Printed in U.S.A.

70-WA/GT-4

an ASME publication

$2.00 PER COPY

$1.00 TO ASME MEMBERS

Results of Experiments for Determining the Influence of Blade Profile Changes and Manufacturing Tolerances on the Efficiency, the Enthalpy Drop, and the Mass Flow of Multi-Stage Axial Turbines

K. BAMMERT

Director, Institute of
Turbo Machinery and Gasdynamics;
Professor,
Technical University of Hannover,
Hannover, Germany

H. STOBBE

Gutehoffnungshütte
Sterkrade AG, Germany

When gas and steam turbines are in use, the blade profiles can be thinned by corrosion or erosion and thickened under the influence of deposit formation, thus causing a reduction in efficiency and lifetime. During the production of turbine blades, it is possible that the profiles often become thinner or thicker than the given specified profiles, also causing a decline in efficiency. In addition, the production costs of turbine blades are, to a considerable extent, dependent on the manufacturing tolerances. This report details the effects of thinning and thickening of the profiles on the efficiency, the drop, and the mass flow of multi-stage axial turbines.

Contributed by the Gas Turbines Division of The American Society of Mechanical Engineers for presentation at the ASME Winter Annual Meeting, November 29 - December 3, 1970, New York, N.Y. Manuscript received at ASME Headquarters, August 3, 1970,

Copies will be available until October 1, 1971.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS, UNITED ENGINEERING CENTER, 345 EAST 47th STREET, NEW YORK, N.Y. 10017

Results of Experiments for Determining the Influence of Blade Profile Changes and Manufacturing Tolerances on the Efficiency, the Enthalpy Drop, and the Mass Flow of Multi-Stage Axial Turbines

K. BAMMERT H. STOBBE

INTRODUCTION

Many years of observation on the blading of turbines have shown that the shape of the blade profiles and the surface finish are changed under the influence of corrosion, erosion, and deposit formation during operation (1).[1] With gas turbines, especially with blast-furnace gas turbines for driving blast-furnace compressors and generators in steelworks, the first stages are thinned by corrosion, and the rear ones are thickened by slag deposits. On the other hand, the blades of steam turbines at high-pressure stages may be thickened by salt deposits, and at low-pressure stages, they may be eroded by condensing steam. Both effects, the thinning and the thickening of the blade profiles, decrease the efficiency and the lifetime of the turbines. For example, Fig. 1 shows the stator blades in the front turbine stage of a 16-MW blast-furnace gas turbine installation. The blades have been thinned by corrosion during 10,000 running hours. The turbine preserves as a means of driving a generator to produce current. The inlet temperature is about 750 C and the inlet pressure, about 5 bar. In the region of the hot working gases, the blades display clear uniform thinning of the profiles in contrast to the blade tip, which is less corroded as a result of the cooling air flow. The trailing edges are jagged and frayed, and up to 30 percent of the blade chord has gone due to corrosion. The surfaces of the blades are roughened. Fig. 2 shows some stator blades from the rear turbine stage of a 5-MW blast-furnace gas turbine installation after 23,000 working hours.

[1] Underlined numbers in parentheses designate References at end of paper.

Fig. 1 Stator blades of a front turbine stage of a 16-MW blast-furnace gas turbine plant which have been thinned by corrosion during 10,000 running hours

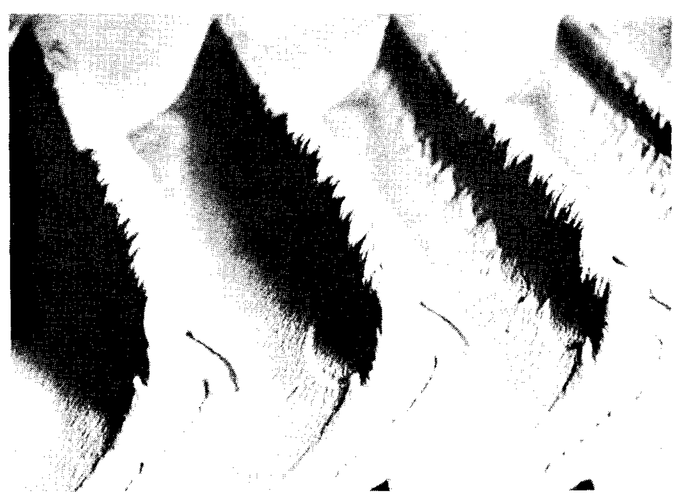
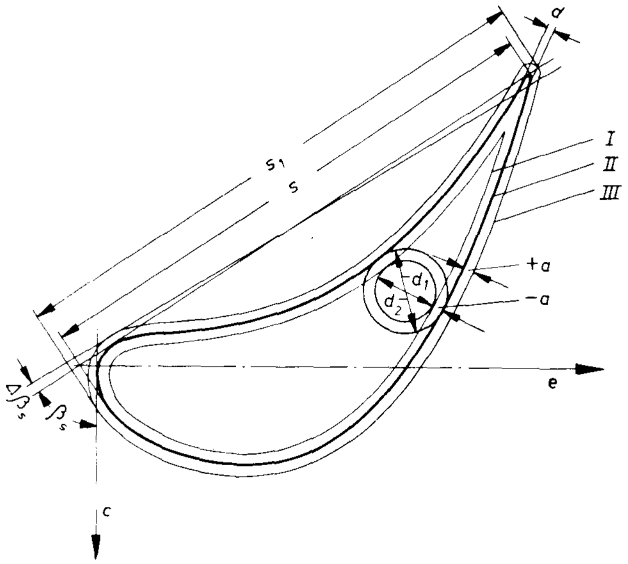


Fig. 2 Stator blades of a rear turbine state of a 5-MW blast-furnace gas turbine plant which have been thickened by deposit formation during 23,000 running hours



I Thinned profile
II Specified profile
III Thickened profile

d = trailing edge thickness
d_1, d_2 = profile thickness

s, s_1 = blade chord

a = contour tolerance
b = d_1-d_2 = thickness tolerance

Δs = s_1-s = blade chord tolerance

$\Delta\beta_s$ = profile twist

e = machine axis
c = peripheral direction
β_s = stagger angle

Fig. 3 Profile section with a definition of the manufacturing tolerances

This gas turbine serves as a means of driving a blast-furnace compressor. The conditions at the inlet of the turbine are 650 C and 3.2 bar. The blade profiles are relatively uniformly thickened by slag deposits, and the surfaces are rough. One can observe the same conditions of corrosion and deposit formation with the rotor blades as well. Even by using special materials for the blading, it has not yet been possible to prevent corrosion. Tests with protective surface layers, as, for example, by chrome plating, have already noticeably lengthened the life of the blades. The use of chrome on blades produced in quantity was, however, affected by many production faults and led to many instances of blade damage. These difficulties have now probably been overcome.

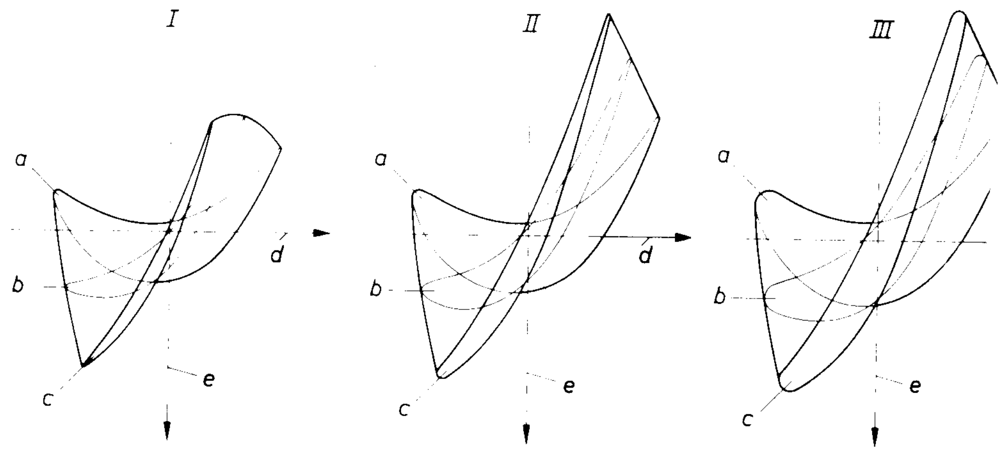
The heavy deposit formation can be reduced by using additives in the form of molecular SiO_2 to a tolerable extent. The result of mixing in additives is that the melting point of the slag is raised, and the slag particles, themselves, are loosened and carried forward by the flow.

The analysis tests of turbine blading made during inspections and because of damage displayed essentially two degrees of change in the blade profiles:

1 The simple roughening of the surfaces of the blades in an almost constant profile shape
2 The smooth or rough surfaces of the blades in a changed profile shape which is mainly indicated by a uniform thinning or thickening of the profiles.

The effect of the surface roughness on the flow losses has already been investigated separately on a two-dimensional turbine blade cascade (2, 3). There the dimensions which characterize the roughness could be ascertained. The object of the measurements given here was to investigate the effect of the change in the profile shape of blades with a smooth surface on the efficiency, the drop and the mass flow of a multi-stage axial turbine (4). In order to do this, the effect of corrosion was artificially copied by using a uniform thinning of the blade profiles and the deposit formation by a uniform thickening. The blades were produced with a smooth surface in order to retain the true effect of the thinning and thickening of the profiles.

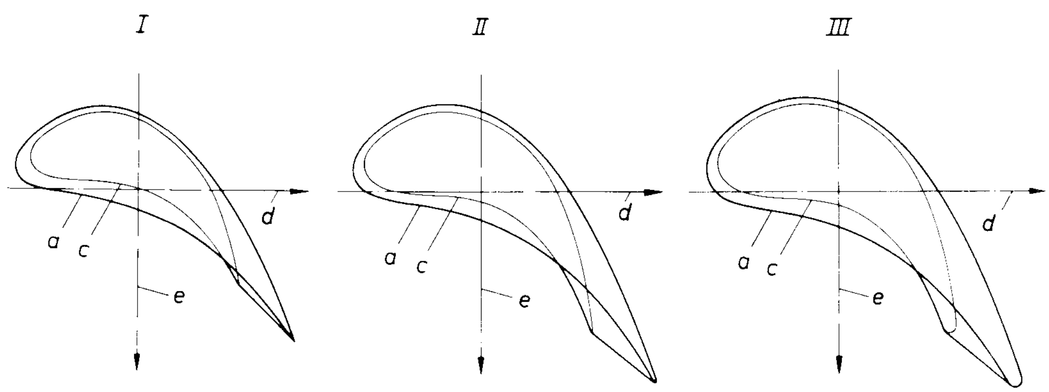
During the production of turbine blades, for example by copy milling, precision forging, or forging press, the blade profiles often become thinner or thicker than the given specified profiles because of the manufacturing tolerances. However, the production costs rise considerably with small manufacturing tolerances, so that the knowledge of their effects on the turbine is of great economic importance. The contour tolerance, the thickness tolerance, the blade chord tolerance, and the profile twist all play a part in judging the accuracy of manufacture of a turbine blade. The tolerances on a profile section can be seen in Fig. 3. The contour tolerance, a, is the permitted vertical deviation of the profile contour from the specified profile. A precondition for this is that the profile contour should not fluctuate because of the deviations within the contour tolerance, nor should it show kinks in the curvature. The thickness tolerance, b, as the difference between the profile thicknesses, d_1 - d_2, gives the permitted deviations from the profile thickness. It is of importance, especially for the thickness of the trailing



I Normal profile uniformly thinned by about 1 mm
II Normal profile
III Normal profile uniformly thickened by about 1 mm

(a) Root section
(b) Mean section
(c) Tip section
(d) Machine axis
(e) Peripheral direction

Fig. 4 The profile sections of the thinned, normal, and thickened rotor blades drawn one on top of the other



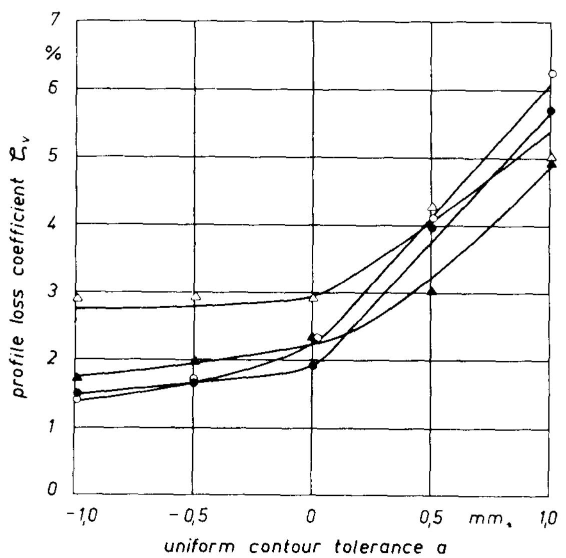
(legend as in Fig. 4)

Fig. 5 The profile sections of the thinned, normal, and thickened stator blades drawn one on top of the other

edges, d. The blade chord tolerance, Δs, is the allowable error in the blade chords, $s_1 - s$. It is important for the direction of the exit flow. The profile twist, $\Delta\beta_S$, is a criterion for the deviation of each profile section from the specified stagger angle, β_S, which is measured between the profile tangents and the front of the cascade.

MEASUREMENTS IN A TWO-DIMENSIONAL CASCADE WIND TUNNEL

The effects of the uniform profile thinning and thickening on the profile loss coefficient and the discharge angle have been investigated in a two-dimensional cascade wind tunnel (3, 5, 6). These investigations have been undertaken

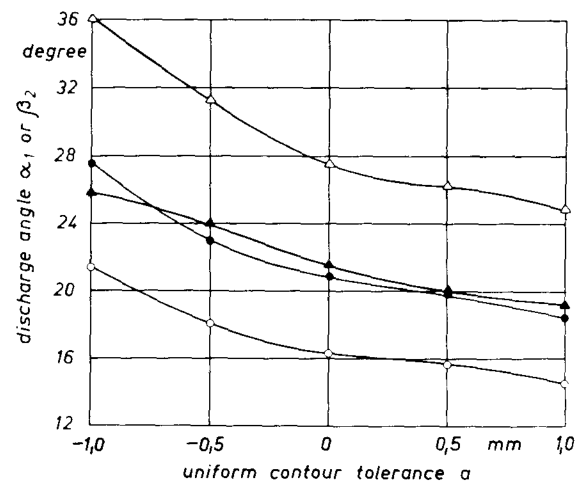


o tip section, rotor blade	}	measuring points with optimum inflow to the cascade
• mean section, rotor blade		
Δ root section, rotor blade		
▲ mean section, stator blade		

Fig. 6 Two-dimensional profile loss coefficient dependent on the uniform contour tolerance

on some characteristic blade profile sections from the potential vortex blading already investigated. Fig. 4 shows the profile sections of the root, mean, and tip sections of the thinned, normal, and thickened rotor blades (a, b, c). These sections here are drawn one on top of the other. The lines, d and e, reproduce the position of the axis of the machine and the peripheral direction. Analogous to it in Fig. 5, the root and tip sections of the thinned, normal, and thickened guide blades are drawn one on top of the other. In each case, 0.5 and 1.0 mm were chosen as the size for the uniform thinning and thickening of the profiles when tests were made on the root, mean, and tip sections of the rotor blade and on the mean section of the stator blade in a two-dimensional cascade wind tunnel. The results of these measurements in a two-dimensional cascade wind tunnel are to be seen in Figs. 6 and 7, and here one can observe the dependence of the profile loss coefficient and of the discharge angle on the uniform contour tolerance during optimum inflow to the cascade. The profile loss coefficient, ζ_v, is supplied by wake surveys along the pitch, t, integrated to

$$\zeta_v = \frac{\frac{1}{t}\int_y^{y+t} \Delta g(y)\cdot dy}{g_1 - p} \qquad (1)$$



(legend as in Fig. 6)

α_1 Discharge angle of the stator blade cascade

β_2 Discharge angle of the rotor blade cascade

Fig. 7 Two-dimensional discharge angle dependent on the uniform contour tolerance

In this y is, in each case, the position along the pitch, t, $\Delta g(y)$, the difference in the total pressures, $g_1 - g_2(y)$, dependent on each measuring position, and $g_1 - p$ the measured timed averaged pressure difference of the total pressure of the inlet flow, g_1, and the atmospheric pressure, p. Thus, the subscripts 1 and 2 term them working planes in front of and behind the cascade. The discharge angle, β_2, is shown from the wake surveys as the average of the discharge angles, $\beta_2(y)$, which were measured separately and which, in addition, are averaged with the local cross section of the flow along the pitch, t, to

$$\beta_2 = \frac{1}{t}\int_y^{y+t} \beta_2(y)\cdot dy \qquad (2)$$

Fig. 6 shows the steep linear climb of the profile loss coefficients in the case of thickened profiles (positive contour tolerance) for all four of the cascade profiles which were investigated. This steep linear climb is essentially due to the linear increase of the trailing edge loss (3). On the other hand, the profile loss coefficients on the thinned profiles (negative contour tolerance) only slightly decrease linearly because of the reducing profile surface. The opposite tendency is to be observed with the discharge angles in Fig. 7. Here the discharge angles increase considerably more with the thin-

Table 1 Blading Variations

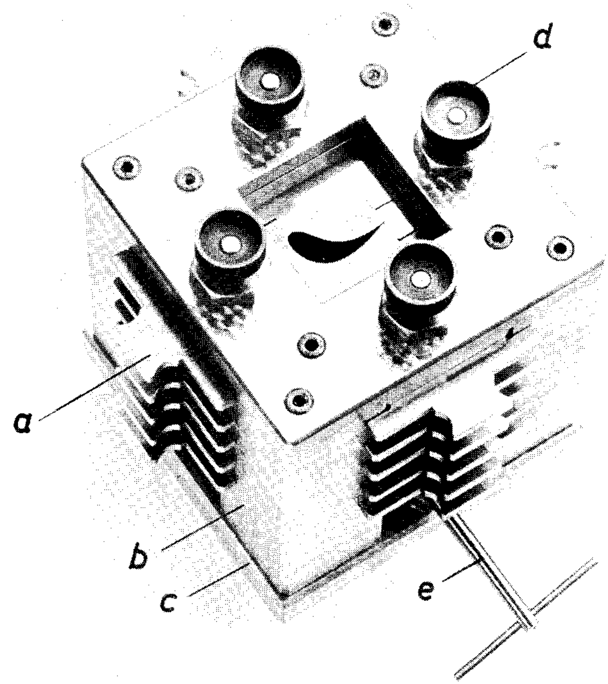
Variation	stage I Sta	stage I Rot	stage II Sta	stage II Rot	stage III Sta	stage III Rot	stage IV Sta	stage IV Rot
0	0	0	0	0	0	0	0	0
1	−1	−1	0	0	0	0	0	0
2	−1	−1	−1	−1	0	0	0	0
3	0	0	0	0	0	0	+1	+1
4	−1	−1	0	0	0	0	+1	+1
5	−1	−1	−1	−1	0	0	+1	+1
6	0	0	0	0	+1	+1	+1	+1
7	−1	−1	0	0	+1	+1	+1	+1
8	−1	−1	−1	−1	+1	+1	+1	+1

0 ≙ normal profile
−1 ≙ normal profile uniformly thinned by about 1 mm
+1 ≙ normal profile uniformly thickened by about 1 mm

ning of the profiles in contrast to the discharge angles which become smaller with the thickening of the profiles. In the case of thinning of the profiles, the flow is conducted less well because of the trailing edges which are set very far back and because of the missing axial overlap.

MEASUREMENTS ON A FOUR-STAGE AIR TURBINE

On a four-stage air turbine, we examined experimentally the effects of the contour tolerance, that is to say, of the profile thinning and profile thickening, on the efficiency, the drop and the mass flow while varying the mass flow and the number of revolutions. As Figs. 1 and 2 showed, corrosion and deposit formation have a comparatively uniform effect on the addition to and reduction of the profile contour. It is obvious that, to determine the profile changes, it is necessary in the case of the original profile to add or reduce a constant thickness normal to the profile contour. In order to measure the uniform thickening and thinning of the normal profile, 1 mm was chosen, as this value is, in practice, still permitted. In all, two complete four-stage turbine bladings were produced. One set of blades has normal profiles as required by the design in all four stages. This is then a homogeneous reaction blading; that is to say, it is equipped on all axis parallel sections with stator blade and rotor blades profiles which are, in each case, identical. This reaction blading is twisted according to the potential vortex law and has a 50 percent reaction in the mean section of the last stage. In the second set of blades which were altered, the normal profiles of the first two stages were uniformly thinned all round



(a) Contour gauge
(b) Stand
(c) Base plate
(d) Knurled-head screw
(e) Locking screw for the supporting device for the blade root

Fig. 8 Blade test apparatus

by 1 mm in each case, normal to the profile contour, and the normal profiles of the last two stages were uniformly thickened by 1 mm in each case (Figs. 4 and 5). By making good use of the combination of both sets of blades, one can obtain nine different turbine bladings, as they are assembled in Table 1. In it one finds the following signs 0 for normal profiles, -1 for profiles which have been uniformly thinned by a millimeter, and +1 for those which have been uniformly thickened by a millimeter. The abbreviations, Sta and Rot, stand for stator and rotor. The variation 0 corresponds to the normal blading. In the variations 1 to 8, the blade profiles of a stage, that is, the blade rows of the stator and rotor, were always varied in each case. For each of these nine blading variations, measurements were taken of the efficiency and the drop in enthalpy in the case of the five mass

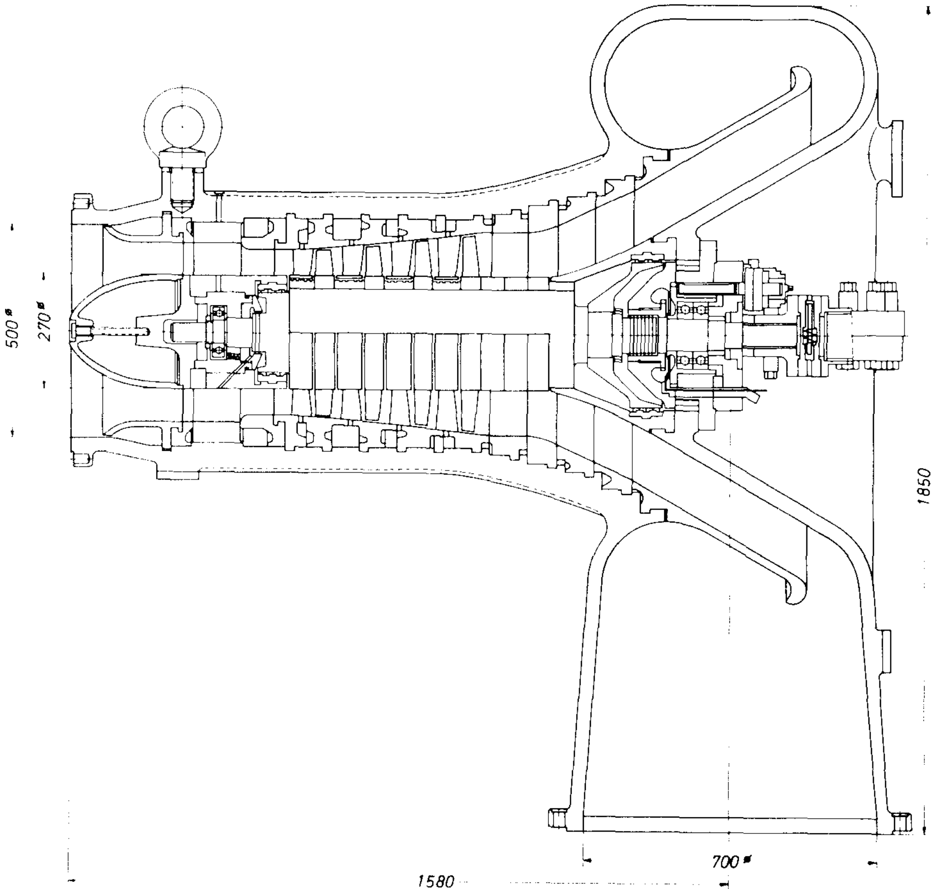


Fig. 9 Sectional view of the four stage air turbine

Dimensions in mm

tion:

$$m/m_o = 1.2 \quad 1.0 \quad 0.85 \quad 0.7 \quad \text{and} \quad 0.5$$

and in each case of the four numbers of revolutions

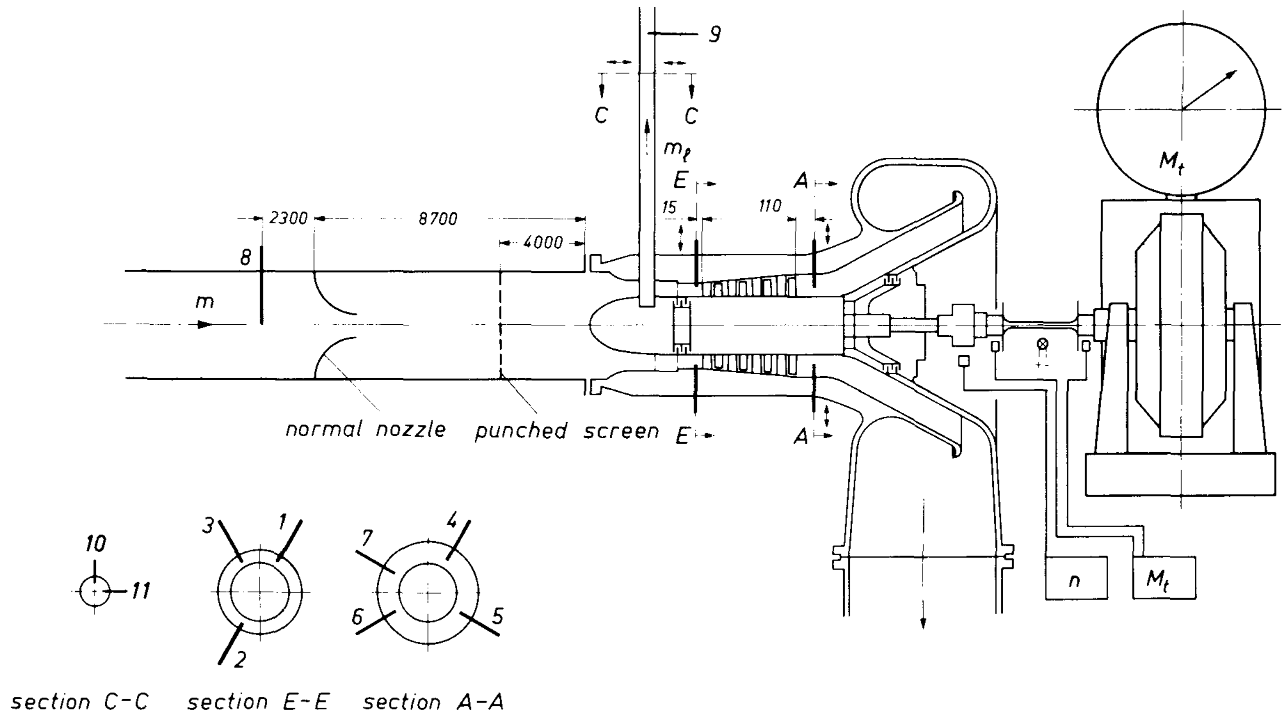
$$n/n_o = 1.0 \quad 0.85 \quad 0.7 \quad \text{and} \quad 0.5 \ .$$

In this m_o = 7.8 kg/sec is the mass flow and n_o = 7500 rpm, the number of revolutions at the design point of the test turbine.

The profile contours of the thinned, normal, and thickened stator and rotor blades were measured in five or six profile sections along the blade height with the blade test apparatus shown in Fig. 8. The blade contour is interpolated between the blade sections. In each of the profile sections, four contour gages, a, are pushed together until they touch the stands, b, to form a complete profile contour. These stands are mounted on a base plate, c. Then the knurled-head screws, d, are tightened, and the deviation of the profile from the specified profile all round is measured by light-gap testing and feeler gages (thickness gages). In order to do this, the blade which is to be tested is first pushed into a supporting device, where it is fixed on the base according to its position and direction and then tightened with the locking screw, e. The profile contour is illuminated by a small lamp which is pushed forward up to the profile contour through drill holes in the distance pieces between the contour gages. The contour gages, a, are ground on a profile grinding machine according to a profile drawing in the scale of 10:1 on synthetic foil to a profile accuracy of 0.01 to 0.02 mm. This tolerance is the accuracy of the blade test apparatus.

During the production of the test blades, the following tolerances could be maintained with high production costs:

1 Contour tolerance, a = ± 0.05 mm, in places up to 0.1 mm
2 Thickness tolerance, b = ± 0.05 mm
3 Blade chord tolerance, Δs = ± 0.1 mm
4 Profile twist, $\Delta\beta_s$ = ± 5 sixtieths of one angular degree.



n = electronic measuring of revolutions

M_t = electronic measuring of the torque

m = measurement of the volume

m_ℓ = measurement of the leakage

1, 4, 6, 10, 11 = pitot tube

2, 8, 9 = thermo probe

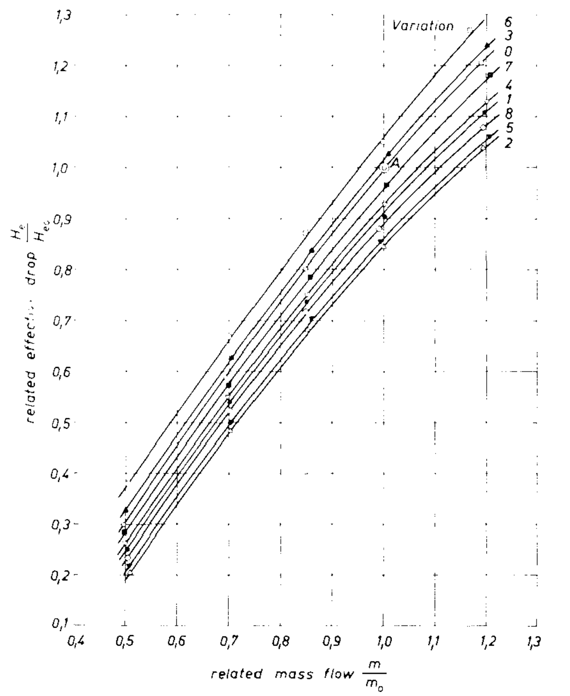
3, 5, 7 = directional probe with thermo-element

Fig. 10 Plan of the measuring points

Dimensions in mm

If the blades are tested with the help of optical measuring methods, then a positional tolerance of the profile sections to the base on the blade must be given in addition. This positional tolerance corresponds to the profile twist in its deviation. The greater the twist of the blade, the narrower is the tolerance to be chosen. When testing the blades in the blade test apparatus by measuring the differences between the profile contour of the blade and the contour gage with thickness gages, the profile twist is sufficiently exact if the contour, thickness, and blade chord tolerances are not exceeded. During the production of cylindrical blades, it is perfectly possible to obtain even smaller manufacturing tolerances than those quoted in the foregoing. During the production of the test blades, the manufacturing tolerances had to be very small, as in the case of the experimental investigations, uniform thinning and thickening of 1.0 mm was needed, and a contour tolerance of 0.05 mm gives a 5 percent error. The usual manufacturing tolerances in industry for the quantity production of twisted blades are mostly roughly several times greater than those quoted in the foregoing, depending on their method of production, because the costs of production increase rapidly as the manufacturing tolerances become smaller.

Fig. 9 shows a section through the test turbine. It is driven by air which is supplied by a compressor installation. The output of the turbine is taken by a hydraulic brake. At the design point, the clutch output is 703 kw and the inlet pressure, 2.6 bar at an inlet temperature of 140 C. The air expands in the turbine to atmospheric pressure. At the entry and exit of the



A = design point

m_o = 7.8 kg/s = design flow

n_o = 7,500 rpm = design number of revolutions

H_{eo} = 89.9 kJ/kg = effective design drop

H_{so} = 96.6 kJ/kg = isentropic design drop

} with normal blading

Fig. 11 Shape of the characteristic curves of the drop for the nine blading variations at rated speed

blading, there are cylindrical measuring sections. A diffuser leads to the spiral volute. With a constant hub diameter of 270 mm, the blade height in the last stage is 103 mm, which corresponds to 0.567 of the hub-to-tip ratio. Split-ring insertions form the outer contour, and, at the same time, they serve as stator blade bearers. Opposite the rotor blade tips, they are covered with a 2-mm-thick synthetic layer in order to prevent the danger of a blade breaking when they are scraped by the tips of the rotor blades which are cut off blunt. The turbine is equipped with ball bearings, and for this reason, the mechanical losses are very small. But above all, extremely small radial gaps can be obtained for the stator and rotor blades. The stator blade rows are sealed on the rotor side by inner shroud bands which are axially split with four labyrinth seals opposite the rotor.

Fig. 10 explains the position and the layout of the measuring points. In order to obtain the isentropic and inner drop, the flow was tested in a working plane, E, before, and in a working plane, A, after the blading at 15 equidistant measuring points along the blade height. Here the variables of state, the total pressure, and the total temperature, as well as the velocity, were measured according to their magnitude and direction. The pressures were shown with U-pipes, and the temperatures were measured with thermocouple elements in compensating circuit. The mass flow, m, was determined with a standard normal nozzle, and the amount of leaking air, m_ℓ, because of the labyrinth gaps at the turbine entrance bearing, was determined by scanning with two pitot tubes in the working plane, C, of a measuring pipe. Independently of that as a check, the mass flow is obtained by scanning the flow before and after the blading in the working planes, E and A. The number of revolutions, n, was obtained with an electronic impulse sender in association with an electronic impulsemeter. The clutch torque, M_t, was measured with a torsion-dynamometer by using torsion rods. By choosing a suitable diameter for the torsion rods, the torque can be suited in such a way to the torsion range of the torsion rods that an accuracy of measurement of between 0.4 and 0.6 percent can be obtained over the whole load range. In addition, as a control, the torque is measured with the precision circular scale balance of the hydraulic brake which is mounted on pivot bearings. The effective drop of the turbine can then be shown as

$$H_e = \frac{M_t \cdot n}{m - m_\ell} \tag{3}$$

In order to determine the isentropic drop, H_{sm}, the tube measurements of the scanning of the flow before and after the blading are taken. The values for the total pressure and the total temperature at the entry to the blading, which were averaged with the mass flow over the height of the blades, were used as a basis for the starting point of the insentropic expansion. With this starting condition and the local total pressure, $p_{gA}(r)$, measured via the radius, r, at the exit from the blading, it was possible to determine the local isentropic drop, $H_s(r)$, for the flow line in question. The averaged isentropic drop can than be seen as

$$H_{sm} = \frac{\int_{r_i}^{r_a} H_s(r) \cdot \varrho_A(r) \cdot c_{zA}(r) \cdot r \cdot dr}{\int_{r_i}^{r_a} \varrho_A(r) \cdot c_{zA}(r) \cdot r \cdot dr} \quad . \tag{4}$$

In this $\rho_A(r) = p_{gA}(r) / \left[R \cdot T_{gA}(r)\right]$ is the local density with R as the gas constant and $T_{gA}(r)$ as the measured local total temperature, $c_{zA}(r) = c_A(r) \cdot \sin \alpha_A(r)$, the local axial velocity with $c_A(r)$ as the measured local discharge velocity, and $\alpha_A(r)$ as the measured local flow angle, r_i the hub radius and r_a the internal radius of the casing in the working plane, A, at the blading exit. As a measurement for the efficiency of the turbine, an effective turbine efficiency is defined as

$$\eta_e = \frac{H_e}{H_{sm}} \quad . \qquad (5)$$

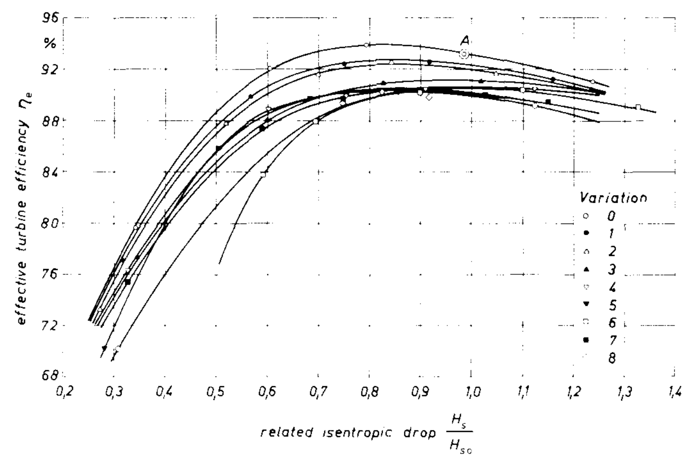
INFLUENCE OF UNIFORM PROFILE CHANGES ON CHARACTERISTIC MAGNITUDES OF TURBINES

In Fig. 11, the related characteristic curves of the drop, H_e/H_{eo}, over the related mass flow, m/m_o, are shown for all the nine blading variations at a rated speed. The indicator, o, refers to the values of the normal blading at the design point.

If one takes the case, $H_e/H_{eo} = 1$ (horizontally through A), then variation 6 has the smallest mass flow because of the thickened profiles of the rear two stages, and variation 2 has the largest mass flow because of the thinned profiles of the two front stages. The absorption capacity changes by more than 20 percent. All the other variations lie in between, according to the profile changes of the individual stages.

If one takes the case, $m/m_o = 1$ (vertically through A), which is characterized by the fact that the turbine has exactly the drop to achieve the mass flow at the design point, then the effective turbine drop falls by over 22 percent between variation 6 and variation 2.

From the set of curves in Fig. 11, one can clearly recognize the dominating influence of the profile thinning of the first stages on the mass flow and the drop of the turbine. The reasons for this are the large increases in the discharge angles through the profile thinning (Fig. 7) which, for example, are 9.1 deg at the root section and 4.5 deg at the tip section. Because of this, the absorption capacity of the turbine increases, and the drop is greatly lessened of the smaller deflection. With profile thickening, the discharge angles, for example in the case of the rotor blades (Fig. 7), become about 2.5 deg smaller at the root section and about 1.9 deg smaller at the tip section, so that the absorption capacity of the turbine is lessened because of it, and the drop, when the design flow is



(legend as in Fig. 11)

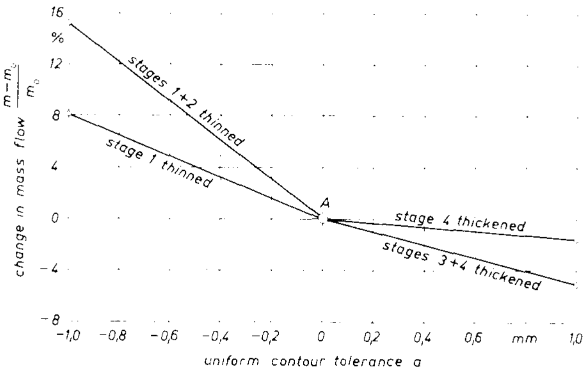
Fig. 12 Run of the effective efficiency of the turbine for the nine blading variations at rated speed

kept constant, increases because of the greater deflection. The drop increases, however, is greatly lessened by the greatly increasing profile losses in the cases of profile thickening because of the thick trailing edges (Fig. 6).

In Fig. 12, the effective turbine efficiency, η_e, over the related isentropic drop, H_s/H_{so}, is shown for all the nine blading variations which are valid for the rated speed. The variations, 0, 1, and 2, which have rear stages with normal profiles, show a clearly defined high level of efficiency of 94 percent in the case of variation 0 (normal blading) and approximately 93 percent in the case of variations 1 and 2. With variations 3 to 8, which have one or two thickened rear stages, the efficiency declines steeply, the characteristic curves are flatter, the optimum point in the case of variation 3 lies at about 91 percent, and with variation 8, it declines to about 90 percent. The gap in the decline in efficiency in the optimum point between the normal blading and variation 1 caused by thinning in the first stage is 1 percent-efficiency point, while the thickening of the last stage results in a decline of 3 percent-efficiency points. The reasons for this are the additional losses caused by the thickened trailing edges in the case of thickened profiles. Therefore, uniform profile thickening has a considerably greater effect on the decline in efficiency than uniform profile thinning.

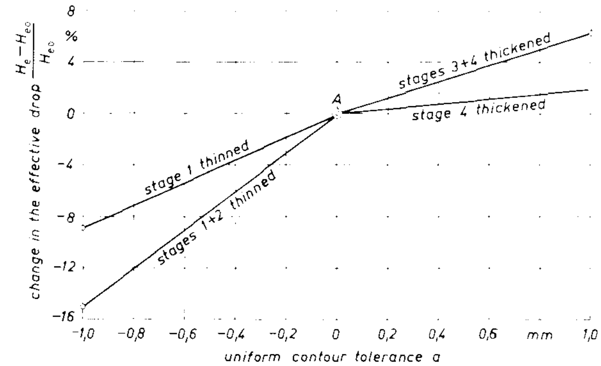
INFLUENCE OF UNIFORM CONTOUR TOLERANCE ON MASS FLOW, DROP, AND EFFICIENCY OF TURBINE

In order to indicate the influence of the



⊙A = design point of the normal blading
o = measuring points on the four-stage turbine with the constant effective design drop, H_{eo}, of the normal blading and at rated speed

Fig. 13 Influence of the uniform contour tolerance on the mass flow of the turbine



⊙A = design point of the normal blading
o = measuring points on the four-stage turbine with the constant design flow, m_o, of the normal blading and at rated speed

Fig. 14 Influence on the uniform contour tolerance on the effective drop of the turbine

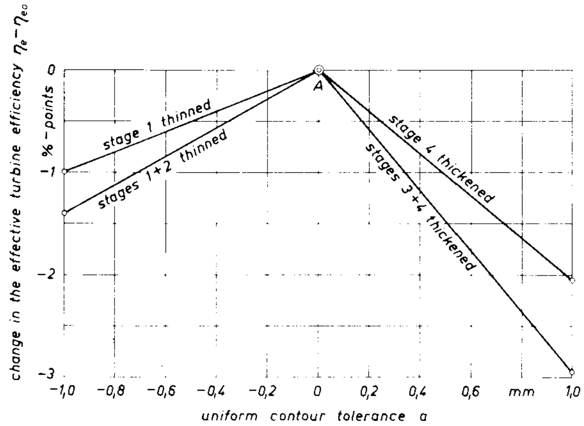
uniform contour tolerance (Fig. 3) on the mass flow and the drop of the turbine, Figs. 13 and 14 show the percentage changes in the mass flow (Fig. 13) and in the effective drop (Fig. 14) for the rated speed, dependent on the uniform contour tolerance, a. As the influence of the uniform contour tolerance on the characteristic magnitude of the turbine will, to a large extent, be dependent on the pitch, it would also be possible to relate the contour tolerance, a, to the pitch, t, and to undertake the representation using a/t. In order to see it more clearly, this was not done. The pitch, t, would have to be taken into account when transferring the test date to other cascade profiles. For the normal profiles which are under investigation here, the pitch in the mean section of the last turbine stage in the case of the stator blade is t_{Sta} = 40 mm (29 blades), and in the case of the rotor blade, t_{Rot} = 39 mm (30 blades); the corresponding blade chords in the mean section are, in the case of the stator blade, 58 mm, and the rotor blade, 56 mm. The measuring points of the turbine drawn in Figs. 13 and 14 are taken from the set of curves in Fig. 11 for $H_e/H_{eo} = 1$ and $m/m_o = 1$. These lines were connected by straight lines to the design point, A, of the normal blading. According to the results of the measurements on a two-dimensional cascade, there is approximately, in each case, a linear connection between the dimension of the uniform profile thickening and thinning and the changes in the two-dimensional profile loss coefficients (Fig. 6) and the discharge angles (Fig. 7). Using this linear interpolation, one can estimate the influence of the uniform contour tolerance on the absorption capacity and the drop of the turbine.

During the production of turbine blades, for example by copy milling, precision forging (7), and forging press, or because of the corrosion of, or deposit formation on, the blades during operation (1), the case of a uniform contour tolerance, that is to say, of uniform profile thinning or thickening very often occurs. During the production of blades, the manufacturing costs rise considerably as the contour tolerances demanded become smaller. When gas and steam turbines are used, the working life and the efficiency are lessened by the thinning and thickening of the blade profiles. The knowledge of the effects of uniform contour tolerances like these on the characteristic magnitudes of turbines is, therefore, of great importance. As Figs. 13 and 14 show, the changes in the mass flow and the effective drop of the turbine in the case of profile thinning (negative contour tolerance) are approximately three times as great as in the case of profile thickening (positive contour tolerance). While in the case of the profile thickening of the two rear stages 3 and 4, the increase in the drop and the decrease in the mass flow is about three times as great as the thickening of the rear stage 4 by itself, one can observe the opposite tendency with profile thinning. Here the decrease in the drop and the increase in the mass flow, because of the profile thinning of the two front stages 1 and 2, is only between 1.7 and 1.8 times as great compared with the thinning of the front stage 1 by itself.

As can be seen from Fig. 13, a uniform profile thinning of stage 1 by about 0.2 mm with a constant effective turbine drop results, for example, in an increase of the mass flow by about

1.7 percent, while a uniform thickening of stage 4 by about 0.2 mm only has the effect of decreasing the mass flow by about 0.3 percent. In the case of a thinning of stages 1 and 2 by about 0.2 mm, the increase in the mass flow is 3 percent, and when there is a thickening of stages 3 and 4 by about 0.2 mm, the decrease in the mass flow is 1 percent. Fig. 14 shows the changes in the effective drop with a constant flow as designed, which is dependent upon the uniform contour tolerance. A uniform profile thinning, for example, of stage 1 by about 0.2 mm causes a decrease in the drop by about 1.8 percent in contrast to the increase in the drop of only 0.4 percent with the uniform profile thickening of stage 2 by about 0.2 mm. The thinning of stages 1 and 2 by about 0.2 mm results in a decline in the drop of 3.1 percent, and the thickening of stages 3 and 4 by about 0.2 mm gives an increase in the drop of about 1.2 percent.

Fig. 15 shows the influence of the uniform contour tolerance on the effective efficiency of the turbine at the rated speed. The drawn measuring points of the turbine, which were taken from Fig. 12 at a constant isentropic design drop, H_{SO}, of the normal blading, are joined by straight lines with the design point A of the normal blading just as in Figs. 13 and 14. As can be seen from Fig. 15, a uniform profile thinning of stage 1 by about 0.2 mm, for example, results in a decrease in efficiency of 0.2 percent-points, while a uniform profile thickening of stage 4 by about 0.2 mm brings about a decrease of 0.41 percent-points. If stages 1 and 2 are thinned by about 0.2 mm, the decrease in efficiency is 0.28 percent-points, and when stages 3 and 4 are thickened by about 0.2 mm, it is 0.59 percent-points. As can be seen from Fig. 12, these values increase at the optimum point of the normal blading and in the partial-load region. In the overload region, the values become a little smaller.



◎ A = design point of the normal blading

η_{eo} = 93.1 percent, effective efficiency of the turbine at the design point of the normal blading

o = measuring points of the four-stage turbine with the constant isentropic design drop, H_{SO}, of the normal blading and at rated speed

Fig. 15 Influence of the uniform contour tolerance of the effective efficiency of the turbine

SUMMARY

The measurements on the turbine showed that the characteristic curves of the drop and the efficiency are heavily dependent on the profile changes. The profile thinning caused by the corrosion of the front stages has a dominating influence on the characteristic curves of the drop and the absorption capacity of the turbine, while the profile thickening caused by deposit formation in the rear stages cause a steep decrease in efficiency. In addition, the turbine measurements show the influence of the uniform manufacturing tolerance of the turbine blades on the efficiency, the drop, and the mass flow of the turbine. A negative contour tolerance (profile thinning) influences primarily the drop and the absorption capacity of the turbine, while a positive contour tolerance (profile thickening) brings about a steep decrease in efficiency. The results given here of the tests on the four-stage air turbine in regard to the influence of the contour tolerance can be applied as well to gas turbines with a different number of stages if one converts the test data in relation to the number of stages, 4/z, in order to estimate the influence of the tolerances.

REFERENCES

1 Bammert, K., "The Gas Turbine in German Steel Works," V.I.K. Berichte, No. 94, 1959; "The Stage of Development of the Fixed Gas Turbine," V.I.K. Berichte, Nos. 121/122, 1961; "Operating Experience with Gas Turbines," V.I.K. Berichte, No. 136, 1963; "Losses in the Operation of Steam Turbines," V.I.K. Berichte, Nos. 141/142, 1963; "Corrosion, Erosion, and Deposit Formation in Blast-Furnace Gas Turbines," V.I.K. Berichte, No. 164, 1965.

2 Bammert, K., and Fiedler, K., "The Friction Loss in Rough Turbine Blade Cascades," Brennstoff-Wärme-Kraft, Vol. 18, No. 9, 1966, pp. 430-436.

3 Bammert, K., and Fiedler, K., "The Trailing Edge Loss and the Friction Loss in Turbine

Blade Cascades," Forsch. Ing.-Wes., Vol. 32, No. 5, 1966, pp. 133-141.

4 Bammert, K., and Stobbe, H., "Measurements on A Multi-Stage Axial Turbine with Normal, Thinned and Thickened Blade Profiles," Motortechnische Zeitschrift, Vol. 31, No. 5, 1970.

5 Bammert, K., "The Influence of Profile Changes on the Characteristics of Turbine Blade Cascades," Wiss. Z. TU Dresden, Vol. 16, No. 2, 1967, pp. 369-375.

6 Bammert, K., and Sonnenschein, H., "The Influence of Thickened and Thinned Turbine Blades on Cascade Characteristics," Archiv f. Eisenhüttenwes., Vol. 38, No. 4, 1967, pp. 287-299.

7 Tarmann, H., Krainer, E., and Kreitner, F., "Precision Forged Turbine Blades: Manufacture, Characteristics and Materials," Berg- u. Hüttenmännische Monatshefte, Vol. 112, No. 11, 1967, pp. 351-361.

CONVERSION FACTORS

Pressure
1 bar = 14.5037 lbf/sq in.
Mass flow
1 kg/sec = 2.2046 lb/sec
Specific drop in enthalpy
1 kJ/kg = 0.42992 Btu/lb