HEAT TRANSFER MEASUREMENTS AT A HIGH PRESSURE TURBINE SHROUD

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ABSTRACT

In context of the German research program “AG-Turbo” preparations were concluded for the measurement of the steady and unsteady heat transfer coefficients at the stationary shroud of a high pressure turbine. For this a new heat transfer sensor was developed by DLR. This sensor allows 25 steady heat transfer measurements to be made simultaneously. Furthermore the marginally elevated hot-wire recently developed by TU-Berlin was tested and the results compared with those of flush mounted hot-film. These pre-tests were performed in the probe calibration facility of DLR.

The actual experiments will be carried out at the windtunnel for rotating cascades (RGG) of DLR, Göttingen. These experiments also include detailed steady and unsteady pressure measurements at the shroud and behind the rotor.

INTRODUCTION

Due to the raising turbine entrance temperatures, much cooling air is needed to keep the temperature of highly thermal loaded parts of the turbine under a bearable limit. However, since cooling air is expensive and reduces the overall efficiency therefore the air has to be used economically. For this detailed knowledge of the heat transfer distribution on the affected areas is necessary.

The shroud, a part of the casing which is especially affected by the hot combustion gases and high heat transfer coefficient, has been excluded so far from research and therefore offers a great potential for saving coolant. The (stationary) shroud is that part of the casing located directly over the rotor. The reason for the high heat transfer rate at the shroud can be found in the presence of the tip leakage flow and the tip leakage vortex. The local thin boundary layer and large circulation of hot fluid at the shroud result in a thermal load at shroud comparable to that of the leading edge of the blade. A detailed overview of these phenomena is given by Sjolander [Sjolander, 1997]

The presented measurements aim to fill this gap. The experiments within the transonic regime will be carried out at the windtunnel for rotating cascades (RGG) of DLR, Göttingen. The rotating cascade offers the most genuine flow conditions, but also puts strong demands on the measuring techniques. Consequently much emphasis was put on the selection, design and testing of the different techniques.

The first objective of the project is to measure the steady heat transfer profile at the shroud. This knowledge helps to predict the hotspots and is therefore valuable information for quality insurance in industry. Additionally the unsteady heat transfer will be measured because this knowledge can help to understand the nature behind the heat transfer at this highly instationary region of the turbine. Furthermore the unsteady data also form a very good benchmark for newly developed CFD tools.

NOMENCLATURE

A	area
h	heat transfer coefficient
m	mass flow
M	Mach number
q	specific heat flux
R	electrical resistance
R	ideal gas constant
T	temperature
U	streamwise velocity
V	voltage
κ	adiabatic component
ρ	density

Subscripts

w	Wall
w	Wire
∞	cold condition
0	Total conditions

1 TEST FACILITY AND MEASUREMENT TECHNIQUES

1.1 The rotating cascade facility of DLR, Göttingen

The experiments described in this paper will be performed using the rotating cascade of the DLR, Göttingen (RGG). The facility is a closed loop windtunnel which can operate at transonic speed with a volume rate up to 15.5 m^3/kg. The continuous air supply is delivered by a four stage axial compressor. The speed of rotation of the rotor is controlled by a 1MW motor/generator. Table 1 gives the most essential characteristics of the present experiment is given in. The RGG distinguishes itself by an excellent periodicity at realistic rotational speed and fluid velocity. However the accompanying complexity of the tunnel exacerbates the instrumentation of the testing objects with the necessary sensors. The use of optical techniques for instance, is possible but only very limited. Also the well established thin film technique or Naphthalene sublimation technique is for a long duration tunnel such as the RGG unsuitable or at least problematic.

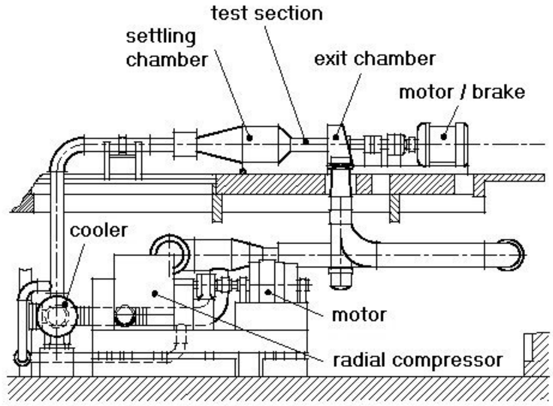


Figure 1: Schematic of the RGG

Total pressure at test section inlet	120 ... 150 kPa
Total temperature at test section inlet	390 K
Compressor pressure ratio	2.3 … 3.8
Rotational speed	8000 … 10000 rpm
Mass rate	3.0 … 3.7 kg / s
Rotor diameter	547 mm
Gap height	1% of blade

Table 1: Summary of the testing conditions

Flexibility in replacing and repairing sensors was created by manufacturing two pockets in the shroud for inserting replaceable “inserts” which are instrumented with different measurement techniques. The following sections address the various measurement techniques used.

1.2 Pressure measurement system

The steady pressure at the shroud is measured by 25 static pressure holes, while the unsteady pressure is measured by 7 Kulites (type XCQ-062). Additionally the total pressure is measured behind the rotor using a steady wedge type probe and an unsteady Kulite probe, special interest lays on resolving the tip leakage vortex near the shroud.

1.3 Thermocouple+ array

The thermocouple+ array shown in Figure 2 is a heat transfer sensor developed by DLR. The sensor consists of a thin flexible Kapton foil with an integrated thermocouple array and an integrated electrical heater on the rear side. The sensor allows the simultaneous measurement of the steady heat transfer at 25 points. During the experiments these points are spread in the axial direction with a spacing of 1mm. The RGG offers the ability to rotate the stator with respect to the sensor, doing this about 250 measurement points per passage can be obtained. The sensor is called thermocouple+ array because it is a thermocouple array, but additionally it has an integrated heating, for measuring the heat transfer directly; this additional feature is symbolized by the “+”.

Figure 2: Insert with thermocouple+ array

Figure 3 shows the composition of the thermo-couple+ array. The Copper and Constantan circuitry of the top two layers joint together form the array of thermocouples. The Manganin circuit path on the bottom Kapton foil acts as a heating element.

The measurement principle of the thermocouple+ array bases upon the simultaneous knowledge of the sensor’s internal heat generation per heated area and the distribution of its surface temperature.

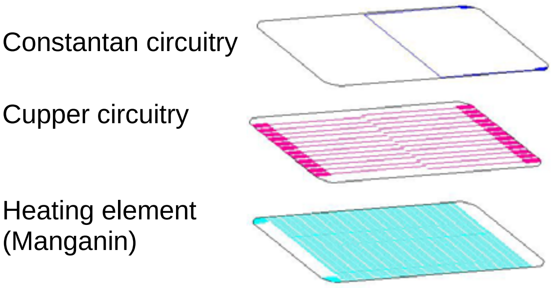


Figure 3: Composition of thermocouple+ array

The heat transfer coefficient can be calculated from:

$$h = \frac{q''}{T_w - T_\infty} \quad (1.1)$$

The heat flux q'' of the electrical heater is generated homogeneously over the entire foil surface. The difference between the wall temperature with heating and without $(T_w - T_\infty)$ is measured simultaneously by two separated sensors.

The advantages of the thermocouple+ array are:

- No need for optical access
- Cost effective
- Very Robust
- Precise

The first criterion is essential for the present application. Furthermore the etching process gives a lot of design freedom. For the costs only the initial costs of the layout have been considered. Because the production process is fully automated and the material costs are low the dynamical costs are negligible. The accuracy of the foil is discussed below in some greater detail.

Formula (1.1) shows that for a good accuracy of the sensor both the heat flux and the surface temperatures have to be accurately known:

The **heat flux** generated by the electrical heater can be determined with great precision, it follows from the layout of the circuitry as well as the power input. The layout with a constant spacing of only 0.1mm between the successive paths guarantees a homogenous and thus clearly definable heat flux. The power input will be supplied by a DC power supply the adjustable accuracy is within the range of 0.01% of the adjusted power value.

However the generated heat will not completely be convected into the flow. A fraction of the heat is either lost to the back were it will be lost to the surroundings or even worse it will be lost in lateral direction were it can still enter the flow but will cause an additional error in this second region. There are two strategies which are used to counter act this error source:

I) The spreading of the heat is reduced by using a good isolator as wall material. For this reason the insert is manufactured from Poly ether ether ketone (PEEK). PEEK is a semicrystalline thermoplastic and possesses a low thermal conductivity and is thermally loadable up to 250°C at least.

II) When the conduction losses are known the heat flux can be compensated. For this reason a second thermocouple+ array is place on the backside of the insert, this sensor allows monitoring heat losses towards the back. Information on the lateral losses can be obtained from the neighboring thermocouples, for this compensation a 2D heat transfer analysis has to be conducted. Since the heat transfer measurement consists of the difference of $T_w - T_\infty$ the spreading of the wall temperature as result of the changing fluid temperature has no influence on the accuracy of the heat transfer coefficient measurement.

The **surface temperature** difference $T_w - T_\infty$ follows from two separate measurements of the thermocouple+ array. The Copper and Constantan circuitry form thermocouples of type “T”. The voltage output is collected by a *Keithely 2100/7100* digital multimeter, which sends the gathered data to a *Labview* program running on a PC.

The accuracy of the thermocouples is of great influence for the overall performance of the sensor. There is no previous experience with etched thermocouples either by DLR or by Isabellehütte the manufacturing company. Therefore the accuracy of the thermocouples of the sensor were extensively tested.

For moderate temperatures up to 80°C a WIKA 9105 commercial calibrator was used. The results are shown in Figure 4.., The maximum deviation is 0.3°C. The high temperatures were calibrated using a Nikkon Laird S270A infra red camera. The measured deviation complies well with the criteria set for class I type T thermocouples. Thus etched thermocouples perform as well as their class I conventional counter parts.

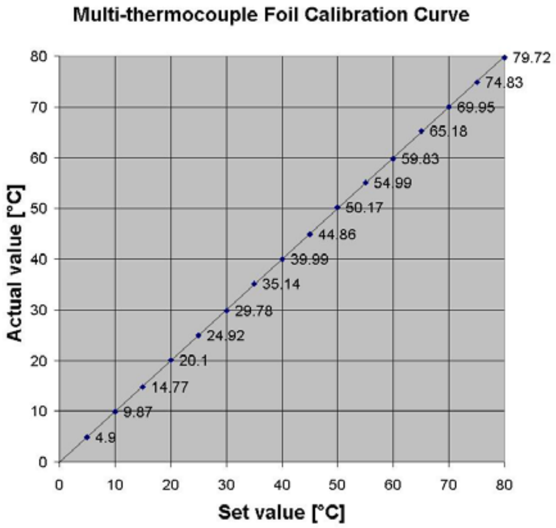


Figure 4: Calibration curve <80°C (Calibrator)

The obtainable accuracy depends for a large extend on the maximum allowable temperature. This maximum temperature is set by the adhesive between the thermocouple+ array and the insert. Experiments were conducted with a variety of adhesives. “Martens 3 Plus” a three component hot tempering epoxy proved to allow an operation temperature >200°C.

1.4 Surface mounted hot-film & hot-wire

The surface hot-film technique offers a very good method to measure the unsteady heat transfer at the wall. The working principle of hot-films in the so called “constant temperature mode” consists of the rapidly controlled and measured voltage which is needed to keep the metallic film exposed to the fluid at an adjusted, constant temperature. The heat transfer rate can be expressed as:

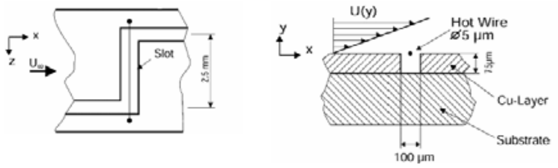
$$q'' = A_w h\left(T_w - T_\infty\right) \qquad (1.2)$$

Based on equation (1.2) King found the following empirical law for hot-films and hot-wires:

$$\frac{V^2}{R_w} = \left(A + B\left(\rho U\right)^n\right)\left(T_w - T_\infty\right) \qquad (1.3)$$

A, *B* and *n* are empirical constants determined by calibration, n being usually ≈ 0.5. Hot-film measurements are frequently used for the measurement of the wall shear stress. In case of compressible flow the signal change caused by the velocity has to be isolated from that caused by the change in density; this process can be very cumbersome. Fortunately, when the heat transfer coefficient is needed it is irrelevant what part causes what, the output of the hot-film is precisely the desired output.

In the preparation phase of the project it was investigated whether the marginally elevated hot-wire technique newly developed by TU-Berlin [Sturzebecher et al., 2001] could be used for the proposed measurements. The marginally elevated hot-wire is in principle comparable to the hot-film, but instead of a thin metallic film a small wire spanned over an etched slot is used. A sketch of the marginally elevated hot-wire is given in Figure 5.



a) top view b) side view

Figure 5: Sketch of marginally elevated hot-wire. [Sturzebecher et al., 2001]

The thermal capacity of the wire is much smaller than that of the film, allowing an increased frequency response. Furthermore the isolation of the wire from the wall by means of the slot reduces the heat losses towards the wall.

Pretests were conducted in the probe calibration facility (SEG) of DLR, Göttingen [Gieß et al., 2000]. For this a flat plate was placed in a free jet. This testing object was instrumented with a multi-thermocouple foil, a hot-film and a marginally elevated hot-wire. A flat plat was chosen as testing object because it allows the best comparison with other results from literature. A marginally elevated hot-wire was mounted such that it could rotate, tests were conducted with an orientation angle of 0°, 45° and 90°. The testing program furthermore included measurements at different total pressures (75kPa, 105kPa, 150kPa) and different Mach numbers (0.6 – 1.15). The simultaneously acquired data of all sensors allow for a direct comparison .

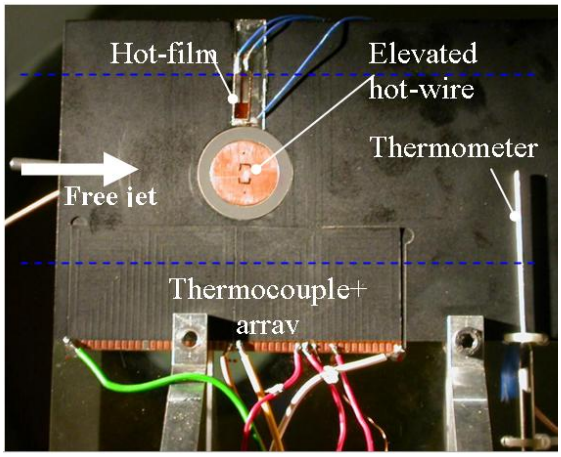


Figure 6: Image of the instrumented testing plate

Equation (1.3) displays that the heat transfer coefficient only depends on the local mass flow.

The mass flow is given by:

$$\dot{m} = \rho U A, \tag{1.4}$$

with,

$$\rho = \frac{\rho_0}{\left(1+\frac{\kappa-1}{2}M^2\right)^{\frac{1}{\kappa-1}}}, U = M\sqrt{\frac{\kappa R T_0}{1+\frac{\kappa-1}{2}M^2}}$$

Equation (1.4) shows that the mass flow and consequently the heat transfer coefficient have a maximum at the speed of sound.

The signal output of the marginally elevated hot-wire for three different total pressure levels as a function of the Mach-number is shown in Figure 7. The curves clearly display a maximum at Mach number of 0.8. At M>0.8 the hot-wire underestimates the wall heat transfer. A possible explanation for this is the acceleration of the flow around the wire causing a local reduction of mass flow and a critical Mach number well below unity. Oddly this peak shift proves to be independent from the orientation of the wire with respect to the flow.

The step at M=0.96 is a result of the shockwave caused by the test-plate it self, the fact that the shock does not occur at unity can be explained by the flow displacement caused by the plate.

Near the maximum the resolution of the marginally elevated hot-wire is very poor. However the expected velocity range near the shroud ranges from M=0.4 to 1.2. Therefore there remains a large domain were the good characteristics such as the high frequency response of the marginally elevated hotwire can be taken as advantage. However due to the ambiguity of the curves the marginally elevated hot-wire can only be used as a supporting technology.

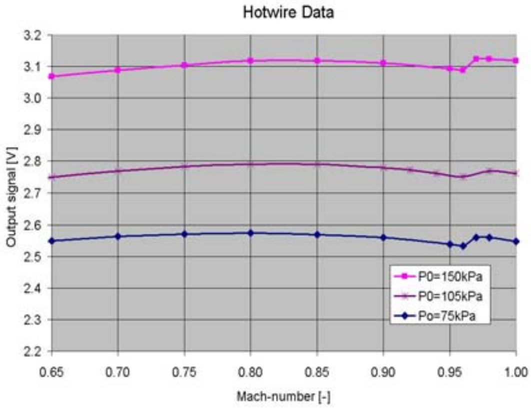


Figure 7: Calibration curve of marginally elevated hot-wire

Figure 8 shows experimental data obtained from the hot-film. Additionally the results of the thermocouple+ array are shown, this serves as a reference.

Because the hot-film and thermocouple+ array are both flush mounted they do not affect the flow. For this reason no peak shift occurs. The output of the hot-film show good agreement with that of the thermocouple+ array. This strong similarity allows an effective in situ calibration of the empirical constants *A*, *B* and *n* of the hot-film with the aid of the output of the thermocouple+ array. Although there is much literature on the analytical determination of these constants, hot-films and hot-wires poses very difficult boundary conditions. This makes a clear definition for the heat transfer coefficient measured only by a hot-film or hot-wire problematic. For the thermocouple+ array this limitation is valid only for the first thermocouples with the others the heated area around the measurement points is assumed to be large enough to create a properly defined boundary condition. For that reason the in situ calibration is very important.

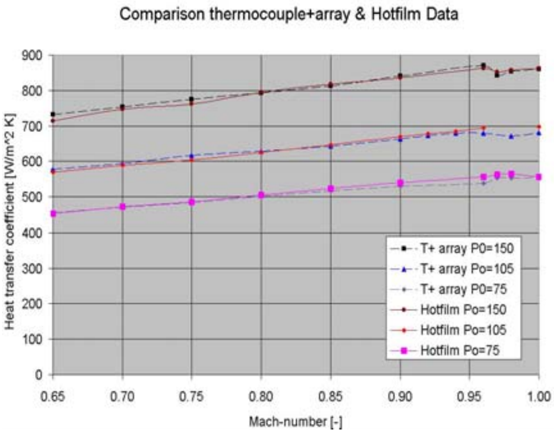


Figure 8: Calibration curve thermocouple+ array & hot-film

1.5 Conclusion

The aim of the preparations and tests was to find suitable measurement techniques which are not based on optical access and are suitable for a continuously running wind tunnel.

With the development of the thermocouple+ array a flexible, robust and precise method was found to measure the steady heat transfer coefficient. Up to 250 measurement points per passage can be obtained. The accuracy depends mainly on the level of unaccounted heat losses, for this reason a second layer of temperature sensor was installed. As important to be proved high operating temperature of the sensor; therefore much value is put on the quality of the adhesive between the sensor and the wall.

The hot-film and the marginally elevated hot-wire were compared. For this extensive pre-tests were performed in the probe calibration facility. These tests showed that in compressible flow the hot-wire underestimates the wall heat transfer. This also results in an area of poor resolution around M=0.8. This effect is believed to be caused by the local acceleration of the flow around the wire. The absence of this distortion with the flush mounted hot-film results in better data output in the transonic regime and a much better correlation with the results of the thermocouple+ array. This also allows a in situ calibration of the hot-film to be made with the results of the thermocouple+ array.

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