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TIP LOSSES IN REACTION-TYPE TURBINE CASCADES IN A WIDE RANGE OF ATTACK ANGLES

by

A. I. Kirillov, A. P. Pavlov, and A. S. Maksudyan

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ABSTRACT

(U) Experimental studies were performed at the Leningrad Polytechnical Institute im. M. I. Kalinin of the tip energy losses in a three reaction-type turbine shrouded cascades. The blade profiles differed mainly by the leading edge thickness while the trailing edges were practically the same. The flow exit angles for the three tested cascades were 24 degrees, 17 degrees, and 23.5 degrees, respectively. The pitch-chord ratio was practically optimal, and the blade assembly was 120 mm high. The inlet flow angle was varied from 20 to 154 degrees. The effective height of the blades was 105 mm. The tip losses were calculated from equation derived at the Central Boiler and Turbine Institue. At high angles of attack, the energy losses for plane, reaction-type cascades can be determined by the TsKTI formula. At high positive angles of attack, the end losses substantially increase. At negative angles of attack, the losses are considered to be approximately equal to those found at rated regimes. The leading edge of the profile practically does not affect the tip losses. Orig. art. has: 5 figures.

TIP LOSSES IN REACTION-TYPE TURBINE CASCADES IN A WIDE RANGE OF ATTACK ANGLES

A. I. Kirillov and A. P. Pavlov, Candidates of Technical Sciences, and A. S. Maksudyan, Engineer

For evaluating the efficiency of a stage operating at rotational speeds considerably different from the calculated magnitude, it is not enough to know only the profile losses of energy in the turbine cascades in a large range of variation of the attack angles [1]. In the designing of such a stage, it is also essential to have experimental data on tip losses of energy in the cascades in relationship to the attack angle. Results of such experiments are essential for calculating the characteristics of the turbine stage in its entire range of rotational speed from start to full throttle.

A number of experimental studies have been done on tip losses of energy in turbine cascades under conditions of shockless entry and comparatively small attack angles. However, experimental data on tip losses of energy in cascades during flow past them with large positive and negative attack angles are lacking.

At the M. I. Kalinin Leningrad Polytechnic Institute experimental studies were conducted on tip losses of energy in the three reaction type foil-shrouded turbine cascades L-1.5, L-6 and L-11 (Fig. 1), whose profiles are notable mainly for the thickness of their leading edges. The thicknesses of the trailing edges of all the profiles were approximately the same (Δ = 0.7-1.0 mm). For these cascades the exit flow angles in the calculated system are 24°, 17°, and 23.5°, respectively. The magnitudes of the profile angle β_y, chord b and cascade pitch t are shown in Fig. 1. The cascades had a nearly optimal pitch-chord ratio. The height of the blades in the bank was 120 mm.

The experiments were conducted for $M_2 = 0.5$ and $Re_2 = (4-4.8) \times 10^5$. The angle of influx β_1 varied within 20°-154°. To eliminate the effect of the boundary layer, increasing on the walls of the feed section of the wind tunnel, on the magnitude of tip losses, all the banks of the blades were fitted with thin cut-off plates. The working height of all the cascades $\ell = 105$ mm. The experimental data were measured and analyzed according to standard methods.

Energy losses along the blade for an L-6 cascade at various attack angles are depicted in Fig. 2. Similar distribution of losses was also obtained for the other examined cascades. Variation in the energy losses along the blade in the zone of comparatively small divergences of the influx angle from the calculated angle ($\beta_1 = 65$-104°) is practically independent of the attack angle. With large positive values of the attack angles the energy losses increased in the central section and near the blade tips. Here the area occupied by secondary currents increased with increasing attack angle, while the section of plane flow past the blades decreased.

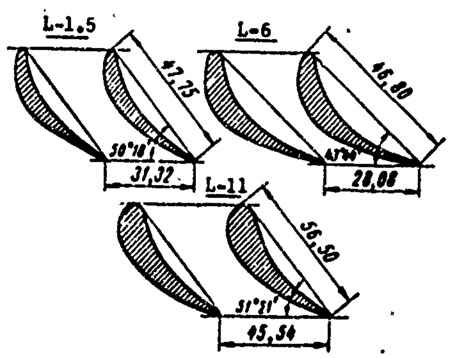

Fig. 1. Profiles of the blades.

It is generally considered [2] that for reaction cascades the minimal relative height $\bar{\ell} = \ell b$, for which joining of the zones

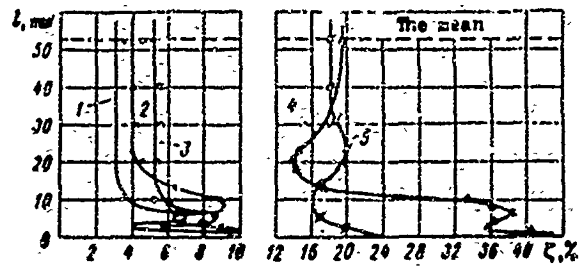

Fig. 2. Distribution of losses along the blade of the L-6 cascade with influx angles β_1:
1 – 65–104°; 2 – 40°; 3 – 130°; 4 – 20°; 5 – 154°.

of secondary currents occurs, is within the limits 0.4–0.5. For large positive attack angles, for example, when $\beta_1 = 20°$, the area encompassed by secondary currents compresses $\sim 0.7\ell$, which approximately corresponds to $\bar{\ell}_{min} = 1.5$. Therefore, for large positive attack angles even in a cascade with relatively long blades a joining of the zones of secondary currents is possible.

With an increase in negative attack angles the tip losses change insignificantly. For large values of β_1 the area encompassed by secondary currents increased, while their intensity decreased sharply.

Figure 3 charts the variation of total ζ_t and profile ζ_{pr} energy losses in the L-6 cascade. In the whole area of change of angle β_1, the absolute magnitude of tip losses of energy is small, while the increase of profile losses is accompanied by a significant variation in tip losses only in the zone of large positive attack angles. However, the proportion of tip losses in total energy losses with large attack angles is reduced in comparison with conditions approximating the calculated influx angle, which is especially apparent in an area of large negative attack angles.

The dependence of the tip losses ζ_k on β_1 for all the tested cascades is represented in Fig. 4. The curves show the general tendency of tip losses to increase with an increase in the positive attack angles and of the coefficient ζ_k to decrease in the range of negative attack angles. A notable differentiation of the curves for cascades with various profile shapes in the range $\beta_1 > 60^\circ$ was not observed. This confirms the insignificant effect of the profile shape on the tip losses of energy [3 and 4].

With large positive attack angles the L-11 cascade, which is most attack-resistant to profile losses, also had the smallest amount of energy losses. This is connected with the fact that flow separation from the convex side of profiles L-1.5 and L-6 near their leading edges sets in with smaller positive attack angles than in the L-11 cascade. As a result of the occurrence of the separation zone on the convex side of the profile, the pressure gradient across the vane channel increases, and the secondary currents are intensified. The difference in tip losses in cascades with a dissimilar thickness of the leading edge amounts to ~1%.

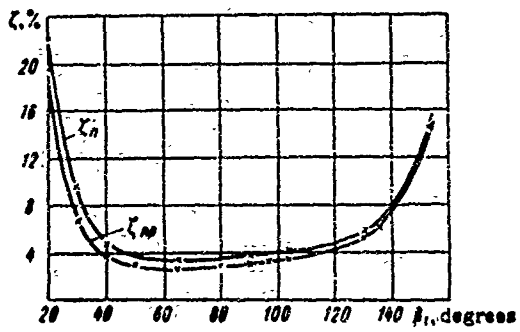

Fig. 3. Dependence of ζ_{pr} and ζ_t on β_1 for the L-6 cascade with $\bar{l} = 2.2$.

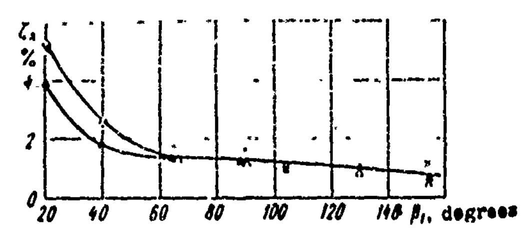

Fig. 4. Tip losses of energy as a function of the flow entrance angle for the relative length of the blades $\bar{l} = 1$ of the cascades:
Δ – L-1.5; × – L-6; ▲ – L-11.

For an approximate evaluation of tip losses of energy in shrouded foil lattices of turbine profiles the TsKTI [Central Scientific Research, Planning, and Design Boiler and Turbine Institute] formula [3] is proposed:

$$\zeta_k = (0.027 - 0.0135K)\frac{1}{l},$$

where $K = 1 - (\sin \beta_2/\sin \beta_1)^2$.

The dependence $\zeta_k = f(K)$ is derived by processing the experimental data for various cascades with influx and zero attack angle. Calculations according to the TsKTI formula satisfactorily coincide with the data of the experiments when the attack angles have small values, if β_1 is considered to be the influx angle.

A comparison of experimental values of tip losses of an L-1.5 cascade for a large range of attack angles with calculations according to the TsKTI formula is shown in Fig. 5. In the area of large positive attack angles the calculation according to the TsKTI formula gives smaller values of the coefficient ζ_k than in the experiments (the divergence is more than 1%).

With large negative attack angles, the TsKTI formula gives excessively high values of ζ_k. This is evidently explained by the fact that in the TsKTI formula only the effect of tip losses of the aerodynamic flow contraction factor is taken into account, while the rotation angle of the flow is not considered. If tip losses are considered to be dependent only on the complex K, in the L-1.5 cascade, for example, for influx angles of 30° and 150°, the magnitude K and, consequently, also the tip losses will be identical. But the character of the flow with the indicated values of β_1 is essentially different. In the first instance the flow rotates at an angle of 126°, in the second at only 6°, which shows up very strongly in the diagram of the distribution of pressures along the profile. With $\beta_1 = 150^\circ$ the pressure gradient across the vane channel is not very large and, consequently, tip losses are also small. The flow with large positive attack angles ($\beta_1 = 30^\circ$) is characterized by a significant difference in pressures between the concave and convex parts of the profile.

Consequently, it is impossible to disregard the effect on tip energy losses [4-6] of the flow rotation angle, which in rough approximation may serve as the parameters characterizing the pressure gradient in the direction across the vane channel and the intensity of the secondary currents. With very large attack angles the magnitude of tip losses is affected by not only the flow rotation angle in the cascade, but also the existence of separation zones on the profile.

Figure 5 shows the results of calculating the tip losses for the L-1.5 cascade according to the MEI [Moscow Power-Engineering Institute] formula [5]; a curve is plotted from Wolf's generalized experimental data [4].

The nature of the dependences according to the data of works [5 and 4] corresponds to the dependence obtained in the experiments, but the absolute values of the coefficients ζ_k are in the first case ~2 times less, and in the second case two times greater than in our experiments. A coincidence with the MEI formula was observed only in the area of very large negative attack angles.

Thus, tip losses of energy in reaction-type turbine foil lattices not having excessively large attack angles may be determined by the TsKTI formula with accuracy sufficient for practical purposes. With very large positive attack angles tip losses sharply increase. In the range of negative attack angles, tip losses may be considered the same as in the calculated system with accuracy of up to 0.5%. The thickness of the leading edge of the profile does not essentially affect the magnitude of ζ_k.

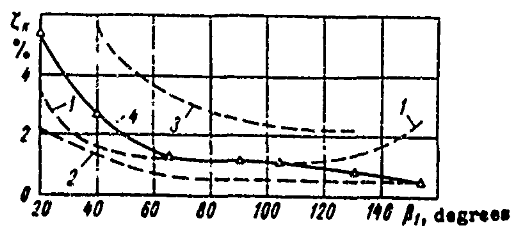

Fig. 5. Compression of tip losses of energy for $\bar{\lambda}$ = 1, per data of:
1 – TsKTI; 2 – MEI; 3 – Wolfe; 4 – experiment for the cascade L-1.5.

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