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TRANSLATION

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By

M. Ye. Deych, A. V. Gubarev, et al

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INVESTIGATION OF NEW M.E.I. NOZZLE CASCADES

FOR SUPERSONIC VELOCITIES

M. Ye. Deych, Doctor of Technical Sciences, A. V. Gubarev, Candidate of Technical Sciences, L. Ya. Lazarev, Engineer, and A. Dzhaganmakhan, Engineer

Moscow Energetics Institute

Recommendations are made for the design of nozzle cascades which are distinguished by high efficiency over a wide range of supersonic velocities. Results of investigations of new cascades are given for Mach numbers from 0.6 to 1.8.

At the present time much attention is being given to the question of the application, in turbines, of stages in which the developed heat drops significantly exceed the critical drops. The application of such stages in vehicle turbines, where weight and size characteristics are of primary importance, holds particular promise. In addition, the questions of efficiency of turbines both under calculated and varying conditions play an essential role in the selection of stage types.

It is known that the efficiency of nozzle cascades under varying conditions (with changing M number) depends mainly on the shape of the vane channels. Thus, convergent cascades are usually characterized by small losses at subsonic speeds and the losses sharply increase for M > 1, while for divergent cascades the losses are small over a sufficiently narrow range of supersonic velocities, but they reach high values at transonic velocities and for $M > M_r$. Therefore, the attempts of several authors to develop such cascades that would have steady efficiency over a wide range of supersonic velocities seem natural.

Let us consider some of the properties of gas flow in guide cascades at supersonic velocities. We will write equations of continuity and energy for two control sections: a narrow one (cr-cr) and one at an infinite distance behind the cascade (2-2) (Fig. 1). Here we will assume that the flow parameters in these sections are constant:

$$\rho_{cr} c_{cr} \sin\alpha_{1\,cr} = \rho_2 c_2 \sin\alpha_2, \quad (1)$$

$$\frac{p_{cr}}{\rho_{cr}} + \frac{k-1}{k}\frac{c_{cr}^2}{2} = \frac{p_2}{\rho_2} + \frac{k-1}{k}\frac{c_2^2}{2}. \quad (2)$$

where $\alpha_{1\,cr} = \arcsin a_{cr}/t$;

$\alpha_2 = \alpha_{1\,cr} + \delta_{cr}$;

δ_{cr} — flow-deviation angle.

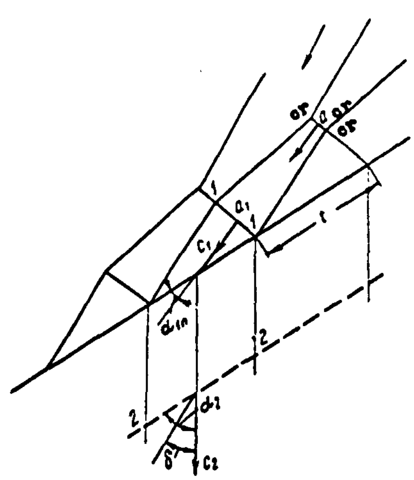

Fig. 1.

Substituting (1) into (2) and converting we obtain:

$$\delta_{cr} = \arcsin\left[\frac{p_{cr}}{p_2}\cdot\frac{1}{\lambda_2}\frac{k+1}{2}\times\left(1-\frac{k-1}{k+1}\lambda_2^2\right)\sin\alpha_{1\,cr}\right] - \alpha_{1\,cr} \quad (3)$$

If, during the flow of gas between the control sections the losses are equal to zero, we obtain the usual Baehr formula:

$$\delta'_{cr} = \arcsin\left(\frac{1}{q_{2r}}\sin\alpha_{1\,cr}\right) - \alpha_{1\,cr} \quad (3')$$

Taking into account losses Formula (3) may be written in the form:

$$\delta_{cr} = \arcsin\left[\frac{1}{q_{2,T} f(\lambda_{2,T}; \zeta)} \cdot \sin \alpha_{1,cr}\right] - \alpha_{1,cr} \qquad (4)$$

where $f(\lambda_{2,T}, \zeta) = \frac{p_{02}}{p_0} \frac{q_2}{q_{2,T}} < 1,0;$ and ζ is the coefficient of energy loss.

The subscript T refers to the flow parameters for $\zeta = 0$. From this it is apparent that for the given value of λ_{2T} (M_{2T}) the flow-deviation angle (δ_{cr}) is uniquely associated with energy losses in the presence of flow expansion, i.e., energy losses in a variable regime for $M > 1$ are determined by the quantity $\Delta\delta = \delta_{cr} - \delta'_{cr}$.

It is known experiments [1] that in divergent cascades of the usual type, for $M_2 < M_r$, the flow outlet angle $\alpha_2 \approx \alpha_{2,r}$, while according to Formula (3') it should decrease. Such constancy of the angles is determined by the presence of a transverse cross section. Let us dwell on this question in more detail. We will write the equations of continuity, energy, and momentum for three control sections (Fig. 1):

$$\rho_{cr} c_{cr} \sin \alpha_{1,cr} = \rho_1 c_1 \sin \alpha_1 = \rho_2 c_2 \sin \alpha_2, \qquad (5)$$

$$\frac{p_{cr}}{\rho_{cr}} + \frac{k-1}{k} \frac{c_{cr}^2}{2} = \frac{p_1}{\rho_1} + \frac{k-1}{k} \frac{c_1^2}{2} = \frac{p_2}{\rho_2} + \frac{k-1}{k} \frac{c_2^2}{2}, \qquad (6)$$

$$\begin{gathered} \rho_{cr} c_{cr}^2 \cdot t \cdot \sin \alpha_{1,cr} + p_{cr} \cdot t \cdot \sin \alpha_{1,cr} + \\ + \left(\frac{p_1 + p_{cr}}{2}\right) \cdot t (\sin \alpha_1 - \sin \alpha_{1,cr}) = \rho_1 c_1^2 t \sin \alpha_1 + \\ + p_1 t \cdot \sin \alpha_1 = \rho_2 c_2^2 \cdot t \cdot \sin \alpha_2 \cos(\alpha_2 - \alpha_1) + p_2 t \cdot \sin \alpha_1. \end{gathered} \qquad (7)$$

where

$$\alpha_1 = \arcsin \frac{a_1}{t}.$$

Solution of this system of equations makes it possible to determine the flow outlet angle for a divergent cascade:

$$\tan(\alpha_2-\alpha_1)=\frac{\sqrt{\left(\frac{k}{k-1}\bar{p}\right)^2\{\cot^2\alpha_{1\,cr}-(\bar{f}^2-1)\}+\frac{k+1}{k-1}\left[k^2-\frac{(k-1)(K-\bar{p}\bar{f})^2-2\bar{p}\bar{f}k(K-\bar{p}\bar{f})}{k+1}\right]}}{K-\bar{p}\bar{f}}-$$

$$-\frac{\frac{k}{k-1}\bar{p}\sqrt{\cot^2\alpha_{1,cr}-(\bar{f}^2-1)}}{K-\bar{p}\bar{f}}, \tag{8}$$

and also wave losses:

$$\zeta_w=1-\frac{\left(K-\frac{\varepsilon_2}{\varepsilon_{cr}}\bar{f}\right)^2}{k^2\left(\frac{k+1}{k-1}\right)\left(1-\varepsilon_2^{\frac{k-1}{k}}\right)\cos^2\delta}, \tag{9}$$

where

$$K=k+1+\frac{1}{2}\left(1+\frac{p_1}{p_{cr}}\right)(\bar{f}-1);$$

$$\bar{p}=\frac{p_2}{p_{cr}};\quad \varepsilon_2=\frac{p_2}{p_0};\quad \varepsilon_{cr}=\frac{p_{cr}}{p_0};\quad \bar{f}=\frac{a_1}{a_{cr}}.$$

For $\bar{f}$ = 1.0, these formulas convert to the well-known Stepanov formulas.

Figure 2a shows a comparison of computational and experimental results for flow outlet angles and Fig. 2b shows the computed curve for wave losses. It is apparent that there is satisfactory coincidence between experimental data and calculation according to Formula (8) for $M_2 < M_r$. It should also be noted that for $M_2 < M_r$, wave losses are very high. Thus, theoretical analysis shows that the flow outlet angle for a divergent cascade in the transonic region is greater than indicated by Formula (3'). This explains the sharp rise in losses in divergent cascades for $M_2 < M_r$. Consequently, divergent cascades cannot in principle operate effectively in transonic regimes.

On the other hand, in convergent cascades there is observed, in supersonic regimes, considerable flow overexpansion at the back of the airfoil, and an edge shock, as a rule, leads to boundary layer separation. Therefore, in convergent cascades operating at transonic and low supersonic velocities, it is necessary to give the back of the airfoil a small curvature, and for $M > 1.2$ it is expedient to make the back concave [2, 3]. This leads to the fact that losses are small not only at subsonic velocities but also at low supersonic velocities because in the latter case the degree of overexpansion of flow on the back is reduced. In this connection, the greater the concavity of the back of the airfoil, the greater the Mach numbers at which the convergent cascade will operate at high efficiency.

This method of designing the cascade is possible only to a Mach number of 1.4 since with an increase in concavity of the back, the rigidity of the airfoil over the transverse cross section is reduced and undercutting of the edge might occur.

Therefore, for cascades designed for Mach numbers greater than 1.4 the following solution suggests itself. The expansion ratio of the vane channel is selected somewhat lower than follows from the well-known dependence $\bar{f} = 1/q(M_r)$ and the back of the airfoil in the transverse cross section is made concave. This method of designing the cascade makes it possible to reduce losses at transonic velocities since their magnitude is mainly determined by the parameter $\bar{f}$. It is possible to determine two calculated Mach values for the cascade: one is determined according to the expansion ratio and the other with regard for the concavity of the back in the transverse cross section. The efficiency of the cascade is sufficiently high over a wide range of Mach numbers greater than 1.0.

The table shows the fundamental geometric characteristics of the cascades studied. Here M_r' was determined according to the parameter $\bar{f}$, and M_r was determined with regard to the curvature of the back in the transverse cross section.

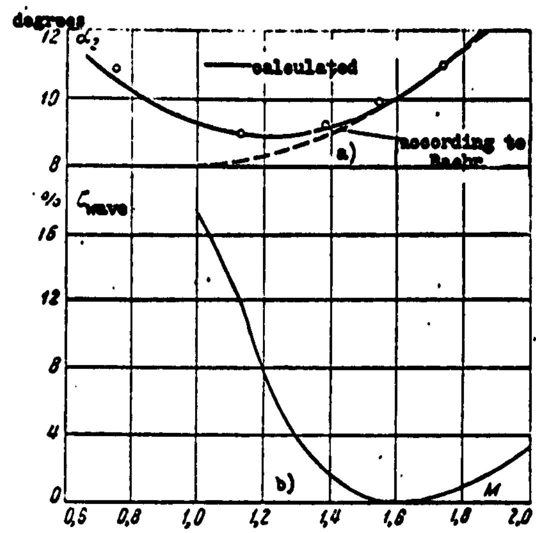

Fig. 2. a) variation of flow outlet angle for divergent cascades; b) wave losses in cascade for $\overline{T}$ = 1.28.

Figure 3b shows the results of an investigation of the influence of the shape of the back of the airfoil on the characteristics of the cascades. The airfoils of these cascades differed only in the curvature of the back by-passes at the outlet section (Fig. 3a). The distribution of pressures along the airfoils in the cascades indicates that with an increase in M overexpansion of flow increases in cascade No. 9 with a straight back and the overexpansion of flow decreases in cascade No. 11 with a concave back in the transverse cross section. As a consequence, there is a variation in the losses in these cascades. Actually, for cascade No. 9 when M > 1.2 the losses rise sharply, while for cascade No. 11 a loss peak is observed in the range M ≈ 1.2 and for M > 1.2 losses decrease and a minimum is reached near M ≈ 1.5.

Also of great interest is the dependence of losses on Mach number for divergent cascades No. 10 and 12. As can be seen, losses for these cascades are the same over the entire range of Mach numbers investigated. Consequently, for M ≈ 1.0, losses in the cascade are practically independent of the shape of the channel and are determined by the parameter $\bar{T}$. In addition, no influence of the concavity of the back for M > 1.0 was discovered. This is explained by the fact that the reverse curvature of cascade No. 12 is concentrated mainly in the divergent part of the channel while in the transverse cross section the back is straight (Fig. 3a).

Figure 4 shows the curves of losses in cascades designed with small flow outlet angles (cascades Nos. 1-8). In addition, for airfoils TS-1VR-1 (cascade No. 1) and TS-1VR-3 (cascades Nos. 5-8) the concavity of the backs reaches 1% and for airfoil TS-1VR-2 (cascades Nos. 2-4) the concavity is small. From the curves considered it is apparent that the losses for all divergent cascades attain large values at transonic velocities and then sharply drop. The loss level at transonic velocities is determined mainly by the parameter $\bar{T}$. However, for cascade No. 1 ($\bar{T}$ = 1.13) at M ≈ 10, smaller losses are obtained than in cascade No. 3 (for $\bar{T}$ = 1.042). The reason for this is that the length of the divergent section of the vane channel in cascade No. 1 is significantly smaller than in the other. It is very interesting to compare the curves for losses in cascades No. 2 and 5 for $\bar{T}$ = 1.0. Thus, in cascade No. 2 (Fig. 4a) the losses are almost constant (ζ = 6%) in the range of Mach numbers from 0.8 to 1.5, and increase for M > 1.5, while in cascade No. 5 the losses increase at the outset, reach a maximum at M = 1.2, and then decrease. Minimum loss (ζ = 6%) is attained at M ≈ 1.5. This characteristic loss variation for cascade No. 5 as well as for cascade No. 11 (Fig. 3b) is caused by the relatively great concavity of the back of the airfoil in the transverse cross section. It should be noted that the maximum loss for cascade No. 5 shifts somewhat toward high Mach numbers as compared with cascades of the divergent type.

Geometric Characteristics of Cascades

Cascade No.	Airfoil	$\bar{t}$	α_y	$\alpha_{1,cr}$	$\bar{l}$	M_r'	M_r
1	TC-1BP-1	0,595	30°00'	8°30'	1,13	1,43	1,76
2	TC-1BP-2	0,703	20°45'	9°05'	1,0	1,00	1,3
3	TC-1BP-2	0,621	20°45'	8°30'	1,042	1,25	1,6
4	TC-1BP-2	0,550	20°45'	8°50'	1,10	1,48	1,6
5	TC-1BP-3	0,745	29°30'	9°30'	1,00	1,0	1,3
6	TC-1BP-3	0,655	29°36'	10°00'	1,06	1,28	1,6
7	TC-1BP-3	0,615	29°36'	9°15'	1,10	1,37	1,7
8	TC-1BP-3	0,550	29°36'	8°05'	1,28	1,63	1,75
9	TC-2BP-4	0,675	40°16'	12°30'	1,00	1,0	1,0
10	TC-2BP-4	0,611	40°16'	12°00'	1,10	1,37	1,37
11	TC-2BP-5	0,675	40°16'	12°30'	1,00	1,0	1,6
12	TC-2BP-5	0,611	40°16'	12°20'	1,09	1,35	1,45
13	TC-2BP-6	0,615	31°36'	10°50'	1,10	1,37	1,7
14	TC-2BP-7	0,620	35°00'	13°30'	1,06	1,28	1,6
15	TC-3BP-8	0,715	40°00'	16°20'	1,00	1,00	1,4
16	TC-3BP-8	0,650	40°00'	16°35'	1,055	1,25	1,55
17	TC-3BP-8	0,583	40°00'	14°10'	1,13	1,43	1,6
18	TC-3BP-8	0,520	40°00'	13°40'	1,24	1,59	1,7
19	TC-4BP-9	0,750	48°00'	21°50'	1,00	1,00	1,3
20	TC-4BP-9	0,698	48°00'	21°10'	1,02	1,15	1,5
21	TC-4BP-9	0,62	48°00'	20°00'	1,07	1,31	1,6
22	TC-4BP-9	0,565	48°00'	19°10'	1,2	1,53	1,65

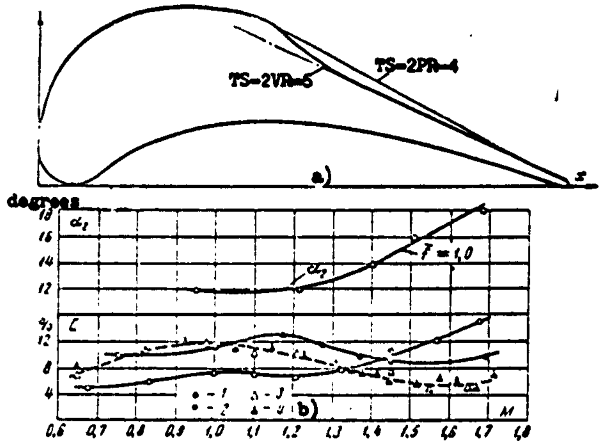

Fig. 3. a) comparison of airfoils TS-2PR-4 and Ts-2VR-5; b) influence of back shape of the airfoil in transverse cross section on the characteristics of the cascades. 1) cascade No. 9 $\bar{t}$ = 1.0; 2) No. 11, $\bar{t}$ = 1.0; 3) No. 10, $\bar{t}$ = 1.1; 4) No. 12, $\bar{t}$ = 1.09.

Analysis of the curves shows that minimum loss in the cascades occurs at M_r determined taking into account the concavity of the back of the airfoil in the transverse cross section, while losses at M_r' are somewhat larger. It must be pointed out that over the entire range of regimes the efficiency of the cascades developed was significantly greater than for those used previously in turbine construction [4].

Figure 5 shows the characteristics of cascades with large flow outlet angles. The above-mentioned character of the variation of losses is preserved for these cascades as well. It should be noted that the length of the divergent section of the vane channel for these cascades is significantly smaller than for the cascades whose characteristics are represented in Fig. 4. As a result, the level of losses for the same $\bar{f}$ in transonic regimes are smaller. It is very interesting to compare the loss curves for $\bar{f} = 1.0$ and $\bar{f} = 1.055$ in Fig. 5a. As is apparent, losses in cascade No. 15 are greater than in No. 16 over the entire range of Mach numbers investigated. In this connection the losses for cascade No. 15 are practically constant and amount to 7-8%. It is interesting to compare loss curves for cascades 21 and 22. It is apparent that minimum loss for these cascades is attained at the same Mach numbers (M = 1.6-1.7), despite a significant difference in the $\bar{f}$ parameters.

Figures 3-5 also show curves of the variation of flow outlet angle for certain cascades. For cascades with $\bar{f} = 1.0$ (Fig. 3) the flow outlet angle begins to increase at $M > 1.0$ whereupon, if for $m = 1.0$, $a_2 = 12^o$, then for $M = 1.7$ the flow outlet angle reaches 18^o. Such a variation in flow outlet angle may seriously impair the operation of the stage in variable regimes. For diverging cascades the flow outlet angles are practically constant for $M < M_r^{\prime}$ and begin to increase only for $M > M_r^{\prime}$. As a result, the variation of the flow outlet angles is significantly smaller over the range $M = 1.0$-1.7.

Figure 6 shows the variation of the loss differences $\Delta\zeta = \zeta_{max} - \zeta_{min}$ for the divergent cascades investigated with respect to the parameter $\bar{f}$. Also shown (dashed line) is the function $\Delta\zeta = \varphi(\bar{f})$ for cascades used earlier. It is apparent that the cascades studied are distinguished from those used earlier by the smaller variations of efficiency in variable regimes. Analysis of the results indicates that the scatter of points is due to the difference of the relative length of the divergent portion of the vane channel of the cascade. In this connection, a large $\Delta\zeta$ is observed for cascades with a smaller exposure angle of the divergent portion of the channel.

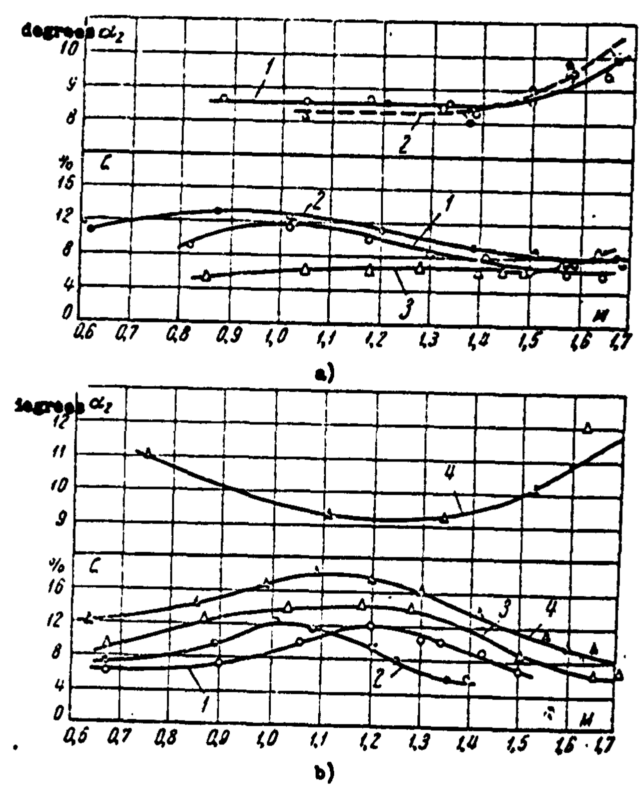

Fig. 4. Characteristics of supersonic guide cascades with small flow outlet angles. a) 1 — cascade No. 1, $\bar{f}$ = 1.13, concave airfoil back; 2 — No. 3, $\bar{f}$ = 1.042; 3 — No. 2, $\bar{f}$ = = 1.0; b) 1 — cascade No. 5, $\bar{f}$ = 1.0; 2 — No. 6, $\bar{f}$ = 1.06; 3 — No. 7, $\bar{f}$ = 1.10; 4 — No. 8, $\bar{f}$ = 1.28.

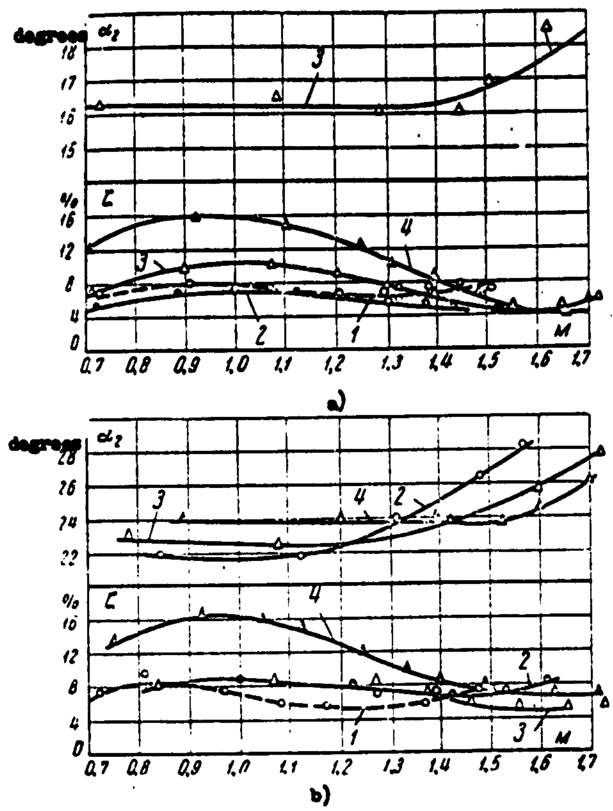

Fig. 5. Characteristics of supersonic directing cascades with large flow outlet angles. a) 1 — cascade No. 15, f = 1.0, concave airfoil back; 2 — No. 16, $\bar{f}$ = 1.055, concave airfoil back; 3 — No. 17, $\bar{f}$ = 1.13, concave airfoil back; 4 — No. 18, $\bar{f}$ = 1.24, concave airfoil back; b) 1 — cascade No. 19, $\bar{f}$ = 1.0, concave airfoil back; 2 — cascade No. 20, $\bar{f}$ = 1.02, concave airfoil back; 3 — No. 21, $\bar{f}$ = 1.07, concave airfoil back; 4 — No. 22, $\bar{f}$ = 1.20, concave airfoil back.

Figure 6 shows the variation of losses in cascades versus $\alpha_{1\ cr} = \arcsin \frac{a_{min}}{t}$ for the calculated M_r value. It is apparent that all of the experimental points lie quite close to a single curve. In addition, losses at the calculated M_r for $\alpha_{1\ cr} \approx 8^\circ$ amount to 7% and decrease with an increase in $\alpha_{1\ cr}$ and for $\alpha_{1\ cr} = 14^\circ$ they amount to 4-5%. It should be noted that in cascades which are in use at the present time, losses reach 6-7% for $\alpha_{1\ cr} = 12$-14° for the calculated Mach value M_r.

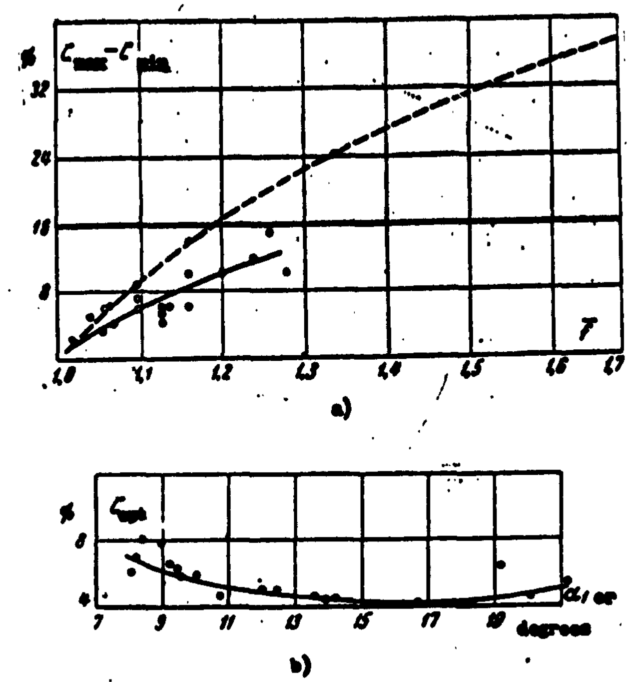

Fig. 6. a) influence of parameter $\bar{T}$ on quantity $\Delta\zeta = \zeta_{max} - \zeta_{min}$; b) influence of $\alpha_{1\,cr} = \arcsin \frac{a_{min}}{t}$ on losses in divergent cascades in calculated regimes.

Conclusions

Theoretical analysis and test results indicate that divergent cascades cannot in principle operate efficiently in transonic regimes. In addition, the loss in transonic regimes is clearly defined by the difference $\alpha_2 - \alpha_{1\,cr}$.

Convergent cascades, from the point of view of operation at variable regimes both at transonic and supersonic velocities up to $M = 1.4$, in principle prove to be much better that divergent cascades. In this connection, it is necessary to make the back concave since such a shape of the back reduces the probability of flow breakaway behind the compression shock which arises as the result of the overexpansion of the flow on the back of the profile. As is known, the flow behind the shock is deflected from the wall and if the wall is deflected in the same direction, the probability of breakaway is reduced.

For $M > 1.4$-1.5, convergent cascades cannot be made with a concave back due to undercutting of the edge. Tests have shown that for $M > 1.5$ the use of divergent cascades is expedient. However, the expansion ratio must be considerably smaller than calculated and it is expedient to make the back of the profile concave. As a result, such cascades yield relatively small losses in the calculated regimes (for $M \approx 1.0$) and are distinguished by high efficiency over a relatively wide range of supersonic regimes.

Losses in divergent cascades under transonic conditions are determined both by the expansion ratio of the vane channel and by the angle of exposure of the divergent portion of the channel. Losses decrease with an increase in the angle of exposure.

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