Aero-Thermal Performance of a Two Dimensional Highly Load Transonic Turbine Nozzle Guide Vane
A Test Case for Inviscid and Viscous Flow Computations

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ABSTRACT

This contribution deals with an experimental aero-thermal investigation around a highly loaded transonic turbine nozzle guide vane mounted in a linear cascade arrangement. The measurements were performed in the von Karman Institute short duration Isentropic Light Piston Compression Tube facility allowing a correct simulation of Mach and Reynolds numbers as well as of the gas to wall temperature ratio compared to the values currently observed in modern aero engines. The experimental programme consisted of flow periodicity checks by means of wall static pressure measurements and Schlieren flow visualizations, blade velocity distribution measurements by means of static pressure tappings, blade convective heat transfer measurements by means of platinum thin films, downstream loss coefficient and exit flow angle determinations by using a new fast traversing mechanism and freestream turbulence intensity and spectrum measurements. These different measurements were performed for several combinations of the freestream flow parameters looking at the relative effects on the aerodynamic blade performance and blade convective heat transfer of Mach number, Reynolds number and freestream turbulence intensity.

LIST OF SYMBOLS

\begin{align*}
c & : \text{chord} \\
d & : \text{diameter of bars in turbulence grid} \\
f & : \text{frequency} \\
g & : \text{pitch} \\
h & : \text{heat transfer coefficient} \\
k & : \text{isentropic exponent (} = 1.4\text{)} \\
M & : \text{Mach number} \\
o & : \text{throat} \\
p & : \text{pressure} \\
q_o & : \text{wall heat flux} \\
r_{LE} & : \text{leading edge radius} \\
r_{TE} & : \text{trailing edge radius} \\
Re & : \text{Reynolds number} \\
s & : \text{coordinate along blade surface} \\
s & : \text{pitch of bars in turbulence grid} \\
SPS & : \text{pressure side length} \\
SSS & : \text{suction side length} \\
T & : \text{temperature} \\
T_u & : \text{freestream turbulence} \\
u & : \text{velocity} \\
u' & : \text{fluctuating component of velocity} \\
V & : \text{velocity} \\
x & : \text{coordinate along axial chord} \\
y & : \text{coordinate in tangential direction} \\
\gamma & : \text{stagger angle} \\
p & : \text{density} \\
\text{Subscripts} \\
0 & : \text{total condition} \\
1 & : \text{upstream condition} \\
2 & : \text{downstream condition} \\
a\text{z} & : \text{along the axial chord} \\
s & : \text{isentropic condition} \\
w & : \text{condition at the wall} \\
o & : \text{freestream condition}
\end{align*}

INTRODUCTION

The description of the present test case is a follow up of similar events which were presented at the occasion of Lecture Series held at the von Karman Institute for Fluid Dynamics in May 1973 on "Transonic Flow in Turbomachinery" (Sieverding, 1973) and in April 1982 on "Numerical Methods for Flows in Turbomachinery Bladings" (Sieverding, 1982). At these occasions, several two and three dimensional cascade configurations were designed and their aerodynamic performances were experimentally determined as completely and accurately as possible. These measurements mostly served for comparisons with results obtained from inviscid flow calculation methods and presented by different Lecture Series participants. Ever since many other researchers have used the VKI subsonic and transonic turbine cascade test cases to evaluate the accuracy of their two and three dimensional Euler codes.

A general review on "Test Cases for Computation of Internal Flows in Aero-Engine Components" by AGARD Working Group 18,
headed by Prof. Fottner, led to the conclusions that further cascade test cases should provide more information on boundary layer characteristics including heat transfer and turbulence data (Fottner, 1989) for comparison with the numerous Navier-Stokes numerical codes developed over the last years.

Based on these recommendations, the guidelines for the present experiment were established as follows:

- The experimental data should be as reliable as possible and lend themselves to as little criticism as possible. The choice was therefore limited to axial turbine bladings;
- The experimental data should be used for validation of both inviscid and viscous calculation methods. They should provide information on blade velocity distributions, blade convective heat transfer distributions and downstream loss and flow angle evolutions.

The present experimental programme consists of flow periodicity checks by means of wall static pressure measurements and Schlieren flow visualizations, blade velocity distribution measurements by means of static pressure tappings, blade convective heat transfer measurements by means of platinum thin films, downstream loss coefficient and exit flow angle determinations by using a new fast traversing mechanism and freestream turbulence intensity and spectrum measurements. These different measurements have been performed for different combinations of the freestream flow parameters looking at the relative effects of Mach number, Reynolds number and freestream turbulence intensity on the aerodynamic blade performance and blade convective heat transfer.

A preliminary set of results was presented during the Lecture Series on 'Numerical Methods for Flows in Turbomachinery' (Arts et al, 1989) held at the VKI in May 1989, and compared to the numerical predictions provided by a number of participants. The complete, detailed measurement results are available upon request.

**EXPERIMENTAL APPARATUS**

Description of the facility

The present experimental investigation was carried out in the von Karman Institute Isentropic Light Piston Compression Tube facility CT-2 (Fig.1). The operating principles of this type of wind tunnel were developed by Jones et al (1973) and Schultz et al (1978) about 15 years ago. The VKI CT-2 facility, constructed in 1978, is basically made of three main parts: a 5 meters long and 1 meter diameter cylinder, the test section and a downstream dump tank. The cylinder contains a light weight piston driven by the air from a high pressure reservoir (150...250 bar). The cylinder is isolated from the test section by a fast opening "shutter" or slide valve. As the piston is pushed forward, the gas located in front of it is almost isentropically compressed until it reaches the requested pressure, and hence temperature, levels. The valve is then opened, allowing the pressurized and heated gas to flow through the test section, providing constant freestream conditions, i.e. total temperature, pressure and mass flow, until the piston completes its stroke. The freestream gas total conditions can be varied between 300 and 600 K and 0.5 and 7 bar. The 15 m³ downstream dump tank allows exit static pressure adjustments between 0.15 and 3 bar. This provides an independent selection of both Mach and Reynolds numbers. The typical test duration is about 400 ms. Air is used as working fluid. Further details about the VKI CT-2 facility have been described by Richards (1980) and Consigny and Richards (1989).

**Fig. 1: VKI CT-2 facility**

Description of the model

The different measurements described in the present contribution were carried out on a high pressure turbine nozzle guide vane profile especially designed for this purpose at the von Karman Institute. The blade shape was optimized for a downstream isentropic Mach number equal to 0.9 by means of an inverse method, developed at VKI by Van den Braembussche et al (1989). The blade profile is plotted in figure 2 whereas its coordinates are listed in table 1. The blade was mounted in a linear cascade, made of 5 profiles, i.e. 4 passages. The central blade was instrumented either for static pressure measurements (blade velocity distributions) or for heat flux measurements (blade convective heat transfer distributions). The inlet flow angle to the cascade is 0 deg. The most important geometrical characteristics of the cascade are summarized as follows:

- \( c \) : 67.647 mm
- \( g/c \) : 0.850
- \( \gamma \) : 55.0 deg (from axial direction)
- \( o/g \) : 0.2597
- \( r_{LE}/c \) : 0.061 (evaluated around stag. point)
- \( r_{TE}/c \) : 0.0105

**Fig. 2: Geometry of the tested profile**

Measurement techniques

Freestream total pressure and temperature, static pressure and turbulence intensity were measured 55 mm (x/c₇₅ = -1.487) upstream of the leading edge plane, respectively by means of a Pitot probe, connected to a variable reluctance Valdyne differential pressure transducer, a small type K thermocouple probe, wall static pressure tappings connected to National Semi Conductor differential pressure transducers and a constant temperature hot wire probe. Wall static pressure tappings were also installed downstream of the cascade, in a plane parallel to the trailing edge plane and located 16.0 mm (x/c₇₅ = 1.433) (measured along the axial chord direction) downstream of the latter. They covered a distance of 130 mm, i.e. a little more than 2 pitches.
to verify the downstream periodicity of the flow and to determine the
exit Mach number to the cascade. Blade velocity distributions were
obtained from 27 static pressure measurements performed along the
central blade profile and referred to the upstream total pressure. The
downstream loss coefficient evolution as well as the exit flow angle
were obtained by means of a fast traversing mechanism, transporting
a Pitot probe over 2 pitches.

Local wall convective heat fluxes were obtained from the corre-
sponding time dependent surface temperatures evolutions, provided
by platinum thin film gauges painted onto the central blade, made
of machinable glass ceramic. The wall temperature/wall heat flux
conversion was obtained from an electrical analogy, simulating a one
dimensional semi-infinite body configuration. A detailed description
of this transient measurement technique has been presented by Schultz
and Jones (1973). The convective heat transfer coefficient  used in
this contribution is defined as the ratio of the measured wall heat
flux and the difference between the total freestream and the local wall
temperatures. It is also worth mentioning that the heat transfer
measurements discussed in the present paper describe a spanwise av-

eraged behaviour as the different thin films were about 20 mm long,
but nevertheless situated only in the clean flow region.

Freestream turbulence generation

One of the important parameters considered in this investigation
is the freestream turbulence. The complete definition of this pa-

ter is not only involves its intensity but also its spectrum. These
measurements were rather difficult to perform in the CT-2 facility be-
cause of the nature of the flow, i.e., an abrupt establishment of a high
speed hot stream, leading to some difficulties in the calibration pro-
dure of the hot wire probe. The freestream turbulence was generated
by a grid of spanwise oriented parallel bars ($d = 3$ mm; $s/d = 4$). The
turbulence intensity was varied by displacing the grid upstream of the
model: a maximum of 6% could be obtained. The natural turbulence
of the facility is about 1%. The turbulence intensity quoted in this
contribution is defined as:

$$Tu_{\infty} = \frac{\sqrt{u'^2}}{U}$$

and was measured using a VKI manufactured constant temperature
hot wire probe. The frequency response of this part of the measure-
ment chain was observed to be of the order of 10 kHz.

In order to measure the freestream turbulence spectrum, the raw
signal of the hot wire probe was processed by means of a Fast Fourier
analysis. A typical example is shown in figure 3. This result is repre-
sentative of a 4% turbulence intensity. Discrete peaks are observed at
5.5 and 11 kHz. In order to investigate the nature of this phenomenon
and to determine if it could have any influence on the boundary layer
development, a microphone was mounted inside of the test section.
The fluctuating component of the output signal was also processed
by a Fast Fourier Transform. This analysis revealed the existence of
peaks similar to those from the hot wire signal. Therefore they are
obviously of acoustic nature. The information accumulated on this
subject up to now seems to indicate that no effect on the boundary
layer development is expected from those frequencies. Further inves-
tigations on this subject are currently underway at the VKI for high
speed as well as low speed flows.

Data acquisition system

All pressure, temperature and heat flux measurements were di-
rectly acquired by a VAX 11/780 computer by means of a VKI manu-
ufactured 48 channel data acquisition system through a direct memory
access principle. The analog ($\pm 0.5$ V) signals were digitized using
12 bits words. For the present measurements, the sampling rate was
selected to be 1 kHz for pressure, temperature and heat flux mea-
surements and 25 or 50 kHz for turbulence intensity and spectrum
measurements.

Measurement uncertainty

The uncertainty on the various measured quantities was carefully
evaluated and led to the following error bars, based on a 20:1 con-
fidence interval. The uncertainty on pressure measurements was of
the order of $\pm 0.5\%$, on temperature measurements of the order of
$\pm 1.5$ K, on the heat transfer coefficient of the order of $\pm 5\%$, on the
integrated loss coefficient of the order of $\pm 0.2$ points and on the exit
flow angle of the order of $\pm 0.5$ deg.

TEST CONDITIONS

The test programme was built up by varying the freestream con-
ditions according to the following limits:

$$\begin{align*}
T_{\infty} & : 420 \text{ K} \\
M_{2,\infty} & : 0.70 \ldots 1.10 \\
Re_{5,\infty} & : 0.5 \times 10^6 \ldots 2.0 \times 10^6 \\
Tu_{\infty} & : 1.0 \ldots 6.0 \% 
\end{align*}$$

The different flow conditions were defined by all possible combinations
of these parameters. All the tests were conducted at least 2 times to
verify the repeatability of the results.

PERIODICITY OF THE FLOW

In order to correctly model the flow in a cascade, one must en-
sure periodic inlet and outlet conditions. The higher the number of
the blades, the easier it is to establish periodic flow conditions, but
for aerodynamic measurements one generally considers 8 to 10 blades
to be a minimum. In the present experiment, however, the scale of
the blade has been chosen as large as possible to allow a dense instru-
mentation, required by the particular goal of this investigation. As a
result, only 5 profiles, i.e. 4 passages, were used. A careful verifica-
tion of the flow periodicity was therefore absolutely necessary. Dis-
tributions of the downstream wall static pressure were measured and
Schlieren flow visualizations were performed for different exit Mach
and Reynolds number values. The effect of turbulence intensity was not considered; the measurements were conducted without turbulence grid (Tu = 1 %).

The downstream static pressure measurements were performed in a plane parallel to the trailing edge plane, located at x/c = 1.433. The different pressure tappings, located 5 mm from each other, covered 130 mm, i.e. a little more than 2 pitches. Each tapping was connected to a National Semi Conductor differential pressure transducer; the low pressure port of the latter was connected to a vacuum pump to allow a continuous calibration of the system. In order to correctly calculate the downstream flow Mach and Reynolds numbers, the upstream total pressure and temperature were also measured (see section 2.3). The frequency response of the pressure instrumentation was of the order of 150 Hz; the sampling rate was set at 1 kHz. All tests were performed for an upstream total temperature of about 420 K. The useful testing time was of the order of 450 ms. The results are presented as isentropic downstream Mach number distributions versus a coordinate measured along the pitch, towards the lowest profile of the cascade and basically capturing the wakes of blades 3 (the central profile of the cascade) and 4. From these results the averaged exit isentropic Mach number of the cascade was calculated. Based on these measurements, the flow proved to be reasonably periodic for M2,i up to 1.15, as can be seen e.g. from figure 4. Similar measurements were repeated for different downstream Reynolds numbers ranging from 5.0 10^6 to 2.0 10^6; they provided the same conclusions.

**Fig.4 : Downstream static pressure measurements**

Flow visualizations were obtained in the transonic regime from a single pass Schlieren system. Figures 5 and 6 present typical results obtained for M2,i = 1.03 and Re2,i = 10^6 and 2.0 10^6 respectively. Profiles 3 (the central profile of the cascade) and 4 are shown on these pictures. The spark was initiated about 150 ms after the beginning of the test, to be sure that the flow was correctly established in the cascade. A normal shock is observed on the rear part of the suction side; no definite separated flow regions can clearly be identified for any value of the Reynolds number. These visualizations confirm the periodic character of the downstream flow. For values of M2,i in excess of 1.2, however, the flow periodicity deteriorates very quickly. Additional measurements are presently underway to overcome this difficulty by modifying the downstream tailboard arrangement.

**Fig.5 : Schlieren visualization**

M2,i = 1.03, Re2,i = 10^6

**Fig.6 : Schlieren visualization**

M2,i = 1.03, Re2,i = 2.0 10^6

**BLADE VELOCITY DISTRIBUTIONS**

Blade isentropic Mach number distributions were obtained for different loadings from local static pressure measurements, referred to the upstream total pressure. The central blade of the cascade was therefore replaced by a similar profile equipped with 27 static pressure tappings, each of them connected to a National Semi Conductor differential pressure transducer; the low pressure ports were again connected to a vacuum pump to allow a regular verification of the calibration characteristics. The uncertainty on the measurements, the frequency response of the measurement chain and the sampling rate have been quoted in sections 2.6 and 4. The repeatability of the results was verified and proved to remain within 0.5 %. The influence of freestream turbulence intensity and Reynolds number on the blade velocity distributions were not considered at this stage. All tests were performed for an upstream total temperature of about 420 K. The useful testing time was of the order of 450 ms. Typical measurement results are presented in figure 7. They are plotted as an isentropic Mach number evolution in function of a reduced coordinate (s/c) measured along the profile surface, starting from x/c = 0. Starting from this theoretical stagnation point, the flow steeply accelerates along the suction side up to s/c = 0.3. A
small plateau (s/c = 0.35 ... 0.40) is followed by a reacceleration. For the lowest exit Mach number (M2,i = 0.875), the velocity distribution is then rather flat with a weak adverse pressure gradient starting from s/c ≈ 0.75. Let us remember that the blade was initially designed and optimized for about this value of the exit Mach number. For the higher exit Mach number (M2,i = 1.02), the flow accelerates up to s/c ≈ 0.85 ... 0.95. A shock is then observed (s/c = ... 1.05 ... ); this position is consistent with the one deduced from the Schlieren pictures. The velocity distribution along the pressure side varies smoothly, with no existence of a velocity peak downstream of the leading edge.

These measurements were compared to the results obtained from a two dimensional inviscid prediction code (Arts, 1982), based on a time marching integration technique and a finite volume discretization method. For a subsonic exit Mach number, the calculated results nearly match the measured data (Fig. 7). For transonic exit Mach numbers, only small differences are observed.

Fig. 7: Blade velocity distributions

BLADE HEAT TRANSFER DISTRIBUTIONS

Blade convective heat transfer distributions were obtained for different Mach and Reynolds numbers and freestream turbulence intensities by means of 45 platinum thin films, painted on a machinable glass ceramic blade replacing the central profile of the cascade. The frequency response of the measurement chain associated with the thin films (gauges, analogs, amplifiers) is far above 1 kHz. The sampling rate was selected to be 1 kHz, and the signals were filtered at 800 Hz. The useful testing time was of the order of 300 ms. The repeatability of the results was verified and proven to remain within 1%. All tests were performed for an upstream total temperature of about 420 K. The different results are presented on figures 8 to 14 under the form of a heat transfer coefficient distribution (W/m²/K, see section 2.3) versus a length (mm) measured along the suction and pressure sides of the blade, starting from the theoretical stagnation point (x/c* = 0).

Influence of freestream turbulence

The influence of freestream turbulence is presented on figures 8 to 14 for 3 different Mach and Reynolds numbers. The turbulence intensity was varied between 1.0 and 6.0%. At low Reynolds numbers (Fig. 8, 9), Tu∞ mainly affects the laminar part of the boundary layer. After having reached relatively high values in the region of the leading edge, the heat transfer falls quite rapidly on either side of the blades: this behaviour corresponds to the development of a laminar boundary layer. The level of heating is slightly but distinctly increased by increasing Tu∞; this effect is however less important than at the stagnation point. Similar results were obtained for constant pressure and accelerating laminar boundary layers developing on a flat plate (Smith and Kuethe, 1966). For the lowest Mach number (M2,i = 0.92) (Fig. 8), the position of the transition onset (s = 62 ... 68 mm) on the suction side does not seem to be greatly affected by Tu∞. For the highest Mach number (M2,i = 1.12) (Fig. 9), the boundary layer transition starts at the shock position (s = 71.0 mm). These measurements confirm the shock location observed from the Schlieren pictures and the velocity distributions. Along the pressure side, the boundary layer is most probably in a laminar state.

Similar conclusions are drawn for the intermediate Reynolds number value (Fig. 10, 11, 12), and for the 2 lowest values of Tu∞ (Tu∞ = 1%, 4%). For the highest value (Tu∞=6%) however, the onset of transition is observed earlier along the suction side. This position corresponds to the small plateau observed on figure 7 along the suction side (s/c = 0.36 ; s = 24.0 mm). This phenomenon is not marked for the highest exit Mach number where the acceleration rate is high enough to prevent the onset of transition. The behaviour along the pressure side is rather similar to what has been observed for Re2,i = 5.0 10⁵.

The behaviour of the boundary layer seems to be quite different for the highest value of the Reynolds number (Fig. 13, 14). Along the suction side, it appears that the transition onset is very much influenced by the velocity distribution (Fig. 7). It appears in the present case that this transition is triggered by the first important decrease in velocity gradient. Along the pressure side the boundary layer is much more sensitive to freestream turbulence. It appears that a fully turbulent state is obtained for the highest value of Tu∞.

Influence of freestream Reynolds number

The influence of freestream Reynolds number is deduced by comparing figures 8 to 14. Different Mach numbers and freestream turbulence intensities were considered. The Reynolds number was varied between 5.0 10⁵ and 2.0 10⁶. The first effect of Reynolds number is, as expected, to increase the overall level of heat flux. This seems to be the only significant effect at low turbulence intensity (Tu∞ = 1%). For M2,i = 0.92 the suction side boundary layer transition onset seems to depend only on the velocity distribution, whereas for M2,i = 1.10, the start of transition moves towards the leading edge for the highest value of the Reynolds number. The boundary layer moves gradually upstream with increasing Reynolds number for the two values of the Mach number. For M2,i = 1.1 and Re2,i = 2.0 10⁶, the stabilizing effect of the favourable pressure gradient is clearly observed between s = 25 mm (onset of transition) and s = 40 mm.

Influence of freestream Mach number

The influence of freestream Mach number is deduced by comparing figures 8 to 14. Along the pressure side, the velocity distributions are almost similar. As a result, no significative differences appear in the heat transfer coefficient distributions for a given value of the Reynolds number. The behaviour of the suction side boundary layer is basically a function of the different acceleration rates observed in figure 7.
Fig. 8 : Blade heat transfer distributions
\[ \text{M}_{2,i} = 0.92, \text{Re}_{2,i} = 5 \times 10^5 \]

Fig. 9 : Blade heat transfer distributions
\[ \text{M}_{2,i} = 1.12, \text{Re}_{2,i} = 5 \times 10^5 \]

Fig. 10 : Blade heat transfer distributions
\[ \text{M}_{2,i} = 0.70, \text{Re}_{2,i} = 10^6 \]

Fig. 11 : Blade heat transfer distributions
\[ \text{M}_{2,i} = 0.90, \text{Re}_{2,i} = 10^6 \]

Fig. 12 : Blade heat transfer distributions
\[ \text{M}_{2,i} = 1.07, \text{Re}_{2,i} = 10^6 \]

Fig. 13 : Blade heat transfer distributions
\[ \text{M}_{2,i} = 0.92, \text{Re}_{2,i} = 2 \times 10^6 \]
Numerical predictions

An attempt was made to numerically predict these heat transfer measurements. A two-dimensional boundary layer code "TEXSTAN" (Crawford, 1988) was used for this purpose. This program is based on the classical Spalding-Patankar approach (1967) to compute boundary layer or pipe flows. It uses a finite difference technique to solve, through a streamwise space marching procedure, the simplified two-dimensional boundary layer equations as applied to flows developing along, e.g. a flat wall or in an axisymmetric tube. In the present paper, the modelling of the turbulent quantities was provided through a Prandtl mixing length approach. The initial velocity and enthalpy profiles were determined 0.5 mm downstream of the theoretical stagnation point by means of the analytical solution of laminar flow around a cylinder (Schlichting, 1968). The predictions (full line) are compared with the measurements (open symbols) on figures 8 to 14. This boundary layer code performs rather well as far as laminar boundary layers are concerned, both on the suction side and on the pressure side. The weak point remains the prediction of the suction side transition onset. Attempts were made to use more sophisticated two-equation turbulence models provided into the programme (Crawford, 1985). This led to rather disappointing comparisons. More work should be performed in this area from a transition modelling point of view.

DOWNSTREAM LOSS COEFFICIENT AND ANGLE DISTRIBUTIONS

Although the VKI CT-2 facility was originally designed for convective heat transfer measurements only, it is evident that it would also be extremely attractive for aerodynamic performance measurements, if the problems related to the short running time ... 400 ... ms and the relatively high air temperature of 400 ... 450 K could be overcome. The first problem was solved by designing a fast traversing mechanism, transporting a Pitot probe at a maximum speed of 800 mm/s over at least 2 pitches in a plane parallel to the trailing edge plane. The probe carriage is driven by a pneumatic piston. The traversing speed is controlled by the air supply pressure and choked air bleeds. The position of the probe is measured by a linear variable differential transducer. The frequency response of the complete system was evaluated to be 150 Hz. The second problem was solved by locating the transducer outside of the wind tunnel, taking advantage of the conduction effect in the pneumatic pipe between the head of the probe and the transducer. The probe used with this carriage is a classical total, left/right pressure probe except for the absence of the cone head for the static pressure, which was taken instead from the side wall pressure tapping. The performance and accuracy of the complete system were demonstrated in an earlier paper (Sieverding et al, 1988).

Rigorously constant downstream conditions, imperatively needed for this type of measurements, were ensured downstream of the cascade (even with a closed dump tank) by means of a second sonic throat. The total pressure heads of the upstream and downstream Pitot probes were connected respectively to the high and low pressure ports of a National Semi Conductor differential pressure transducer, providing a direct measurement of \( \Delta p_{01-02} \). The left and right heads of the downstream probe were connected to the two ports of a variable reluctance Valdyine differential pressure transducer, providing a measure of \( \Delta p_{0LR} \), proportional to the exit flow angle. The downstream probe was inclined in such a way to have its head located in the same axial plane \((x/c_x = 1.433)\) as the wall static pressure tappings tapping already described in section 4. The sampling rate was set at 4 kHz to have a sufficient number of points to resolve the wake. The influence of freestream turbulence has not been considered up to now. All tests were performed for an upstream total temperature of about 415 K. The useful testing time was of the order of 250 ms.

Typical examples of measured wakes are shown in figure 15 \((M_{2,ts} = 0.85, 1.0)\). They correspond from left to right to the wakes of blades 2 and 3 (central blade). The resolution of the deepest point of the wake was confirmed by running different tests with the probe blocked at different positions in this wake, i.e. without being influenced by the frequency response of the system. The loss coefficient was defined as follows:

\[
\zeta = 1 - \frac{\nu^2}{\nu_{2,ts}^2}
\]

\[
\zeta = 1 - \frac{1 - \frac{\rho_{2,ts} k_{1s}}{\rho_{01-02} k_{1}}}{1 - \frac{\rho_{01} k_{1s}}{\rho_{01-02} k_{1}}}
\]

Fig.14 : Blade heat transfer distributions

\(M_{2,ts} = 1.09, \ Re_{2,ts} = 2.0 \times 10^6\)

Fig.15 : Measured downstream wakes
The downstream integrated loss coefficient distribution of figure 16 was finally obtained as a function of the isentropic exit Mach number. The uncertainty on this loss coefficient was estimated to be 0.2 points. No significative effects of downstream Reynolds number were observed. The general level of the losses, measured for 1% freestream turbulence, is quite low. This is explained by the late transition observed for all Mach and Reynolds number configurations at low turbulence intensity during the heat transfer measurements. Some more confidence in these results was found when comparing them with a classical boundary layer calculation performed by Happel and Ramm (1989) at MTU, Germany for $M_{2u} = 1.0$. This boundary layer program, based on an integral method, predicted boundary layer losses of the order of 1%. To this number one should add trailing edge losses, evaluated at 0.95%, base pressure losses, almost zero in this particular situation and shock losses, estimated at 0.5%. This reasonable overall estimation is consistent with the measured value.

Because of the lack of a detailed angular calibration of the probe at different Mach numbers, only one result will be presented here (Fig. 16) and compared with the calculated values obtained from the two dimensional inviscid predictions. The uncertainty associated with this angle measurement is most probably of the order of ±0.5 deg. More detailed work on this subject is presently underway.

**SUMMARY - CONCLUSION**

Detailed aerodynamic and convective heat transfer measurements have been obtained on a high pressure turbine nozzle guide vane, looking at the effect of freestream Mach and Reynolds numbers as well as turbulence intensity. The measurements were taken using the VKI short duration compression tube facility and were compared to some extent to the results obtained from in-house available two dimensional inviscid and boundary layer programs.

The aim of this investigation is to provide detailed information about the flowfield in this cascade for operating conditions similar to those observed in real engines in order to allow the evaluation of both advanced inviscid and viscous turbomachinery calculation methods. A complete, tabulated, description of the aerodynamic and heat transfer experimental results is available from the authors upon request.
LIST OF REFERENCES


