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Investigation of the possibilities of trailing edge shock waves intensity reduction by means of the edge geometry modification

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METHODS of transonic turbine blade shock waves weakening are proposed. A theoretical analysis of the methods based on an ideal gas model shows them to be effective. The analysis is carried out for a single trailing edge. The use of simple theoretical model requires an experimental verification. Theoretical and experimental results show good agreement except for the nearest vicinty of the edge. This allows for considering the method to be effective and justifies further investigation in cascade application.

Zaproponowano metody osłabienia intensywności spływowych fal uderzeniowych za transoniczną łopatką turbinową. Teoretyczna analiza tych metod oparta na modelu płynu idealnego wykazała ich efektywność. Analiza została przeprowadzona dla pojedynczej krawędzi. Zastosowanie prostego modelu teoretycznego stwarza konieczność eksperymentalnej weryfikacji. Uzyskano dużą zgodność wyników teoretycznych i eksperymentalnych z wyłączeniem obszaru bezpośredniego sąsiedztwa krawędzi. Pozwala to uznać zaproponowaną metodę za efektywną i uzasadnia przystąpienie do dalszych badań w zastosowaniu do palisad łopatkowych.

Предложены методы ослабления интенсивности сплывающих ударных волн за сверхзвуковой турбинной лопаткой. Теоретический анализ этих методов основан на модели идеальной жидкости выявил их эффективность. Анализ был произведен для одного ребра лопатки. Применение простой теоретической модели создает необходимость экспериментальной проверки. Получено большое совпадение теоретических и экспериментальных результатов за исключением области непосредственного соседства ребра. Это позволяет считать предложенный метод эффективным и обосновывает дальнейшие исследования применительно к каскадным системам.

1. Introduction

STREAM flow through a fluid flow machinery channels is always connected with energy loss. This is due to nonuniformity of stream resulting from stream turbulence and the existence of intense energy loss areas. In the case of cascade flow the areas of intense energy loss which contribute to so-called profile loss are:

boundary layer on profile,
wake behind profile,
shock waves in the case of transonic flow.

Literature data [1, 2] on transonic cascade flow show that energy loss connected with the existence of shock waves is at least of the same order of magnitudes as frictional loss even for not very high exit Mach numbers. This accounts for interest in the possibilities of loss reduction by weakening shock waves.

2. Theoretical analysis

To find a way to reduce shock wave intensity, the theoretical analysis of flow round a trailing edge is needed. This is a very difficult problem from the theoretical point of view because near wake in supersonic stream consists of subsonic and supersonic regions and in the case of turbine blade trailing edge the flow is unsymmetrical and the boundary layers on the edge are turbulent. This complex problem has not been solved yet (no reference known) except for symmetrical flow with laminar boundary layers on the edge. Regarding this fact, the theoretical analysis presented in this work was conducted on the basis of an ideal gas model. This is a serious simplification but allows to analyse shock waves loss using a not too complicated mathematical theory. Consequently, experimental verification of the theoretical results is needed.

To simplify the problem the flow of two uniform streams of different Mach numbers around a single trailing edge was investigated. Figure 1 shows the topography of such a flow. A rectangular edge was used to avoid problems of separation point searching. Just behind the trailing edge there is a dead flow area bounded by streamlines of separated streams. On each corner of the trailing edge an expansion wave is generated and on the dead flow area apex shock waves are created. Shock waves interfere with expansion waves and, in consequence, the first is weakened to disappear on the pressure side and only partly weakened on the suction side.

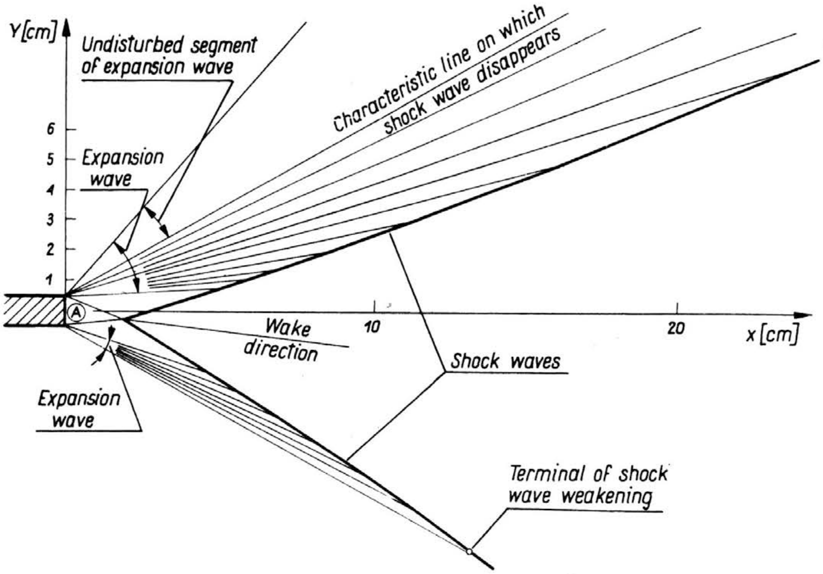

FIG. 1. Flow topography.

The intensity of the generated shock waves is directly connected with the stream deflection angle at the dead flow area apex. This angle depends on the flow area geometry. On the other hand this geometry results from the base pressure value. The higher the base pressure value is, the longer the dead flow area and the smaller the deflection angle.

The base pressure value cannot be calculated on the basis of an ideal gas model. Hence for theoretical analysis this value was taken from literature [6].

If shock wave intensity is to be lowered, the stream deflection angle must be reduced. This can be achieved by adding to the trailing edge a wedge which is longer than the dead flow area (Fig. 2). From the point of view of energy loss reduction it is important that the flow of round wedge be symmetrical [8]. This can be done by representing the wedge geometry by means of the base pressure value.

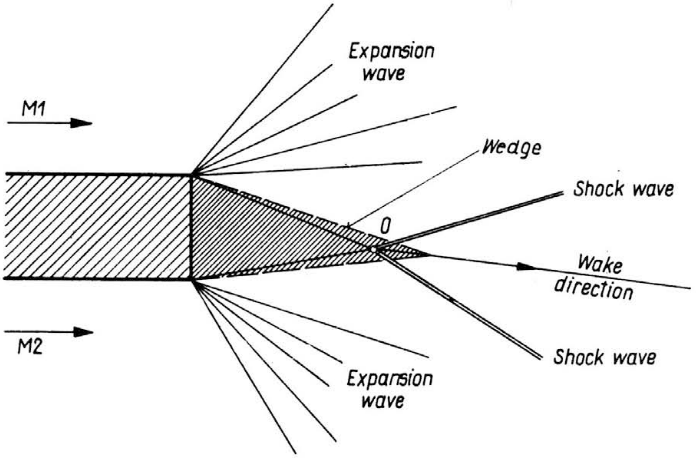

FIG. 2. Trailing edge modification.

The flow with a wedge-shaped trailing edge is characterized by having the first segment of the shock wave (between the dead flow area apex and the starting point of shock wave-expansion wave interaction) of constant intensity and this is the highest intensity along a shock wave. Another possibility of loss reduction is eliminating this shock wave segment. This can be done by trailing edge wall curving. Then the expansion wave source is extended on the whole wall and penetrates the shock wave right from its beginning.

The effectiveness of these two methods of trailing edge modification was the subject of numerical analysis. The most important results for the exit Mach number $M = 1.5$ on the pressure side and $M = 2.0$ on the suction side are shown in Fig. 3. This shows the relation of the efficiency against the stream width parameter.

Flow efficiency for total stream width $t = GR1+GR2+H$ is defined as follows:

$$\eta = \frac{\frac{G1}{G2}\sum_i \left[\frac{GR_i}{GR1}\eta_i\right]_1 + \sum_i \left[\frac{GR_i}{GR2}\eta_i\right]_2}{\frac{G1}{G2}+1},$$

where G is mass flux, GR — stream width before the edge, H — trailing edge thickness, and the subscripts: 1 — stands for pressure side, 2 — stands for suction side, i is the shock wave segment number.

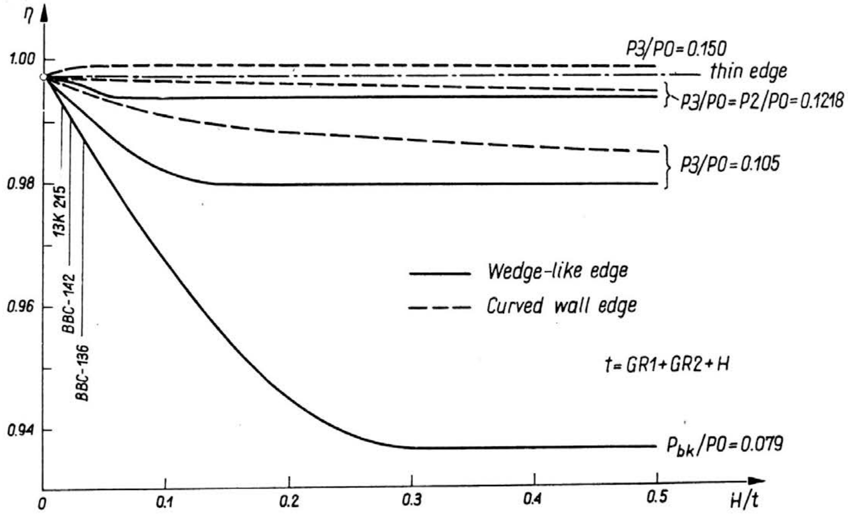

FIG. 3. Flow efficiency for different geometry trailing edges, $P0$ — total pressure, $P2$ — suction side pressure, $P3$ — pressure behind a trailing edge, P_{bk} — base pressure from literature, BBC-136, BBC-142, 13K215 — transonic turbine blades for which H/t value is given for comparison.

Each curve is for a different base pressure value, hence for different trailing edge shape. When $H/t = 0$, this means that we come up to the case of flow with an infinitely thin trailing edge. That explains why for $H/t = 0$ all curves achieve the same efficiency value of flow with a thin edge.

The lowest curve refers to flow round a rectangular edge with base pressure taken from literature. The change of pressure up to the value of suction side pressure $P2$ (when the suction side wall is flat to the trailing edge apex) causes an intense efficiency rise up to the value which is very close to flow efficiency with a thin edge. The use of a curved edge wall (here it is circular), for the same base pressure as for the wedge-like edge, causes a noticeable efficiency rise especially in the area where the wedge curve flattens.

The highest curve indicates that by rising base pressure it is even possible to achieve an efficiency higher than for the thin edge.

The method of trailing edge modification presented here is theoretically unlimited and involves still longer trailing edges. The limitation is of a constructional and technological nature. Figure 4 shows the relation of flow efficiency against trailing edge length related to its thickness. Additionally the pressure determining edge shape is given. Wedge-like edges giving the same efficiency results as curved wall edges are much shorter. When a wedge-like edge with a flat suction side wall is employed, an intense efficiency rise is obtained, but the wedge length is only twice as long as the dead flow area. Lengthening the wedge farther would be far less effective, considering the high efficiency value already reached.

In the case of curved wall edges for the same pressure value as for wedge, better efficiency is achieved but the edge length is greater. For long edges efficiency effects are very small.

The main conclusion drawn from the theoretical analysis states that the proposed method of shock wave intensity reduction by means of edge geometry modification is unexpectedly effective and worth further studies on the matter.

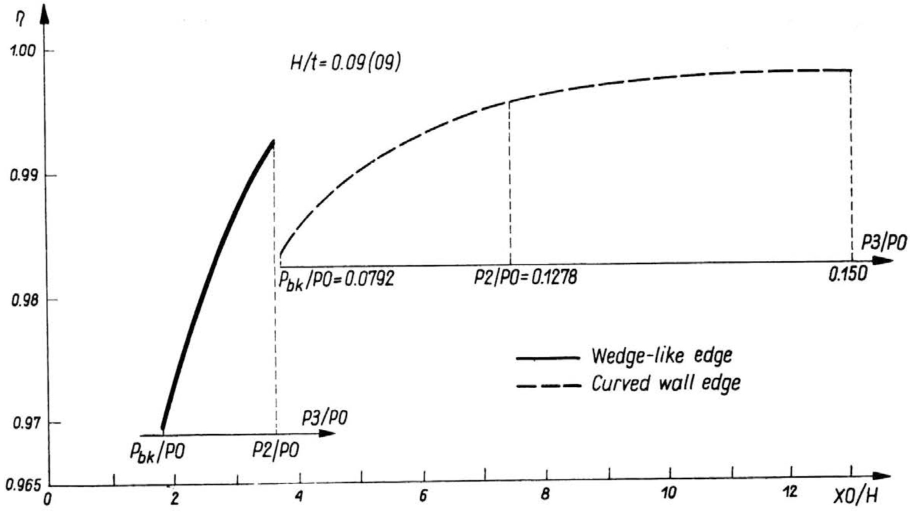

FIG. 4. Flow efficiency against trailing edge length.

3. Experimental investigation

The promising conclusion stated above, which is to be adopted for real flow, must be experimentally verified.

The experiment was done in an injector supersonic wind tunnel. For this particular investigation it had to be adopted. A special nozzle was built. It is shown in Fig. 5.

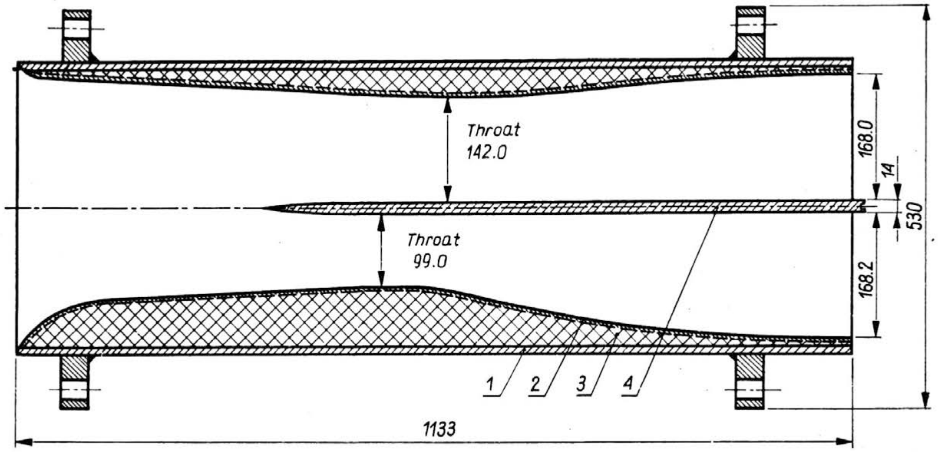

FIG. 5. Nozzle used for tests, 1 — steel box, 2 — fibreglass layer, 3 — poliuretane foam, 4 — middle plate.

There is a flat middle plate dividing flowing stream. On both sides of it there are nozzles accelerating air to different speeds. On the extending end of the middle plate there is a special lock for trailing edge fitting.

Six different shape edges were chosen for test (Fig. 6). First, a rectangular one, then a series of four different lengths wedge-like edges with the last one having the flat wall on the suction side, and one curved wall edge.

The experiment was divided into two parts.

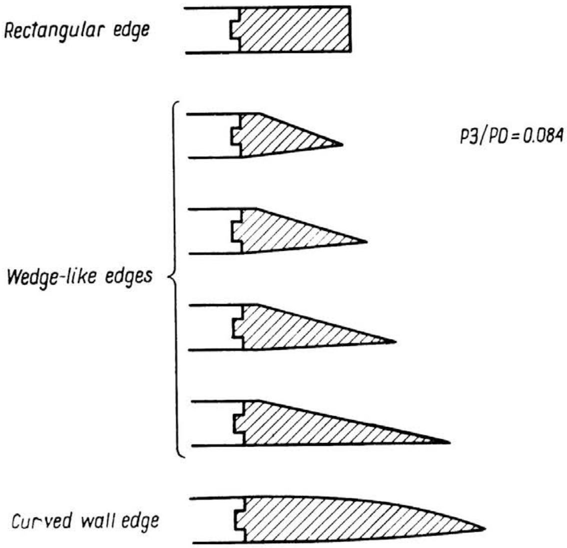

FIG. 6. Trailing edges chosen for tests.

3.1. Part I

The first part was devoted to an investigation of flow with a rectangular trailing edge. At the beginning it was important to verify the correctness of construction and the make of the nozzle. Mach numbers of exit streams were measured in two ways:

by pressure measurements,

by Mach angle measurements.

Designed Mach numbers of exit streams were achieved within measurement error.

The measurement of base pressure showed that its value is a bit lower than that taken from literature for calculations. Therefore, if the measured value was used for calculation, the curve for the rectangular edge in Fig. 3 would be lower and shock weakening effects would be greater.

It is also essential to know whether the investigated flow is similar to the flow round the trailing edge of a transonic blade. This similarity can be judged from the value of boundary layer thickness related to trailing edge thickness. Total pressure distribution near the wall was measured, which allowed to determine boundary layer thickness (Fig. 7).

The measured value of the boundary layer to trailing edge thickness are of the same order of magnitude as given in literature [5]. This determines the similarity of the investigated flow to the blade trailing edge flow.

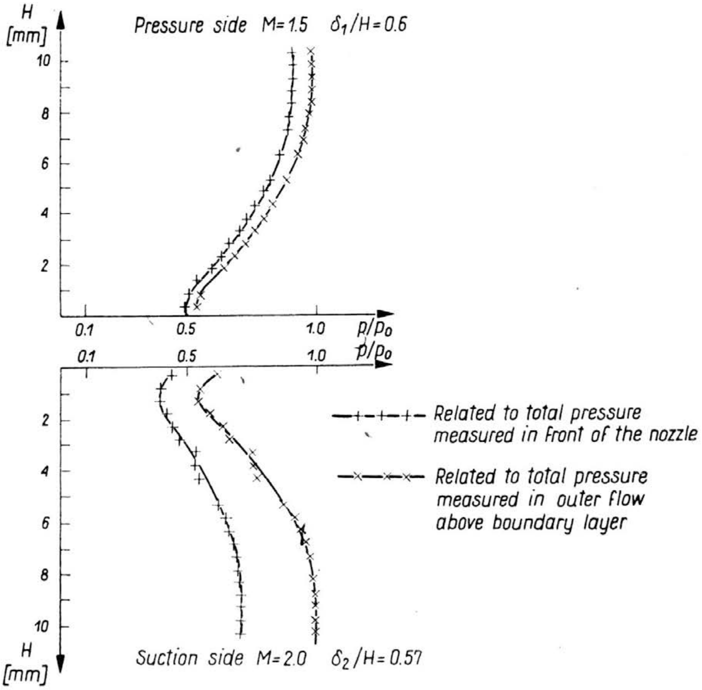

FIG. 7. Total pressure distribution in boundary layer, H — distance, δ_1 — pressure side boundary layer thickness, δ_2 — suction side boundary layer thickness.

A Schlieren picture of the investigated flow was taken and is shown in Fig. 8.

The qualitative flow picture agrees well with model taken for theoretical analysis. All characteristic items of the flow topography are described in the picture.

Theoretical results obtained for the measured base pressure value concerning dead flow area geometry, shock waves position and wake direction are plotted on the picture. Due to viscosity effects shock waves in real flow are generated ahead of the calculated position. As the distance from the trailing edge rises, the difference between the calculated and observed in real flow shock position decrease. At some distance from the trailing edge these positions overlap. The calculated and observed in real flow wake direction agree very well. Summing up the first part of the experiment it should be pointed out that:

the nozzle had been properly constructed and made hence so designed Mach numbers of exit streams were achieved,

the base pressure in real flow is lower than the value taken from literature for calculation, so better shock weakening effects should be expected in real flow,

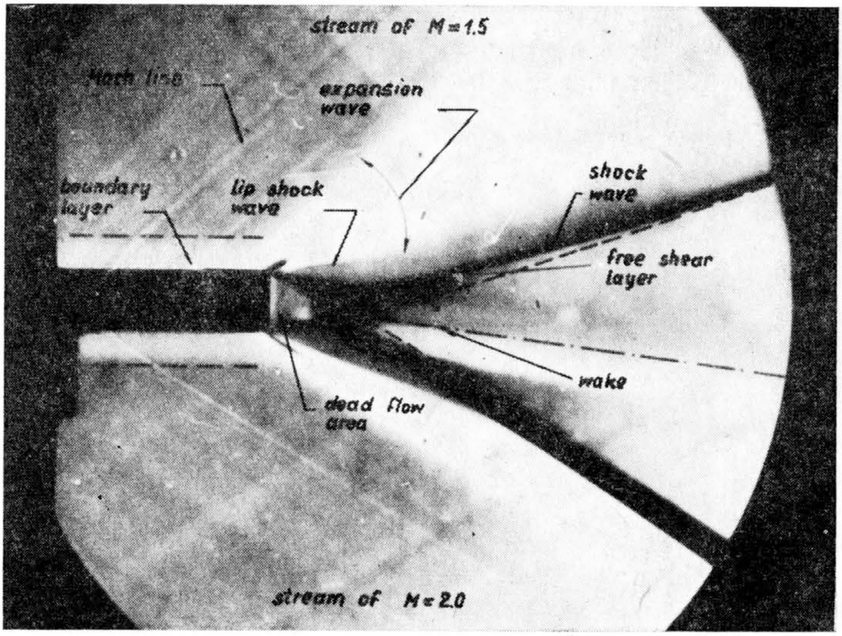

FIG. 8. Real flow topography.

expected flow topography was observed in real flow,

the investigated flow is similar to blade trailing edge flow,

in the case of ordinary trailing edge the viscous effects cause shock generation ahead of the calculated position, but it is only for an area close to the trailing edge, at some distance calculated and observed shock position agree very well,

theoretical and experimental wake direction agree very well.

3.2. Part II

The second part of the experiment concerned modified trailing edges. For each case a Schlieren picture was taken and the total pressure distribution in section at a 100 mm distance from the edge apex was measured. Since the comparison of theoretical and experimental results is similar for each case, only one example concerning the comparison of wave topography and pressure distribution will be presented.

Figure 9 shows a real flow picture with a modified trailing edge.

The theoretical shock wave position and wake direction are plotted in the picture. Because of the boundary layer to wake transition in real flow, shock waves are generated a little ahead of the calculated position. This shift is very small, and calculated and observed waves are parallel to themselves. The observed wake direction agrees very well with the theoretical one. Two shock waves originating on the plate surface are caused by edge mounting, but they are very weak as they are parallel to Mach lines observed in exit streams.

Figure 10 presents the comparison of measured and calculated total pressure distribu-

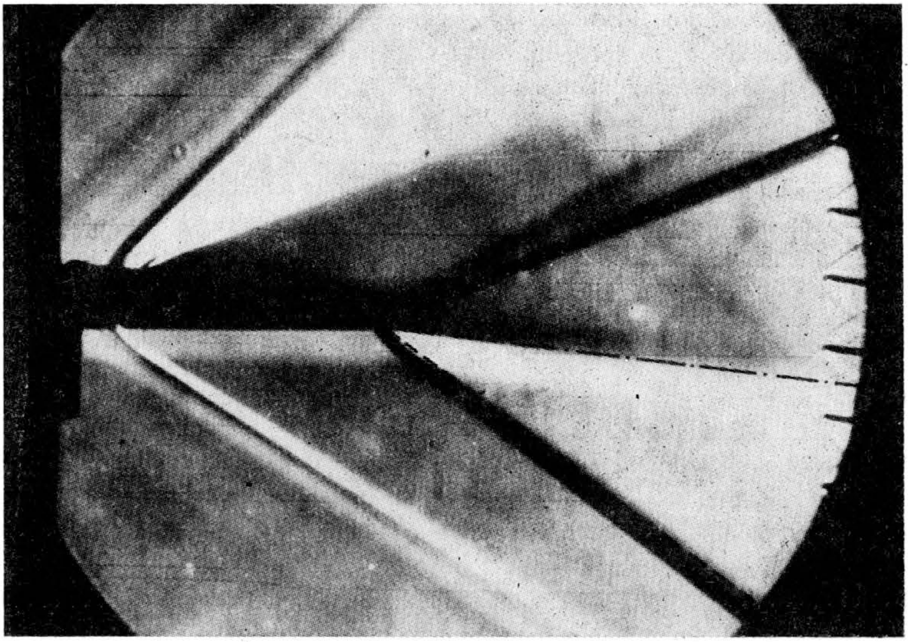

FIG. 9. Flow with modified trailing edge (wedge like edge $P_3/p_0 = 0.128$).

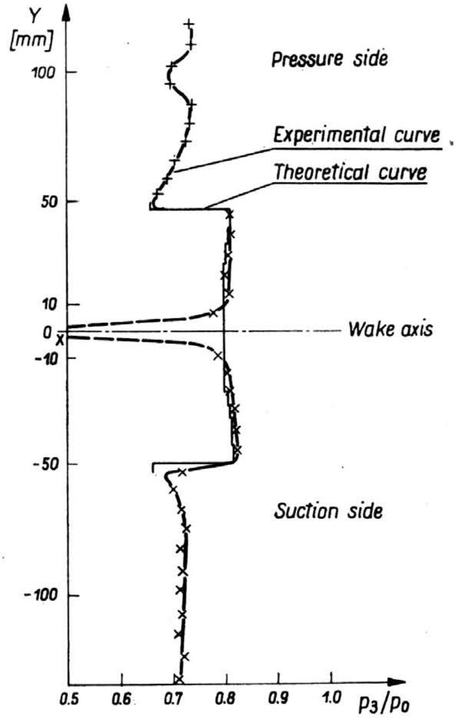

FIG. 10. Total pressure distribution in test section (wedge like edge $P_s/p_0 = 0.084$).

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tion in the test section. Horizontal segments of curves are connected with shock existence. Good agreement of theoretical and experimental results is quite obvious even for shock wave position and intensity. This does not apply to the wake region although the wake axis position on the diagram is determined theoretically and agrees well with the measured wake position.

The results of the second part of the experiment bring us to the following conclusion: for modified trailing edges excellent agreement of theoretical and experimental results was obtained. This is because no separation exists on modified trailing edges. This means that an ideal gas model is good enough for the analysis presented above.

Conclusion

Presented here experimental results support theoretical conclusions. Hence the proposed method of energy loss reduction by means of shock waves weakening based on trailing edge geometry modification is effective and should be investigated further in cascade application.

There is also one additional advantage of the method. Sharpening of the trailing edge as proposed here leads to wake narrowing, hence to wake loss reduction. This phenomenon, however, was not a subject of presented investigation.

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