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Experimental investigation of the flow field downstream of a plane turbine cascade in transonic flow

by

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Summary

The aerodynamic coefficients of a cascade are mostly evaluated from pressures and flow angles, which are measured in a moderate distance downstream of the cascade. But in some cases, the local flow parameters close behind the cascade are of interest: for the consideration of the flow field at inlet of a rotor following a stator or vice versa, from fluid mechanical reasons as well as from the point of view of noise generation. This goal requires a probe, which allows measurements in a flow field of high pressure gradients. For this purpose, a three-finger probe was designed and calibrated. The paper now describes the measurement of total pressure, static pressure and flow angle in several distances close behind a turbine cascade. Average values are evaluated from these local values by means of the laws of conservation. The flow field is discussed on the basis of these wake flow quantities and of schlieren picture, too. Investigations were carried through in the High Speed Cascade Wind Tunnel at an isentropic Mach number of $Ma_{2th} = 1.00$ and at a Reynolds number of $Re_2 = 5 \cdot 10^5$.

Notation

e_M, u	coordinates of wake traverse
l	blade chord
$Ma_{2th} = f(p_K/p_{o1})$	exit Mach number of isentropic cascade flow

p_o	total pressure
p	static pressure
$q_{2th} = p_{ol} - p_K$	exit dynamic pressure of isentropic cascade flow
$Re_2 = w_{2th}\, l\, \rho_2/\mu_2$	exit Reynolds number
t	blade pitch
$Tu_1 = 100 \sqrt{\overline{w_1'^2}}/w_1$	degree of turbulence
w	flow velocity
β	flow angle
β_S	blade angle
ρ	density
$\Omega = \frac{\rho_2}{\rho_1} \frac{w_2}{w_1} \frac{\sin\beta_2}{\sin\beta_1}$	ratio of axial mass flow densities
μ	dynamic viscosity

Subscripts

1	plane far upstream of the cascade
2u	plane close downstream of the cascade
2	plane far downstream of the cascade
K	tank
th	theoretical, i. e. isentropic cascade flow

Abbreviations

PS	pressure surface
SS	suction surface

1. INTRODUCTION

Cascade research is restricted in many cases to the average flow coefficients: wake traverse measurements are taken in some distance downstream of the cascade, and the local flow parameters are transferred to average values using the laws of conservation. These results are completed by pressure distributions, schlieren observations and boundary layer measurements. However, the local flow values in the vicinity of the blade trailing edge are of interest in some cases. Let us consider the flow through an axial turbomachine, the axial gap between a stator and a rotor is of the order of 20 to 50 % of the blade chord. In this distance, the flow parameters change strongly along one blade pitch, especially in the transonic flow range. Now the rotor inlet flow has to be known from aspects of fluid mechanics, noise and strength as it was mentioned on the AGARD conference of "Unsteady Phenomena in Turbomachinery" [1]. These data can be achieved by theory and by experiment. Anyhow, they should be compared with one another.

These local flow data can be measured downstream of a plane cascade. But most probes do not allow to take measurements in a flow field with pressure gradients in the exit flow direction, because the distance of the individual probe tappings is not constant to the plane of the blade trailing edges. Therefore, a probe was designed, which avoids this disadvange. With this probe, measurements of total pressure, static pressure and flow angle were taken in several distances downstream of a gas turbine cascade.

2. PROCEDURE OF TESTING

The measurements were carried out in the high-speed cascade wind tunnel of the Institut für Aerodynamik, DFVLR Braunschweig (figure 1), [2]. This facility operates in a closed circuit with an open test section.

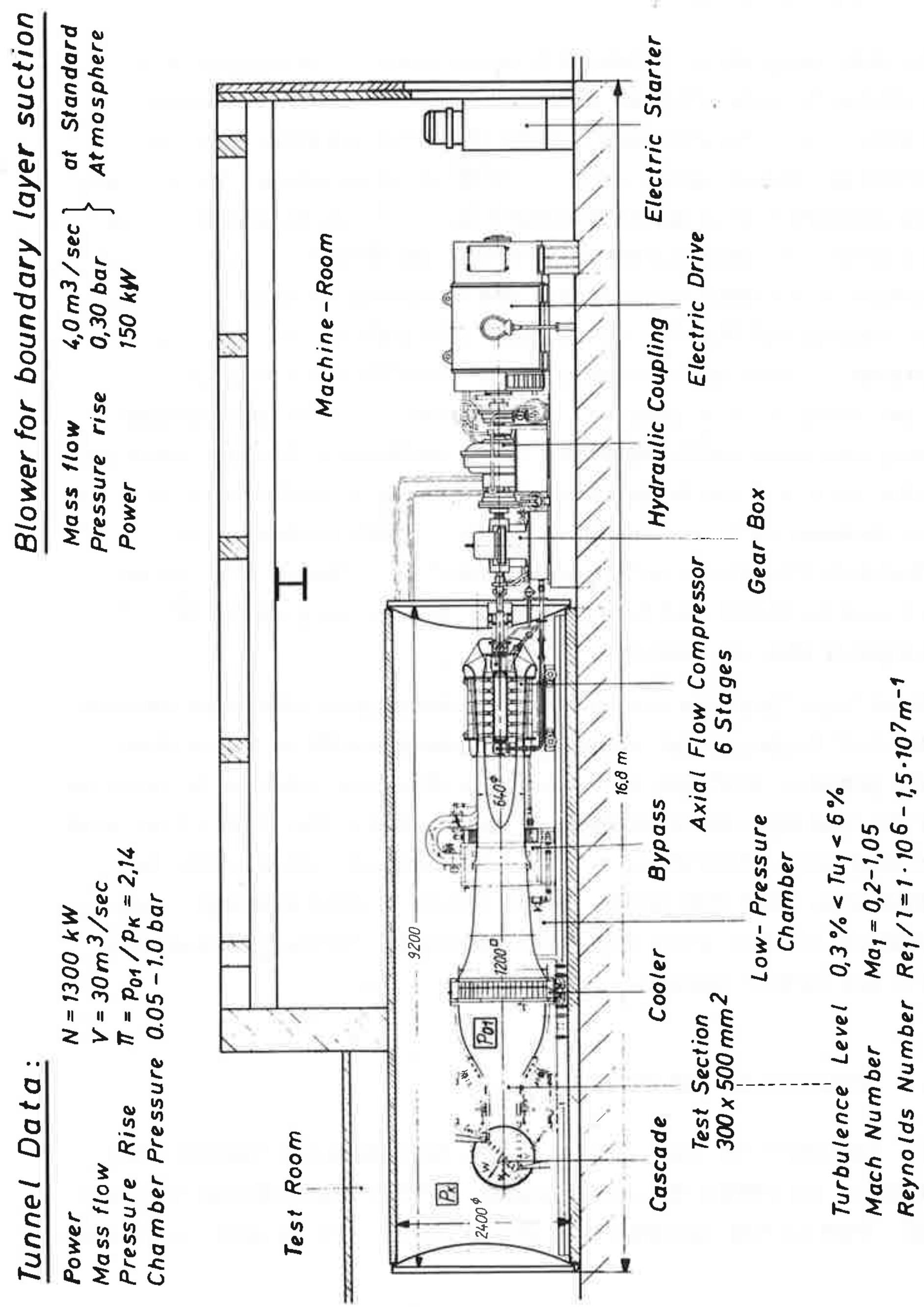

Fig. 1 High Speed Cascade Wind Tunnel

It is installed in a tank whereby the pressure level can be chosen between p_K = 0.05 and 1.0 bar. In that way, the important parameters Mach number and Reynolds number can be varied independently. Investigating a turbine cascade the maximum exit Mach number amounts to Ma_{2th} = 1.05. The Reynolds number ranges more than one decade from $Re/l = 1 \cdot 10^6$ up to $1.5 \cdot 10^7\ m^{-1}$.

The wake traverse measurements were carried through with a three-finger probe (Neptun probe, figure 2). The flow parameters are measured by three separated tubes, so that the distance of all probe tappings to the plane of the blade trailing edges is constant. The ratio of the probe size (60 mm between the outer tubes) to the tunnel width (300 mm) is small enough to ensure that all probe tappings feel the same flow conditions. The arrangement of this probe allows correct measurements in the complete subsonic flow range. Pressure gradients in the circumferential direction u and in the flow direction may occur. Further information about this probe is given in [3]. A similar probe is used at the Lewis Research Center [4].

The local flow values measured downstream of the cascade were transferred to average values of a homogeneous flow using the laws of conservation. The energy equation, the continuity equation and the momentum equations were applied and solved exactly (see J. AMECKE [5]). All parameters are defined in the notation.

The main geometric and flow parameters are given in figure 3. The turbine cascade accelerates the flow from the incompressible state in the axial direction up to the speed of sound. The contour points reaching sonic conditions are known from the blade pressure distribution. The straight line between them is arbitrary. Downstream of it a shock configuration is generated as indicated by the dark areas. This is a result of schlieren observations. The dashed lines show the planes of the wake traverses which will be discussed below. The relation of the wake centre line to the blade was found by the relative probe location.

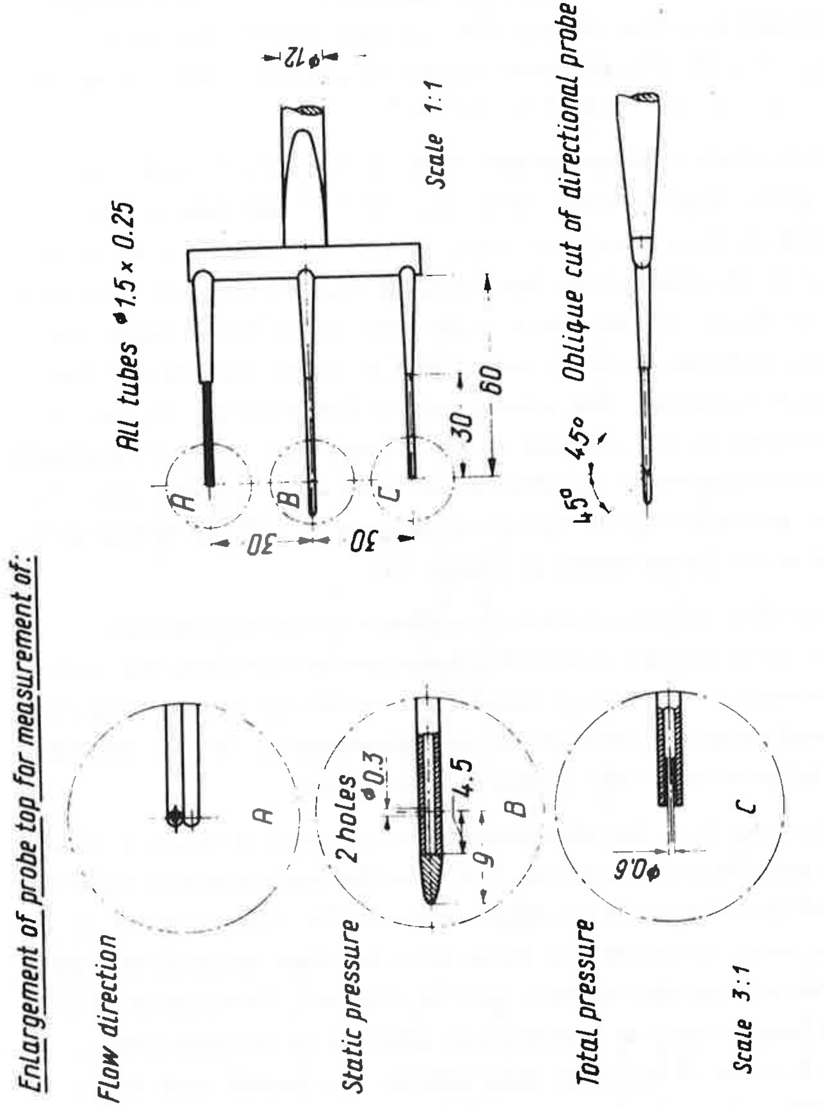

Fig. 2 Neptun probe for wake traverse measurements in 2D-flow

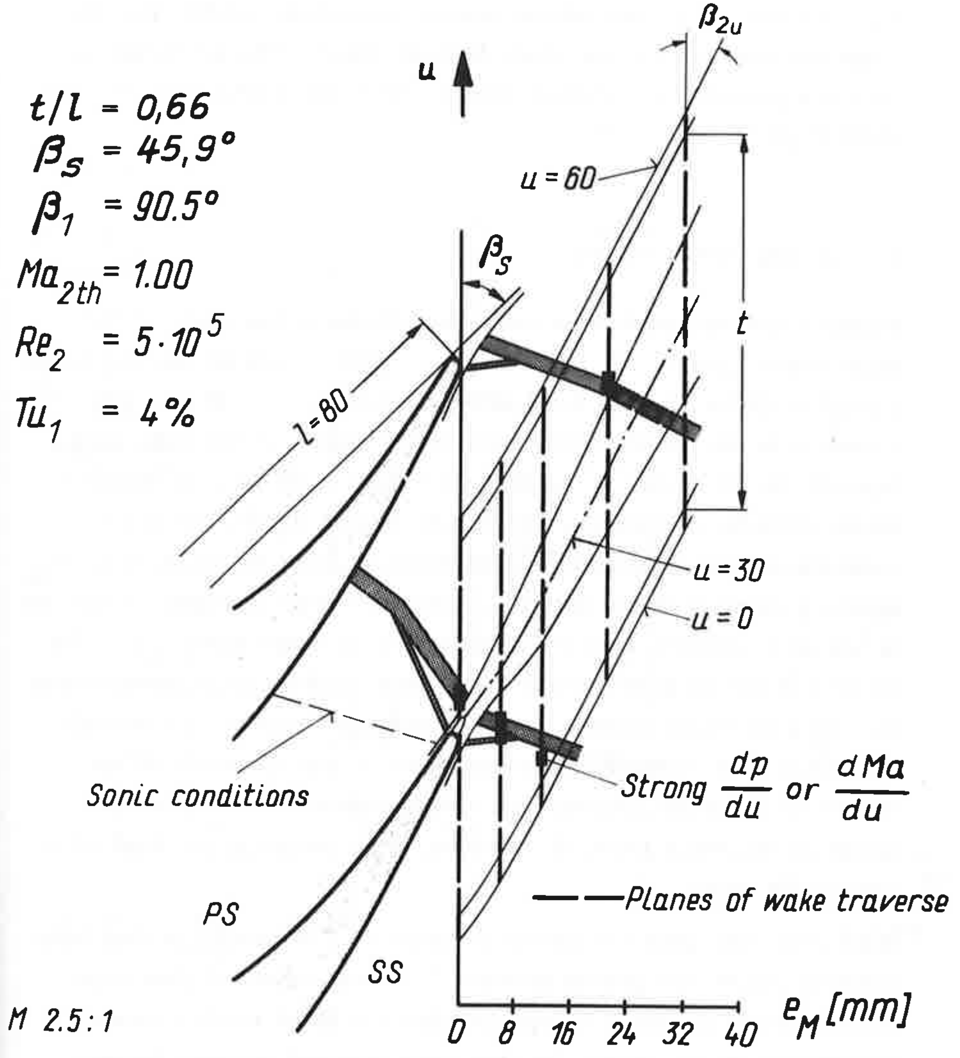

Fig. 3 Flow field downstream of the cascade

The black areas indicate the range of a strong pressure gradient from the wake traverse measurement. The agreement with the shocks from the schlieren observations (density gradients) verified that the probe blockage effects are small in these cases. The schlierens also showed a periodic flow pattern with no reflected shocks from the free shear layer.

3. LOCAL WAKE DATA

Figure 4 demonstrates some local flow values in the plane of the blade trailing edges. All parameters are plotted against the coordinate u parallel to the cascade front along one pitch t · u = 30 mm was chosen to be the centre of the blade or the centre of the wake (next figures). In the region of the blade u = 22 up to 33 mm, no measurements could be carried out, of course. In this figure, the static pressure and the flow angle change strongly along the pitch, e. g. β_{2u} covers a range of more than 10^{o}. Therefore these parameters may not be put as a constant as this has been done in some cases [6]. The location of the jump in pressure and Mach number again agrees fairly well with the shock location from the schlieren picture (u = 34 mm). The figure also contains the pressure which was measured at the tapping in the blade trailing edge. That pressure looks to be the lowest of the whole pitch. It indicates the pressure in the dead water zone of the blade.

Some real wake data are shown in figure 5. The results of four wake traverse planes are plotted abreast: The local values of flow angle (above), static pressure change (middle) and Mach number (below). Downstream of the profile the flow angle changes strongly because the flow is highly accelerated and turned along the suction surface. Acceleration and turning are much lower along the pressure surface.

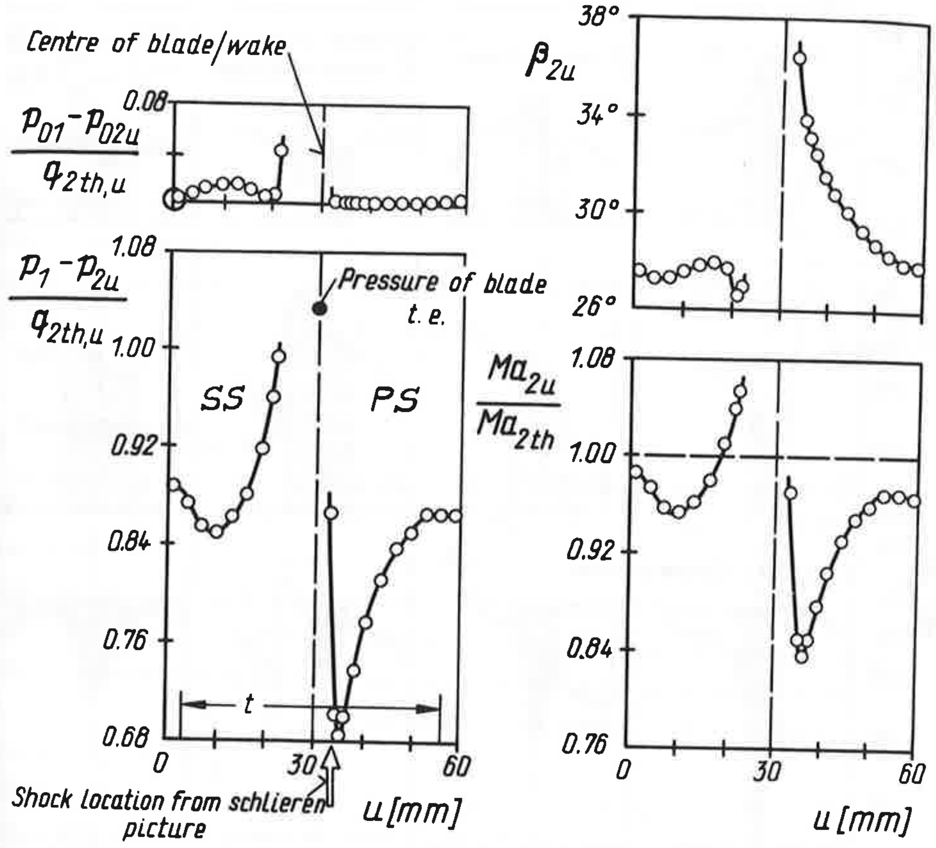

Fig. 4 Local values in the plane of the blade trailing edges, $e_M/1 = 0$

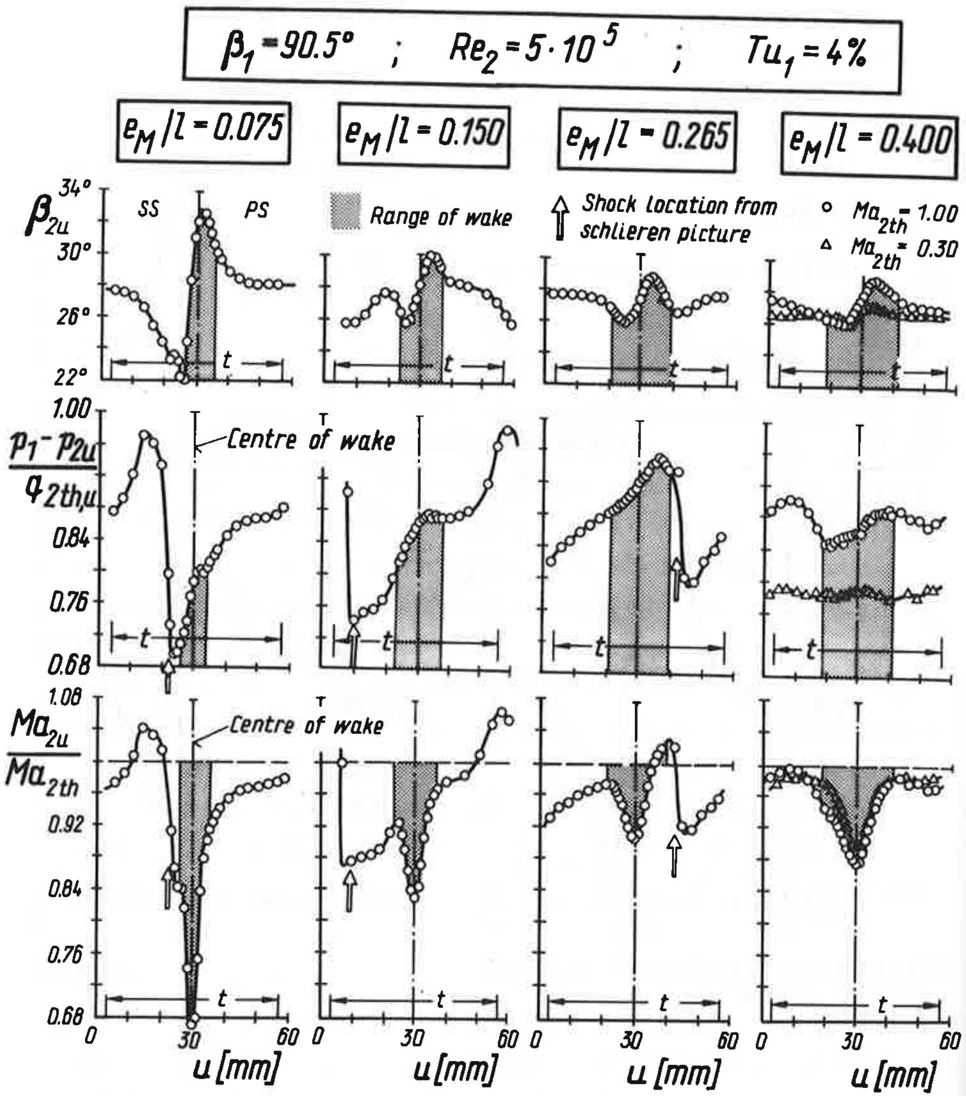

Fig. 5 Local values of flow angle, static pressure change and Mach number downstream of the cascade

From these diagramms it can be stated that the flow is periodically because the local flow values at the begin and at the end of the pitch agree fairly well.

The static pressure as well as the flow angle vary along one pitch even in a distance of 40 % of chord length downstream of the cascade. Moreover, the flow angle changes outside the wake. Since in other cases the flow angle is not measured along the whole pitch the choose of the traverse distance and of the origin of the wake coordinate are important.

The biggest distance investigated here, $e_M/l = 0.400$, is adequate to the normal wake traverse plane. In that plane, an example of lower Mach number is given for comparison. The difference of both wakes is small, i.e. the shocks are not severe.

4. AVERAGE WAKE DATA

The local data discussed above were averaged for a homogeneous flow and plottet over the distance e_M/l in figure 6. The results should be constant in all planes since the laws of conservation have been used, see J. MEYER [7]. First of all, the cascade flow can be denoted as two-dimensional because the ratio of the axial mass flow densities is $\Omega = 1.00 \pm 0.03$ (left lower diagramm). The average static pressure change $(p_1 - p_2)/q_{2th}$ does not change with e_M/l at the low Mach number. But in the high Mach number case, the results at low e_M/l are a bit too low due to the fact that the probe was designed for subsonic flow. In both cases, the static pressure change is 3 % lower than that value which is evaluated with the tank pressure p_K. That means p_2 is higher than p_K. This result can be explained with the distribution of the static pressure in a free jet. H. FIEDLER [8] found that $(p - p_K)/q = 0$ through 0.05 close to the jet exit, i.e. in a distance of $x/D = 0$ through 4, D meaning nozzle diameter. On the

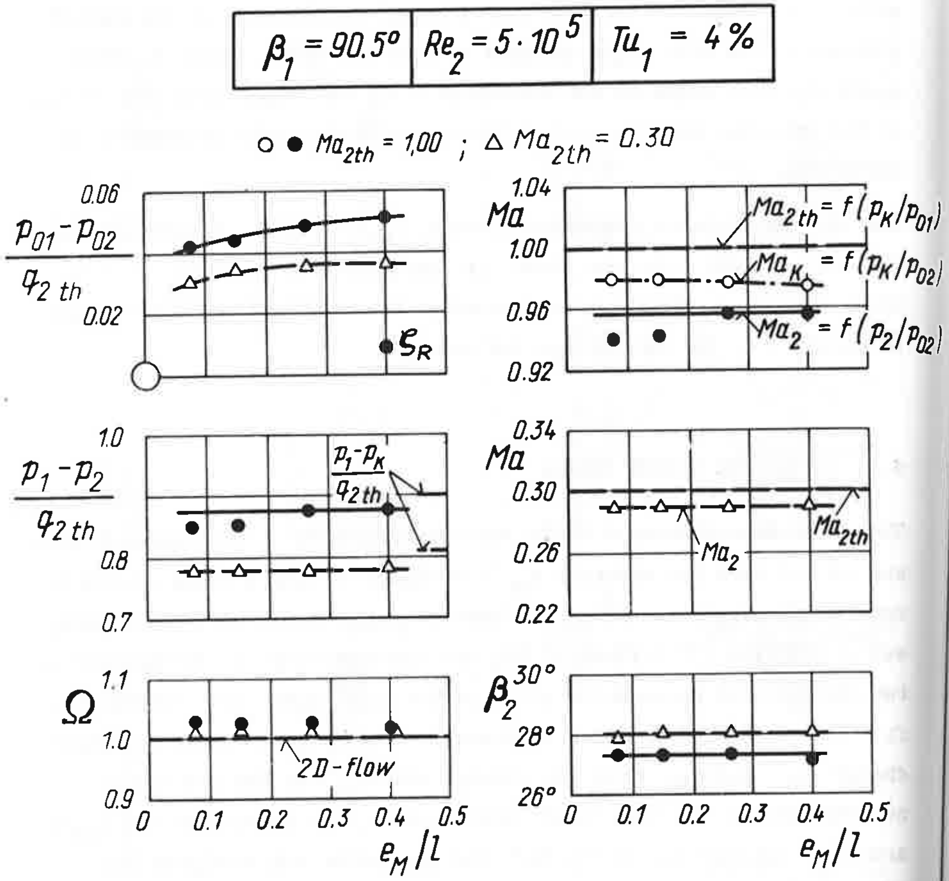

Fig. 6 Average values of flow parameters downstream of the cascade

other side the exit flow energy is unimportant in our case, because the area ratio between cascade exit and tank cross section is 1:100. Hence, the tank pressure level is not increased by the cascade exit flow. These results verify that the back pressure may not be used as mean static pressure for cascade investigations.

The loss coefficient $(p_{o1} - p_{o2})/q_{2th}$ increases with the distance from the cascade, left upper diagram. Both Mach numbers show the same tendency. Mixing losses are included, since the laws of conservation are applied on an area with streamlines as lateral limitations. It is supposed that the results at low e_M/l are too low caused by some assumptions during the data evaluation. According to J. AMECKE [5] the tangential stresses of friction and turbulence have been neglected. However, close to the cascade strong pressure gradients dp/du occur as it is shown in figure 4. Furthermore, the turbulence in the near wake is of high intensity [9]. Therefore, these assumptions should be checked at future investigations as far as they concern traverses close to the cascade.

The tendencies of total and static pressure are reflected in the exit Mach number. The right upper diagram shows Mach numbers of different definitions. The basis is the isentropic Mach number Ma_{2th} = 1.00 depending on back pressure p_K and total inlet pressure p_{o1}. Replacing p_{o1} by the average exit total pressure p_{o2} one gets Ma_K which is 2% lower than Ma_{2th}. If also p_K is replaced by p_2 the average exit Mach number $Ma_2 = 0.96$ is found. The importance of a clear definition and of a correct measurement is quite obvious.

The average exit flow angle β_2 does not change from one traverse plane to the other. Therefore, the angle measurement can be denoted as rather accurate.

5. CONCLUSIONS

Compressor and turbine design requires some knowledge about local flow data along one pitch. For measurements of these near wake data a special probe was developed which allows accurate measurements in flow fields with pressure gradients in the circumferential direction and in the flow direction as far as the flow is two-dimensional in the range of the probe tappings. The local flow values were transferred to those of a homogeneous flow using the laws of conservation.

The main results of the measurements with this probe downstream of a plane transonic turbine cascade may be summarized as follows:

1. Not only the total pressure, but also the static pressure and the flow angle do strongly change along one pitch.
2. Shock location of the schlieren picture agrees fairly well with the range of the high pressure gradient in the wake traverse.
3. The average static pressure of the wake traverse differs from the back pressure by $(p_2 - p_K)/q_{2th} = 3\%$.
4. Average static pressure change and average flow angle are not affected by the distance from the cascade.
5. The loss coefficient increases with the distance due to some assumptions in the evaluating procedure.

6. References

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