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REDUCTION OF THE SHOCK WAVE INTENSITY BY MODIFYING THE TRANSSONIC BLADE TRAILING EDGE

Piotr Doerffer

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16. Abstract It is shown that the shock wave intensity can be decreased by using modified trailing edge configurations to reduce or even completely compensate for the effect of the finite thickness of the trailing edge. A theoretical analysis is presented together with numerical results for two supersonic streams flowing off the trailing edge at different velocities. The analysis is based on an ideal fluid model.

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REDUCTION OF THE SHOCK WAVE INTENSITY BY MODIFYING THE TRANSSONIC BLADE TRAILING EDGE

Piotr Doerffer

Gdansk

The paper contains a theoretical analysis and results of numerical calculations for a supersonic flow-off from a trailing edge of two homogensous streams of different velocities. The model of the ideal fluid was assumed for the analysis. /3*

Designations

H - trailing edge thickness

k - isentropic exponent

M_1 - Mach number on the overpressure side

M_2 - Mach number on the vacuum side

M_{red} - reduced Mach number

p_o - ram pressure

p_1 - pressure on the overpressure side related to the ram pressure

p_2 - pressure on the vacuum side related to the ram pressure

p_{red} - reduced pressure related to the ram pressure

p_b - basic pressure determined according to Korst related to the ram pressure

t - sum of stream width and edge thickness

x_o - length of trailing profile

η - flow efficiency

$$\eta = \frac{\sum_i [(1-\zeta_i)\times G_i]_1 + \sum_i [(1-\zeta_i)\times G_i]_2}{\sum_i G_{i1} + \sum_i G_{i2}};$$

G_1 - mass discharge in the stream tube

ζ_1 - loss of energy in the wave in stream tube

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

The indexes are related to:

1 - overpressure side

2 - vacuum side.

1. Introduction

The following zones of intensive losses of energy can be singled out in a transsonic canal: boundary layer, aerodynamic track and shock waves. The losses due to shock waves, which are the subject of the present paper, increase with the increase of the Mach number in front of the wave. According to literature data [1, 2], already at velocities smaller than M=2 the value of losses /4 due to the waves can be higher than those in the boundary layer. The losses related to shock waves are caused by:

- losses of energy on the cascade,
- losses in the flow separations on profiles in the places of shock wave incidence.

The aim of the analysis presented in this paper was to increase the flow efficiency in a supersonic canal by reducing the intensity of shock waves. The goal has been achieved by modifying the shape of the trailing edge.

2. Flow Model

The photograph (Figure 1) [7] presents an interference pattern of a transsonic flow through a cascade. It is a cascade of tip profiles of a modern high-duty blade in the last stage of a high-power turbine, designed by the Japanese Mitsubishi company in 1977.

As may be seen in the photograph, behind the trailing edge of the blade occurs a formation of two shock waves and an aerodynamic track. In the section perpendicular to the profile, at the height

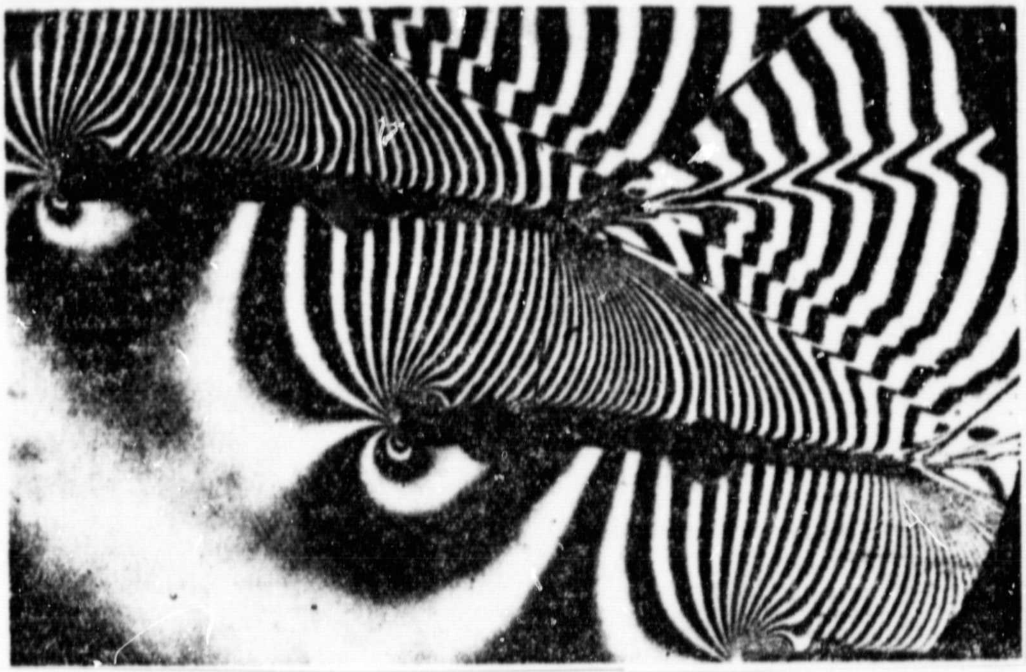

Figure 1. Interference photograph of the flow through tip profiles cascade in the last stage of a high-power turbine [7].

of the trailing edge, the velocity of the stream is slightly changeable along the segment marked on the picture. At the outflow from the cascade, on the overpressure side of the blade, there occurs a strong expansion focussed just on the trailing edge. This means that the stream velocities are different on both sides of the blade and the associated difference of static pressures causes a deflection of the stream behind the blade.

So it seems to be justified to assume for the analysis of the pattern of shock waves behind the trailing edge homogeneous streams of different supersonic velocities on both sides of the blade. /5

The interest in an analytical method for the determination of the flow parameters in the zone of the flow-off from the edge is very high, but the complexity of this problem resulting, in this case, from the strong influence of viscosity upon the flow and the vicinity of super- and subsonic zones caused the question still to be open. So far, solutions were obtained for a symmetrical flow, on the assumption of equal stream velocities and laminar boundary layers.

But because these assumptions are not adequate to the situation of the flow-off from the blade, in the present work the model of an ideal fluid has been assumed. It is a great simplification, leading to neglecting the boundary layers and aerodynamic track, but this model enables a relatively simple analysis of the location of formed shock waves and the losses associated with them. The method of characteristics was used in the calculations.

When using such a model for the calculations, it is necessary to know the flow separation point on the trailing edge. This imposes that we assume, as starting point for the analysis, a rectangular edge on which the flow separation occurs at the corners. As the experimental research proves [8], the shape of a track behind a generally used rounded edge and a rectangular one is nearly identical.

3. Methods of Reducing Shock Wave Intensity

At the flow-off from an edge, there exist two factors generating shock waves:

- pressure difference of the streams flowing off,
- finite thickness of the edge.

The difference in pressures of the streams flowing off is caused by the shape of the blade and is the source of the aerodynamic lift. A reduction of the wave intensity by reducing the difference of pressures of the streams flowing off would cause a decrease of the profile's aerodynamic lift.

The attenuation of the shock waves must be limited, therefore, to the reduction of the finite thickness effect on the trailing edge.

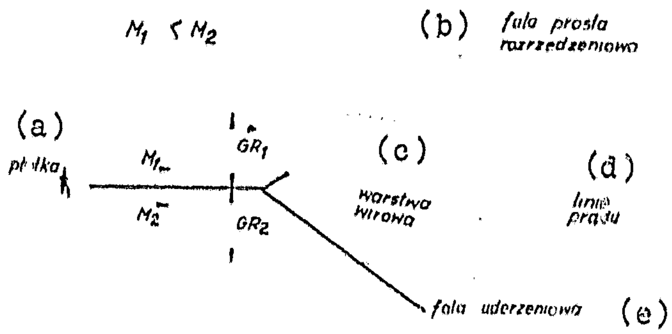

Figure 2. Wave pattern during supersonic flow-off from an infinitely thin plate.

Key: (a) Plate; (b) Straignt rarefaction wave; (c) Vortex layer; (d) Current lines; (e) Shock wave

As a comparative flow, enabling the evaluation of the effects of attempts undertaken to reduce the shock wave intensity, there may be assumed a flow-off from an infinitely thin plate (Figure 2). In such a flow, the effect of finite edge thickness does not appear at all. The flow is characterized by the appearance of a straight rarefaction wave on the overpressure side and a skew shock wave on the vacuum side. Because the shock wave intensity is, in this case, constant over the whole length, the summary flow efficiency is expressed by the dependence: /6

$$\eta=\frac{G_1+(1-\zeta_2)G_2}{G_1+G_2}=1-\frac{\zeta_2}{\frac{G_1}{G_2}+1},$$

thus, it does not depend on the absolute widths of the flowing off streams but on their ratio.

The pattern of the flow-off from an edge of finite thickness has a more complicated character and, within the model of an ideal fluid, it can be presented as in Figure 3. Directly behind the edge there is a zone of stagnation determined by the current lines of the flowing off streams. Their deflection depends on the basic pressure in this zone. This pressure has been determined according to the publication of Korst [4], who gave the dependence $p_b/p_{red}=f(M_{red})$ for $k=1.4$, where

$$p_{red}=f(M_{red}), \quad M_{red}=f(M_1,M_2).$$

On the corners occurs the formation of straight rarefaction waves and on the crest of the flow-off zone the shock waves are generated. Beginning from point I, at the overpressure side the rarefaction wave weakens the shock wave up to its total fading.

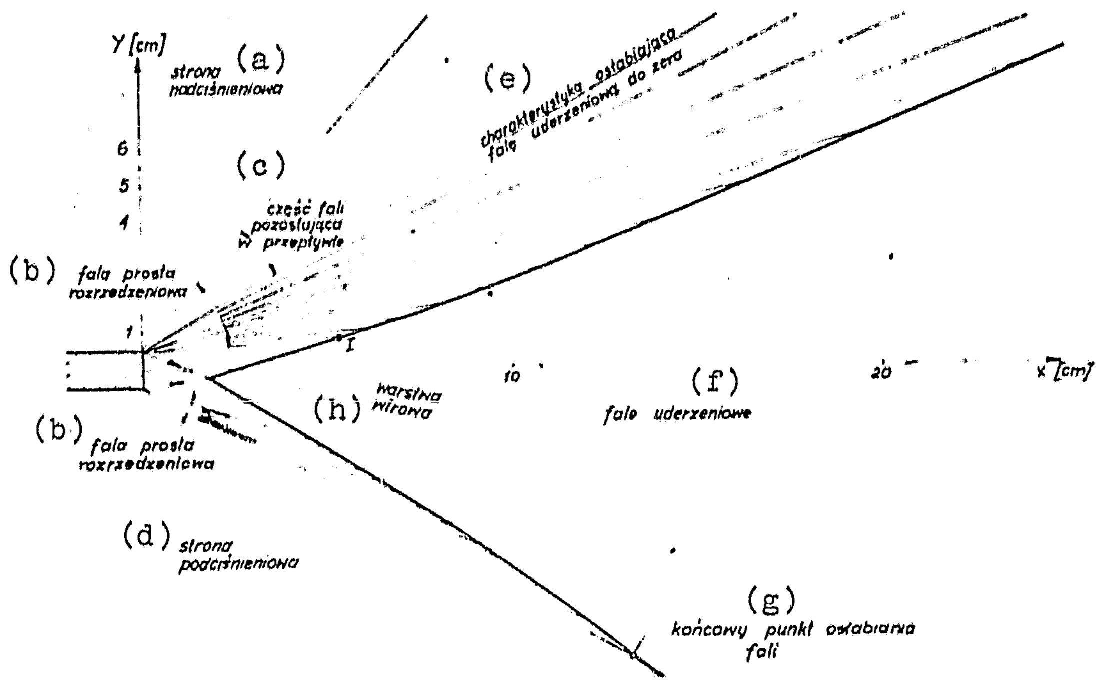

Figure 3. Wave pattern during supersonic flow from a plate.

Key: (a) Overpressure side; (b) Straight rarefaction wave; (c) Part of wave remaining in flow; (d) Vacuum side; (e) Characteristic weakening shock waves up to zero; (f) Shock waves; (g) Wave weakening end point; (h) Vortex layer.

Only the remaining part of the rarefaction wave spreads further in /7
the flow. The existence of the shock wave on the overpressure side is caused, exclusively, by the finite thickness of the trailing edge. On the vacuum side, the shock wave is weakened only in a certain segment.

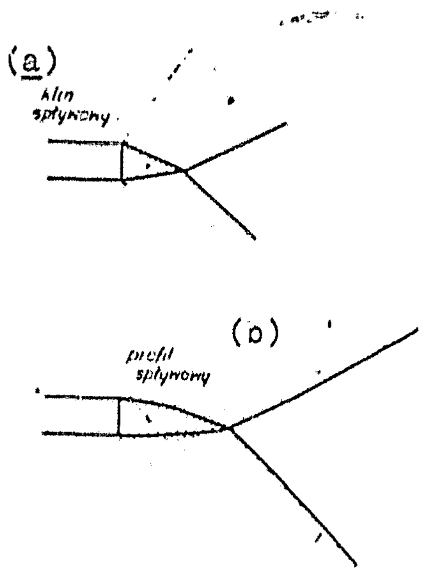

Figure 4. Trailing edge shapes.
Key: (a) Trailing wedge;
(b) Trailing profile

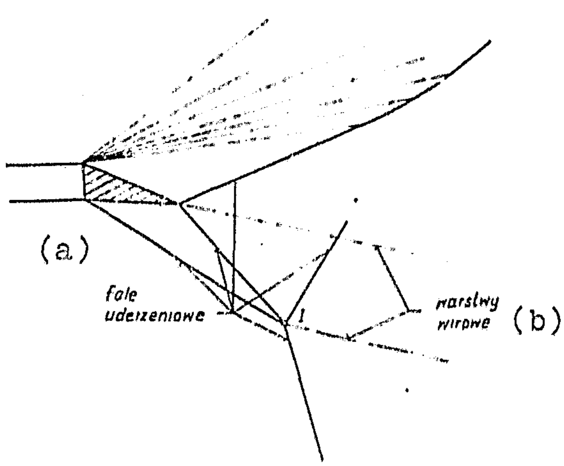

Figure 5. Wave pattern behind a wedge-shaped edge for assumed $p_b > p_2$.
Key: (a) Shock waves; (b) vortex layers

The shock wave that spreads farther back in the flow on the vacuum side and the remaining part of the rarefaction wave in the neighboring stream respond to the waves generated at a flow off from a thin plate. The zone of influence of the trailing edge finite thickness is, thus, enclosed between the characteristic weakening the shock wave up to zero on the overpressure side and the last characteristic weakening the shock wave on the vacuum side.

The shock wave intensity is directly related to the expansion range at the corners. If this range is reduced, the intensity of the waves will also decrease. This effect can be obtained by modifying the shape of the trailing edge consisting in the flow-off zone of a wedge longer than the length of this zone. Very important is the selection of the proper shape of the wedge. The best is a wedge providing a symmetrical flow-off [6], as happens in the case of the stagnation zone. The shape of the wedge was calculated on the basis of assumed basic pressure and the longer the wedge used had to be, the higher basic pressure had to be assumed.

In a flow of this kind there appear initial segments of shock waves having a constant intensity and just in those segments the shock wave intensity is highest. Their inactivation ensures a further possibility of increasing the flow efficiency. The flow efficiency increase has been achieved by modifying the trailing edge shape that consisted in replacing the trailing wedges by trailing profiles with curved walls (Figure 4). With a geometry of this kind, the rare- /8
faction wave weakens the shock wave from the beginning.

Using longer and longer trailing profiles or wedges, which is equivalent to assuming higher and higher basic pressures, up to a value equal to the pressure on the vacuum side (let us call it p_2), a flow off pattern is kept with expansions in both streams. If the basic pressure exceeds the value p_2, the flow pattern on the vacuum side will change.

When a wedge is used (figure 5), the formation of two waves intersecting in point I occurs, generating two new shock waves and a vortex layer.

If a trailing profile with curved walls is used (Figure 6), a straight compression wave and a flow off shock wave are formed. In such a case there exist two possibilities:

- the straight compression wave strengthens the shock wave and itself forms a shock wave, and the waves intersect (Figure 6a),
- the straight compression wave strengthens only the intensity of the flow-off shock wave (Figure 6b).

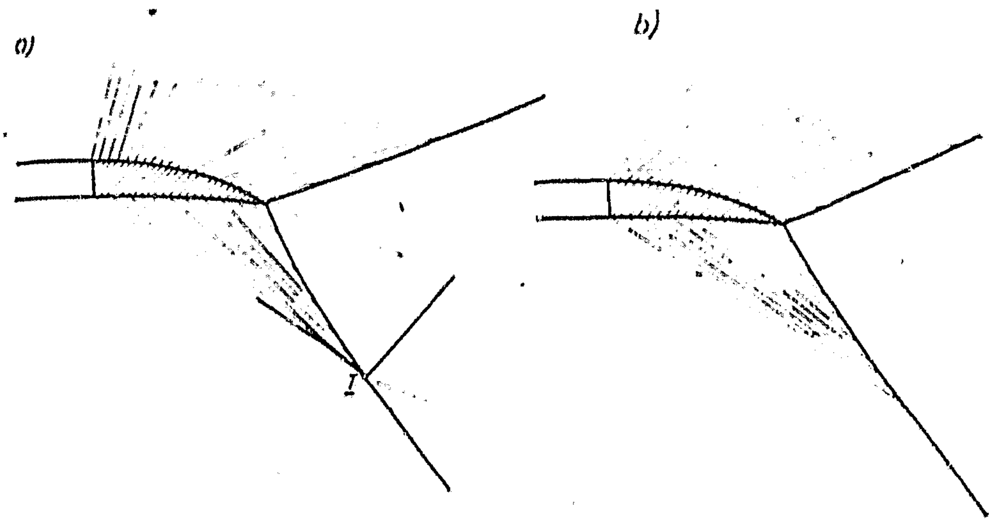

Figure 6. Wave patterns behind an edge with rounded walls for assumed $p_b>p_2$.

4. Calculation Results

The velocities of the streams flowing off from the edges were assumed to be $M_1=1.5$ and $M_2=2.0$ according to literature data [9, 10, 11].

Apart from the assumptions indicated when discussing the flow model (Par. 2), there was assumed an equal width of both streams and the shape of the trailing profile walls corresponded to circular segments.

The diagram (Figure 7) represents the dependence $\eta=f(H/t)$. In the drawing the basic pressure p_b was shown corresponding to respec- /9 tive trailing wedges or profiles and the pressure p_2 - on the vacuum side for this calculation example. The horizontal dotted line determines the efficiency of the flow-off from a thin plate, which means

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that it takes into account only the losses resulting from the difference in the stream pressures. The trend of parameter H/t to zero indicates an approach to just such a case of flow, and that is why all the efficiency curves have their beginning from a common point representing the efficiency of a flow-off from a thin plate. The maximum value of the parameter is H/t=1. In the diagram the range of changes was shown only up to H/t=0.5, because already at this value the curves have a very flat course.

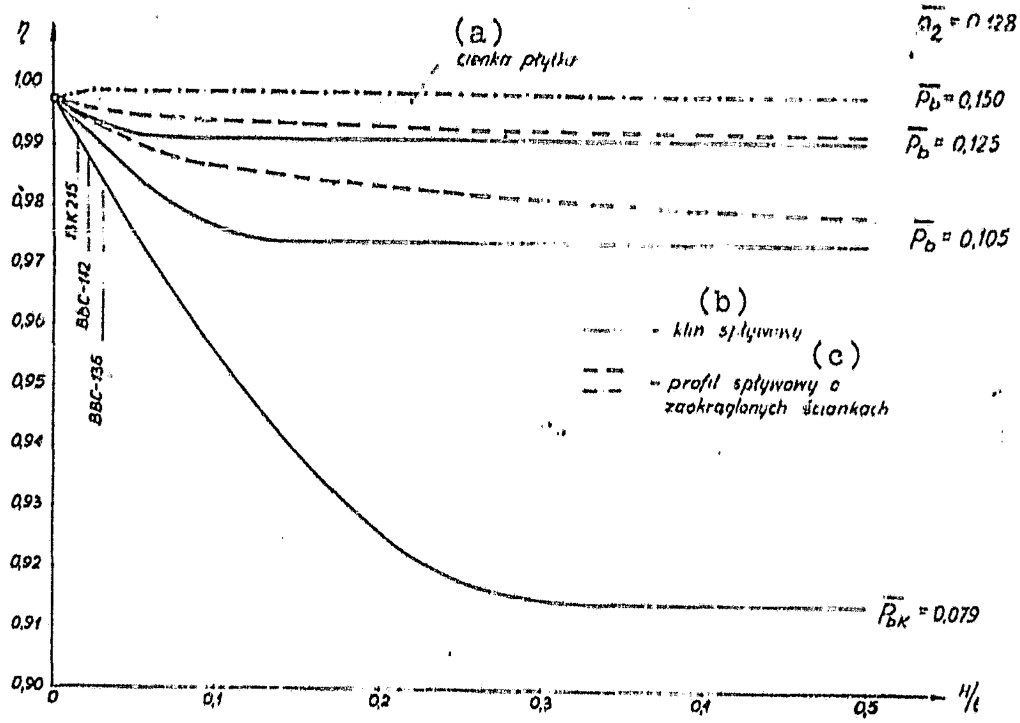

Figure 7. Diagram of the function η=f(H/t) for various shapes of trailing edges.

Key: (a) Thin plate; (b) Trailing wedge; (c) Trailing profile with rounded walls.

The lowest continuous curve corresponds to the basic pressure appearing in the stagnation zone behind a rectangular trailing edge shown in figure 3. At the beginning, the drop in efficiency resulting from the narrowing of the zone around the edge (H/t increases) is very strong. Then the curve begins to get flat and attains a constant value of efficiency. This constant value of efficiency is associated with the appearance of the initial segments of the shock wave having a constant intensity. In the diagram were indicated the values of H/t parameters for the transonic profiles BBC-136, BBC-142 and the tip profile of the last stage of the 13K215 turbine. The losses due to shock waves for those H/t parameters are 1-2%. At such values of the H/t parameter the losses associated with the effect of finite edge thickness are many times higher than the losses caused by the difference of flowing off stream pressures.

The setting of longer and longer wedges in the stagnation zone, i.e. the application of higher and higher basic pressures, results in a very distinct increase of the flow efficiency. At a basic pressure close to the value p_2/p_0 (for $p_b/p_0=0.125$) the efficiency curve /10
lies very close to the flow efficiency at a flow off from a thin plate.

The replacement of trailing wedges by trailing profiles with rounded walls results in a further increase of the flow efficiency. The fact is here important that at low values of the H/t parameter, the efficiency decreases much more slowly than in the case of wedges.

The calculations for flows at basic pressures above the value p_2 were made only for trailing profiles with rounded walls. They proved that at the assumed shape of the walls there occurs the flow presented in Figure 6b. At adequately high pressures p_b, the flow efficiency is in excess of the flow efficiency of a flow-off from a thin plate. This is witnessed by the curve for $p_b/p_0=0.150$. With a modification of this kind, the length of the trailing profile is essential, because it is decisive for the usefulness of the solution. In Figure 8 the dependence $\eta=f(x_0/H)$ is shown.

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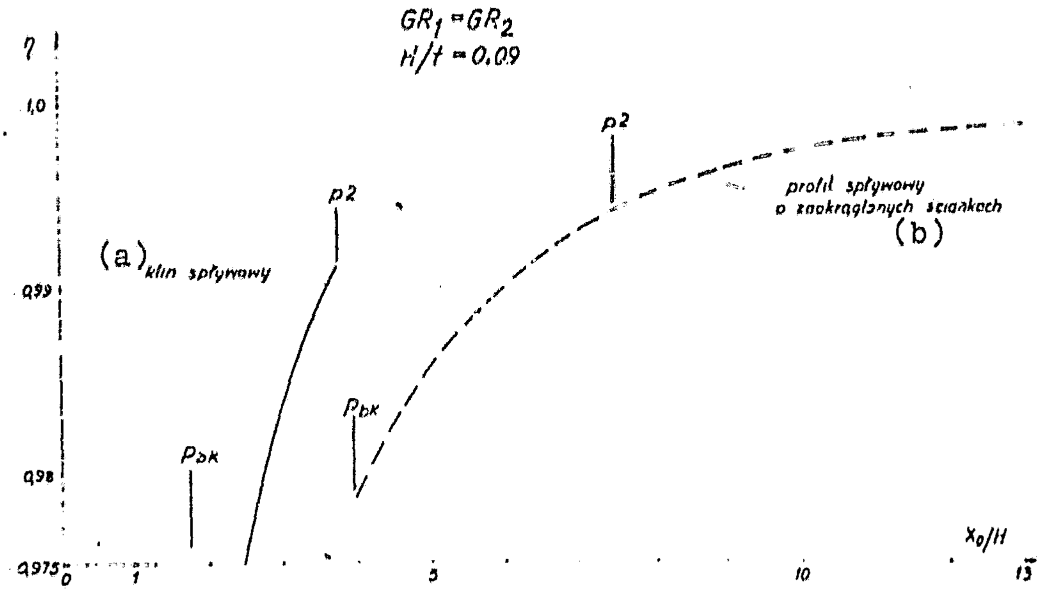

Figure 8. Diagram of the function $\eta=f(x_0/H)$ for a trailing wedge and profile at H/t=0.09.

Key: (a) Trailing wedge; (b) Trailing profile with rounded walls

In the case of trailing profiles with rounded walls, corresponding to basic pressures below p_2, there exists a strong influence of the profile length upon the flow efficiency. At pressures p_b higher than p_2, the influence of the profile length upon the efficiency distinctly decreases. When using trailing wedges, the influence of the wedge length upon the efficiency is much bigger than for profiles with rounded walls, and the length of the wedge is smaller than the length of the trailing profile.

In the calculation example presented above, the length related to the stagnation zone is about 1.8, but the trailing wedge with a basic pressure $p_b=p_2$ has a related length of about 3.6, i.e. only two times larger. The trailing profiles are, on the other hand, two times longer than the wedges, at the same basic pressures.

5. Conclusions /11

1. At H/t corresponding to transsonic cascades, the effect of the trailing edge finite thickness has a much higher influence upon the losses than the effect of the pressure difference on both sides of the blade.

2. The reduction of the effect of the edge finite thickness can be obtained by modifying the shape of the edge:

a) the use of trailing wedges enables one to weaken the waves by reducing the expansion at the corners,

b) the introduction of rounded walls of a trailing profile additionally inactivates the wave initial segments of highest intensity.

3. The use of modified trailing edges causes a very distinct decrease of the effect of the edge finite thickness and may even result in the efficiencies higher than the efficiency of the flow-off from a thin plate.

The real value of the presented analysis depends on the neglected essential influence of viscosity upon the pattern of the flow-off from a blade edge, but the model of ideal flow is relatively easily submitted to a theoretical analysis, giving a certain view of the flow pattern.

The results of the analysis suggest shapes of more efficient trailing edges for experimental verification.

The paper was submitted to the Editor's Office in June, 1981.

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