\tau) d\tau \end{aligned} \qquad (3)$$

If an analytical solution for the response of the wall temperature to a step in surface heat flux is known, the transfer function will be calculated with the deconvolution of Eqn. (3). For a semi-infinite system this response is (Oldfield (2008)):

$$T_w(t) = \frac{2}{\sqrt{\rho c k}} \sqrt{\frac{t}{\pi}} \qquad (4)$$

It can be seen from Eqn. (4), that the characteristic of the time-resolved wall temperature is only dependent on the thermal product $\sqrt{\rho c k}$. Additionally, it can be derived from Eqn. (4), that the characteristic will be a linear curve if the wall temperature is plotted against $\sqrt{t}$. The analytical solution for a two-layer system is given by Doorly and Oldfield (1987). It will be shown later, that the fast-response total temperature probe can be treated as a semi-infinite system, because the difference of the thermal products of the two topmost layers, polyimide and epoxy glue, is negligible.

The application of the impulse response technique is validated with a comparison to alternative methods for the computation of the conductive heat flux and to analytical functions. The results of this validation are shown by Arenz *et al.* (2016).

PROBE CALIBRATION

The calibration of the fast-response total temperature probe consists of two main parts, the calibration of the probe's sensitivity of its electrical resistance to temperature changes, and the calibration of the thermal products of the probe materials. The former is realized with an Ametek RTC-157 temperature calibrator. With it, the probe is exposed to various specified temperatures. The probe's electrical resistance is measured by the calibrator at each calibration point. The entire calibration is performed several times and is both, heated and cooled to the specified temperatures in order to account for repeatability and hysteresis. The latter is typically below 0.1%. A linear fit is determined for the calibrated points. It is found, that the linearity error is below 0.05%. This result confirms that no quadratic term is needed for the conversion of the measured electrical resistances into the wall temperatures of the probe during the data reduction process. A typical result of the calibration is shown in Figure 2.

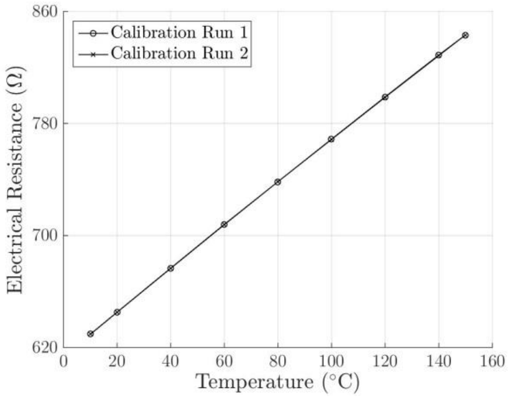

Figure 2 Typical dependence of the electrical resistance of the fast-response total temperature probe to temperature changes

The calibration of the thermal products of the first two material layers of the probe is performed with the superposition method introduced by Piccini, Guo, and Jones (2000). For this, the probe is exposed to a step in surface temperature. This step is produced by means of a jet of hot air with constant temperature hitting the probe. The recorded wall temperatures can be transformed into the response of the probe for a step in heat flux. This is done with the aid of a convolution sum. The algorithm used for the computation is presented by Piccini, Guo, and Jones (2000). The transformed wall temperatures for a step in wall heat flux can be compared to the theoretical response of the probe given by Eqn. (4) for a semi-infinite system or the solution for a two-layer system provided by Doorly and Oldfield (1987). As stated above, the response of a semi-infinite system will be a linear curve if the data is plotted against $\sqrt{t}$.

A typical result of the calibration is shown in Figure 3. The comparison of the originally measured wall temperature difference after the impingement of the hot jet and the transformed wall temperature difference is presented. It is evident that the wall temperature difference follows a linear trend after the transformation. This validates that the topmost two layers of the probe show no distinct difference in their thermal products. Hence, the fast-response total temperature probe can be treated as a semi-infinite system for the determination of the impulse response function.

In order to account for differences, which might occur due to the manufacturing process, the calibration of the thermal product is performed with three different probes. Each probe is tested at least ten times under the same conditions to validate the reproducibility of the calibration. It is found, that the variation of the mean values of all tests of each probe is negligible. The mean value of all calibration runs accounts for $\sqrt{\rho c k} = 435\,\frac{W}{m^2 K\sqrt{s}}$. The experimental standard deviation of all calibration runs is $\sigma = 5\%$, which is greater than the sole measurement uncertainty of the measurement chain. This is due to the fact that the experimental standard deviation also includes additional sources of uncertainty as, e.g., variations in the opening time of the valve, which directs the hot air towards the probe. Hence, the experimental standard deviation is taken for the evaluation of the measurement uncertainty of the fast-response total temperature probe. For a more elaborate description of the complete procedure of the calibration of the thermal product please refer to Arenz *et al.* (2016).

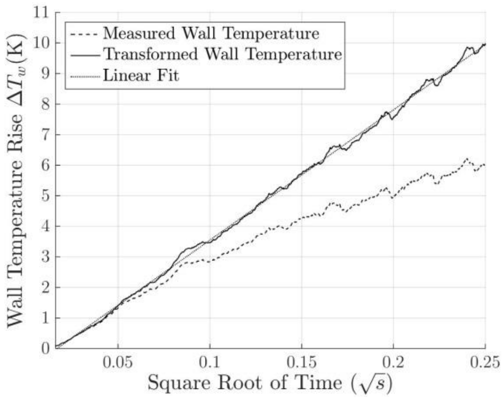

Figure 3 Comparison of the measured and transformed wall temperature rise of the total temperature probe after the impingement of the hot jet.

MEASUREMENT UNCERTAINTY

The estimation of the measurement uncertainty is done by means of a Monte-Carlo-Simulation according to JCGM (2008). The simulation includes the uncertainties due to the static calibration, the calibration of the thermal product, and the measurement. The uncertainties of the single input quantities for the Monte-Carlo-Simulation are taken from the datasheets of the measurement devices or from experimental investigations, such as the calibration of the probe's thermal product.

The mean values for the estimation of the uncertainty of the measurement are taken from tests downstream of the first rotor of a two-stage low pressure turbine operated at the High Altitude Test Facility at the Institute of Aircraft Propulsion Systems (c.f. Arenz *et al.* (2016)). The turbine rig is described by Schinko *et al.* (2009). Hence, the mean values for the input quantities of the static calibration are taken from the calibration of the probe being used for this turbine test. Thus, it needs to be noted, that the measurement uncertainty of the fast-response total temperature probe is related to this specific experiment. However, the results provide a good basis for the expected measurement uncertainty for other experiments, but still needs to be re-evaluated prior to these.

The results of the Monte-Carlo-Simulation provide an absolute measurement uncertainty of $\pm 3.47\,K$ for the time-averaged total temperature, and of $\pm 0.83\,K$ for the amplitude of the total temperature fluctuations.

YAW ANGLE SENSITIVITY

The operating principle of the fast-response total temperature probe is based on the assumption, that the meander shaped sensor element is placed at the stagnation point at the surface of the quartz rod. It has previously been discussed, that this assumption is valid according to literature studies investigating the flow around cylinders at low Reynolds numbers. However, the assumption needs to be verified experimentally prior to the use of the probe in turbomachine environments as the flow angle, particularly the yaw or circumferential angle, varies unsteadily due to the rotation of the rotor blades. The calibration tunnel of the Institute of Aircraft Propulsion Systems is used for this purpose. The calibration tunnel is described by Schinko *et al.* (2009).

The total temperature probe is exposed to a yaw angle range of $\pm 25°$ at two Mach numbers, Ma=0.3 and Ma=0.5. The total temperature of the air in the calibration tunnel is at ambient level. The static pressure for the test is set to represent the conditions of a low pressure turbine operating at flight conditions. Figure 4 shows the results of the sensitivity study. The percentage deviation of the total temperature related to the total temperature at a yaw angle of 0° is presented. No distinct trend for the variation of the measured total temperature can be identified for the test at Ma=0.3. The maximum deviation accounts for -0.05%. At Ma=0.5 an expected trend of a decreasing total temperature with a greater yaw angle deviation from 0° can be found. The deviation is below 0.1% for a range of yaw angles of about $\pm 15°$. This is considered to be sufficient for many applications of the probe in turbomachines. To give an example, the work of Schneider *et al.* (2014) shows, that the unsteady yaw angle fluctuation downstream of the rotor of the previously mentioned two-stage low pressure turbine is only $\pm 10°$ at its maximum in the secondary flow regions at the turbine hub and casing.

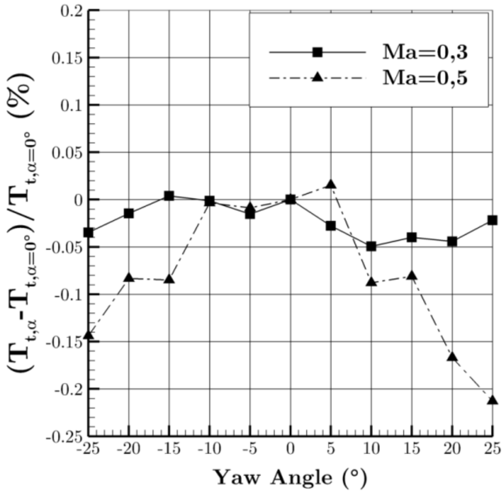

Figure 4 Percentage deviation of the measured total temperature for a flow yaw angle variation

VALIDATION OF THE FREQUENCY RESPONSE FOR THE USE IN A TURBINE RIG

Another preliminary test, which needs to be performed prior to tests in turbomachines, is the verification of a sufficient frequency response of the probe for the desired application. In order to investigate the dominant loss phenomena, which arise due to the unsteadiness of a specific machine, the probe must at least be able to resolve the blade passing frequencies with their higher harmonics. A simple test bed is constructed for the purpose of the experimental verification of the frequency response. This test bed consists of a electronic motor equipped with a punched disc, which cuts through a jet of air. The frequency can be adjusted by means of different discs with a varying number of holes, and the rotational speed of the motor.

The turbine rig described by Schinko *et al.* (2009) is operated at the Institute of Aircraft Propulsion Systems and is therefore used for the first application of the probe under realistic conditions. The ability of the fast-response total temperature probe to resolve the harmonics of the blade passing frequencies of the turbine has been tested prior to the experiment. For this, a frequency of f=6 kHz is produced with the aid of the simple test bed described above. This frequency is around twice the blade passing frequency of the first rotor of the turbine. The DFT of the measurements of the total temperature probe is shown in Figure 5. It can be seen that the probe is capable of resolving the first two harmonics of the produced frequency. This covers more than 3.5 times the blade passing frequency of the first rotor of the turbine rig. This is considered to be sufficient to

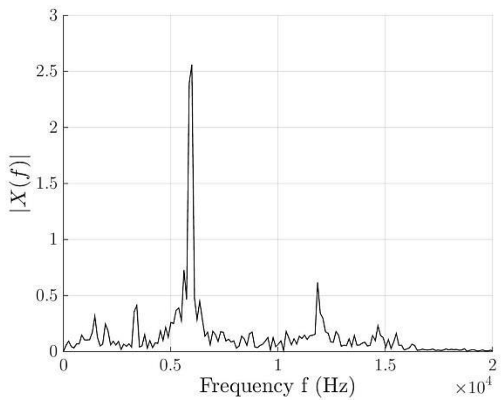

Figure 5 Discrete Fourier Transformation (DFT) of the measured total temperatures in a jet of air being cut by a punched disc

investigate the main aerodynamic effects inside the turbine. Two subharmonics are measured by the probe as well (c.f. Figure 5).

CONCLUSION

A new fast-response total temperature probe is presented. The probe consists of meander shaped platinum thin-film manufactured on a layer of polyimide. The thin-film is glued onto a cylindrical quartz rod by means of an epoxy resin. The operating principle and the data reduction process of the probe is based on an energy balance of the electrical energy put into the probe and the conduction, convection and radiation heat fluxes to the surrounding fluid and the probe's material. The main challenge of the evaluation of the energy balance is the estimation of the conduction heat flux. This is resolved by the use of an impulse response method. The probe is operated at two different overheat temperatures at each measurement point. With the use of the energy balance and the equations for the one-dimensional conduction heat transfer at each measurement point, the total temperature can be computed.

The probe is calibrated in two steps. First, a static calibration of the probe's sensitivity of its electrical resistance to changes in ambient temperature is performed. In a second step, the thermal products of the two topmost material layers of the probe are calibrated. The calibration shows, that the difference of the thermal products of the two topmost layers is negligible. Hence, the probe can be treated as a semi-infinite system, which simplifies the data reduction method.

Two basic tests validating the design of the fast-response total temperature are performed with the new probe. First, the dependence of the measured total temperature to variations of the flow yaw angle is presented. It is shown, that the probe's measurement principle is insensitive to a broad range of yaw angle changes. At a flow Mach number of Ma=0.5, the variation of the measured total temperature is below 0.1% in a yaw angle range of $\pm 15°$. The variation is even smaller at lower Mach numbers. Second, the frequency response of the total temperature probe is examined. A frequency representative of the first two harmonics of the blade passing frequency of a two-stage low pressure turbine is produced by a simple test bed. It is proven, that the total temperature probe is able to resolve this frequency with a higher harmonic. This test shows the ability of the new probe to be used in this turbine.

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