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TOTAL TEMPERATURE PROBES FOR TURBINE AND COMBUSTOR APPLICATIONS

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Abstract

Rakes for the measurement of total pressures and temperatures in gas turbine flow channels have been designed and used for decades in a vast variety of shapes and applications. For low temperature applications there is enough literature available how to optimize the design of the stagnation tubes and the probe shaft to get a reasonable recovery factor and good agreement between the measured and the real total pressure and temperature.

The indicated temperature is influenced by the flow stagnation, the convectional heat transfer to the temperature sensor and the thermal conduction through the sensor. In the temperature range above 900 K radiation effects have to be taken into account additionally. Especially above 1200 K the probe design has to be optimized to minimize errors caused by the radiation heat exchange between the sensor and surrounding parts as this cannot be corrected using a calibration curve taken at ambient temperature.

To quantify the effects mentioned a numerical tool has been developed to simulate the thermal behavior of total temperature probes. Results will be shown in the following that give a better understanding and a base for better design criteria. Optimizing the design of the stagnation tube in a typical application at e.g. 1370 K, the measurement error caused by the sensor design could be reduced from 0.7% to 0.4% of the measured value.

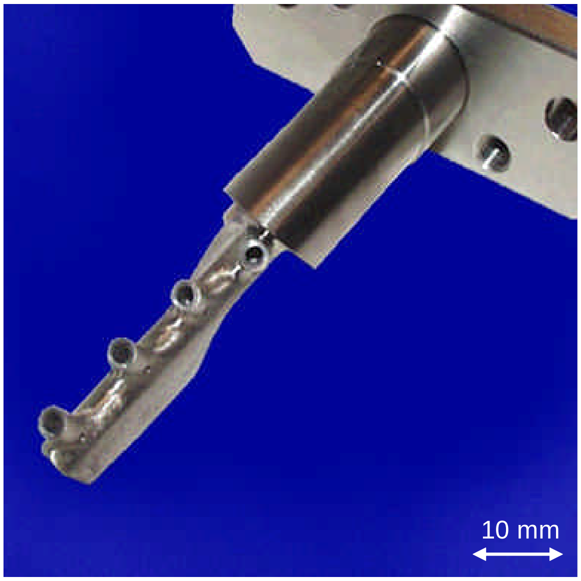

figure 1: typical total temperature rake for a low pressure turbine inlet, single crystal body for up to 1400 K

Nomenclature

A	area	m^2
D	diameter	m
h_c	heat transfer coefficient	W/m^2K
k	thermal conductivity	W/mK
L	length	m
M	Mach-Number	-
$\dot{Q}$	Heat flow	W
T	temperature	K
x	position	m
Y	temperature error	K
γ	adiabatic coefficient	-
ε	emissivity	-
Γ	recovery factor	-
σ	Boltzmann constant	W/m^2K^4

Subscripts

c	convection
i	internal or indicated
k	conduction
m	material (rake shaft)
r	radiation
s	static condition
t	total condition

TC	thermocouple
v	velocity
w	surrounding wall
∞	environment

Introduction

When testing gas turbine engines there is a variety of flow parameters that have to be monitored. The precise measurement of total pressure and total temperature values is especially important to evaluate the performance of the whole engine and of single engine components. To calculate the aerodynamic efficiency of e.g. a turbine stage you need these values at the inlet and the outlet plane. The actual sensor design is often challenging due to the high temperatures and flow velocities within a gas turbine. Usually the sensor consists of the sensing element surrounded by a stagnation tube or so called Kiel head where the flow velocity is reduced to a level where no further compressibility effects occur and the temperature under total conditions can be measured. Typically several of these sensors are combined along the shaft of a total temperature rake. **Figure 1** shows the photograph of a total temperature rake for an aero engine low pressure turbine inlet and **figure 2** the schematic cross section of such a sensor design with the basic heat transfer phenomena indicated.

The temperature of the sensing element (usually a thermocouple) is not only influenced by the surrounding temperature that has to measured but by a well known group of erroneous effects[1].

Velocity error

The actual velocity inside the Kiel head depends mostly on the free stream velocity and the area of the Kiel head inlet and exit (bleed holes). The remaining flow speed will be different from zero and there will be a significant deviation of the measured temperature from the total temperature to be measured. This deviation is described with the so called recovery factor Γ and is defined as

$$\Gamma = \frac{T_i - T_s}{T_t - T_s} \qquad (1)$$

where T_i is the indicated temperature and T_s and T_t are the static and total temperature of the flow. This represents the ratio of the actually measured to the total thermal energy available from the adiabatic deceleration of the flow. Due to the incomplete deceleration a velocity error remains that can given as[1]

$$Y_v = T_t - T_i = (1-\Gamma)\frac{\frac{\gamma-1}{2}M_i^2}{1+\frac{\gamma-1}{2}M_i^2}\cdot T_t \qquad (2)$$

The velocity error can be minimized reducing the Mach number of the internal flow M_i by reducing the inlet to exit ratio.

Conduction error

The conduction error is caused by the heat flux along the thermocouple wire(s) and can be given to[1]

$$Y_k = T_t - T_i = \frac{T_i - T_m}{\cosh L\left[\frac{4h_c}{Dk}\right]^{1/2}} \qquad (3)$$

As the cross section and the thermal conductivity of the thermocouple is mostly given by the available materials only the length of the Kiel head can be

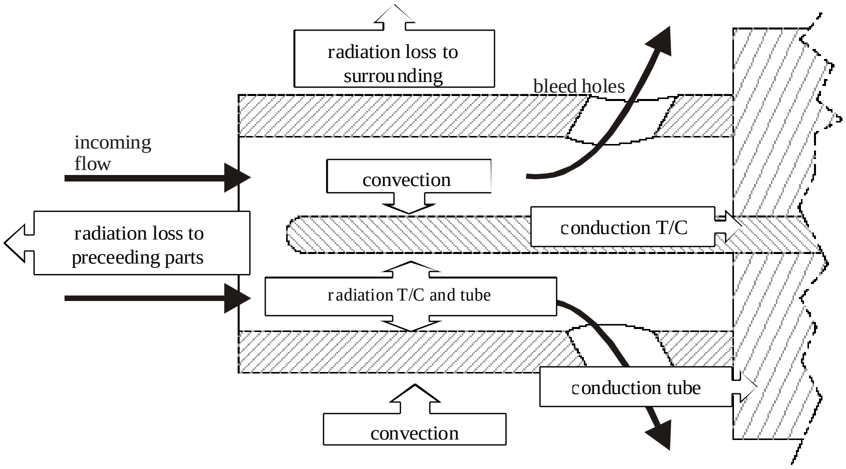

figure 2: schematic cross section of total temperature sensor

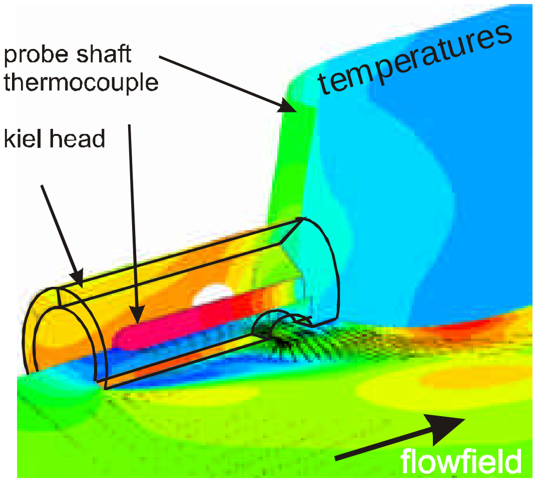

figure 3: Flow field and temperatures around a total temperature sensor, low velocities and temperatures are indicated blue, high values red

modified. A possible enhancement of the convective heat transfer coefficient is directly coupled with a higher flow velocity within the sensor and therefore increases the velocity error.

Radiation error

Due to the flow deceleration towards the total condition the thermocouple is on a temperature level above that of the surrounding parts. Caused by a large heat transfer to the free stream the stagnation tube has a significantly lower temperature near the static temperature. Engine parts in front of the sensor might have a higher or lower temperature (e.g. due to flame radiation or excessive air cooling). When the sensor is used in a high temperature application this results in a significant radiation heat transfer that can be expressed approximately by

$$Y_r = T_t - T_i = \frac{1}{h_c}\,\frac{\sigma\varepsilon}{1+\frac{A_{TC}}{A_w}(1-\varepsilon)}\left(T_i^4 - T_w^4\right) \qquad (4)$$

Where A_w and T_w are the surface area and the temperature of the surrounding “wall”. Accordingly the radiation error is not only affected by the temperature difference but also by the emissivity of the used materials and the area ratio of the participating surfaces.

Combination of all errors

It can be seen that the errors have a significant influence on the measurement precision and have to be taken into account when measuring total temperatures. One measure to minimize one of these errors often increases another as the flow field around the sensor interacts with the thermal field within the sensor. In **figure 3** the combination of the phenomena mentioned can be seen. The image has been created using a standard 3D flow simulation software (CFX®). The three dimensional temperature field was calculated in interaction with the flow field but the radiation heat transfer has been neglected.

It is noticeable that in the inlet of the Kiel head the free stream velocity (green) is decelerated to a significantly lower value (blue). This results in a flow temperature near the total temperature, the tip of the thermocouple is heated to a value close to that total temperature. The flow continues through the Kiel head along the thermocouple, leaves through the bleed holes, and merges with the free stream.

Due to the blockage of the probe shaft regions of higher and lower flow velocities can be seen around the configuration that affect the heat transfer to the surfaces. The temperature of the probe shaft (the rear surface is shown from the inside in **figure 3**) is on a temperature level significantly below the total temperature, a little higher along the stagnation line and a little lower sideways. This results in a significant thermal gradient within the thermocouple and leads to a reduced value of the measured temperature.

Additionally it has to be mentioned that the resulting errors are strongly pressure and temperature dependent so that no easy calibration and correction is possible and a significant error remains. The presented paper shall give an idea about the remaining errors and help finding an optimized solution for the design of total temperature sensors. Errors of the sensing element (thermocouple error) will not be discussed here.

State of the art

In the known literature not many publications can be found that cover the problems of total temperature sensors. Some papers concentrate on the optimized design of total pressure sensors[2]. This helps only to reduce the velocity error of total temperature probes an gives no information about the other errors mentioned. The AGARD report on gas path measurements[1] gives beside a lot of other information a complete overview and quantification of the phenomena affecting total temperature sensors. Clear design rules are missing.

Simulation tool

A simulation tool has been created to help with the optimization of total temperature sensors. It calculates an estimated indicated temperature for given geometrical and flow parameters.

Description

The tool incorporates a one-dimensional model of the thermocouple and the Kiel head and considers the following effects

- Internal flow velocity (inlet and exit area)
- Thermal conduction in the thermocouple, the stagnation tube and the rake shaft.
- Convectional heat transfer to the thermocouple, the stagnation tube and the rake shaft
- Radiation heat transfer between
  - thermocouple and stagnation tube
  - thermocouple and surroundings
  - stagnation tube and surroundings
  - rake shaft and surroundings

As a result not only the temperature of the tip of the thermocouple (the indicated temperature in the real measurement) is given but the complete temperature profiles in the thermocouple, the stagnation tube and the rake shaft (see **figure 6**). This can be used by the designer to optimize the sensor.

As the existence of radiation leads to a heat transfer between any visible fractions of the affected surfaces the governing equations are relatively complicated. To solve the problem the calculation domain has been divided in discrete volumes and the temperatures have been determined in multiple iterations. While standard equations[5] have been used to cover the conduction and convection heat transfer the method of Hottel[4] has been applied for the radiation heat transfer.

Comparison of Measurement and Calculation

To prove the reliability of the calculated values the known calibration curves of available total temperature rakes have been used for comparison (see **figure 4**). In the region with Mach numbers below 0.3 the difference between indicated and real total temperature is smaller than 0.4 K and the measured values become more and more unreliable. Theoretically for flow velocities approaching 0 m/s the sensor arrangement becomes isothermal at a temperature in between the static and total temperature. The recovery factor should approach a value between 0 and 1.

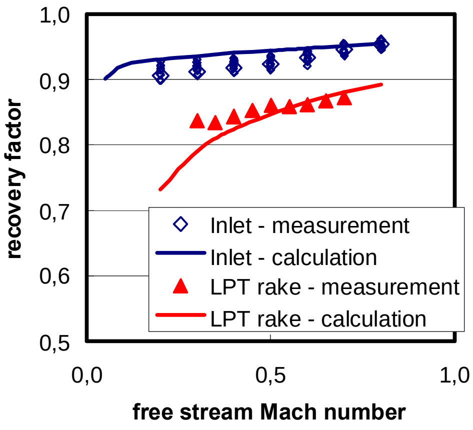

figure 4: calculated and measured recovery factor

For higher Mach numbers the calculated recovery factor represents the measured values. The higher values of the inlet rakes can be explained with longer thermocouples (reduced conduction error) and a larger inlet to exit ratio (reduced velocity error) compared to the values of a very small rake at the inlet of a low pressure turbine where no better design could be realized.

Despite all simplifications of the model (one-dimensionality, constant heat transfer coefficients, neglect of local effects around the bleed holes and manufacturing details) it seems to give reasonable results that can be used for a quantitative discussion of the phenomena.

Analysis of the heat flow in the sensor

The temperature of the thermocouple tip is governed by the balance of all heat flows in the surrounding area. This is the convection, conduction, and radiation heat transfer.

$$\begin{aligned} &\dot{Q}_c(T_i;T_t;p_t;M_i)+ \\ &+\dot{Q}_k(T_i;T_{TC}(x);h_c)+ \\ &+\dot{Q}_r(T_i;T_w;\varepsilon) \qquad =0 \end{aligned} \tag{5}$$

To receive a good indication of the total temperature it is necessary to maximize the convective heat transfer Q_c and minimize the other heat flows. Unfortunately an increase of the convective heat transfer is directly coupled to an increase of the velocity error, while the other errors are mostly influenced by geometrical restrictions. Therefore the velocity error has

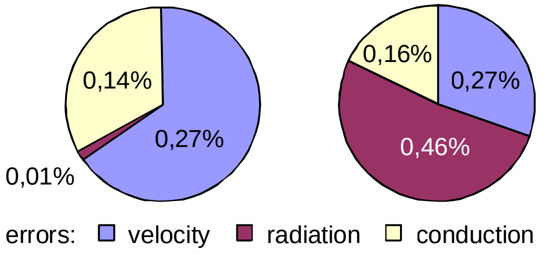

figure 5: deviation of a typical total temperature measurement and influence of separate effects at M=0.5: left: calibration at 96 kPa and 315 K; right: application at 0.5 MPa and 1370 K

to be traded against the conduction and the radiation error.

Figure 5 shows the influence of the different effects on the measurement of total temperature with a typical rake. In a test stand for dynamic calibration at low temperature and ambient pressure a deviation from total temperature of 0.42% is detected (left diagram) for a Mach number of 0.5. This is mainly caused from the velocity error as the internal flow velocity has a Mach number of 0.12 which results in a velocity error of 0.86 K. In the original gas turbine application the temperature and pressure is much higher. Here the radiation error becomes dominating and the deviation from the real total temperatures more than doubles to an assumed value around 0.9%. A correction with the calibrated recovery factor only eliminates the velocity and the conduction error. Therefore an error of 0.48% will remain after the correction. This is in the same order as the thermocouple error and must not be neglected.

The temperature distribution within the sensor head is displayed in **figure 6**. The shaft temperature rises from a low value at the cooled engine casing to a stable value in between the static and the total temperature that is determined from the recovery factor of the shaft (the value for a cylindrical body under cross flow conditions is given to 0.68[1]) and the radiation heat exchange with surrounding surfaces.

Starting from this temperature level the temperature of the Kiel tube decreases as heat is transferred to the colder free stream (static temperature) and via radiation to other surfaces. The leading edge of the Kiel head is heated from the impinging flow with total conditions in the stagnation region. Within the Kiel tube the decelerated flow is on a temperature near the total temperature and transfers heat to the tube. As the heat transfer coefficient is much lower than on the outside this does not effect much the temperature of the Kiel tube.

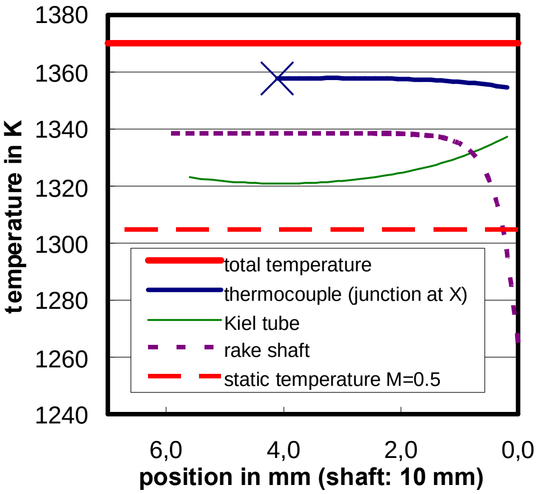

figure 6: temperature distribution in sensor (length of Kiel head 5.6 mm

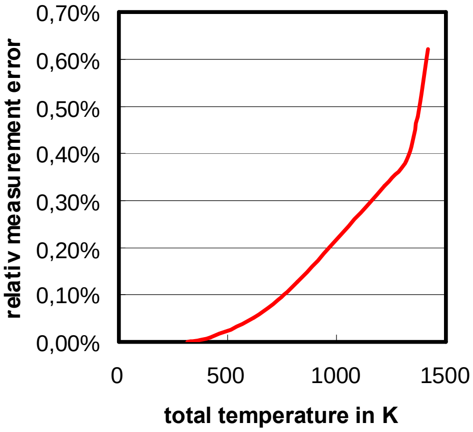

figure 7: error due to radiation heat transfer

The temperature curve of the thermocouple starts near the shaft with a temperature slightly above the Kiel temperature because of the electrical and thermal insulation between the thermocouple and the rake shaft and approaches the static temperature of the internal flow. The main heat transfer mechanism in this high temperature application is the radiation heat transfer as discussed before (see **figure 5**). In **figure 6** it can be seen that this is mostly the radiation heat exchange between the thermocouple and the surrounding Kiel tube.

Figure 7 illustrates the influence of the radiation heat transfer. The points selected for **figure 5** are displayed here as a continuous curve. It can be seen that starting from temperatures around 500 K an influence of the radiation exists. Around 1000 K this effect becomes noticeable even in comparison with other errors like the thermocouple error. The significant change of the gradient around 1300 K is caused by the assumption that the maximum temperature of all engine parts is limited. Above this limit the surrounding surfaces will be cooled and the temperature difference to the sensor grows. This results in a sharp increase of the radiation heat transfer.

Optimization of total temperature sensors

Results from the calculations can now be used to optimize the geometry of total temperature sensors. In principle the requirements for total pressure Kiel heads and total temperature Kiel heads for low and high temperature applications are very similar. Common objectives for the design is a minimum sensitivity to variations of the flow angle and pressure gradients. Available design rules[2] give a minimum length of the Kiel head or a maximum ratio of outer and inner diameter. Such effects are not covered by a one dimensional thermal analysis and have still to be obeyed.

The variation of a few parameters that are not essential for total pressure sensors can be very helpful for the optimization of total temperature sensors. These are mainly

- the ratio of the Kiel head inner diameter to the thermocouple diameter
- the position/length of the thermocouple
- the size of the bleed holes and the internal flow velocity

Other variations as a better thermal insulation of the thermocouple in the probe shaft, a modified thermal conductivity of the thermocouple or a modification of the surface emissivities could be theoretically helpful. Practically these parameters are given by the available materials and geometries.

Kiel head inner diameter

As in high temperature applications the radiation heat transfer between thermocouple and Kiel tube becomes the dominant factor, the Kiel head inner diameter d_i can influence the accuracy of the sensor. As it can be seen in equation 4 the radiation error Y_r is proportional to

$$Y_r \propto \frac{1}{1+\frac{A_{TC}}{A_w}(1-\varepsilon)} = \frac{1}{1+\frac{d_{TC}^{\ 2}}{d_i^{\ 2}}(1-\varepsilon)} \qquad (6)$$

This factor increases with an increasing Kiel head diameter (see **figure 8**). For a low radiation error the diameter should be as small as possible even if the effect is small. In addition a small Kiel head might reduce the visible solid angle of cold surfaces before the thermocouple tip and therefore reduce the radiation heat transfer to adjacent parts.

Length of the thermocouple

Two effects are influenced by the length of the thermocouple within the Kiel head. First the conduction heat transfer from the sensing tip of the thermocouple is reduced with increasing length. Second the solid angle in that cooled parts in front of the sensor can be seen – mentioned in the last section – is increased with a smaller distance from the Kiel head inlet to the tip of the thermocouple and the radiation error rises.

In low temperature applications without the domination of the radiation heat transfer it is helpful to manufacture the thermocouple as long as possible. For a maximum insensitivity to flow angle variations the ideal position is commonly chosen between 0.5 and 1.0 of the inner diameter. But as flow angle variation above 15° usually do not occur or the sensor head is limited to such an angle because of other restrictions, this parameter can be reduced to a value around 20% of the inner diameter.

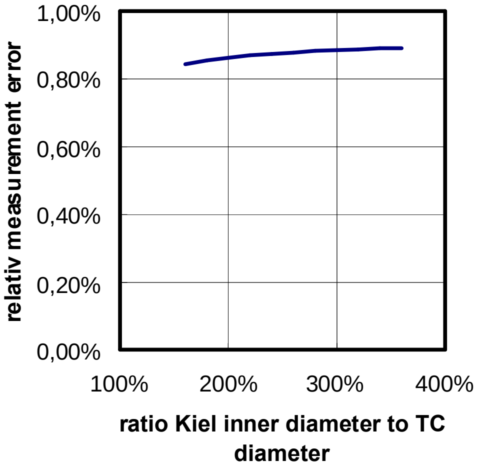

figure 8: deviation from total temperature over Kiel head diameter (related to thermocouple outer diameter)

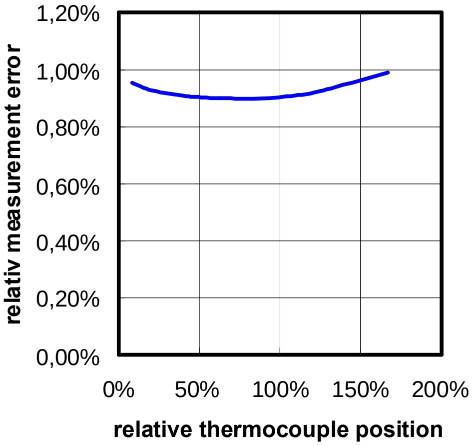

figure 9: distance between Kiel head inlet and thermocouple tip in relation to the thermocouple diameter

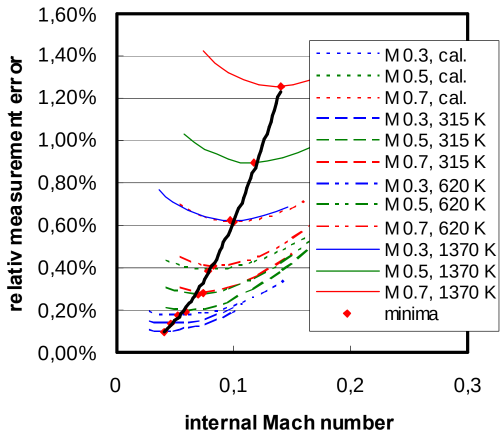

figure 11: influence of the internal Mach number on the measurement error.

In high temperature applications there may be an optimum length with a minimum between radiation and conduction error (see **figure 9**). Where this optimum can be found depends on geometrical and flow parameters and has to be investigated for every single application.

Size of the bleed holes

The size of the bleed holes determines the flow velocity within in the sensor. Numerical calculations (see **figure 3**) show, that the maximum Mach number through the holes is usually similar to the free stream Mach number. This can be explained with the pressure ratio between the internal flow of the sensor (near total pressure) and the static pressure of the external flow that automatically leads to a theoretically equal Mach number. The influence of frictional losses, the stagnation zones along the shaft and the inclination of the bleed hole have only of marginal influence.

As the mass flow through the bleed holes is fixed the flow velocity within the Kiel head is influenced only by the ratio of the internal flow area and the area of the bleed holes and therefore a nearly linear relation exists between internal velocity, area ratio and free stream velocity.

The conduction and radiation errors depend strongly on the heat transfer coefficient of the flow along the thermocouple (h_c in equations 3 and 4). The velocity error is a function of the internal Mach number. To get an optimum result the internal Mach number should be small enough to keep the velocity error small, but high enough to avoid large conduction and radiation errors.

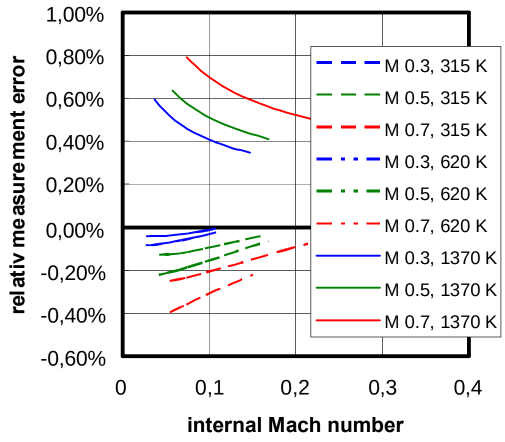

figure 10: influence of the internal Mach number on the measurement error with recovery correction.

These contrary effects are displayed in **figure 11**. The measurement errors shows a minimum at a determined internal Mach number. But these curves are only valid for a specific sensor design and can be different for other configurations. Even for the example discussed here the minima shift significantly with the temperature and the Mach number, i.e. the total relative measurement error. The reason is that for high temperatures the large radiation errors have to be in balance with a larger convective heat transfer caused by a higher internal flow velocity.

In real applications the sensor is calibrated in a cold flow dynamic calibration setup. Therefore a calibration curve of the recovery factor over the free stream Mach number exists (see **figure 4**). If these values are used to correct the measured temperatures (to calculate the “real” total temperature) the curves from **figure 11** shift to lower values as displayed in **figure 10**. It can be seen that a standard recovery correction based on the free stream Mach number is less than perfect. In the real application the pressure is higher than the pressure in the calibration, leading with higher Reynolds numbers to higher estimated heat transfer values (reduced measurement error). The higher temperature induce a radiation error that did not exist in the calibration setup. As a result for low temperature, high pressure applications the recovery correction is overcompensating the real error (see the curves for 315 and 620 K in **figure 10**), while the correction is not sufficient for high temperature applications (curves for 1370 K). The small errors of the curves for 620 K are caused by the superposition of negative pressure and positive radiation effects.

Higher internal Mach numbers improve the heat transfer to the thermocouple and reduce the influence of the erroneous effects. The lower recovery factor (higher velocity error) is not significant because it is compensated with the recovery correction. This implies that the internal Mach number should be as high as possible. But other effects will destroy the gained accuracy: higher internal Mach numbers cause a higher calculated value for the recovery correction. This depends on the possibly estimated local free stream Mach number and the experimentally determined recovery factor, both of them having significant errors. On the other side the Kiel head design makes the sensor insensitive to flow angle variations. This benefit disappears with increasing internal flow speeds.

In reality there will be an optimum internal Mach number that is strongly influenced by the need for flow angle insensitivity and the measurement errors of the dynamic calibration and the local Mach number determination. This cannot be seen in the theoretical analysis discussed here. Additionally the results have to be viewed in comparison with the thermocouple error, which is in the area of 0.4 to 0.75% (class 1 or class 2 thermocouples type K[3]). Above internal Mach numbers around 0.15 the thermocouple error will dominate the total error. A compromise between all effects seams to be possible with internal Mach numbers between 0.1 an 0.15.

Conclusion

A numerical analysis of common total temperature sensor designs with Kiel heads (stagnation tubes) has shown that there are several geometrical parameters that influence the performance of the sensor. The standard design rules are mostly derived from the design of total pressure sensors and adapted to create a maximum recovery factor at calibration conditions (low temperature and low pressure).

It has been discussed how radiation, conduction and convection affects the deviation of the measured temperature from the total temperature. The main factor is the Mach number of the flow within the sensor tube that depends on the flow area ratio of the tube inlet and the bleed holes. High internal flow velocities result in a higher heat transfer to the thermocouple and reduce the influence of the conduction and the radiation errors. This advantage has to be traded against a higher velocity error, i.e. a lower static temperature around the thermocouple. In principle this can be corrected using the recovery factor measured in a dynamic calibration test. But as the measured recovery factor has errors and the real local Mach number in the application is not exactly known this can be only an imperfect correction.

It can be summarized that common inlet to bleed area ratios between 3 and 4 are not optimal for all applications especially in combination with temperatures above 1000 K. In this area radiation effects become significant. A minimized recovery error in realistic cases ca be realized with internal Mach numbers between 0.05 and 0.15. In application with very high radiation and conduction errors (high temperatures, low pressures) the internal Mach number is the most important factor and should be chosen in a range around 0.15.

The result of such an optimization is a significant reduction of the remaining measurement error. A total temperature rake in a low pressure turbine inlet with a Kiel tube inlet to bleed hole area ratio of 3.7 (using the effective inlet area considering the thermocouple cross section) may have a calibrated recovery factor around 0.94. Used at 1370 K the recovery factor drops to 0.79 and after the recovery correction an error of 0.7% from 1370 K will occur.

Using an optimized sensor design based on the criteria discussed above, the calibrated recovery factor will be only around 0.89 but the non correctable measurement error may drop to 0.4% from the real total temperature. This means a significant reduction of the overall measurement error even if other errors like the thermocouple error still have to be added.

The one dimensional heat transfer calculation has been proven as a vital tool for the design of total temperature sensors especially for high temperature applications.

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