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REDUCING SECONDARY LOSSES BY BLOWING COLD AIR IN A TURBINE

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A77-16558

16. Abstract

Experimental investigations are described, the purpose of which is to determine whether local blowing on the profile suction side of the turbine guide wheel blades can be effective in preventing the propagation of secondary flows, that is, casing and hub boundary layers being transported by pressure gradients. Some preliminary results on how the blowing should be accomplished in order to influence the secondary flows in the desired manner are given. The effectiveness of blowing is demonstrated by comparing to performance without blowing. Blowing is also seen to be more effective than using boundary layer slots as far as diminishing losses in the rim zones is concerned.

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# REDUCING SECONDARY LOSSES BY BLOWING COLD AIR IN A TURBINE

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## Introduction

In the case of axial turbine stages with small blades the de-/164-1*
gree of efficiency is considerably affected by the amount of the
losses which can be caused by secondary flows. The creation of
secondary flows is to be attributed to the fact that the casing
wall and hub wall boundary layers coming into the incoming flow of
the turbine are transported by the pressure gradient in the blade
channel to the profile suction side. If the dimensions of the
blades are unfavorable -- small height in relation to the chord
length -- the secondary flows can involve the entire height of the
blade and lead to flow separations on the profile suction sides.

The studies done so far on reducing secondary flows and
losses associated with these in axial turbine nozzles can in
principle be broken down into the following methods:

-- elimination of incoming boundary layers by sucking them
away at the turbine input;

-- affecting the shape of the secondary flows by giving the
blade channel a meridianal cross-section;

-- preventing the casing and hub boundary layers from ex-
tending to the profile suction sides of the turbine blades by
setting up overflow slits, boundary layer fences and grooves.

The sucking away of oncoming casing boundary layers has no
practical importance because of the high expenditure of energy
required for the suction device, which has also been confirmed /164-2
in experimental studies by Prümper [1]. By contrast, the second
method listed above has found industrial application. Measure-

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* Numbers in the margin indicate pagination in the foreign test.

ments on smooth turbine nozzles with a small blade height, in which the exterior casing wall in the rear region of the blade channel is tapered asymmetrically, show that in this way the secondary flow losses can effectively reduced [2]. Overflow slits, i.e., connections from the profile pressure side to the profile suction side in the region of the casing wall or hub wall have proved to increase the amount of loss when used in turbine guide vanes [3]. Extensive experimental studes which were carried out by Prümper [3 and 4] at the Institute for Jet Propulsion and Turbomachines, RWTH [Rheinisch-Westfälische Technische Hochschule], Aachen, has shown that with the arrangement of boundary layer fences and boundary layer grooves on the profile suction sides in a region of the casing wall and hub wall a considerable reduction in secondary flow losses can be achieved, whereby the best results are obtained with the use of grooves. Similar investigations by Sieverding [5] on turbine guide vanes with boundary layer fences and grooves are well known.

The design of hot gas turbine blades with sharp-edged boundary layer fences or with grooves in the form of sharp-edged milled slots can cause operational problems because of possible overheating of edges. Therefore in 1975, with the support of the special research branch, 83 experimental studies on an axial turbine stage were begun whose purpose is, by means of locally blowing air onto the profile suction sides of the turbine guide vanes to prevent secondary flows from spreading out, as in the case of grooved blades, and thus reduce the secondary flow losses. The basic idea here is that in the practical application of this method for internally cooled hot gas turbine blades a portion of the cool air can be used to blow on the profile suction side. In the following discussion are presented results of the ongoing studies which should show how the blowing can be accomplished to affect the secondary flow and which limiting quantities are to be borne in mind.

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## 2. Experimental setup

The experimental studies are carried out on a one-stage axial cold air turbine which is acted upon by compressed air. This is a stage with a low degree of reaction. A sectional view of the construction of the turbine stage shown in figure 1. The turbine can be fitted with blades with a variable hub ratio. For the present studie" a hub ratio $\nu = 0.9$ was chosen with a ratio of blade height to the chord length of the turbine guide wheel $h/l = 0.239$. This presents an extreme case with respect to the formation of secondary flows in the turbine.

Additional dimensions of the turbine stage and data on the geometrical layout of the blade are listed in figure 2. In addition, from this figure one can obtain the location of the measuring planes in the oncoming flow of the turbine (plane 0), between the stator blade and the rotor blade (plane 1) and in the outcoming flow of the turbine (plane 2). This figure also shows the terms for the corresponding flow dimension data.

The compressed air for lowing out the turbine guide vanes is blown into a separate measuring section provided with a flow meter for measuring the amount of blown air.

## 3. Secondary flow in an unmodified turbine guide wheel

The formation of secondary flows in a turbine nozzle depends basically on the velocity distribution or boundary layer thicknesses in the oncoming flow and on the pressure gradient in the blade channel. The size of the latter is in turn determined by the shape of the profile, the deflection of the main flow in the cascades, the relative cascade spacing $t/l$ and the Mach Number of the Primary Flow. In the present experiments the geometry of the turbine blades was not changed, while the outflow Mach number of

the turbine cascades

$$M_{c1} = \frac{c_1}{\sqrt{k\ R\ T_1}}$$

was varied as the main parameter in the range of $M_{c1} = 0.3 + 0.9$. /164-4

The velocity distribution in the incoming flow was determined by means of hot-wire anemometer measurements.

The velocity distribution in the incoming flow (measuring plane 0) is shown in figure 3 for the case of an average outflow Mach number $\overline{M}_{c1} = 0.49$. For the Reynolds number in the oncoming flow one obtains a value $Re_0 = 1.8 \times 10^5$, whereby 2h (with h = the height of the channel or blade height) is used as the characteristic length. The degree of turbulence Tu is 0.91% according to the following definition:

$$Tu = \frac{1}{\overline{c}}\ \sqrt{\overline{c'^2}}$$

with $\overline{c}$ = fluctuation velocity with isotropic turbulence
and $\overline{c}$ = main velocity of the stationary flow.

The relative thickness of the boundary layer δ/h and the relative displacement thickness δ'/h are determined from the measured velocity distributions as the characteristic quantities of the boundary layers on the casing wall and respective hub. The boundary layer thickness δ was evaluated according to the usual definition of the distance from the wall in which the local velocity assumes the value c = 0.99 c∞. The displacement thickness δ' is determined according to the following definition:

$$\delta^* = \int_0^{\overline{\phantom{a}}} (1 - \frac{\overline{c}}{\overline{c}})\ .\ dh$$

From the values given in figure 3 for the boundary layer thicknesses and the displacement thicknesses we see that the boundary layer on the hub is considerably thinner than that on the casing wall. This difference in boundary layer formation is related to

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the heterogeneity of the oncoming flows on the hub and on the casing wall.

Figure 4 shows the average outflow Mach number $\bar{M}_{c1}$ = 0.487 for the curve of measured wall pressure distributions in the central section for the pressure side and suction side of the turbine guide wheel profile. The local wall pressure p was here related to the total pressure $p_{t0}$ of the oncoming flow. To distinguish the cascade flow the accompanying Reynolds number $Re_1$ is given for all measurements. The Reynolds number $Re_1$ is formed by the variables of state or flow in plane 1 and by chord length 1.

The losses in the case of various shapes of secondary flows in the turbine guide wheel are determined by means of total pressure measurements in plane 0 and in the plane between the guide wheel and the rotor (plane 1). On the basis of these measurements and with the help of a so-called contour line program the lines of an equal pressure ratio in the form of $p_{t1}$ - $p_a$ / $p_{t0}$ - $p_a$ (with $p_a$ the reference pressure) were calculated and plotted over a scale. Figure 5 shows such a representation of the total pressure distribution in the outflow plane of the turbine guide wheel.

The areas of increased loss in the outflow on the suction side due to secondary flows can easily be seen. It is found that nearly the entire height of the blade is affected by the casing boundary layers and hub boundary layers flowing over the suction side.

4. Design of guide vanes with blown air

The basic idea in the design of turbine guide blades in conjunction with blown air is to achieve a blocking effect, as in the case of blades with boundary layer fences or grooves, with

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respect to the spreading out of secondary flows on the profile suction side by correct positioning of the blow holes. Therefore the blow holes were located in the region near the wall based on the optimal dimensions for boundary layer grooves specified in [4], since the same blade profile was also used. Figure 6 shows a comparison of turbine guide blades with blow holes and with boundary layer grooves. The blow holes were arranged at three different distances from the rear edge and at various distances from the <span>/164-6</span> casing wall and hub wall ($a_o$ and $a_u$ respectively). Of the many possible blade configurations with blow holes e'... blade configurations (A to H) were selected to represent tendencies with respect to the effect of secondary flows as a function of the design parameter of the blow holes. Table 1 shows the respective arrangement of the blow holes in the guide blade configurations discussed below.

Table 1

| Schaufelkonfiguration A | B Lage der Bohrungen ($\emptyset$ = 1.1) | | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| | $l_1 = 70$ | | $l_2 = 50$ | | $l_3 = 30$ | |
| | $a_o$ | $a_u$ | $a_o$ | $a_u$ | $a_o$ | $a_u$ |
| A | 1.8 | 1.5 | - | - | - | - |
| B | 2.0 | 2.0 | - | - | - | - |
| C | - | - | 2.0 | 2.0 | - | - |
| D | - | - | - | - | 2.0 | 2.0 |
| E | - | - | 4.0 | 3.0 | - | - |
| F | - | - | 3.0 | 2.0 | - | - |
| G | - | - | 1.8 | 1.5 | - | - |
| H | 1.8 | 1.5 | 1.8 | - | - | - |

Maße in mm C

Key:

A. Blade configuration

B. Location of holes

C. Measurement in mm

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Figure shows a turbine guide blade with six blow holes on the profile suction side. The blow holes are placed in such a way with respect to the direction of the outcoming flow that as gentle a flow as possible along the profile surface was achieved -- insofar as possible with a given construction and strengthening conditions.

The total amount of air blown out of a turbine guide blade $m_L$ is related to the primary mass flow $\dot{m}_G$ passing through the corresponding blade channel and is represented as a percentage:

$$p = \frac{\dot{m}_L}{\dot{m}_G} \cdot 100 \ [\%]$$

However, it is to be noted here that the parameter p is only conditionally transferable, since with an equal absolute amount of blown air nearly the same blockage effect with respect to secondary flows can be achieved with larger blade heights.

## 5. Results of the studies with blown air

Figure 8 shows the effect of blowing air on the total pressure distributions in the outcoming flow of the turbine guide wheel. This compares the corresponding total pressure distributions for the guide vane without air blown on it and for a guide vane with air blown on it according to configuration A for various blade heights expressed in percentages. Whereas by blowing an amount of air of p = 1.9% a good blockage effect could be achieved together with a loss reduction in the range of h = 40% and 25%, only a small improvement between h = 50% and 70% can be found in the upper blade range. From the comparison of boundary layer thicknesses on the hub and on the casing wall based on figure 3 it follows that in the upper blade range the amount of air blown out is too small to achieve a similar blockage effect as on the hub.

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Typical for all measure to reduce secondary flows by means of boundary fences, grooves, or, in this case, blowing air is the increase in loss in the marginal zones. This phenomenon can also be seen from the distributions shown in figure 8.

The effect of blowing air can be illustrated by a visualization of the wall flow lines on the profile suction sides of the turbine blades. Figure 9 shows photographs of the rear portion of the profile suction side of turbine guide blades with and without the blowing of air, seen from the down stream side. The visualization is accomplished by means of a white film of oil which was sprayed onto the blades. In the case in which air is blown onto the blades a displacement of flow lines towards the wall is clearly recognizable.

Figure 10 shows the distribution of the exit angle of the $\alpha_1$ of the turbine guide field over the periphery of blades of various heights expressed in percent for the turbine guide blades with and without air blown on them and with the same outflow Mach number $\overline{M}_{c1}$. A small change in angle due to the blown air was detected only in the regions close to the wall. <u>/164-8</u>

For the effect of blowing air with respect to reducing secondary flow losses the selection of the location of the blow holes on the profile pressure side is of critical importance. In order to better evaluate the blade configurations under consideration the cascade loss coefficient $\zeta_T$ was determined from the measured total pressure distributions and plotted over the blade heights expressed in percent. In determining the cascade loss coefficient $\zeta_T$ the following definitions or equations were used:

$$\zeta_T = 1 - \frac{\dot{m}_G \cdot \overline{c}_1^{\,2}}{\dot{m}_G \cdot c_{1sG}^{\,2}}$$

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or
$$\zeta_T = \left[ \frac{1}{\frac{k-1}{k+1} \, M_{1s}^*} - 1 \right] \left[ \frac{1}{\pi_G^{\frac{k-1}{k}}} - 1 \right]$$

with $\Pi_G = \dfrac{p_{t1}}{p_{t2}}$ as the average total pressure loss

and $M'_{1s}$ = isentropic critical Mach number in plane 1.

With larger percentage amounts of blown air the added kinetic energy of the blown air $\dot{m}_L \cdot c_L^2$ is also to be taken into consideration in the equation for determining the cascade loss coefficient [6]:

$$\zeta_T' = 1 - \frac{(\dot{m}_G + \dot{m}_L) \, \bar{c}_1^2}{\dot{m}_G \, c_{1sG}^2 + \dot{m}_L \cdot c_L^2}$$

Figure 11 shows the cascade loss coefficient curve plotted over the percentage blade height for three blade configurations with various blow hole locations on the profile periphery, the distances from the casing or hub being equal. From the corre- /164-9 sponding curves it can be seen that an arrangement of the blow holes as much as possible in the region of the strongest acceleration on the profile suction side (also see figure 4) is to be selected for a favorable effect on secondary flows. If the blow-holes are shifted too far back towards the rear edge, i.e., into an area on the profile suction side which is already completely covered by the secondary flows, there occurs an increase in loss due to the blown air in comparison to the case in which the guide veins are not changed. Such an increase in loss was found for the curve shown for configuration D in the regions at h = 60%, h = 30% and in the vicinity of the hub wall.

Another important parameter for determining the position of the bore holes is the distance from the casing wall $a_o$ and from the hub wall $a_u$. Figure 12 shows the effect of various distances from the wall on the curve for cascade loss coefficient plotted with respect to the blade height. In accordance with the variable boundary layer thickness the distance of the blow hole from the casing wall with these configurations was chosen greater in each case than the distance from the hub wall. From this graph can clearly be seen that in order to achieve a reduction in loss the bore holes must be located at small distances from the wall. If the distances from the wall are too great blowing air onto the blades can cause an increase in loss, as is shown by the curve for blade configuration E.

To interpret the cascade loss distribution as a function of the exit Mach number of the turbine guide wheel the boundary layer development in the oncoming flow for different oncoming flow velocities is referred to. Figure 13 shows the change in boundary thicknesses and in displacement thicknesses on the hub and on the casing wall with a Reynolds number $Re_0$ for the oncoming flow. In addition, this graph also shows the relationship of the Reynolds number $Re_c$ and the exit Mach number $M_{c1}$ of the turbine guide wheel. The curves for the boundary layer or displacement thicknesses show a similar tendency, whereby the values for the casing wall boundary layer are considerably greater. The boundary layer thicknesses at first become smaller with increasing Reynolds numbers and then pick up again starting at $Re_0 \simeq 1.1 \times 10^5$ or $Re_0 \simeq 1.5 \times 10^5$. The shape of this curve is explained by the fact that no completely developed turbulent flow has yet formed in front of the turbine, rather what is involved here are starting flows with variable conditions on the casing wall and on the hub.

In figure 14 the cascade loss distributions with respect to blade heights expressed in percent for four difference Mach num-

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bers are compared for the case of the unmodified turbine blade and for one case with air blown onto the turbine blade. For the guide blade with air blown onto it a configuration with two blow holes in the vicinity of the casing wall and one blow hole next to the hub wall so that, taking into consideration the larger boundary layer thickness on the hub wall, more air would be blown into this area thus achieving a blocking effect or loss reduction equal to that in the vicinity of the hub. The percentage amount of air blown onto the blade was $p \approx 3\%$ for all Mach numbers.

The connection between loss distribution and boundary layer formation shown in figure 13 as a function of the Mach number can be seen from the shift in the relative loss maximum in the blade range $h = 20 - 30\%$ with the Mach numbers $\overline{M}_{c1}$ for the unmodified blade. With larger boundary layer thicknesses in the oncoming flow, as are present in the cases of the smallest and largest Mach numbers $M_{c1}$ in the vicinity of the hub, the relative loss maximum is shifted towards the middle of the blade. Moreover, it is found that the loss reduction due to the blowing of air turns out to be smaller with the presence of greater boundary layer thicknesses, as is shown by a comparison of cascade loss coefficient distributions for $\overline{M}_{c1} = 0.454$ and $\overline{M}_{c1} = 0.659$ or for $\overline{M}_{c1} = 0.280$ and $\overline{M}_{c1} = 0.851$. This example clearly shows the problem of designing guide blades with air blown onto them, namely that it is possible to optimize the geometry of the blow holes with respect to cascade losses only for a limited range of turbine exit Mach numbers. This difficulty turns up in the same way also in designing guide blades with boundary fences or grooves.

## 6. Summary

The results of the studies show that by means of suitably blowing air onto the profile suction sides of turbine guide

blades it is possible to affect the secondary flows and reduce cascade losses.

In conclusion, figure 15 compares the cascade loss distributions for an unmodified guide blade, for a guide blade with air blown onto it and for a guide blade with boundary layer grooves, all under the same flow conditions. The blocking effect both of the blown air and the grooves can be seen with respect to the spreading out of secondary flows, whereby the blown air method seems more advantageous with respect to the development of losses in the marginal zones. Using the blown air technique does not lead to a reduction in turbine guide wheel losses, but as a result of improving the outflow in the central region of the blades it leads to a reduction in guide wheel losses and thus contributes to an effective increase in stage efficiency, in particular of axial turbine stages.

7. References

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5.  Sieverding, C., <u>Education and Research 1956 - 1976</u>    /164-12
    Karman Institute for Fluid Dynamics (VKI), 1976, p. 41

6.  David, O., <u>Einfluß der Hinterkanterform einer Turbinenleit-
    schaufel auf die Profilverluste</u> [The effect of the shape of
    the rear edge of a turbine guide blade on profile losses]
    Report number 74-06 of the Jet Propulsion and Turbo Machine
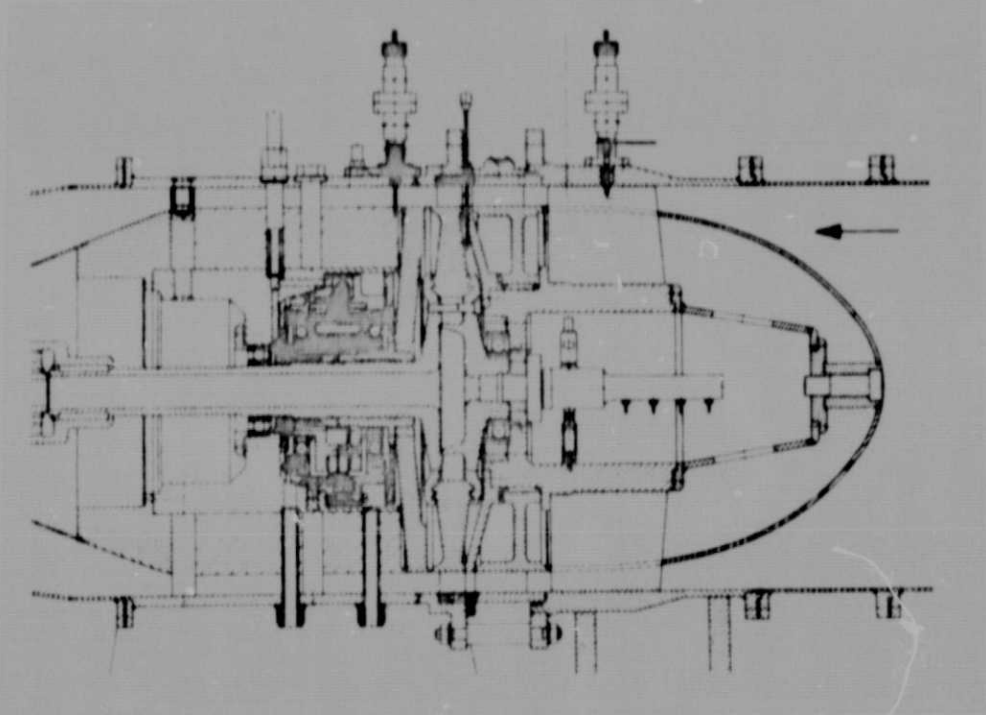    Institute, Rheinisch-Westfälische Technische Hochschule,
    Aachen, June 1974.

Figure 1 - Sectional drawing of a cold air turbine

| | | A Leitrad | B Laufrad |
|---|---|---|---|
| E | Mittl. Durchmesser | 380 mm | 380 mm |
| F | Schaufelhöhe h | 20 mm | 20 mm |
| G | Profilsehnenlänge l | 83,6 mm | 26,3 mm |
| H | Relative Teilung t/l | 0,595 | 0,582 |
| I | Schaufelzahl z | 24 | 78 |
| J | Gitterbreite b | 50 mm | 25 mm |
| K | Geom. Austrittswinkel $\alpha_1'$ | 14° | |
| L | Geom. Eintrittswinkel $\beta_1'$ | | 40° |
| K | Geom. Austrittswinkel $\beta_2'$ | | 156° |

Figure 2 - Characteristic data for the turbine stage

Key:

A. Stator  
B. Rotor  
C. Measuring plane  
D. Measurement data  
E. Average diameter  
F. Blade height  
G. Chord length  
H. Relative spacing  
I. Number of blades  
J. Grid width  
K. Geometric exit angle  
L. Geometric entering angle  

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Figure 3 - Velocity distribution and boundary layer thicknesses in the flow
onto the turbine guide wheel (IE) for an outflow Mach number
$\overline{M}_{c1} = 0.49$

Key:

A. Casing wall                B. Hub

Key:

A. Pressure side
B. Suction side
C. Grid width
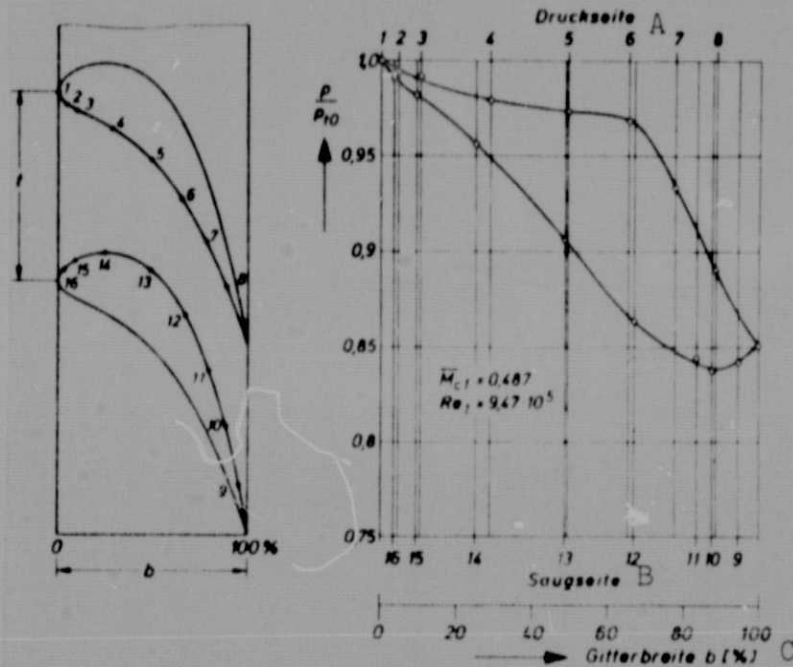


Figure 4 - Pressure distribution for the central section of the turbine
guide blade channel at $\overline{M}_{c1} = 0.487$

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Key:
A. Pressure side
B. Suction side
C. Casing
D. Hub
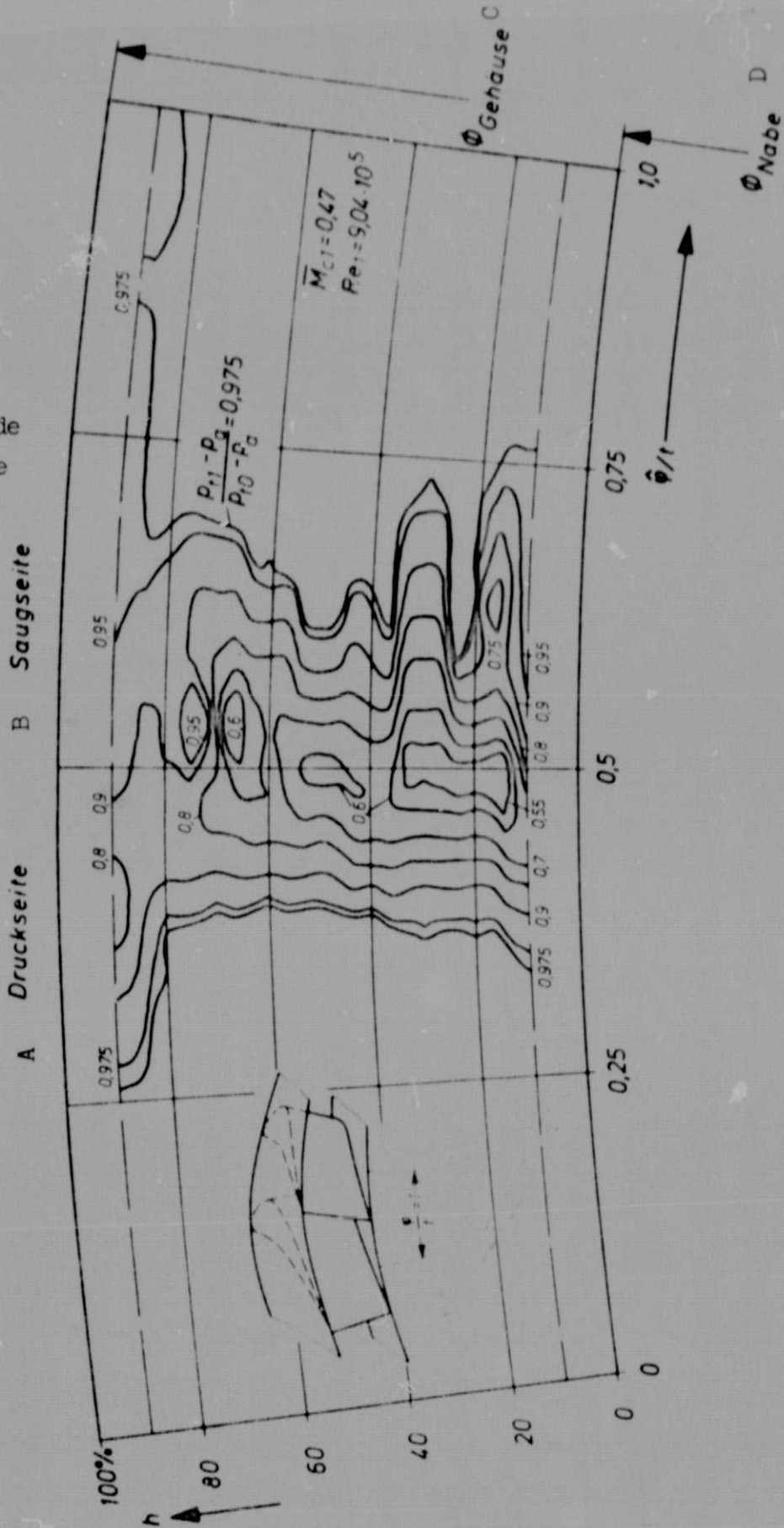
Figure 5 — Pressure distribution in the outflow plane of the turbine guide wheel

Leitschaufel mit Ausblasung    A

Leitschaufel mit Grenzschichtnuten    B

Figure 6 — Location of the blow holes and boundary layer groove dimensions
           according to [2]

Key:

A.  Guide blade with air blown onto it

B.  Guide blade with boundary layer grooves



Figure 7 — Turbine guide blade with bore holes.

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a) Schaufelhöhe h = 10 - 40 % A

b) Schaufelhöhe h = 50 - 90 % A
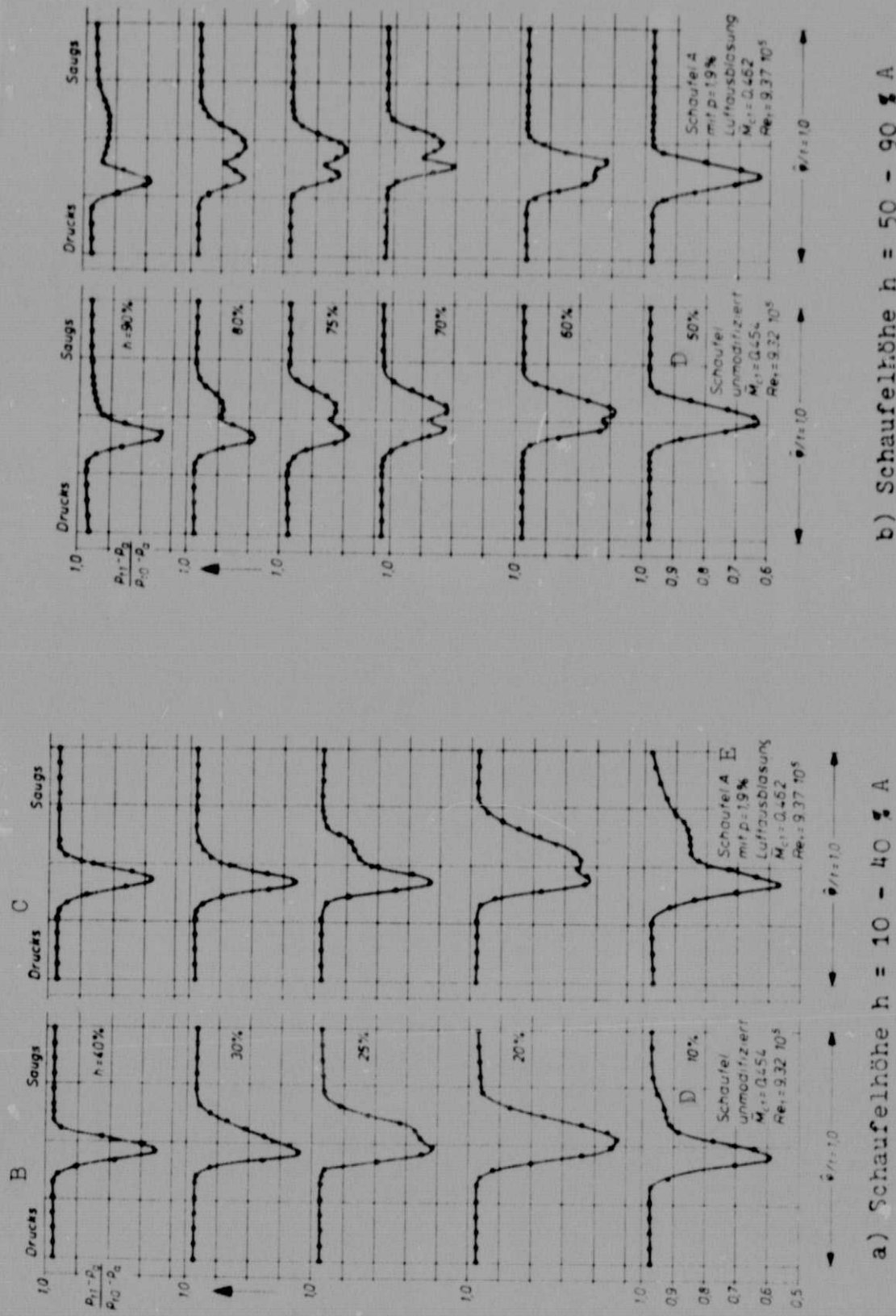
Figure 8 — The effect of blowing air on the total pressure distributions in the outflow plane of the turbine guide wheel

Key: 
A. Blade height
B. Pressure side
C. Suction side
D. Unmodified blade
E. Blade A with air blown onto it with p - 1.9%

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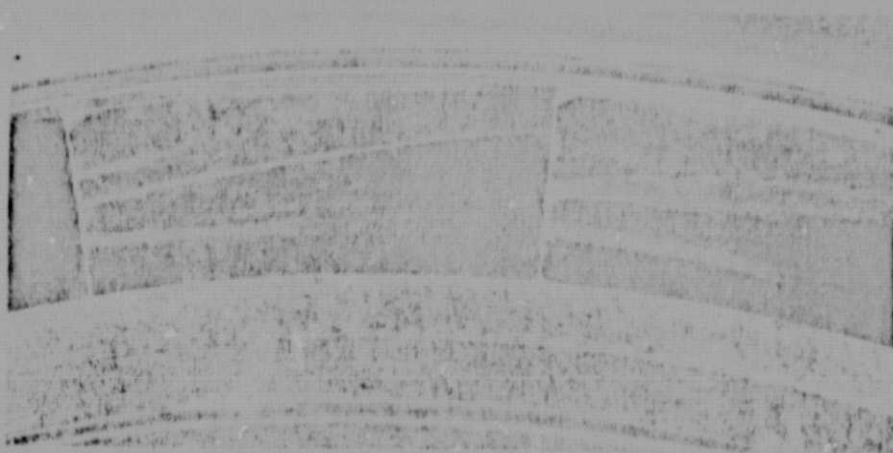
ohne Aus-
blasung          A
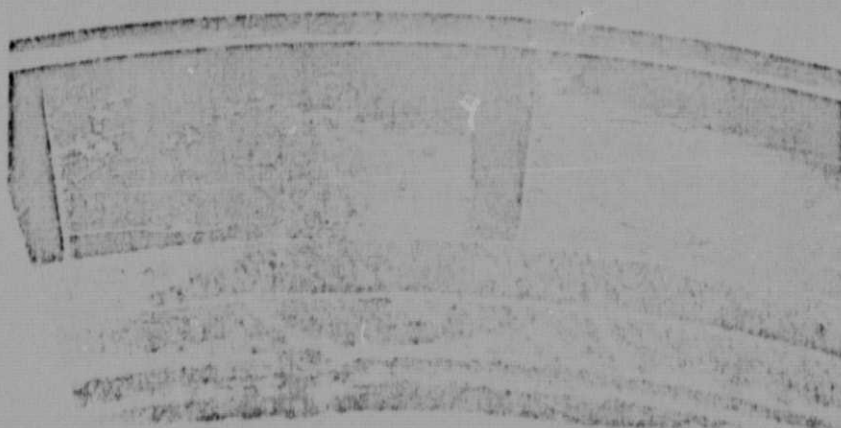
mit Aus-
blasung          B

p = 2 %

Figure 9 - View of the profile suction sides of turbine guide blades
with visualized flow lines of the wall boundary layers
with and without air blown onto the blades, $\overline{M}_{c1} = 0.45$

Key:  A.  Without air blown onto the blades  B.  With air blown onto the blades

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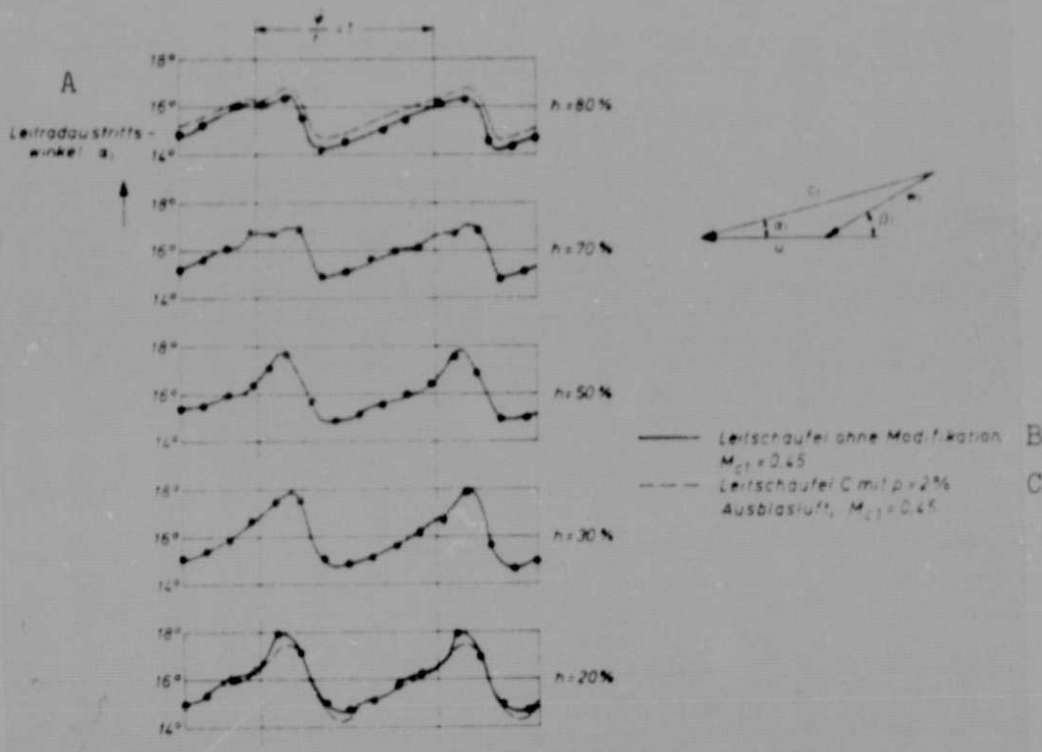
Figure 10 - Effect of blowing air on the exit angle $\alpha_1$ of the turbine guide baffles

Key:

A. Guide wheel exit angle

B. Unmodified guide blade

C. Guide blade C with air blown onto it, small $p = 2\%$, $M_{c1} = 0.45$
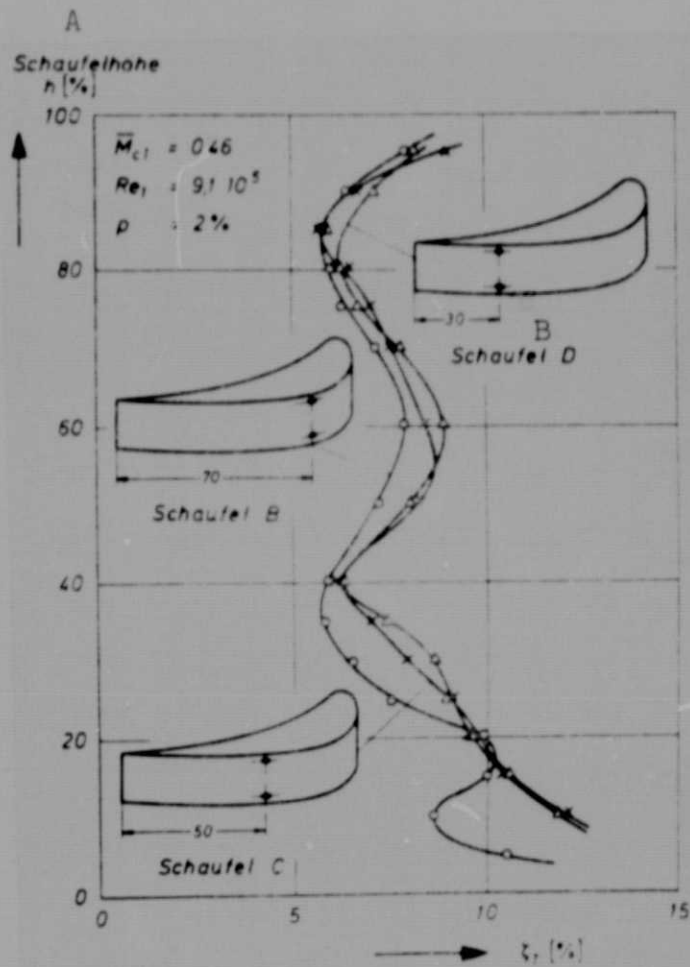
Figure 11 - Effect of the location of the blow holes on the baffle loss
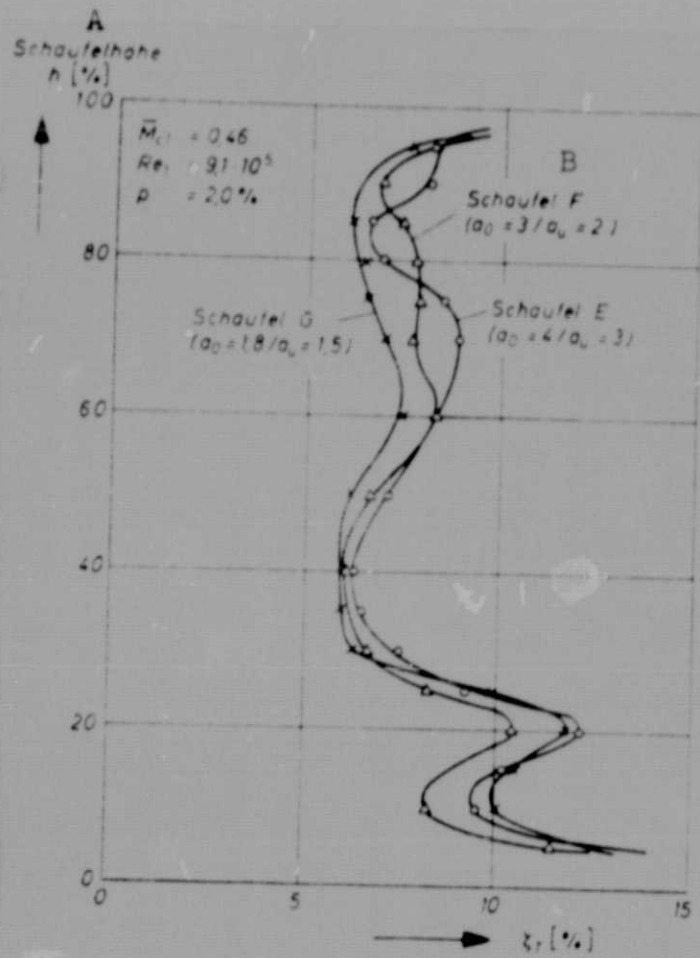          coefficient

Key:

A.  Blade height

B.  Blade

Figure 12 – Effect of the distance of the blow holes from the wall on
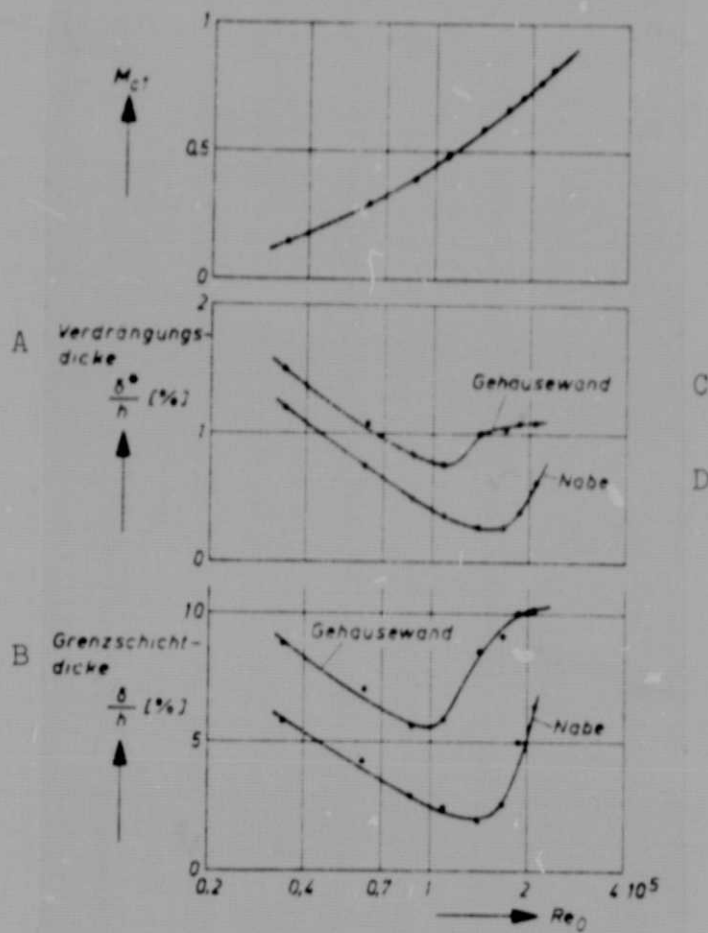the baffle loss coefficient

Key:

A. Blade height

B. Blade

Figure 13 – Boundary layer formation in the oncoming flow as a
function of the Reynolds number

Key:

A.  Displacement thickness

B.  Boundary layer thickness
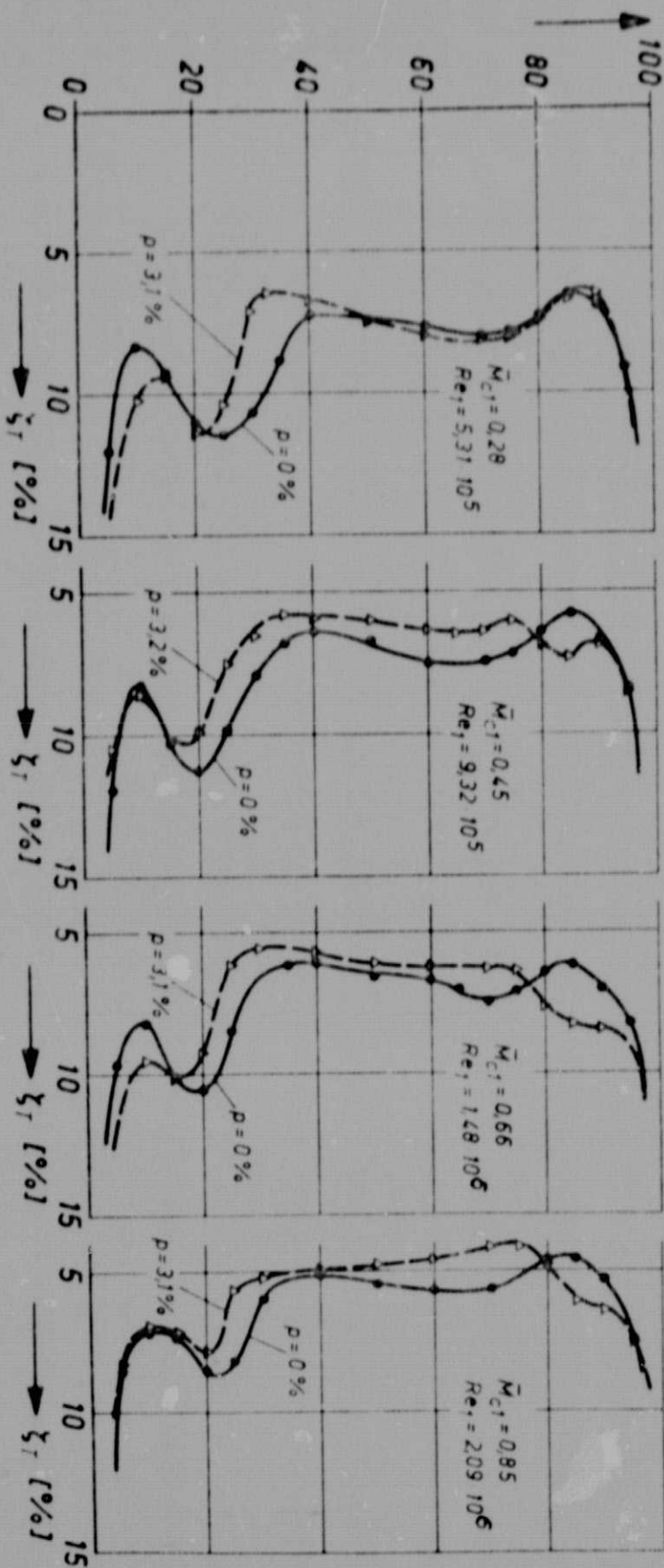
C.  Casing wall

D.  Hub

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Figure 14 – Effect of the outflow Mach number $\overline{M}_{c1}$ on the baffle loss coefficient with and without air blown onto the blade
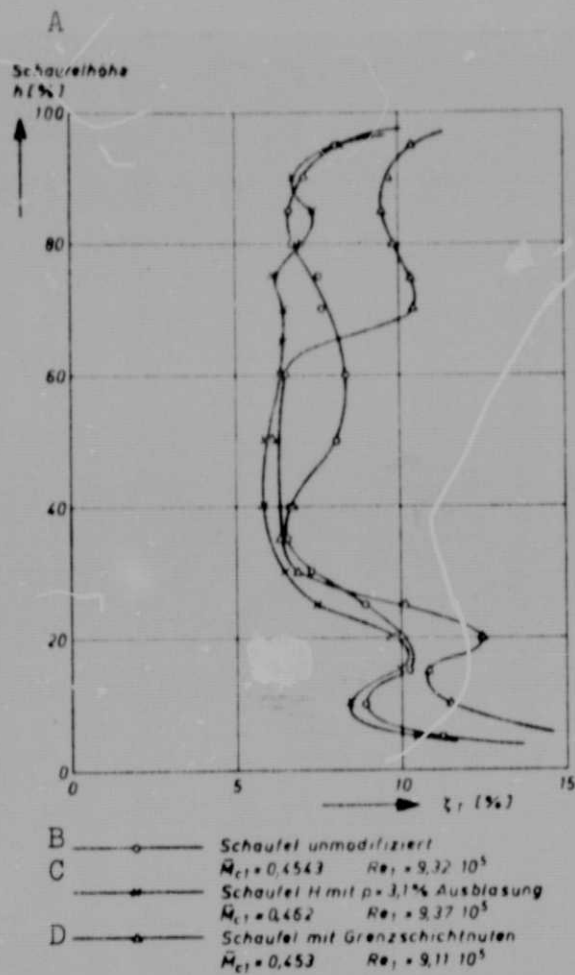
Key:

A. Blade height

Figure 15 - Comparison of turbine guide blades with air blown onto them
and with boundary layer grooves

Key:

A. Blade height

B. Unmodified blade

C. Blade H with air blown onto it, p = 3.1%

D. Blade with boundary layer grooves