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RESEARCH MEMORANDUM

VISUALIZATION OF SECONDARY-FLOW PHENOMENA IN BLADE ROW

By H. Z. Herzig, A. G. Hansen, and G. R. Costello

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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VISUALIZATION OF SECONDARY-FLOW PHENOMENA IN BLADE ROW

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SUMMARY

Flow-visualization methods were applied in a preliminary study of the streamline pattern of secondary flows in a blade row. The investigation demonstrated flow of the inlet-wall boundary layer in a blade passage into the corner between the blade suction surface and the wall to form a vortex. This vortex formation occurs well within the passage and is not a trailing-edge phenomenon. The magnitudes of the velocity gradients and angle deflections make the significance of quantitative measurements in this region questionable.

INTRODUCTION

Various theoretical and experimental investigations have been made, each of which, by means of various assumptions, partially describes the manner in which secondary flows (deviations from the flow behavior as predicted by potential-flow analyses) affect the performance of turbomachines. In these analyses, usually one of two methods has been used to estimate the deviations in the exit-flow angles and velocities due to the inlet boundary layer. The first method (reference 1) is based principally on airfoil theory, and the flow deviations are considered as arising from trailing-edge vortices associated with spanwise variations in circulation. The second method (references 2 and 3, for example) is based on the flow of an ideal fluid in a channel with varying inlet total pressure.

In the investigations listed, attempts were made to give a qualitative picture of secondary-flow behavior and to provide some foundations for approximate loss calculations. Because of the simplifying assumptions involved, however, the question remains as to how accurately the various methods describe flow phenomena in an actual cascade. Furthermore, knowledge concerning the detailed streamline pattern of the flow in a blade row is essential to an accurate understanding of the nature and influence of secondary flows. Such information is not obtainable from the aforementioned techniques.

As a first step in answering these questions, an experimental investigation was conducted at the NACA Lewis laboratory to determine the streamline patterns in a two-dimensional cascade. The streamline patterns were determined by flow-visualization methods such as smoke and chemical traces. Although the investigation is still in a preliminary stage, the results obtained are considered to be of sufficient general interest to warrant presentation at this stage of the program. Accordingly, photographs of various flow patterns in the cascade are presented with a brief discussion of what is revealed concerning the nature of the flow.

APPARATUS AND TEST PROCEDURE

Experimental Setup

The initial experimental investigation, which was purely exploratory, was intended to serve as a guide to more extensive research. It was considered satisfactory, therefore, to carry out these basic tests in a two-dimensional steady-flow cascade (see fig. 1). The air to the cascade was supplied by the laboratory combustion-air system and was discharged directly into the room. Because of the construction of the cascade, the inlet-air velocities were limited to Mach numbers of approximately 0.4.

The blade row consisted of six NACA 65(12)-10 blades mounted between two channel walls at a stagger angle of 45°, an angle of attack of 11°, and a turning angle of 20°. The solidity of the cascade was 1.5; the aspect ratio for the blades was 2.34. A row of static taps was located on one wall one-half chord upstream of the blades. At this same axial location, a 1/16-inch-outside-diameter probe was mounted in a slot in the other wall for the introduction of smoke into the air stream at any desired point. All tests were conducted in the half of the passage adjacent to the smooth wall containing the static taps in order to avoid any disturbances that might arise because of the probe slot.

Flow-Visualization Methods

Two methods were used to visualize the flow patterns: (a) smoke traces in the passage and on the blades and walls and (b) hydrogen sulfide gas reacting with lead carbonate in glycerin painted on the walls and blades. The flow-visualization methods were used in the cascade for tests made at low speeds (30 ft/sec) and at high speed (Mach numbers of approximately 0.4). Photographs were taken of the traces obtained by admitting the smoke and hydrogen sulfide through the wall static taps, and through the probe at either the wall or in the passage. The agreement between the probe and static-tap traces showed that the probe did not disturb the flow in the passage sufficiently to affect these tests.

Smoke traces. - Smoke was produced by burning oil-soaked cigars with service air (fig. 2). This method of generating smoke was found to be superior to other methods which have been used. In particular the smoke was nontoxic, noncorrosive, easily generated, and of sufficient intensity to be photographed. The rate of smoke production and injection into the airstream were carefully controlled by means of settling bottles, pressure regulators, and bleeds so as to match closely the local direction, velocity, and density of the airstream. In order to maintain the smoke traces intense enough for photographing, the inlet-air velocity was held at approximately 30 feet per second when the smoke-visualization method was used. The smoke traces were particularly advantageous because it was possible to visualize the streamlines any place in the passage as well as on the walls and blades, and there was no difficulty encountered with diffusion of smoke into the air. However, it is difficult to present the results photographically because the photographs cannot show the three-dimensional movement of the traces and are difficult to obtain for regions of low contrast.

Hydrogen sulfide traces. - In order to obtain traces at higher air speeds, the following procedure was adopted. The wall and the blades were covered with a paint of lead carbonate in glycerin and alcohol. As the hydrogen sulfide was introduced through the static taps, or the probe, its path along the blades and on the wall was observed as a brown trace on the white background. This reaction is semipermanent and accumulative. It was therefore possible to introduce the hydrogen sulfide at such rates that the local velocity and direction of the airstream could be matched closely, and the disturbance of the local flow minimized. Furthermore, the molecular weight of hydrogen sulfide is close to that of air, which minimizes the diffusion due to density differences. Disadvantages of the method are that the gas is highly toxic and the reaction must proceed for a long time in order to obtain sufficient color contrast.

RESULTS

Low-Speed Investigation

Spanwise variation of deflection. - The initial phase of the experimental program was concerned with determining the nature and magnitude of the deflection of the wall boundary layer from the pressure surface of one blade to the suction surface of the adjacent blade. The progressive increase in flow deflection as the wall is approached is qualitatively discussed in the literature. The flow deflection of smoke traces for three spanwise positions is shown in figure 3. In figure 3(a), the smoke is admitted from the static tap with a velocity sufficient to project the smoke tube approximately 1/4 inch from the wall. In figure 3(b), the smoke velocity is reduced to the point where the smoke is projected approximately 1/8 inch from the wall. In figure 3(c), the smoke velocity is further reduced so that the smoke tube lies against the wall in the vicinity of the tap. By superimposition of these three pictures (fig. 3(d)) the magnitude of the variations in deflections is evident. The same variations in deflection in the boundary layer when the smoke was admitted through the probe are shown in figure 4.

The superimposition of figure 3 on figure 4 is shown in figure 5. The close agreement between the streamline patterns obtained demonstrates that the presence of the probe does not unduly disturb the flow, and that under the test conditions the probe results are reliable.

Deflections along wall. - The deflection in the boundary layer along the wall when smoke was admitted through two static taps located upstream of the blades is shown in figure 6. The upper smoke trace in figure 6(b) was made by the smoke that remained in the static tap from the time of the previous photograph (fig. 6(a)). The pressure drop from outside the tunnel to the static pressure at the wall inside was too small to be read on a water manometer and so the smoke must be considered to enter the air flow at the wall itself. Figure 6(c), made by superimposing figures 6(a) and 6(b), indicates that as these tests were conducted, each of the smoke traces presented must be considered as lying along the wall in the neighborhood of its respective tap.

The smoke traces in figures 7(a) to 7(d) were obtained by a probe traverse along the wall. Figure 7(e) is the result of superimposition of figures 7(a) to 7(d) for purposes of comparison of the streamline paths.

Deflections on blade. - The streamline deflection on the blades caused by secondary flow has been noted and pictured in reference 1. Figure 8 presents the smoke-trace patterns of this deflection on the blades. The smoke (fig. 8(a)) was admitted through the probe approximately 3/16 inch from the wall and in such a position that the smoke stream split and divided on the blade. In figure 8(b) the probe was positioned so that the smoke path lay on the pressure surface of the blade. In figure 8(c) the smoke follows the suction surface of the blade.

High-Speed Investigation

Deflections in two-dimensional cascade. - The visualization of the flow along the passage wall and blade at Mach numbers of approximately 0.4 is shown in figure 9. The pattern in figure 9(a) was made by hydrogen sulfide H_2S introduced through a static tap upstream of the blades. In figure 9(b) the H_2S was introduced through a static tap in the passage. The flow onto the blade is shown more clearly in figure 9(c).

Deflections in three-dimensional cascade. - The deflection patterns at Mach numbers higher than 0.4 were obtained by applying the H_2S flow visualization method to the annular nozzle ring of a typical modern high-speed turbine. Figure 10 shows the H_2S traces obtained with this annular cascade at hub-discharge Mach number of approximately 0.9 and a tip-discharge Mach number of approximately 0.7. In figure 11 are presented the H_2S traces for the same annular cascade when the approximate hub and tip discharge Mach numbers were 1.5 and 1.2, respectively.

A view of the cascade inner shroud at the blade-row inlet is shown in figure 10(a). The H_2S was admitted through one wall static tap in each of two adjacent passages. The same tap positions relative to the blades were used for the outer-shroud traces. These same inner- and outer-shroud static taps were used for the traces shown in figure 11.

DISCUSSION

Low-Speed Investigation

Deflections along wall. - The results of the spanwise survey shown in figures 3 and 4 demonstrate visually the increase in flow deflection in the wall boundary layer as the wall is approached, as anticipated in the literature. In figures 3(c) and 4(c), the streamline path in the boundary layer at the wall is clearly seen to cross the passage and arrive at the suction surface of the passage upper blade well upstream of the trailing edge. This particular type of streamline path was not described in the literature surveyed.

Spanwise surveys at other positions across the passage yielded essentially similar patterns. In each case the streamlines at the wall arrived at the suction surface of the blade at some point upstream of the trailing edge. Figure 7 enables a direct comparison of representative paths of the streamlines obtained in one passage by a probe traverse along the wall. The paths are seen in figure 7(e), made by superimposing figures 7(a) to 7(d), to be confluent in the corner at the suction surface of the passage upper blade near the trailing edge. This particular phenomenon of the convergence of the streamlines to a small region in the corner was neither anticipated nor implied elsewhere.

Vortex formation. - The smoke traces are seen in the photographs only as projections against the passage walls or against the blades. To an actual observer, the streamlines pictured in figures 7(a) to 7(d) appeared to be drawn, as if by a flow sink, to the corner made by the passage upper blade suction surface and the wall, as shown in figure 7(e). As the streamlines approached this corner, their paths took on a spiral twist (counterclockwise in the figures presented herein). Thus the smoke streamline crossing the passage in figure 7(d) remained on the wall until it reached the corner. Upon reaching the corner, the major portion of the smoke trace rolled up in the vortex and came off downstream; however, the smoke in the vortex was diluted by the rest of the boundary-layer air comprising the vortex to the extent that it could not be perceived photographically at this camera angle.

At the flow speeds used for these tests, laminar separation probably occurred on the suction surfaces of the blades near the trailing edges. When smoke was introduced into the wall boundary layer (fig. 7) a small portion of this smoke eddied out onto the blades. This slow accumulation of smoke in the stagnant region produced the dense trace on the blades.

As the smoke, for the probe traverse along the wall, was introduced progressively closer to the suction surface of the blade (figs. 7(c), 7(b), and 7(a), respectively) the smoke streamlines were observed to deflect away from the walls as they proceeded downstream. The spanwise deflections of these smoke traces increased in the same order and the curvature of their paths of approach to the upper blade decreased in the same order. Therefore, in figure 7(e) although the streamline of figure 7(a) appears to cross the other streamlines, which is patently impossible, it actually passed over these streamlines.

The vortex formation, as described here, occurred well in the passage itself and not as a trailing-edge phenomenon. A smoke stream was introduced near the leading edge in the corner formed by the suction surface of the blade and the passage wall. It was observed to assume the same type of counterclockwise spiral rotation in the passage at approximately the blade midchord position. Because of the tightness of the spiral and because the photographs show only path projections, it has not been possible to obtain a suitable photograph of this evidence of vortex formation within the passage.

Deflections on blade. - The manner in which the flow on the blade was deflected spanwise toward the wall on the blade pressure surface and spanwise away from the wall on the blade suction surface is shown in figures 8(a) to 8(c). A comparison of figures 8(b) and 8(c) shows that the deflection on the suction surface was much greater than that on the pressure surface. Such large deflection differences were not anticipated from secondary flow-mechanisms similar to that described in reference 1. The large deflection difference evident in figure 8 is principally attributed to the area-blockage effect of the passage vortex near the suction surface, which causes a large deflection of the flow on the blade suction surface. The region between the smoke trace in figure 8(c) and the wall is, therefore, a rough measure of the size of the passage vortex.

As a result of the deflection on the blade pressure surface, air flowed onto the passage wall and was observed to become the wall boundary layer for the region downstream of the smoke trace of figure 7(d). The capture of this instructive phenomenon photographically was prevented by the rapid thinning of the smoke as it left the blade and diffused on the wall.

High-Speed Investigation

Two-dimensional cascade. - Because of the increased turbulence at the air velocities used in figure 9(a), the H_2S trace spread out and was impossible to maintain as a well defined line. Nevertheless, the pattern of flow deflection up the wall followed closely that of the low-speed tests. Because of the turbulence at this Mach number, the H_2S could not be confined to a layer at a specified distance from the wall but was distributed throughout the entire height of the boundary layer; therefore, the H_2S traces indicate the flow paths of a region of the entering boundary layer instead of an individual path. Hence, figure 9(a) very closely resembles figures 3(b) and 4(b) where the smoke was introduced in the boundary layer at some position away from the wall. A portion of the H_2S trace actually reached and flowed onto the suction surface of the blade but was too faint to photograph and so is shown by the dotted line in figure 9(a). The toxicity and obnoxious odor of the H_2S prevented its use in this cascade for the extended period of time required to darken the trace further.

In order to circumvent this difficulty, an effort was made to concentrate the H_2S trace in the region of chief interest by use of the passage-wall static tap. The flow (fig. 9(b)) to the corner and onto the blade can be seen somewhat more clearly.

The dark trace on the bottom blade shown in figure 9(c) was due to H_2S released from a wall static tap so located that the flow divided on the blade. A faint H_2S trace is, of course, obtained immediately upon release of the gas but it is necessary to run the test for a prolonged period of time in order to intensify the trace sufficiently for photographing. During this protracted run, the paint on the rest of the blades in figure 9(c) was observed to flow slowly until it assumed the final pattern apparent in the picture. The similarity between the H_2S trace and the paint patterns is noteworthy.

Three-dimensional cascade. - In the annular-turbine-nozzle cascade it was possible to use the H_2S for a sufficient length of time to make the clear, dark traces presented in figures 10 and 11. Figure 10 presents the traces obtained at the high subsonic air velocities, while the results in figure 11 were obtained at the supersonic velocities.

Again the pattern has been repeated where in each case the flow crosses the passage, at both inner and outer shrouds, arrives at the suction surface of the blade, and flows out on the blade itself. The shape of the flow traces on the blades and walls indicates the formation of a vortex within the passage in the annular cascade as well as in the two-dimensional cascade.

CONCLUDING REMARKS

The formation of a vortex pattern in the corner formed by the suction surface of the blade and the cascade wall is indicated for the entire range of air velocities used and appears in both the two-dimensional and annular-turbine-nozzle cascades. This vortex pattern starts well up in the passage and is definitely not a trailing-edge phenomenon. Furthermore, the complicated nature of the flow makes questionable the applications, to date, of any two-dimensional, or quasi-three-dimensional, analyses of flow patterns in the wall region and certainly influences the entire flow through the passage.

In the region of extremely large velocity gradients, both as to magnitude and direction, the accuracy of such measurements as total pressure and flow angle is severely limited, and the interpretation of such quantitative measurements must be made with care.

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2. Squire, H. B., and Winter, K. G.: The Secondary Flow in Cascade of Aerofoils in Nonuniform Stream. Jour. Aero. Sci., vol. 18, no. 4, April 1951, pp. 271-277.

3. Hawthorne, William R.: Secondary Circulation in Fluid Flow. Gas Turbine Lab., M.I.T., May 1950.

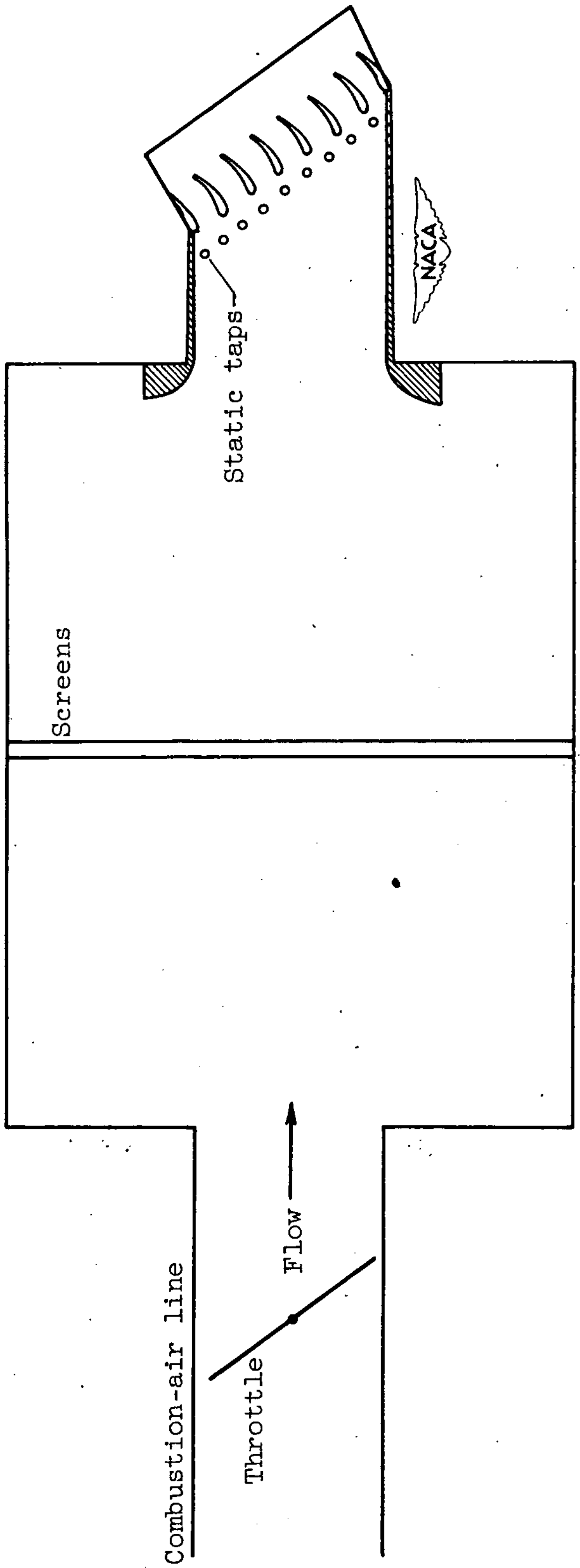


Figure 1. - Two-dimensional steady-flow cascade.

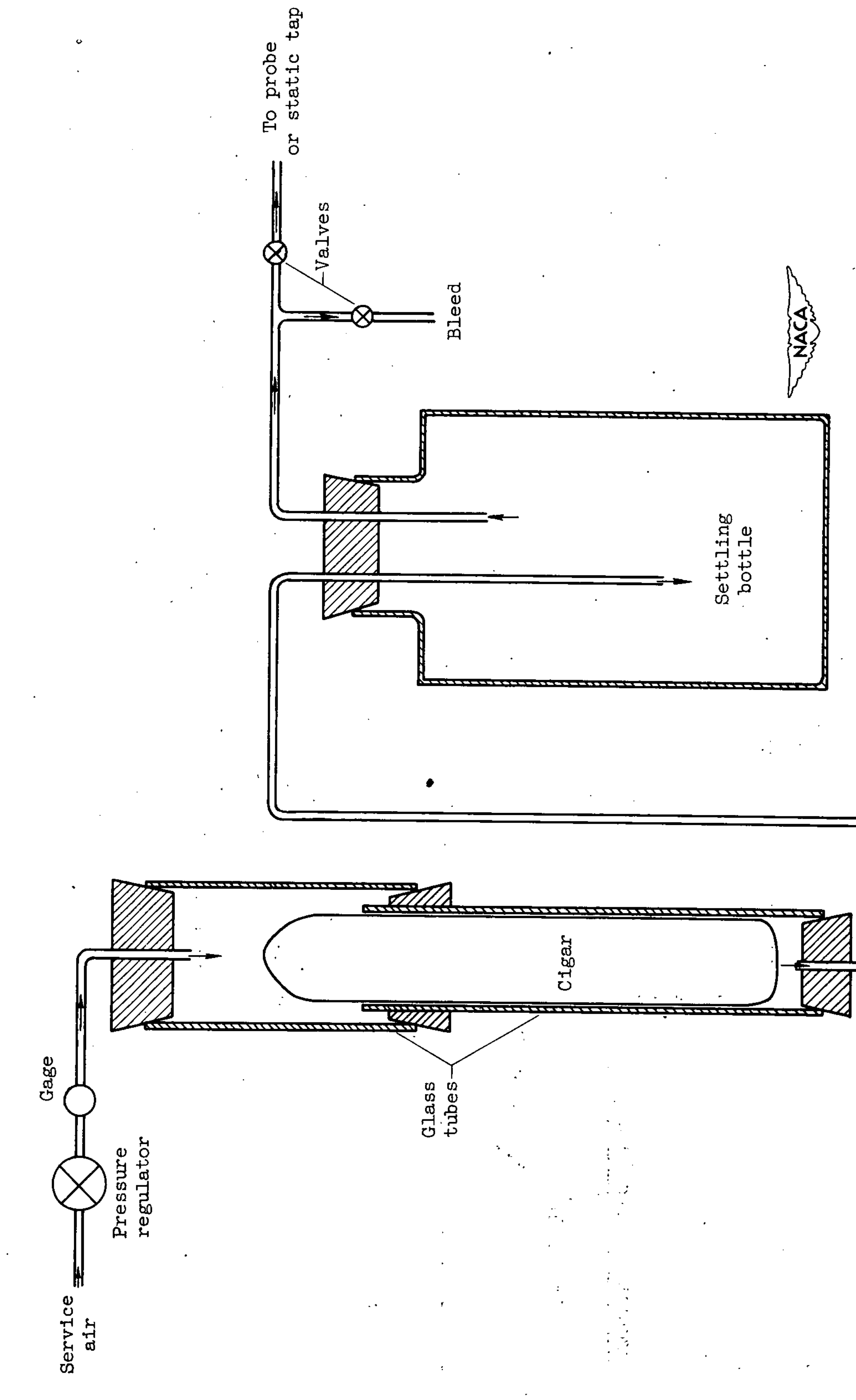
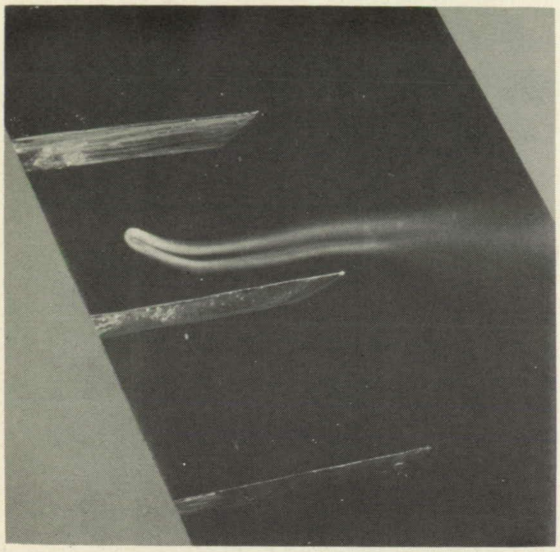
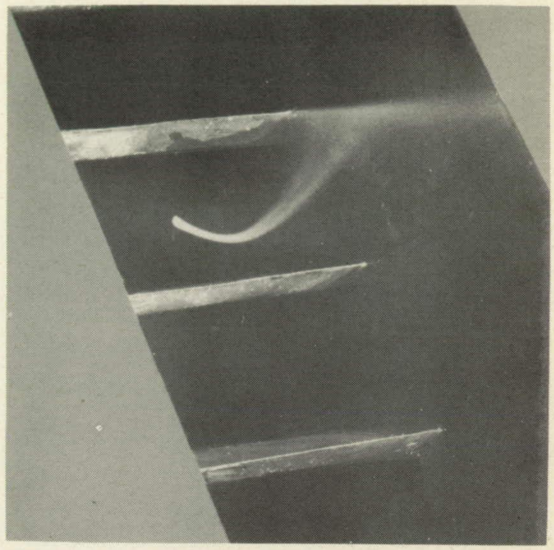


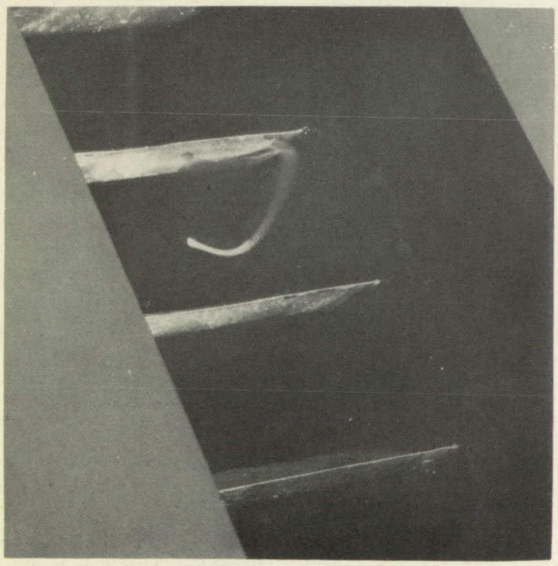
Figure 2. - Smoke generator.



(a) Smoke trace 1/4 inch from wall.



(b) Smoke trace 1/8 inch from wall.



(c) Smoke trace on wall.

(d) Superimposition of (a), (b), and (c).

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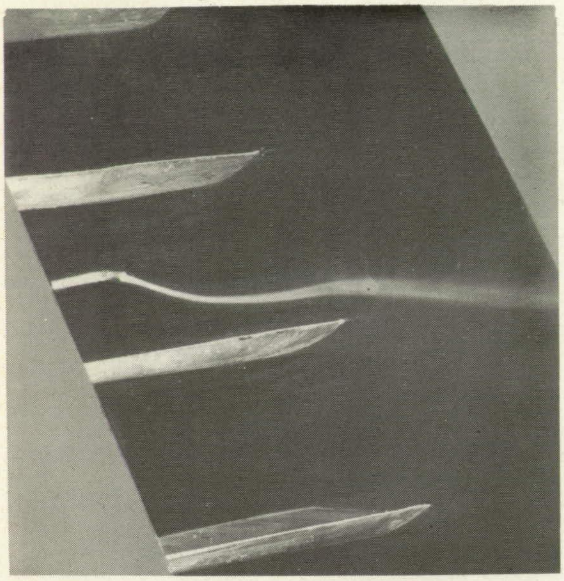
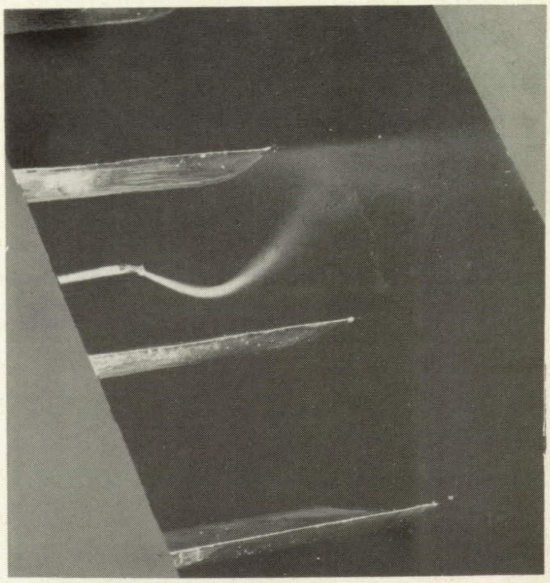
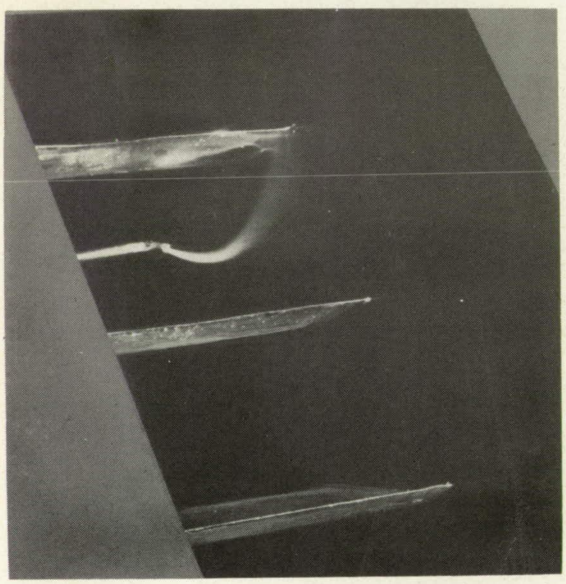
Figure 3. - Variation of flow deflection in boundary layer. Smoke introduced through wall static tap.



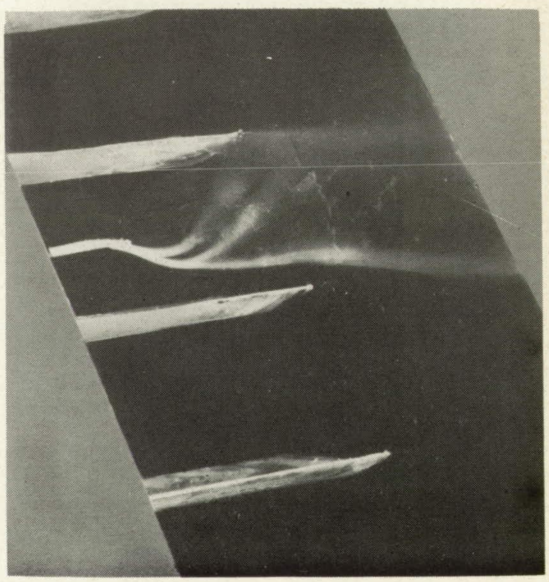
(a) Probe 1/4 inch from wall.



(b) Probe 1/8 inch from wall.



(c) Probe against wall.



(d) Superimposition of (a), (b), and (c).

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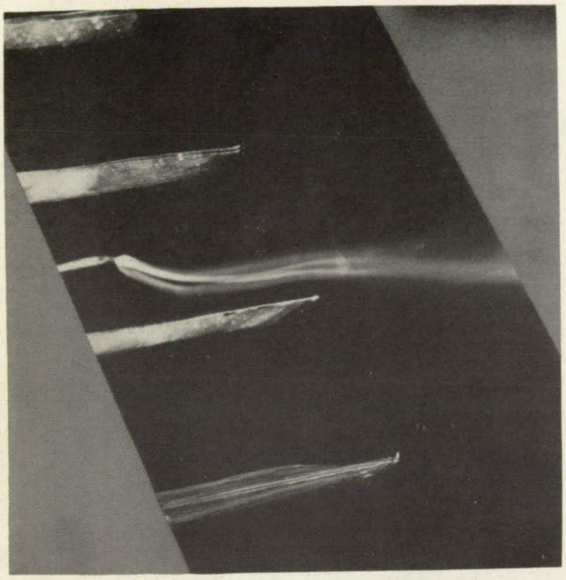
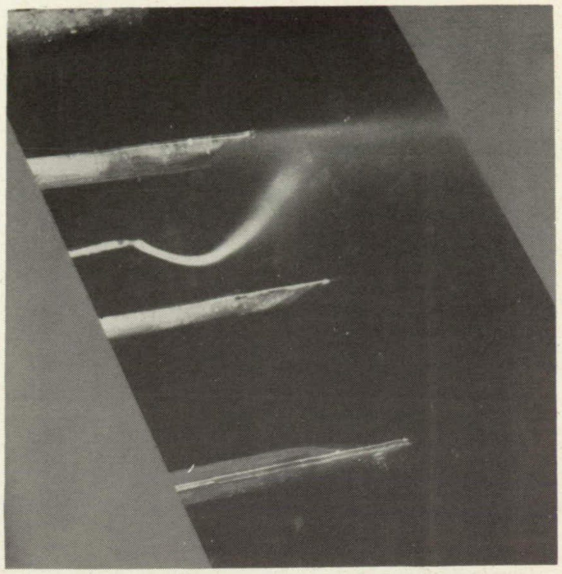
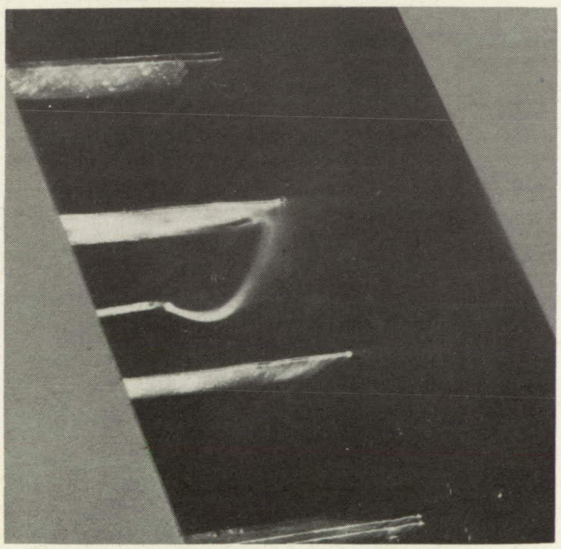
Figure 4. - Variation of flow deflection in boundary layer. Smoke introduced through probe.



(a) Figures 3(a) and 4(a).



(b) Figures 3(b) and 4(b).



(c) Figures 3(c) and 4(c).

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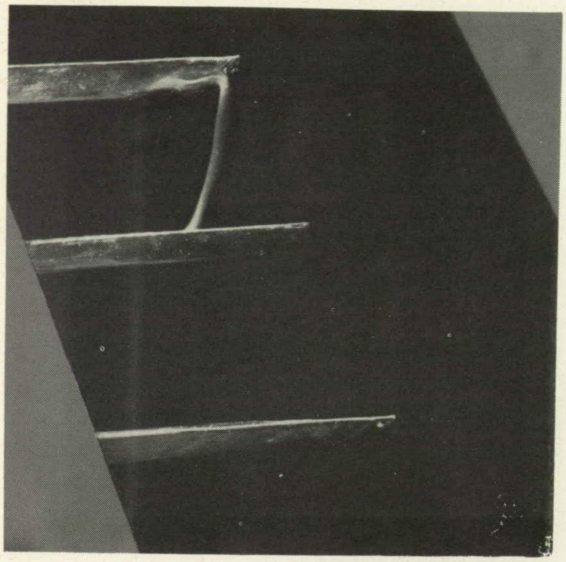
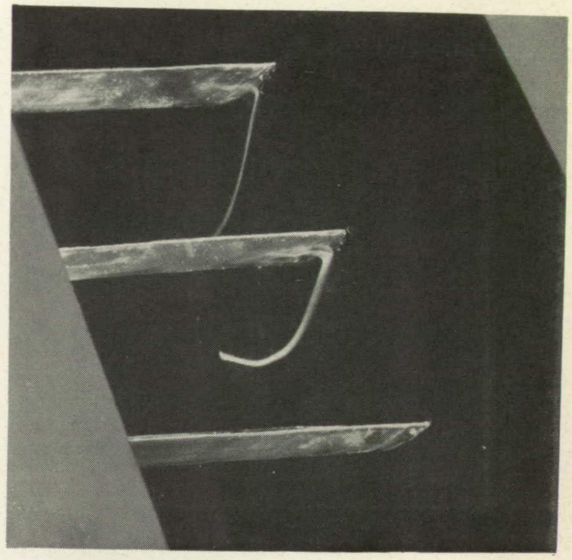
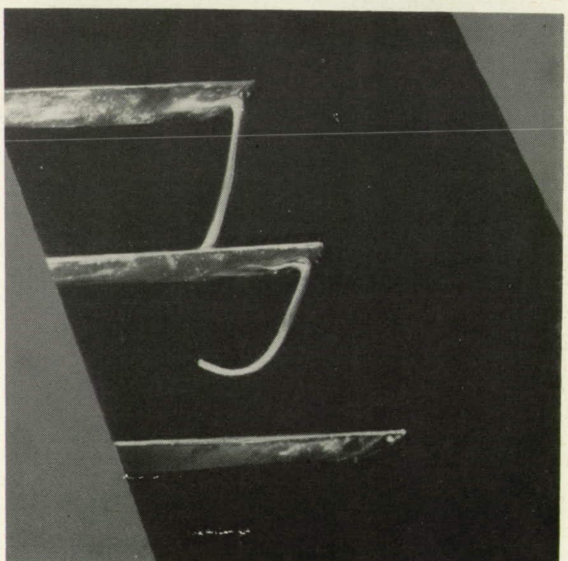
Figure 5. - Superimposition of figures 3 and 4 demonstrating the reliability of probe results for flow visualization.



(a) Smoke through first static tap.



(b) Smoke through second static tap.



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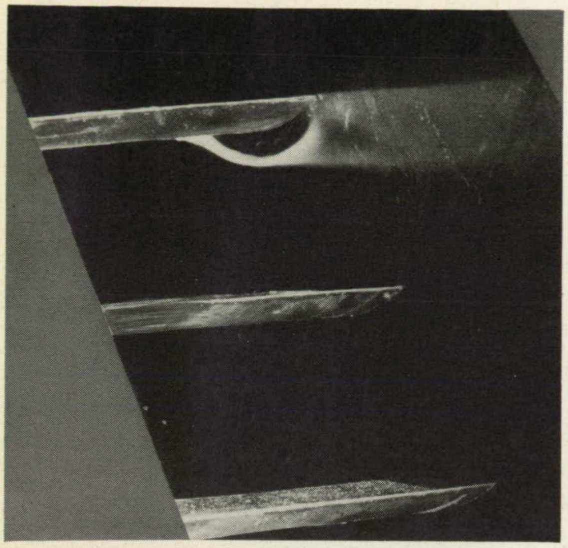
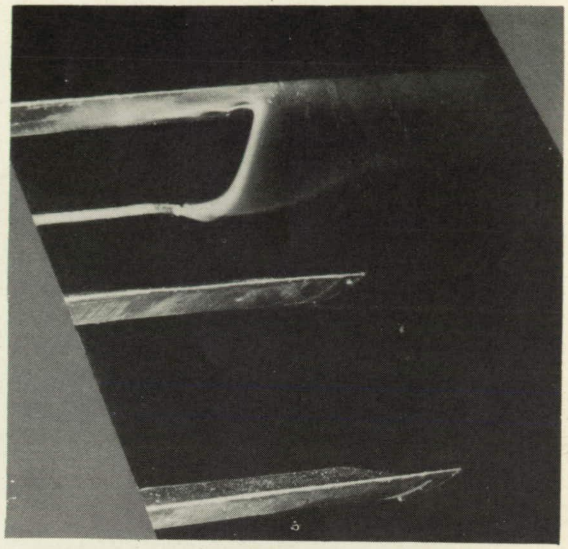
(c) Superimposition of figures 6(a) and 6(b).

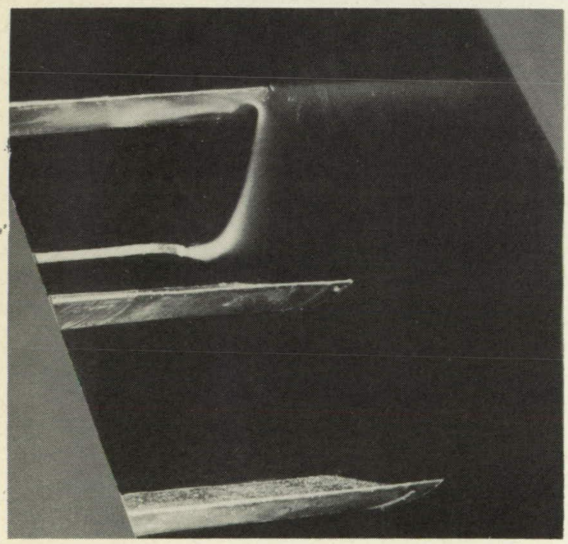
Figure 6. - Deflection in boundary layer along wall. Smoke introduced through various static taps upstream of blades.



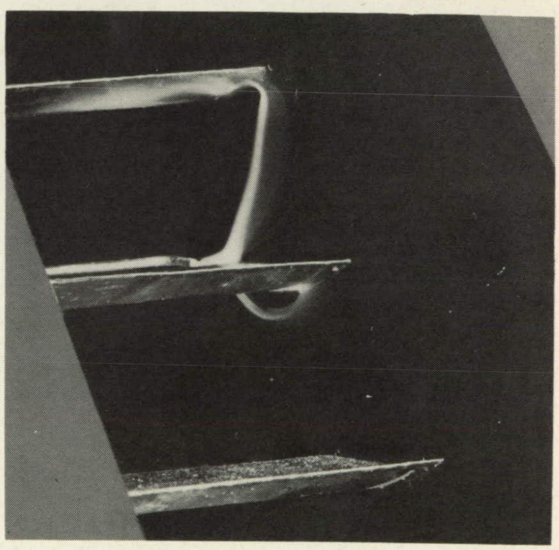
(a) Probe in position a.



(b) Probe in position b.



(c) Probe in position c.



(d) Probe in position d.

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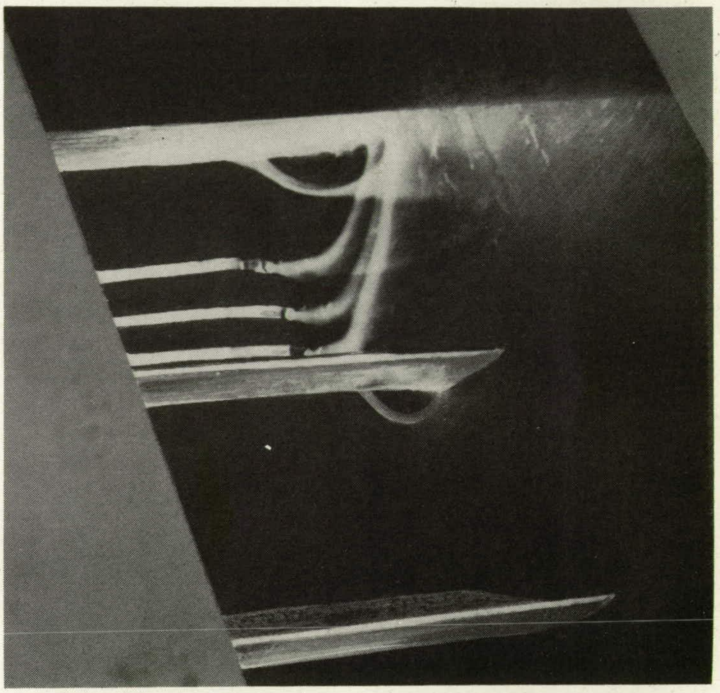
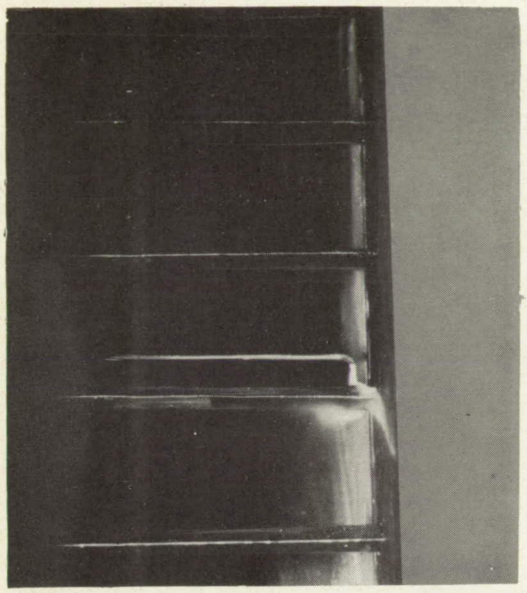
Figure 7. - Flow deflection in wall boundary layer of one passage. Smoke introduced by probe traverse along wall.

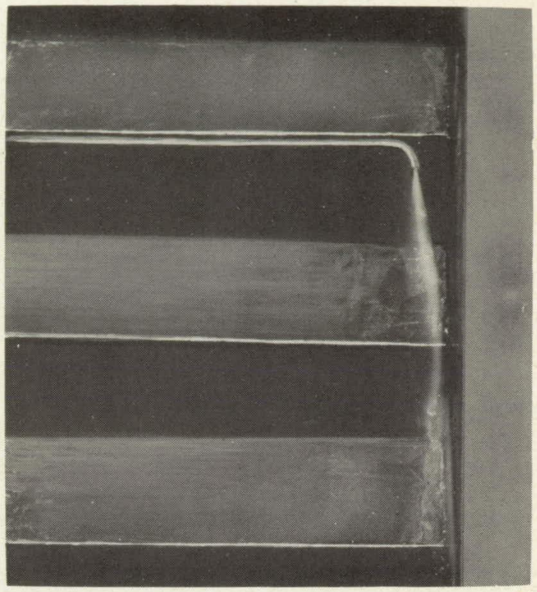


(e) Superimposition of figures 7(a) to (d).

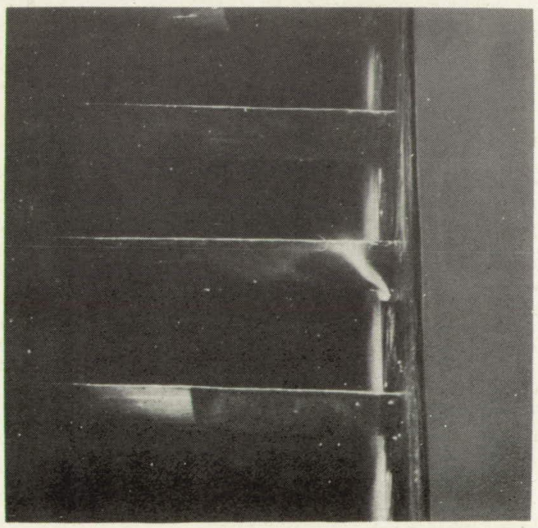
Figure 7. - Concluded. Flow deflection in wall boundary layer of one passage. Smoke introduced by probe traverse along wall.



(a) Smoke tube divided on blade.



(b) Smoke tube on pressure surface of blade.



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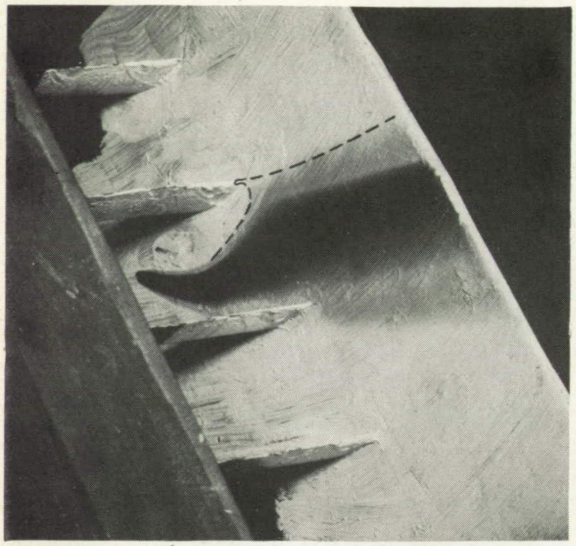
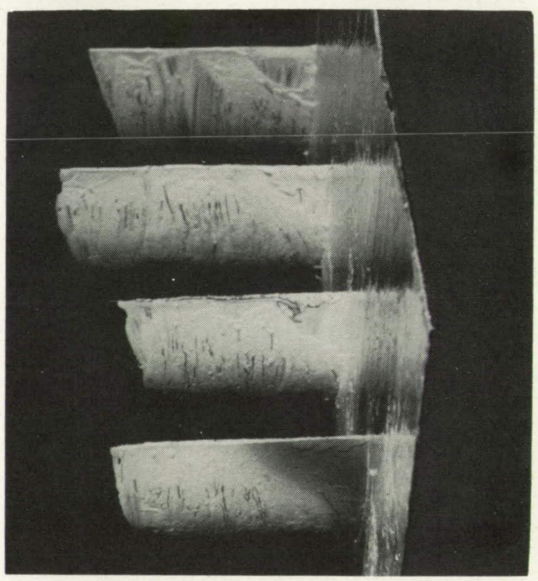
(c) Smoke tube on suction surface of blade.

Figure 8. - Flow deflections on blade.



(a) Hydrogen sulfide introduced through static tap upstream.

(b) Hydrogen sulfide introduced from tap in passage.



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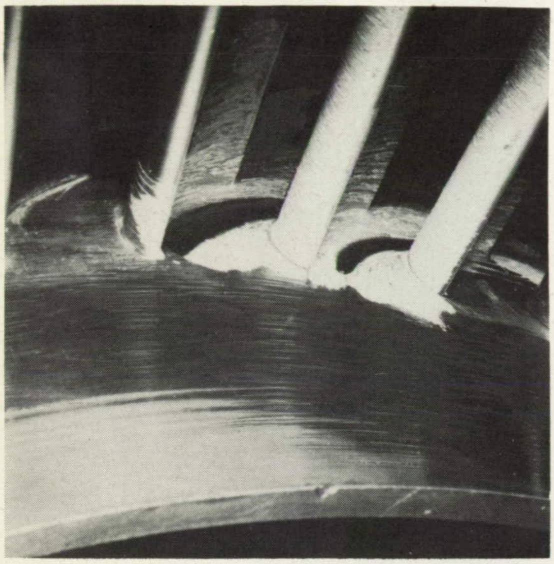
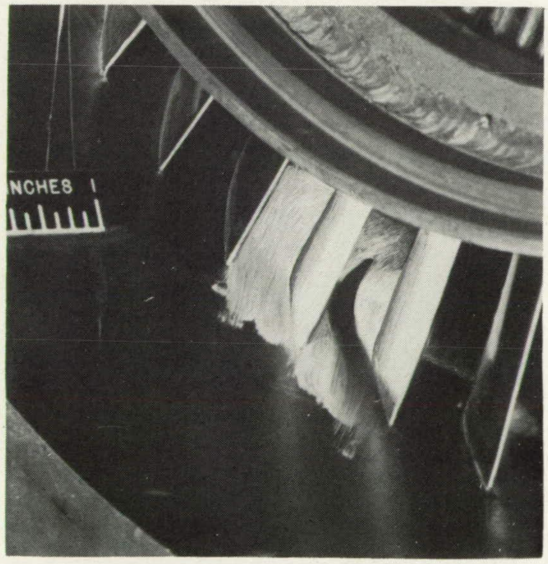
(c) Hydrogen sulfide trace on blade suction surface.

Figure 9. - Flow traces in two-dimensional cascade at Mach numbers of approximately 0.4.



(a) Upstream view of inner shroud.

(b) Downstream view of inner shroud.



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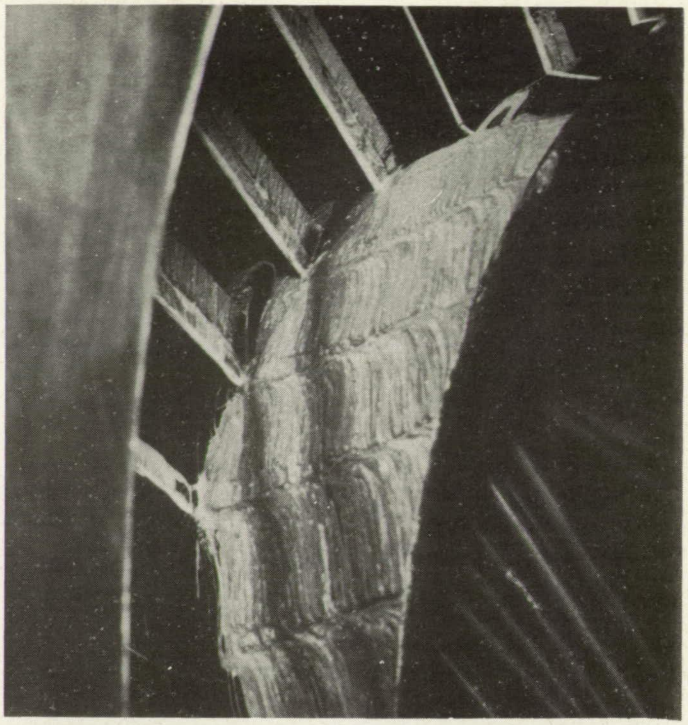
(c) Downstream view of outer shroud.

Figure 10. - Hydrogen sulfide traces in annular-turbine-nozzle cascade at high subsonic velocities. Hub-discharge Mach number, approximately 0.9; tip-discharge Mach number, approximately 0.7.



(a) Downstream view of inner shroud.

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(b) Downstream view of outer shroud.

Figure 11. - Hydrogen sulfide traces in annular-turbine-nozzle cascade at supersonic velocities. Hub-discharge Mach number, approximately 1.5; tip-discharge Mach number, approximately 1.2.

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