Paper 10

12th Symposium on Measuring Techniques
for Transonic and Supersonic Flow in Cascades and Turbomachines

Prague, Czech Republic, September 12-13,1994

HEAT -TRANSFER MEASUREMENTS ON A PLANE TURBINE CASCADE

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Introduction

In the high temperature gas turbine project (AG-Turbo), the validation of numerical results obtained with navier stokes codes with independent enforced windtunnel measurements on transsonic turbine cascades are performed. These investigations are carried out using a transonic turbine cascade in the windtunnel for straight cascades of the DLR Göttingen(EGG).

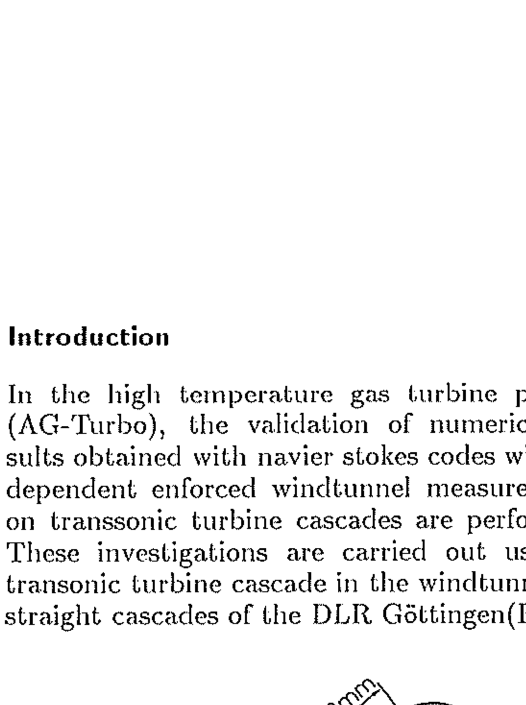


Figure 1: Test setup

Besides pressure distribution measurements, the skin friction or heat-transfer are the only measurable variables on the blade surface, which can be used to validate numerical codes. Because of the relationship between skin friction and heat transfer [2, 3] it is sufficient to determine the heat transfer.

Heat-flow sensors

Owing to the construction of the used windtunnel which is of blow-down type with atmospheric inlet, the most heat-transfer measurement techniques like the one dimensional analysis of heat-transfer gauges are impossible because of the long time the EGG needs to run with constant downstream pressure. In addition the time of measurement is too short as methods could be used which need much time to reach a thermal equilibrium. Because of this a method basing on the multilayered temperature measurement is used.

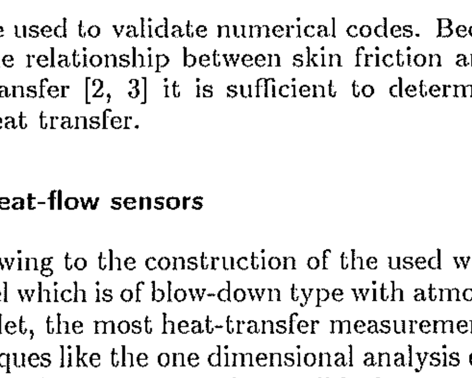


Figure 2: Schematic drawing of the RdF-sensor. On the left the thermoelement for differentional and on the other side for the absolute temperature is shown.

These heat-flow sensors are manufactured by RdF - Corporation and are composed of a kaptonfoil with two copper-konstantan thermocouples mounted on either side of the foil. The connection of the thermocouples provides a proportionality between the temperature difference and thermovoltage. Sensors with one thermocouple just as 10 thermocouples in series circuits on either side of the kaptonfoil are used. These two types of sensors are shown in Figure x.

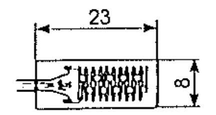
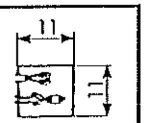
all scales in mm		
type of sensor	20455-3	20453-3

Figure 3: The two types of used heat-flow sensors manufactured by the RdF-Corporation

As described in Fourier's law of heat conduction a linear correlation of temperature difference and heat-transfer exist. In this equation

$$\dot{q} = -\lambda \frac{dT}{dx} \; ; \; \dot{q}_{Str.} = -\lambda \frac{\Delta T}{d} \qquad (1)$$

the heat-resistence and thickness of the foil are the only material parameters which have to be known. The according calibrations are carried out at RdF-Corporation, so that for each sensor a calibration curve was delivered. The sensors are glued to the blade surface so that for operation a temperature difference to the fluid is needed. Therefore a hollow plastic blade is used feeded with a hot waterstream of 353K. When the windtunnel is operating, the heat-flow is adapted to the thermal boundary layer and belonging to this a temperature difference is provided in the kaptonfoil of the sensor. So the heat-flow through the plastic surface doesn't represent a limit and according to every heat-flow the temperature difference through the foil adjusts itsself. The uneven surface thickness causes a varying isothermal boundary condition so it is necessary to measure the surface temperature at the position of each sensor to determine the heat transmission coefficient. All of the choosen sensors are equipped with a thermocouple to measure the absolut temperature in addition to the differential thermoelements so that it is possible to eliminate the influence of temperature differences along the blade contour.

Hot-film sensors

Due to the fact that these heat-flow sensors are quite large in comparison to the blade an additonal measurement technique is desired to improve the spatial resolution. Thus additional heat-flow measurements are performed by means of heated thin-film sensors. The used hot-films are produced by MTU. The heating elements consists of a nickelfilm deposited on a kaptonfoil. The manufacturing process makes it possible to deposit 30 elements with their electrical supplies on one sheet at the same time. The distance from sensor to sensor is 2,5mm. The hot-film elements and the heat-flow sensors are additionaly mounted on the same blade. The fact that the effective heated area of a thin-

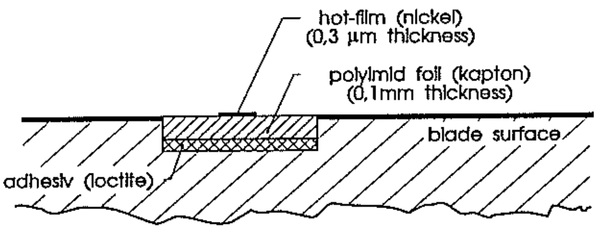


Figure 4: Schematic representation of a thin-film element mounted on a surface.

film is unknown must be taken into account. The reason for this is the heat conduction in three dimensions. So it is impossible to determine the heat transfer coefficient with hot-films. Nevertheless a normalized power can be defined by the mean voltage divided by the overheat resistence. This normalized power fits the area between two heat-flow sensors. Dividing the normalized power by the heat transfer coefficient like it is done in formula (2), coefficients are received which are proportional to the effectivly heated area F. The equation also takes into account that a different boundary condition exist which is represented by the factor β. This is necessary because of the impossibility to operate the thin-films under isothermal boundary conditions.

$$\frac{L_{Str.}}{\Delta T_{ü}} = \alpha_{Str.} \cdot F \cdot \beta \qquad (2)$$

For a flat plate under laminar conditions the following formular for β yields:

$$\beta = 1,6556 \cdot \left(\frac{x}{L_H}\right) \cdot \left[1 - \frac{L_H}{5x}\right] \qquad (3)$$

The formular shows a parabolic shape for β so

Nomenclature

L	=	length	T	=	temperature	fl	=	flow
Ma	=	Mach number	**Subscripts**			AX	=	axial coordinates
$\dot{q}$	=	heat-flow	is	=	isentropic	o	=	overheating
α	=	heat-transfer coefficien	2	=	homogeneous outlet flow	01	=	total temp. in the settling chamber

that it is nescessary to calibrate the hot-films with the prevailing nearest heat-flow sensor to minimize this error. The reason for the overheating of the hot-films are the indistinctable signals under isothermal boundary conditions. Therefore an overheating temperature above 10K against the surface temperature is chosen. For the measurements a DANTEC 55M01 anemomenter is used which operates the heated thin-films in constant temperature mode (Figure 5).

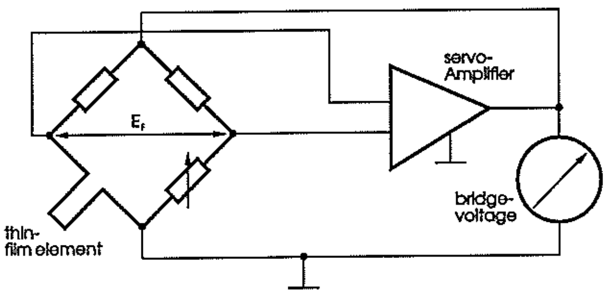


Figure 5: Wheatstone bridge

Apart from the recording of the mean voltage the alternating voltage is digitized and saved by a transient-recorder. Owing to the inertness of the heated thin-films it is impossible to resolve the turbulence. For the investigated blade a typical boundary layer thickness of 1mm is yield. With a flow velocity of 300m/s a turbulence frequency of 300kHz is received.

$$f \approx \frac{\text{flow velocity}}{\text{boundary layer th.}} \approx \frac{300\text{m/s}}{1\text{mm}} \approx 300\text{kHz} \quad (4)$$

Belonging to this it is only possible to resolve intermittence from the laminar to the turbulent boundary layer or other low frequency oszillations of the flow.

The windtunnel measurements

For the windtunnel test two blades are manufactured to investigate the heat-flow of nearly the whole suction side. One of the two blades is equiped with a heat-flow sensor at the position X_{AX}/L_{AX}=0.06 and thin-film elements reaching from X_{AX}/L_{AX}=0.07 until X_{AX}/L_{AX}=0.53. This blade is shown in Figure 6.

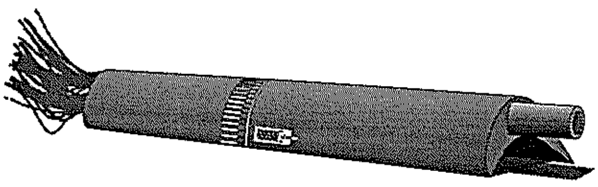


Figure 6: Heat-flow sensors and hot-films mounted at the leading edg of the hollow blade.

On the second blade heat-flow sensors are mounted on the positions X_{AX}/L_{AX}=0.62, 0.84, 0.73 and 0.88. The hot-films are reaching from X_{AX}/L_{AX}=0.74 to X_{AX}/L_{AX}=0.99 (Figure 7).

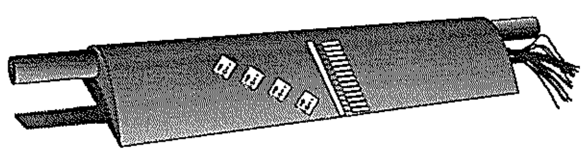


Figure 7: Heat-flow sensors and hot-films mounted at the rear suction side.

Before running a windtunnel test the blade is heated up to 353K by a waterstream which is controled by a thermostat. As expected the blade is cooling down by the air flow after starting the windtunnel. There the cold resistence of the thin-films shows clearly cooler wall temperatures (up to 10K) then the thermocouples of the heat-flow sensors. This temperature difference has multiple reasons. On the one hand the nickel film of the heated thin-films is exposed to the fluid motion whereas the thermocouples of the heat-flow sensors are placed under the kapton foil wich results in a temperature difference of up to 0,9K depending on the heat-flow. On the other hand there is a temperature difference of 5K along the surface despite of the very good mixing of the running through water which is a result of the differerent wall thickness of the blade. These reasons in connection with the other boundary conditions are the explanation for such a difference in the surface temperature. After reaching a thermal equilibrium the different surface temperatures are determined. The higher temperature of the absolute thermocouples is converted and afterwards used as the overheating resistance of the prevailing hot-films. Both the thermovoltage of all heat-flow sensors and the power signal of the hot-films are recorded parallel with a PC-data acquisition card after starting the overheat. Despite of the small overheating temperature in face of the isothermal boundary layer, we achieved a direct voltage of the hot-films of approximately 4V. With the determinated cold resistance at steady flow conditions it is possible to calculate the overheat temperature of the hot-films in the later analysis wherby the mean values of the saved data are used. The heat-transfer of the heat-flow sensors con be ascertained directly out of the data file which contains the thermovoltage and its corresponding calibration.

The difference between the total flow temperature was determined in the settling hamber and the surface temperature (T_{01}-T_W) is needed to calculate the heat transmission coefficient. The heating power of the hot-films is determined out of the mean voltage and the overheat resistance squared. The necessary temperature difference to normalize the power is achieved from the corresponding temperature of the cold resistance of the cold hot-films and the higher temperature shown by the heat-flow sensor wich is used as overheating resistant.

Determination of the heat-flow with hot-films

To convert the normalized power of the hot-films into heat transmission coefficients it is a great advantage that simultaneously to the hot-film voltage the heat-flow is determined. Thereby at every time of the measurement the hot-film measurement can be compared with the heat transmission coefficient. To determine the calibration factor the size of the heat-flow sensors must be taken into account, especially where a thin-film element is mounted not exactly at the middle position of the heat-flow sensor. An interpolation of the hot-film signal in this region solves the problem. The average of the normalized power in this intervall is used to determine the prevailing calibration factor. For the conversion of the remaining hot-film results the normalized axial coordinates of the heat-flow sensors are used to determine intervalls by averaging the distances of each sensor where the specified calibration factors come into effect. These intervalls are schematicly shown in Figure 8.

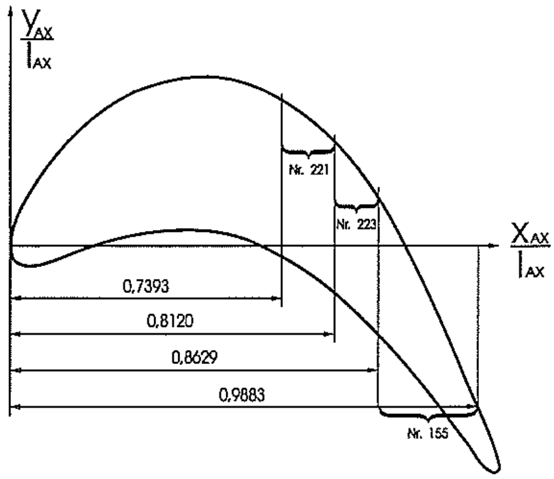


Figure 8: Choosen intervalls to calibrate the thin-film elements which are mounted on the blade with sensors mounted at the rear suction side.

Physical Interpretation of the measured values

For the examinations of te heat-flow at the leading edge of the suction side of the blade, the heat transmission coefficient must be determined with only one heat-flow sensor. In the region of the hot-films which are reaching from the stagnation point to the middle of the suction side of the blade a laminar boundary layer is expected, owing to the acceleration of the fluid flow. The failure of the thin-film sensors mounted at the stagnation point makes it impossible to compare the done measurements with a numerical calculation at the stagnation point. The comparison with a boundary layer calculation shows that the wall shear stress at the position of the thin-films has already dropped down and got only a small gradient like it is recognizable by the hot-film measurements. Measurements are carried out for three isentropic Mach numbers Ma_{2is}=0.3, 0.9, 1.1 and show an equivalent course with distingushable groundlevel of the heat transmission coefficients according to the prevailing Mach number (Reynolds number). This shape of heat-transfer will be confirmed by the data of measurements carried out with a second blade where sensors are mounted at the suction side from the middle to the trailing edge of the blade. The first measuring points are still located in the laminar boundary layer which will be confirmed by the RMS values of the hot-films recorded by the transient recorder. At Ma_{2is}=0.3 the transition to the turbulent boundary layer is shown by a sharp peak of the RMS value. Afterwards the RMS values are dropping down to the same level than in the laminar area which is a result of the insufficient frequency resolution of the hot-films. On the other the heat-flow increases when the boundary layer is becoming turbulent and keeps this high value until the trailing edge which is shown in Figure 9.

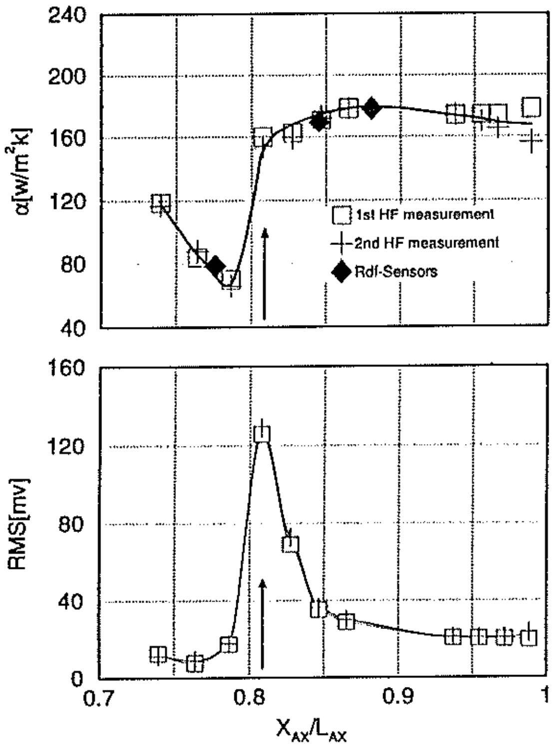


Figure 9: Heat-transmission coefficient and RMS distributions versus normalized axial coordinates for an isentropic outlet Mach number Ma_{2is}=0.3. The arrows show the middle position of the separation bubble.

The next exit Mach number is still subsonic, Ma_{2is}=0.9, whereas some local Mach numbers on the suction side are already supersonic. On this occasion an incident shock from the trailing edge of the upper blade hits the observed boundary layer where a separation bubble is indicated. In relation to the incompressible case the separation bubble is much bigger and at its front and rear side shocks are reflected which are oscillating with a resolveable frequency. The shape of the RMS values only shows the rear shock while the front side of the separation bubble is not visible. The reason for this might be the oscillation takes place between two hot-films. The shape of the heat transition coefficient shows clearly an increase at the position of the incident shock. The position of the decrease behind the rear side of the separation bubble is exactly the same asshown by the decrease of the RMS values. The explanation for the decrease is the reattaching of the turbulent flow which provides higher wall shear stresses (Figure 10).

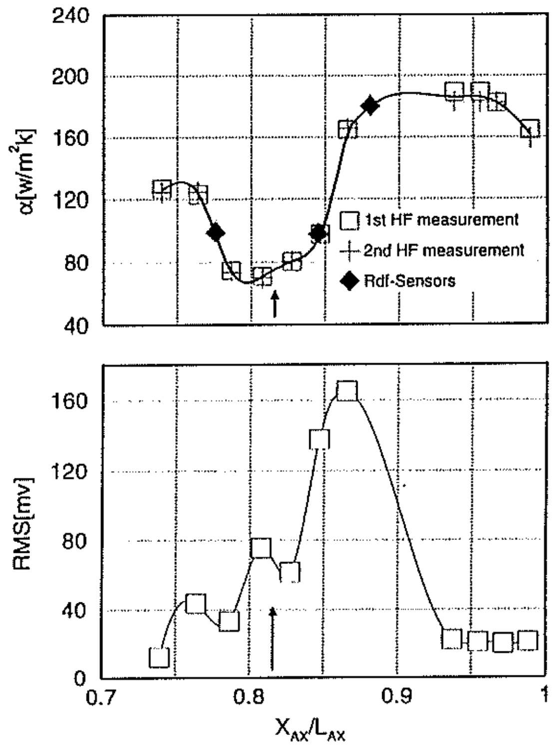


Figure 10: Heat-transmission coefficient and RMS distributions versus normalized axial coordinates for Ma_{2is}=0.9

For Ma_{2is}=1.1 a similar shape appears with a higher ground level because of the higher Reynolds number [4]. The RMS values for this Mach number show a little peak at the front side of the separation bubble while the decrease at the rear shows only a small gradient. The reason for this might be the larger amplitude of the oscillation of the shock(Figure 11).

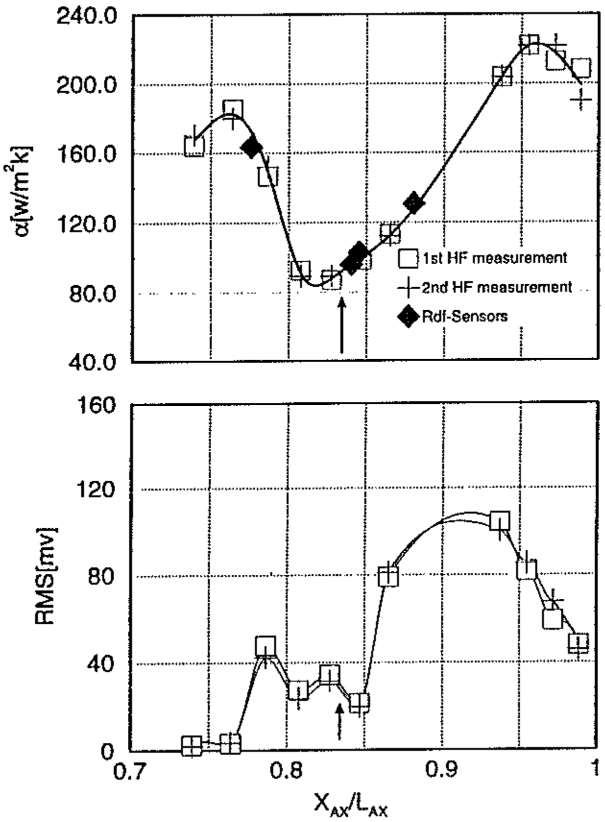


Figure 11: Heat-transmission coefficient and RMS distributions versus normalized axial coordinates for Ma_{2is}=1.1.

The whole shape of the heat-transmission coefficients from the stagnation point until the trailing edge for the suction side of both blades is shown in Figure 12.

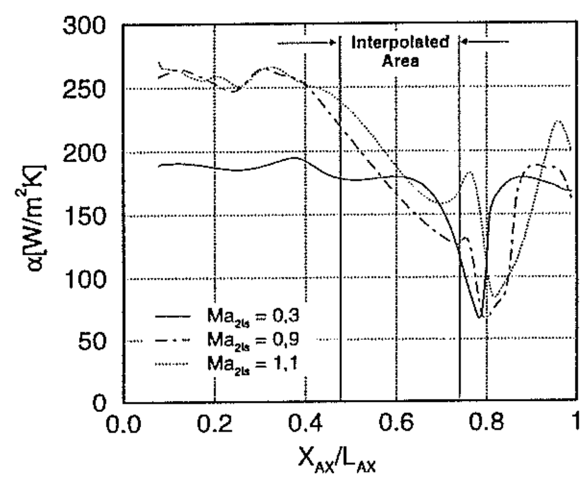


Figure 12: Complete distribution of the heat transmission coefficient α for the suction side of the blade.

Conclusions

The combination of hot-films with heat-flow sensors reveals a good accuracy in spite of low cost. The stream of a warm water flow through the hollow blade represents a simple method for a constant heating of the blade's surface. The precision of the RdF heat-flow sensors was confirmed by premeasurements on an incompressible flow through a cylinder(Acton [1]). The achieved error of 10% seems to be equal to other heat-transfer measurements. Errors only occur because of the off-line recording of T_{01} in the settling chamber. The atmospheric inlet of the windtunnel causes a temperature gradient during the measurement so that it is impossible to determine the exact temperature T_{01} for every heat-flow value. At last the hot-films introduce an inacuracy because of the sensitivity of the resistance to a temperature difference. Therefore a precise temperature measurement better then 0.5K is impossible. Since these measurments are only used to fit the other with heat-flow sensors performed measurments these errors should not be as important.

Against this an advantage of the whole measurement process would be the renunciation of an additional hot-film measurement and the substitution of this with smaller heat-flow sensors where for example 10 or more sensors are deposited on one kapton foil.

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