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VISUALIZATION STUDY OF SECONDARY FLOWS IN TURBINE ROTOR TIP REGIONS

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SUMMARY

Smoke was used to visualize the secondary-flow phenomena in the rotor-blade tip region of a low-speed turbine, and measurements of the factors affecting the flow patterns were recorded from visual observations.

Cross-channel flow and passage vortex formation observed in rotor-blade passages were similar to those found in stationary shrouded blade rows. However, because of the clearance space and relative motion between blade tip and shroud, additional flows and modifications of cross-channel flow resulted. The clearance space gave rise to a tip-leakage vortex at low rotor speeds; and, when the relative motion between blade tip and shroud was of sufficient magnitude, a scraping vortex was produced.

A region of rotor speeds with no definite vortex pattern existed between the tip-leakage vortex region and the scraping vortex region. This region of transition appeared to represent a condition of reduced disturbance in main flow at the rotor-blade tip. At large clearances where the mainstream air governed the flow pattern, the rotor speed required to reach transition was a function of axial airspeed and did not depend on clearance. For smaller clearances where the rotor-blade tip was in the shroud boundary layer, transition depended on clearance and boundary-layer velocity profile. Results of large changes in blade camber showed no observable effect on transition rotor tip speed. Increases in angle of incidence from zero resulted in increased transition rotor tip speed due to increases in the component of air flow normal to the mean camber line at the point of smoke introduction and observation. Installation of a flow fence on the rotor-blade tip as a means of reducing tip-clearance flow across the blade tip from pressure to suction surface resulted in a reduction of transition rotor speed.

Preliminary comparison of results at low speed with actual turbine operating data indicates that turbines normally operate in a region where scraping effect would be expected. Although the results obtained from this investigation are not intended to be applied directly to blade design at higher airspeeds, they should serve as a guide in extending the investigation to higher values of airspeeds and tip speeds which are encountered in actual turbine operation.

INTRODUCTION

One of the principal problems in the design of turbomachines is an understanding of the flow process taking place through the turbine rotor. Flow phenomena in the rotor-blade tip region where rotor tip-clearance space exists are discussed in reference 1. Smoke-flow patterns for a two-dimensional cascade having a moving wall indicated that air flow from pressure to suction surface through the clearance space resulted in a vortex near the corner between the wall and the suction surface. Increased wall speed caused formation of a vortex of opposite rotational direction in the same region due to a scraping effect of the blade. It was suggested that at the proper wall speed a balance or transition condition might be established between these two types of rotation, with the result that minimum flow disturbance would exist in the rotor-blade tip region. This condition, if established, could, under actual turbine operating conditions, result in a reduced disturbance in main flow at the rotor-blade tip.

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In order to investigate further these types of flow behavior, smoke-visualization techniques were applied to a low-speed turbine setup. This constitutes a continuation of the fundamental investigation of secondary flows in turbine blade passages which are reported in references 1 to 3. The objectives of the present investigation were to obtain a good visual picture of the tip-flow phenomena and to determine what factors of blade geometry and tip condition influence or govern the types of secondary-flow behavior encountered at the blade tip.

Although the results obtained from this investigation are not intended to be applied directly to blade design for high speeds, it is felt that an interpretation of the secondary-flow phenomena observed at low airspeeds would serve as a guide in extending the investigation to airspeeds and tip speeds encountered in actual turbine operation.

In the present investigation, therefore, photographs as well as visual observations of the influence of blade geometry, solidity, and tip conditions on tip secondary-flow phenomena were made at the NACA Lewis laboratory by independently varying inlet blade angle, camber, tip clearance, and airspeed, and varying the solidity in a low-speed turbine.

APPARATUS AND PROCEDURE

Test Unit

A schematic view of the test unit used in the investigation is shown in figure 1. The outer casing (hereinafter referred to as the outer shroud) was constructed of Lucite to facilitate the use of a light synchronized with the blades for visual inspection and photography of the smoke pattern through the turbine. The speed of the rotor was controlled by a variable-speed electric motor, and the rotor speed was measured with an electric tachometer. Air to the test unit was supplied by the laboratory combustion air system and was discharged directly into the room. The axial air velocity was determined by several independent methods, the final values of velocity being obtained through the use of a Hastings electronic manometer, which was calibrated against a thin-plate orifice.

Introduction of smoke used for observation of the secondary-flow behavior was generally made through the Lucite outer shroud at an axial location corresponding to approximately the rotor-blade midchord. Smoke-flow patterns of the cross-channel flow and passage vortex were obtained by introducing smoke through the shroud at an axial location just ahead of the rotor-blade leading edge. Smoke was produced by burning oil-soaked cigars in a forced draft of air. The rate of smoke production and injection into the air stream was carefully controlled by a pressure regulator so as to match closely the local direction, velocity, and density of the air stream.

Nozzle Blades

A set of 48 airfoil-shaped nozzle blades having a hub-to-tip radius ratio of 0.730 and a tip diameter of 16.250 inches was designed for a constant discharge angle of 30.2° from tangential. These nozzle blades were also reset for a constant discharge angle of 37.2° from tangential. A complete description of the blades with profile coordinates is given as blade type B in reference 2.

Rotor Blades

Three sheet-metal circular-arc rotor-blade configurations which differed mainly in amount of camber (20°, 61°, and 98°) and a conventional airfoil-type blade of 70° camber were investigated. The rotor consisted of 29 blades for the circular-arc blade configurations having tip chord lengths of 2.15, 1.87, and 2.12 inches for the 20°, 61°, and 98° blades, respectively. The rotor for the conventional airfoil-type configuration consisted of 60 blades having a tip chord length of 1.125 inches. The blade tip solidities, therefore, were 1.23, 1.07, 1.21, and 1.31 for the 20°, 61°, 98°, and 70° rotor blades, respectively. The circular-arc sheet-metal blades were mounted on circular bases in the rotor disk to facilitate changes in inlet blade angle (angle formed by tangent to blade camber line near leading edge and tangential direction). The airfoil-type rotor blade, however, had the conventional mounting base, which prevented any changes in blade inlet angle. Profiles of the rotor blades are shown in figure 2.

Test Procedure

The three sheet-metal circular-arc rotor-blade configurations and the airfoil-type blade were investigated over the range of variables shown in table I. Nozzle and rotor-blade nomenclature is shown in figure 3; symbols are defined in the appendix. The influence of blade geometry and tip conditions on rotor tip secondary-flow phenomena was systematically investigated by independently varying inlet blade angle, camber, solidity, tip clearance, and airspeed.

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Observational Procedure

In order to eliminate any possible effect on the results due to a variation in smoke pattern along the blade tip from leading to trailing edge, a single smoke inlet was used for all data to be plotted. The smoke inlet through the outer shroud was chosen to be slightly upstream of the rotor-blade midchord position.

The method used for studying the factors governing secondary-flow phenomena in the rotor tip region required the determination of rotor speed which produced a given reference pattern in the flow development. Transition between the tip-clearance-type and scraping-type flow (ref. 1) was thought to be a desirable condition because of reduced flow disturbance. Therefore, this region in secondary-flow development was considered to be advantageous as a reference. However, at this condition no well-defined smoke pattern was formed. Hence the transition region was identified by taking the average between the minimum rotor speed required to produce the scraping vortex and the maximum rotor speed required to produce the tip-leakage vortex. This could be done either photographically or visually.

Because of limitations in photographic techniques, visual observation were more dependable and much less time consuming. Under many conditions, however, even visual observation was difficult. Values of rotor speed required for onset of the scraping vortex or of the tip-leakage vortex were not well defined because of slowness of variation in pattern with rotor speed and because of differences in pattern appearance for different configurations and flow conditions. Therefore, determination of rotor-speed values depended on establishment of arbitrary standards for the shape of the pattern. Measurements were subjective in nature in that memory of reference-pattern shapes was required for comparison of rotor speeds observed under different conditions. Airspeed, tip clearance, blade inlet angle, and camber affected the sharpness and shape of any given pattern. Hence, in accumulating the data reported herein, much care was required in finding similar identifying characteristics for all the variations in appearance of the reference pattern, and the individual values of rotor speed obtained were understandably limited in accuracy. Although the plots of original data show much scatter of points, the results show unmistakable trends.

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RESULTS AND DISCUSSION

General Description of Smoke Patterns

In reference 1 are reported visual and photographic observations of a number of blade-end-region secondary flows in a two-dimensional cascade with moving wall. Among these were cross-channel flow, tip-clearance flow, and a scraping effect, each resulting in a vortex formation in the blade passage. These have been observed in the same general form in the rotor tip region of the present low-speed turbine.

In this investigation, the flows as traced by smoke involved only air in or from the outer-shroud boundary layer. The flows may be divided into two general types. One type, including the cross-channel and scraping flows, had a relative velocity across the channel opposite to the direction of rotor motion and culminated in a vortex which was clockwise as viewed looking into the rotor exit. A vortex with this rotation appeared with the rotor stationary or moving at low speeds (the passage vortex) and another at high rotor speeds (the scraping vortex). The other type, tip-clearance flow, had a relative velocity in the direction of rotor motion through the clearance space between the blade tip and the shroud and culminated in a counterclockwise vortex at low rotor speeds (the tip-leakage vortex).

Each of the two types of flow was thought to be the resultant of three velocity components in the boundary layer, each being taken in the direction across the channel. These components were due to (1) the cross-channel pressure difference, (2) the boundary-layer velocity at the rotor inlet, and (3) the rotor motion. Depending upon the magnitudes of these components, one or both of the two types of flow usually appeared in a blade passage. However, for a given passage configuration and flow condition, a range of rotor speeds existed for which these boundary-layer secondary-flow disturbances appeared to be at a minimum. This has been termed a transition condition. As would be expected, the conditions under which transition appeared involved not only rotor speed but also the blade and flow parameters which affected the velocity components previously mentioned. Evaluation of the influence of these parameters on blade-passage secondary-flow patterns was one of the principal objectives of the present investigation.

The method used for the evaluation involved systematic changes in blade and flow parameters. Such changes influenced the previously noted velocity components which were due to the cross-channel pressure difference and the boundary-layer velocity at the rotor inlet. The amount of such influence was measured by observing the rotor speed required to produce the transition condition for each passage configuration and flow condition. Transition was observed by the use of smoke visualization. The transition condition was of interest in itself, because it appeared to present a pattern of minimum flow disturbance.

Before discussion of measurements of the rotor speed required for transition, a general description of the flows as observed herein will be presented. Flows discussed will include cross-channel, tip clearance, and scraping flows with their resulting vortices and the flow in the rotor-speed region of transition where there was minimum disturbance of normal flow. Smoke-pattern photographs will be included to aid in visualizing the flows. The same patterns appeared for all blade configurations, but not all could be readily photographed. Each of the photographs was selected to show a type of pattern, as indicated by the diagram accompanying it. Extraneous smoke appearing in the photographs was due to diffusion of the smoke from the pattern into the surrounding air as it moved downstream. This diffusion was aggravated rapidly as airspeed increased. Thus most photographs of vortices show the smoke defining only a single turn or less.

Cross-channel flow and passage vortex. - With the rotor stationary and with the rotor-blade tip clearance less than the inlet boundary-layer thickness on the outer shroud, cross-channel flow toward the rotor-blade suction surface appeared on the shroud. This occurred in much the same way as in a shrouded nozzle (ref. 3) where the nature of the flow was governed chiefly by the turning of the channel. The main difference herein was that some of the boundary-layer air nearest the pressure surface was forced through the clearance space instead of overturning toward the suction surface. As in some shrouded nozzles, the passage vortex also appeared.

In figure 4 are shown views through the transparent outer shroud of cross-channel-flow patterns with roll-up in passage vortices as the smoke approached the suction surface. The blades shown in figure 4(b) were the same as those in figure 4(a), except that the solidity was doubled for the former. It can be seen that the patterns were the same in essence and different only in detail. The configurations involved (A_2 and A_6) are described in table I. Figure 5 shows the beginning of the passage vortex with clockwise rotation as viewed from downstream. Here the cross-passage motion of the smoke on the shroud was toward the blade suction surface on the right until it suddenly dipped away from the shroud and turned toward the left. About one-half turn of the clockwise rotation is shown.

The effect on cross-channel flow of an increase in tip clearance with the rotor stationary is shown in figure 6. For figure 6(a) the blade tip was well inside the outer-shroud boundary layer at the rotor inlet. As the cross-channel flow approached the suction surface, it reached a point where it rolled up in the passage vortex, which carried it downstream toward the rotor exit. Figure 6(b) shows the blade tip still in the boundary layer, but the roll-up was a little farther from the suction surface because of an increase in the tip-clearance flow through the widened clearance space.

The diagram in figure 6(c), descriptive of figures 6(a) and (b), shows that, when the blade tip was in the boundary layer, the mainstream flow (solid line) near the blade tip followed the blade contour approximately. Flow through the clearance space increased slightly with increase in tip clearance but was kept small by viscosity effects, and the cross-channel pressure difference was maintained with only a little reduction due to such flow. The cross-channel flow observed (dashed line) had a large component toward the suction surface. This resulted from two velocities in the cross-channel direction. One was the cross-channel component (if any) resulting from the relative boundary-layer velocity at the rotor inlet. The other was introduced by the cross-channel pressure difference.

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The photographs of figures 7(a) and (b) show the effect of increasing the tip clearance until the blade tip was in the mainstream outside the shroud boundary layer. Only a small amount of smoke remained in the boundary layer long enough to map out the cross-channel flow. This small amount of smoke indicated that the cross-channel flow was less prominent and the roll-up occurred farther from the suction surface at these tip clearances than for the tip clearance of figure 6(b).

The diagram of figure 7(c) shows that mainstream flow in the vicinity of the blade tip spilled through the clearance space, reducing the mainstream turning in the passage near the shroud boundary layer. This meant that the cross-channel pressure difference in the boundary layer and its effect on boundary-layer velocity were also reduced. Thus the cross-channel flow had only a small resulting component in the direction toward the suction surface. In the clearance space between the actual blade tip and the shroud, the pressure gradient was reversed so that both boundary-layer and mainstream flows through the clearance space acquired a locally reversed turning as shown in figure 7(c).

When the rotor speed increased from zero, the cross-channel flow was increased by the addition of the relative velocity component toward the suction surface due to the rotor-blade tip speed.

Tip-clearance flow. - When the rotor was stationary or moving at very low speeds, the boundary-layer air near the corner between the outer-shroud surface and the pressure surface leaked through the tip-clearance space. It remained near the shroud after passing the blade tip until it encountered the cross-channel flow in the next passage. The meeting of these two oppositely directed air streams resulted in both turning away from the shroud. Figure 8(a) shows the tip-clearance flow in the process of turning. This started a counterclockwise rotational motion and began the formation of the counterclockwise tip-leakage vortex. The photograph also shows some of the smoke entering the clockwise passage vortex, although this vortex was formed from cross-channel flow into which no smoke had been introduced directly.

An example of a well-defined tip-leakage vortex is shown in figure 8(b). For most configurations the tip-leakage vortex was weak and not well-defined, as in figure 8(a). However, visual indications of counterclockwise rotation seemed always to be present when the rotor speed was sufficiently low.

With the rotor stationary and the blade tip in the boundary layer, increases in tip clearance resulted in increases in boundary-layer air flow through the clearance space and consequently a slightly reduced pressure difference across the blade tip and across the channel in the boundary layer. 3727 The influence of pressure difference on both cross-channel flow and tip-clearance flow was therefore slightly reduced.

Inlet boundary-layer velocity at the blade tip increased with increase in distance of the blade tip from the outer shroud. Therefore there was a similar increase in the component of boundary-layer velocity in the direction over the blade tip at the point of observation. This increase was directed in such a way as to reinforce the tip-clearance flow and diminish the cross-channel flow. The point where these flows met and rolled up would appear to have been a function of the velocities involved. As a result, as tip clearance was increased, the point of vortex formation due to interaction between the two flows moved farther from the suction surface. This effect continued with increase in tip clearance until the tip clearance was of the order of magnitude of the boundary-layer thickness. Beyond this value of tip clearance the effect of inlet boundary-layer velocity on the location of the point of vortex formation remained constant with tip-clearance changes.

As rotor speed increased from zero, the boundary-layer flows relative to the blades were changed. Blade motion reinforced the cross-channel flow and diminished the tip-clearance flow. As a result, the point of interaction between the two flows and of vortex formation approached the suction surface (figs. 9(a) and (b)).

Transition. - For each blade configuration and flow condition tested, there was a limited range of rotor speeds for which vortex formation appeared to reach a minimum. Above and below this rotor-speed range, vortex formations were observed, although these formations differed from each other in character. This particular rotor-speed region appeared to represent a transition between rotor-speed regions of definite vortex formation. Figures 10(a) and (b) illustrate the smoke patterns observed for transition. It can be seen that the tip-clearance flow turned toward the hub as in figure 9 as if to start a counterclockwise vortex. However, the point of interaction between cross-channel and tip-clearance flows appeared to have approached near enough to the suction surface to prevent vortex formation.

Scraping. - With increase in rotor speed beyond the transition region, another vortex appeared as shown by figures 11(a) to (c). Its clockwise rotational direction was the same as that of the passage vortex. Since the motion of the rotor blade relative to the shroud boundary layer rather than the cross-channel pressure difference was of prime importance in producing this vortex, it has been termed a scraping vortex (ref. 1). This is not meant to imply a distinction in the actual mechanics of formation for the scraping vortex as opposed to the passage vortex. A distinction is made only in the factors primarily responsible for producing boundary-layer-flow components normal to the blade suction surface.

A scraping vortex was found to form from boundary-layer air whether the blade tip was inside or outside the boundary-layer region. In the former case the physical presence of the blade probably produced the roll-up. The latter case is illustrated by the photograph in figure 11(d), where the motion of the pressure field in the vicinity of the blade tip was probably responsible for turning the boundary-layer air away from the shroud and rolling it up.

Shroud Boundary-Layer Considerations

The nature and thickness of the boundary layer on the outer shroud were of interest because of the behavior of the smoke pattern as the rotor tip clearance was changed. Earlier work (ref. 2) showed that the shroud boundary layer leaving a nozzle blade row was nonuniform, varying in thickness across the nozzle passage. The range appeared to be from practically zero to 1/10 of an inch or more, depending on air-flow conditions. The low-thickness values were for air leaving the nozzle passage near the pressure surface. The higher values were for the loss region leaving the nozzle passage near the suction surface. This variation, together with the disturbance which a moving rotor-blade tip may impart to the boundary layer, leaves the uniformity of the shroud boundary layer in the vicinity of a rotor somewhat in doubt.

On the average, the outer-shroud boundary layer at the rotor inlet would be expected to be laminar because of the low airspeeds used in this investigation. A calculation of its thickness can be made, based on an equivalent flat-plate length from nozzle trailing edge to rotor leading edge. Such a calculation was found to agree in order of magnitude with indications of boundary-layer thickness obtained from observations made when changing the tip clearance.

Under operating conditions in an actual high-speed turbine, the corresponding boundary layer would be turbulent. The parameters affecting turbulent and laminar boundary-layer flow, however, are the same. Therefore, over-all qualitative similarity might be found between the secondary flows due to the two types of boundary layer.

Transition Rotor Tip Speed

The following manner of assigning responsibility for changes in transition rotor tip speed with changes in configuration or in flow conditions was followed in most of the cases to be discussed in this section.

Results indicated, in general, that a change in configuration or in flow condition which caused an increase or decrease in cross-channel pressure difference did not by this means affect transition rotor tip speed. This apparently was because the cross-channel pressure difference influenced both cross-channel flow and the oppositely directed tip-clearance flow to roughly the same extent, and the relative magnitudes of these two flows determined transition rotor tip speed. 3727

However, a change in configuration or in flow condition which caused an increase or decrease in the inlet boundary-layer velocity (or rather in its component normal to the mean camber line at the point of observation) seemed thereby to affect transition rotor tip speed, possibly because this component acted in a direction to aid tip-clearance flow and oppose cross-channel flow and thus upset any previous balance between them. The rotor speed then had to be adjusted to restore the balance required for transition.

Effect of air-flow rate. - The observations showed that the transition rotor tip speed, taken as the average between the highest rotor tip speed for tip-leakage vortex formation and the lowest rotor tip speed for scraping vortex formation, increased with increasing air-flow rate (as measured by mainstream axial airspeed) when other independent variables were kept constant. Data scatter did not permit accurate determination of the rate of increase. However, in the air-flow range tested, for the largest tip clearances the transition rotor tip speed U_t increased at about the same rate as the mainstream axial airspeed V_x or, possibly, at a slightly greater rate. In other words, the ratio U_t/V_x was a constant or increased only slightly with increase in V_x. An average constant value of U_t/V_x for large tip clearances was estimated for each configuration tested. At the smaller tip clearances tested, the ratio U_t/V_x showed a pronounced increase with increase in V_x.

An increase in axial airspeed would increase both the cross-channel pressure difference and the inlet boundary-layer velocity. An increase in cross-channel pressure difference would be expected to increase both tip-clearance flow and cross-channel flow and have little if any effect on transition rotor tip speed, which was an indication of the relative magnitudes of these oppositely directed flows. However, an increase in inlet boundary-layer velocity would increase tip-clearance flow and decrease cross-channel flow, because of the increased tangential component, and therefore probably was mainly responsible for the increase in transition rotor tip speed U_t as V_x increased.

Effect of tip clearance. - Since at large tip clearances the ratio of transition rotor tip speed to mainstream axial airspeed U_t/V_x was a constant or nearly a constant as airspeed was changed, this ratio was thought to be useful in comparing data at smaller rotor-blade tip clearances. Tip clearance s was considered in terms of the outer-shroud boundary-layer thickness δ at the rotor inlet. Data were plotted with U_t/V_x as ordinate and s/δ as abscissa for all configurations, as shown in figure 12. For each value of tip clearance, six points were plotted, representing six boundary-layer thicknesses (one for each mainstream axial airspeed used).

The transition band changed gradually into the tip-leakage vortex on one side and the scraping vortex on the other. As rotor speed was changed in either direction from the transition region, the vortex formations took shape slowly, so that the edges of the transition band were far from sharp. The smoke patterns used for measurement occurred at values of U_t/V_x differing from the mean ordinates plotted in figure 12 by roughly ± 0.15 at large tip-clearance values.

These curves, taken as a whole, indicate that there were two significant regions of tip clearance. In the region of small tip clearance, 0.023 and 0.040 inch, there is a sharp positive slope indicating that U_t/V_x was definitely increasing with the tip-clearance ratio. This would be expected if the rotor-blade tip was in the outer-shroud boundary layer, since airspeed in the boundary layer flowing through the clearance space increased with distance from the wall. In the region of large tip clearance, a straight line of zero slope was drawn through the points. This straight line seemed to represent the effect of tip clearance on U_t/V_x moderately well in this tip-clearance region. The uncertainity with respect to the effect of airspeed on U_t/V_x is indicated by the tendency of the six points for a given clearance, representing different mainstream airspeeds, to show ordinates increasing somewhat with airspeed. This tendency, however, did not appear for all configurations and may have been due to the uncertainty inherent in the experimental method.

The knee of the curve was thought to give an abscissa roughly representing the effective edge of the boundary layer. On this basis, the average boundary-layer thickness was approximately 0.07 inch at the lowest airspeed used.

The ordinates of the horizontal straight lines in figure 12 provided convenient values for comparing results obtained with different configurations and flow conditions.

Effect of rotor angle of incidence i. - In figure 13 is shown the change in the value of U_t/V_x for large tip clearances ($s/\delta > 1$, horizontal lines in fig. 12) as the configuration was changed toward more positive angles of incidence. The configuration represented by each circle is indicated by the lettering in the circle, with the corresponding data being given in table I. The angles of incidence were computed for large tip clearances, assuming that in this region U_t/V_x did not change with airspeed so that this ratio together with α and θ determined the incidence angle. Both α and θ were changed through wide ranges, and both were found to affect U_t/V_x by their influence on the angle of incidence.

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An increase in angle of incidence for a given axial velocity would mean an increase in the cross-channel component of inlet boundary-layer velocity (toward the pressure-surface side of the blade). This component tends to increase tip-clearance flow (toward pressure surface) while decreasing cross-channel flow (toward suction surface). Thus, the point of vortex formation would be moved farther from the rotor-blade suction surface. An increase in positive angle of incidence would therefore require a higher rotor speed to compensate for it in order to reach the transition condition, as shown in figure 13. A study of data where tip clearance is less than boundary-layer thickness indicates that a similar trend appears, as angle of incidence is changed, as that which appears for large tip clearance. The trend is much less pronounced, so that angle of incidence may have a much smaller effect on transition rotor tip speed for small tip clearances than for large tip clearances.

Also included in figure 13 are points representing three configurations (A_6, A_7, and B_1) which had characteristics that might cause them to represent exceptions to the correlation with angle of incidence, although one (A_6) actually was not an exception. These will be discussed in the following paragraphs.

Effect of solidity and suction-surface separation. - Configuration A_6 had a solidity twice that for A_2. Otherwise the two were the same. The two points representing these configurations in figure 13 are adjacent to each other, indicating that doubling the solidity had little if any effect on the transition rotor tip speed. Doubling the solidity decreased the exit deviation angle considerably and probably eliminated or greatly reduced a region of separation on the suction surface. Thus it appears that suction-surface separation was not an appreciable factor in producing the flow patterns observed, although it almost certainly accompanied the high positive angles of incidence which did affect the flow patterns.

Effect of blade profile. - The value of U_t/V_x plotted in figure 13 and representing a large tip clearance for configuration B_1 was somewhat lower than for the unmodified circular-arc sheet-metal blades. This configuration had an airfoil shape with roughly the same solidity as the others (except A_6), although the chord and pitch were only about half as great. These characteristics may have been responsible for the observation that smoke patterns of vortices tended to be sharper and more concentrated for this blade than for the circular-arc blades. Since any change in appearance of the smoke patterns increased the difficulty of maintaining a fixed reference pattern, this may be at least partially responsible for the low value found for U_t/V_x.

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Effect of flow fence. - Configuration A_7 had a flow fence consisting of a thin sheet of metal extending circumferentially 1/4 inch out from the rotor-blade pressure surface at the tip. Otherwise configuration A_7 was the same as A_2. The flow fence was thought to have no influence on inlet boundary-layer velocity. However, figure 13 indicates that the flow fence caused a reduction in U_t/V_x, since the ordinate for configuration A_7 is lower than that for configuration A_2.

The presence of a flow fence on the blade is thought to have caused a distortion of the pressure distribution across the blade tip and passage in the outer-shroud boundary layer. By blocking the spillage from near the pressure surface, the flow fence reduced the amount of blade tip unloading. Therefore the pressure difference and probably also the pressure gradient in the cross-channel flow region were increased. However, the pressure gradient governing tip-clearance flow was probably decreased because of the increased path length across the blade tip. Also, viscous forces opposing flow over the tip may have been increased because of the increased path length. These effects are thought to have been responsible for a tip-clearance flow which was not increased with increase in cross-channel pressure difference as it normally would be, and hence for the low value of transition rotor tip speed indicated for configuration A_7 in figure 13.

Effect of rotor-blade camber. - Data for three values of rotor-blade tip camber covering a range of 78° for the design camber angle φ are included in figure 13. Blade tip chords were about the same for all blades. Configurations A_3 and C_1, for example, had values of φ differing by 37°. Nevertheless the transition rotor tip speeds were not much different for these two configurations, as indicated by the two points representing them in figure 13. Similarly, configurations C_3 and D_1 had values of φ differing by 41°, but their transition rotor tip speeds were not greatly different. Therefore, it appears that any effect rotor-blade tip camber may have had on transition rotor tip speed was too small to be observed in this investigation.

This result would be expected, since an increase in blade camber would be felt through an increase in mainstream flow-path curvature. This would increase the cross-channel pressure difference. Thus both cross-channel flow and tip-clearance flow would be increased with negligible net effect on transition rotor speed. Furthermore, since figure 13 refers to large tip clearances, flow-path curvature in the neighborhood of the shroud boundary layer was not influenced greatly by changes in blade camber, so that for large tip clearances the effects on boundary-layer-flow components, due to changes in blade camber, were small.

High-Speed-Turbine Operating Conditions

In turbine nozzles the secondary-flow patterns are qualitatively the same at both low and high airspeeds (ref. 2). The same may be true of secondary flows in the rotor tip region. That is, passage, tip-leakage, and scraping vortices may appear at high as well as at low airspeeds. If so, since tip clearance and angle of incidence would fall in the same ranges for a high-speed turbine as for those of the present investigation, it is difficult to see how changes in these quantities could have flow-pattern effects qualitatively much different at high than at low speed.

However, the effect on transition rotor tip speed of airspeed itself, particularly in a quantitative sense, is difficult to estimate so far beyond the observed range. The data reported herein, therefore, are not intended for direct application to high-speed-rotor design, but should be useful as a guide in extending the investigation to high speeds where visualization techniques cannot be used.

Data on design operating conditions for several commercial aircraft turbines give values of U/V_x which are above 1.0. This is much higher than the transition region in the low-speed turbine at zero angle of incidence (fig. 13). Thus it is possible that in investigations at high speeds it will be found that conventional rotor blades have their design operating points in the region of operation that gives a scraping vortex and its attendant losses.

SUMMARY OF RESULTS

The results of a visualization study of secondary-flow phenomena in the rotor-blade tip region of a low-speed turbine are not intended to be applied directly to blade design for high speeds. The interpretation of the secondary-flow phenomena observed at low airspeeds should serve as a guide in extending the investigation to airspeeds encountered in actual turbine operation.

The investigation consisted essentially in measuring the effects of changes in blade and flow parameters which affected the cross-channel pressure difference and the inlet boundary-layer relative velocity. Both of these as well as rotor tip speed were influential in controlling the boundary-layer secondary flows on the shroud over the rotor passages. The results of the changes were measured in terms of the tip speed required for transition, a flow pattern which appears to represent minimum flow disturbance.

The following results were obtained:

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1. Secondary flows which appeared in the rotor tip region included the cross-channel flow in the outer-shroud boundary layer and the passage vortex which appears in some stationary shrouded blade rows. However, the clearance space and relative motion between blade tip and shroud resulted, for the rotor passage, in additional flows and modifications of the cross-channel flow. The clearance space gave rise to a tip-clearance flow and resulting vortex at low rotor speeds. When the relative motion was of sufficient magnitude, it produced a scraping effect in the outer-shroud boundary layer. A region of rotor speeds with no definite vortex pattern existed between the tip-leakage vortex region and the scraping vortex region. This region of transition may represent a condition of minimum flow disturbance. Details of these effects depended on blade configuration, angle of incidence, tip clearance, airspeed, and rotor speed.

2. The rotor tip speed required for transition increased with increasing mainstream flow.

3. The rotor tip speed required for transition increased with increasing tip clearance when the rotor-blade tip was in the outer-shroud boundary layer. With the rotor-blade tip outside the outer-shroud boundary layer, increasing the tip clearance had no observable effect on transition rotor speed.

4. Changes in blade profile, solidity, and camber had no observable effect on transition rotor tip speed.

5. Changing the rotor-inlet angle of incidence toward more positive values increased the value of rotor tip speed required for minimum flow disturbance at the blade tip.

6. Installation of a flow fence on the rotor-blade tip to reduce tip-clearance flow and to maintain blade tip loading resulted in a decrease in transition rotor tip speed.

7. Preliminary comparison of results at low speed with turbine operating data indicated that turbines normally operate in a region where a scraping effect would be expected.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 17, 1955

APPENDIX - SYMBOLS

The following symbols are used in this report:

A configuration symbol for sheet-metal blade, 98° turning

B configuration symbol for airfoil-shape blade, 70° turning 3727

C configuration symbol for sheet-metal blade, 61° turning

D configuration symbol for sheet-metal blade, 20° turning

i angle of incidence, deg

s rotor-blade tip clearance (distance from blade tip to outer shroud), in.

U rotor-blade tip speed, ft/sec

V_x axial air velocity, ft/sec

α nozzle-discharge angle, deg

δ computed boundary-layer thickness, in.

θ inlet angle at rotor-blade tip measured from annulus tangential direction, deg

φ rotor-blade design camber, deg

Subscripts:

t transition

REFERENCES

1. Herzig, Howard Z., Hansen, Arthur G., and Costello, George R.: A Visualization Study of Secondary Flows in Cascades. NACA Rep. 1163, 1954. (Supersedes NACA TN 2947.)

2. Rohlik, Harold E., Kofskey, Milton G., Allen, Hubert W., and Herzig, Howard Z.: Secondary Flows and Boundary-Layer Accumulations in Turbine Nozzles. NACA Rep. 1168, 1954. (Supersedes NACA TN's 2871, 2909, and 2989.)

3. Kofskey, Milton G., and Allen, Hubert W.: Smoke Study of Nozzle Secondary Flows in a Low-Speed Turbine. NACA TN 3260, 1954.

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CO-3

TABLE I. - SUMMARY OF OPERATING CONDITIONS[a]

Blade designation	Design camber, φ, deg	Blade type	Blade inlet angle, θ, deg	Nozzle-discharge angle, α, deg
A_1	98	Circular arc	30	30.2
A_2	↓	↓	45	↓
A_3			60	
A_4			50.5	37.2
A_5			45	↓
A_6		Circular arc, double solidity	↓	30.2
A_7		Circular arc, flow fence		↓
B_1	70	Airfoil	86	
C_1	61	Circular arc	58.4	
C_2	↓	↓	73.4	
C_3			88.4	
D_1	20		93	
D_2	↓		108	
D_3			123	
D_4			123	Nozzles removed 90°

[a]Rotor-blade tip clearances s tested for each value of θ are 0.023, 0.040, 0.063, 0.095, 0.125, and 0.200 in.; axial airspeeds V_x used for each value of s are 2.50, 3.75, 4.50, 5.50, 7.50, and 10.0 ft/sec.

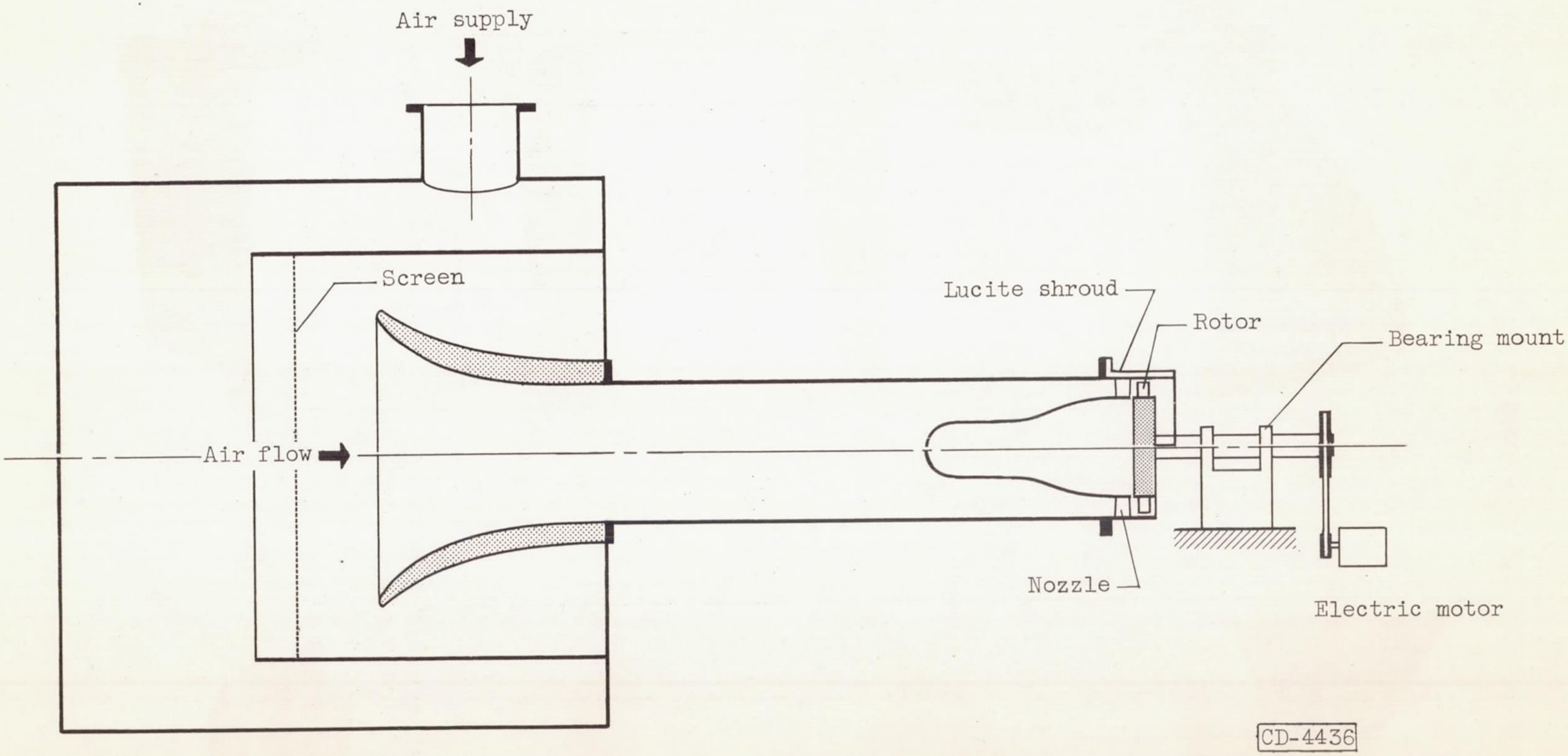
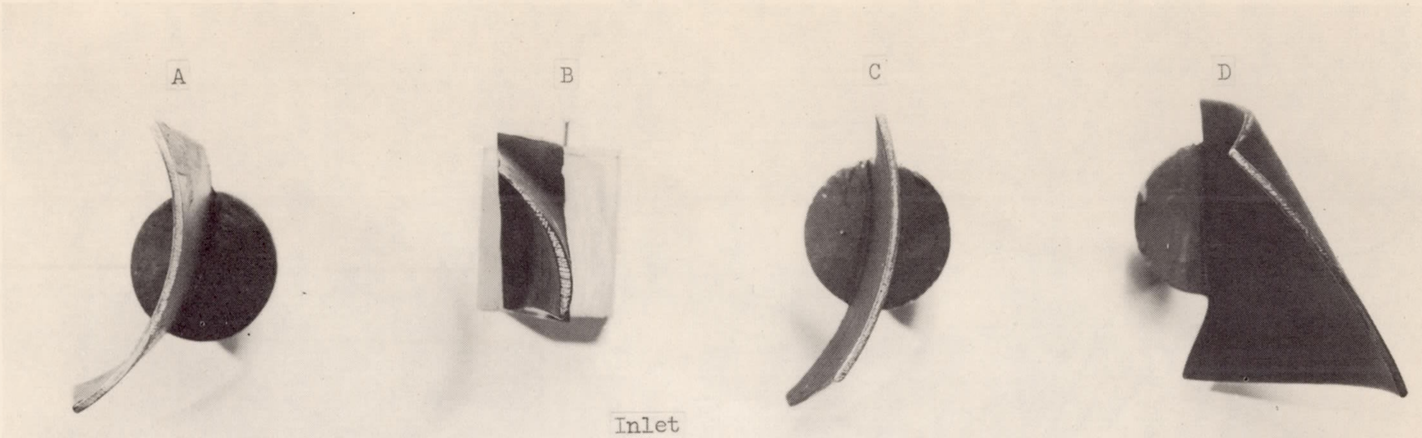
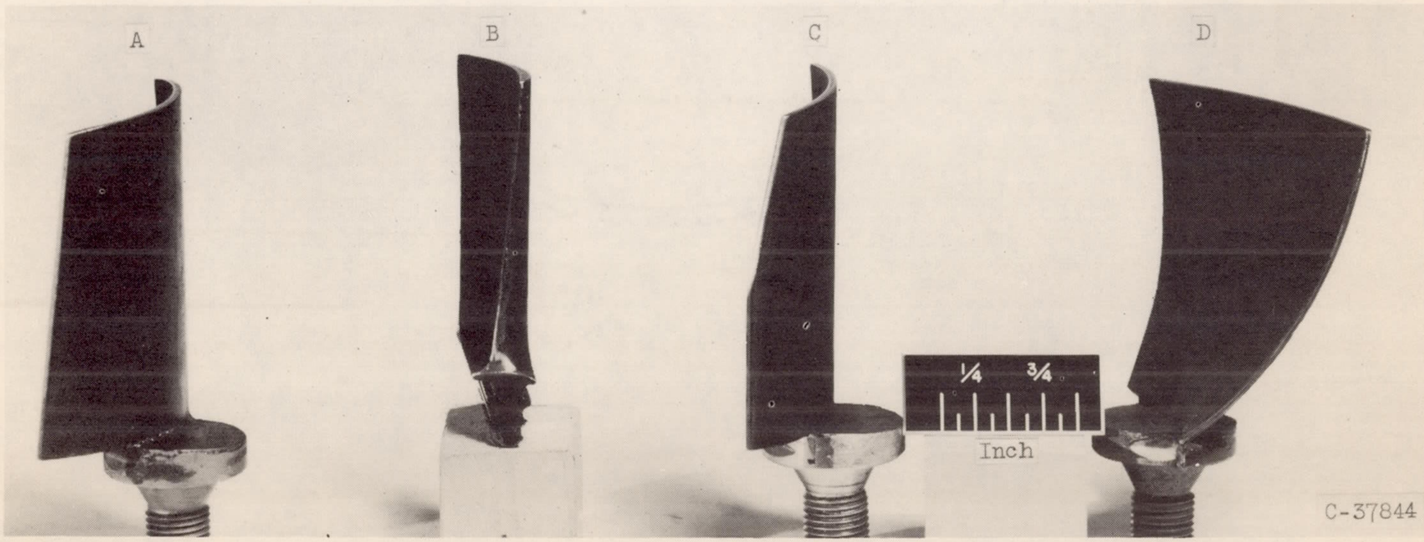


Figure 1. - Schematic view of low-speed turbine.



(a) Top view.



(b) Upstream view.

Figure 2. - Rotor-blade shapes investigated.

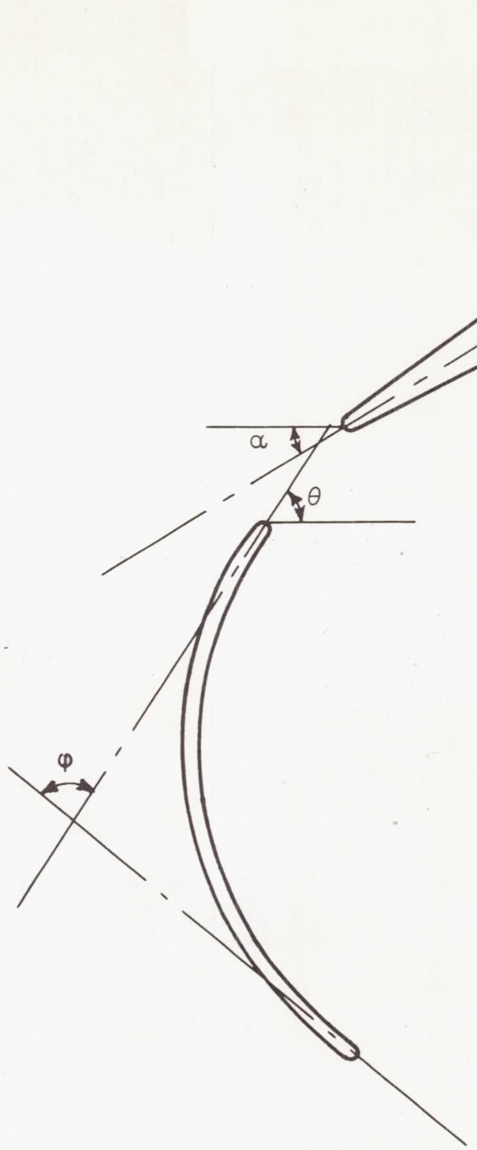


Figure 3. - Nozzle and rotor-blade nomenclature.

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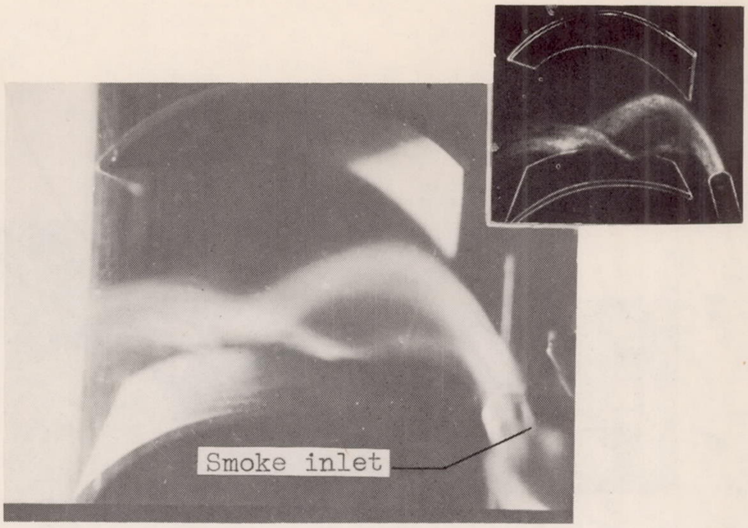
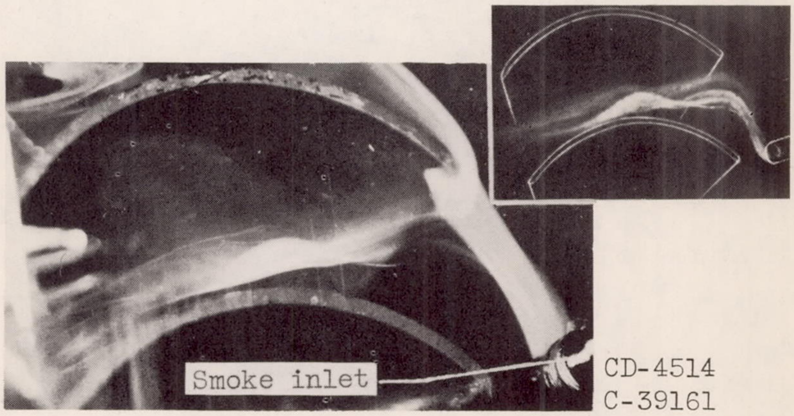


Air flow

(a) Configuration A_2.



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Air flow

(b) Configuration A_6.

Figure 4. - Cross-channel flow and passage vortex. Radial view; rotor stationary.

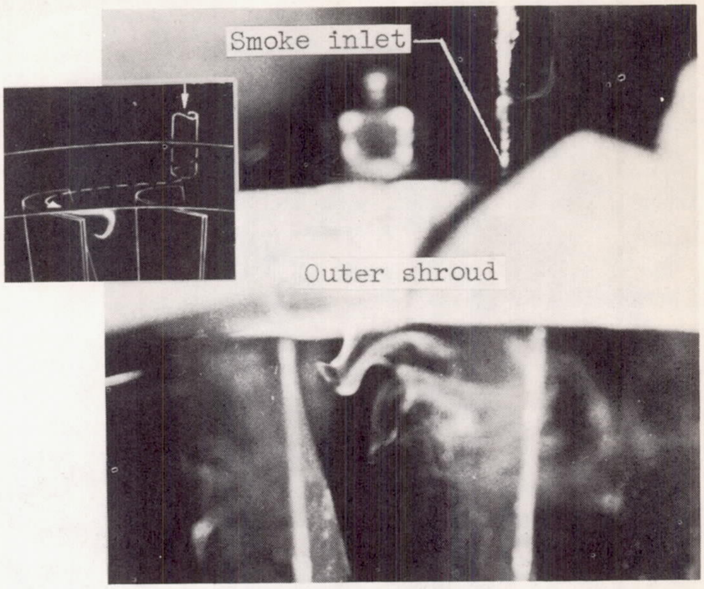
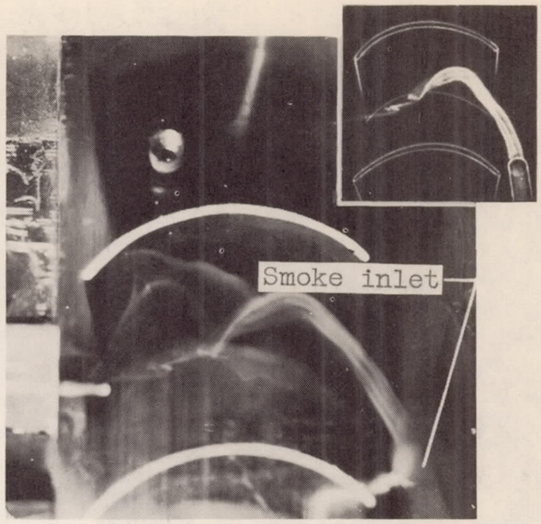


Figure 5. - Cross-channel flow and passage vortex. Downstream view; configuration A_6; rotor stationary.

Air flow ←

(a) Tip clearance, 0.040 inch.



Air flow ←

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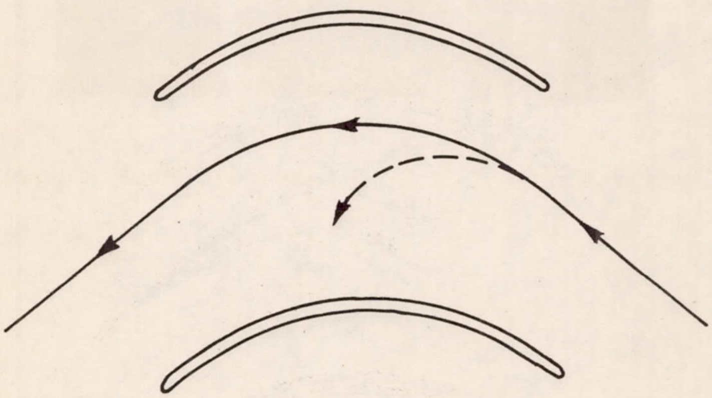
(b) Tip clearance, 0.063 inch.



(c) Flow-path curvatures in mainstream (solid line) and in boundary layer (dashed line).

Figure 6. - Effect of tip clearance on cross-channel flow. Radial view; configuration A_2; rotor stationary; small tip clearance.

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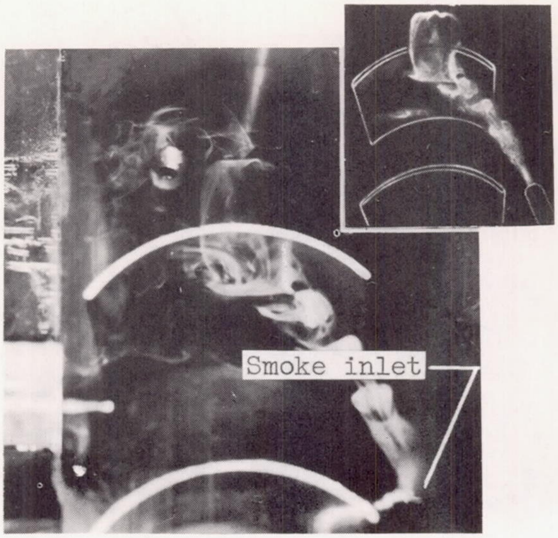
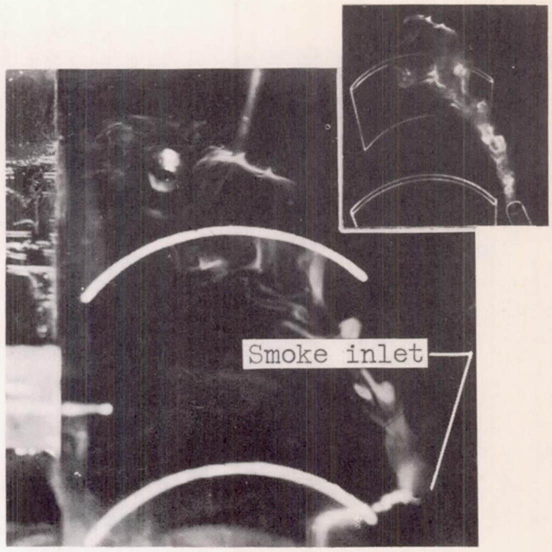


Air flow

(a) Tip clearance, 0.125 inch.



Air flow

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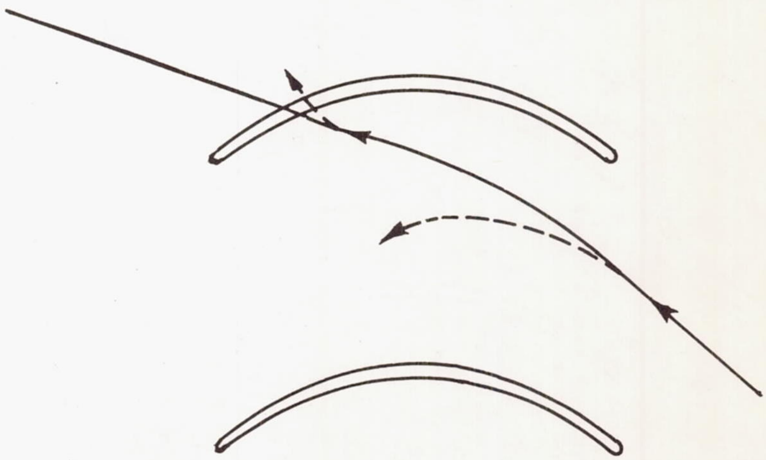
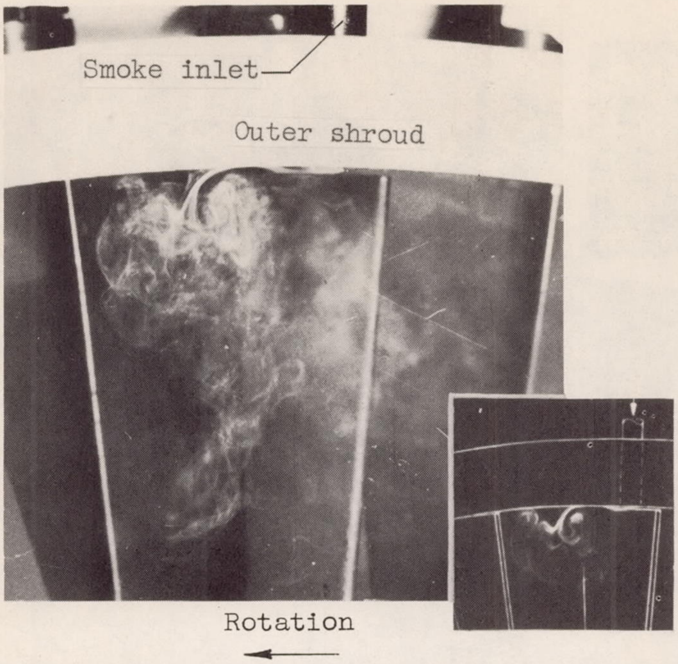
(b) Tip clearance, 0.170 inch.

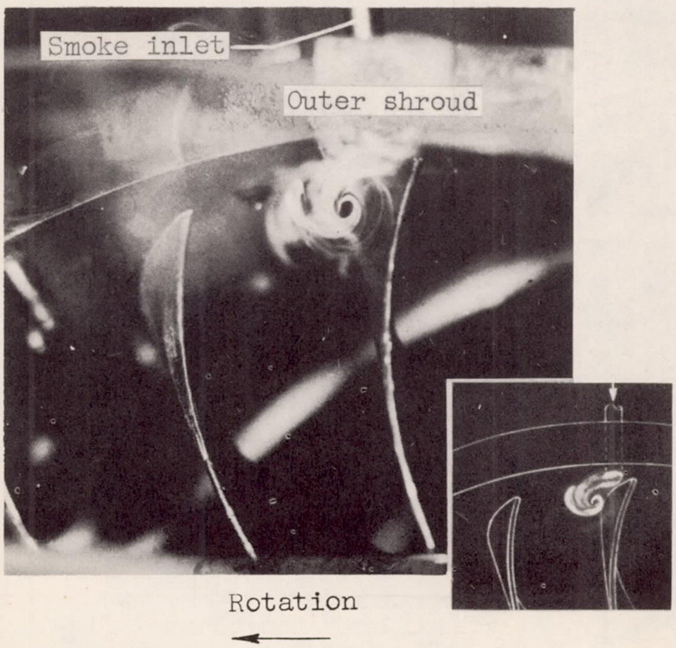


(c) Flow-path curvatures in mainstream adjacent to boundary layer (solid line) and in boundary layer (dashed line).

Figure 7. - Effect of tip clearance on cross-channel flow. Radial view; configuation A_2; rotor stationary; large tip clearance.



(a) Opposite rotations side by side. Configuration A_2; U/V_x, 0.10; tip clearance, 0.023 inch.



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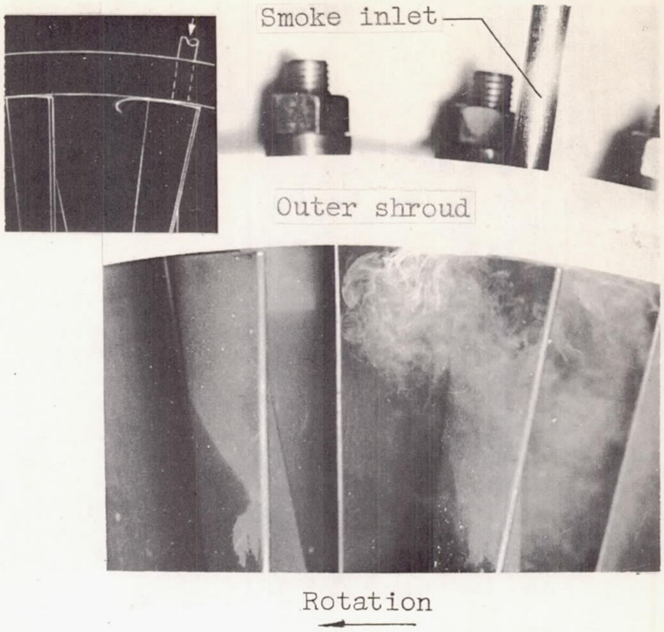
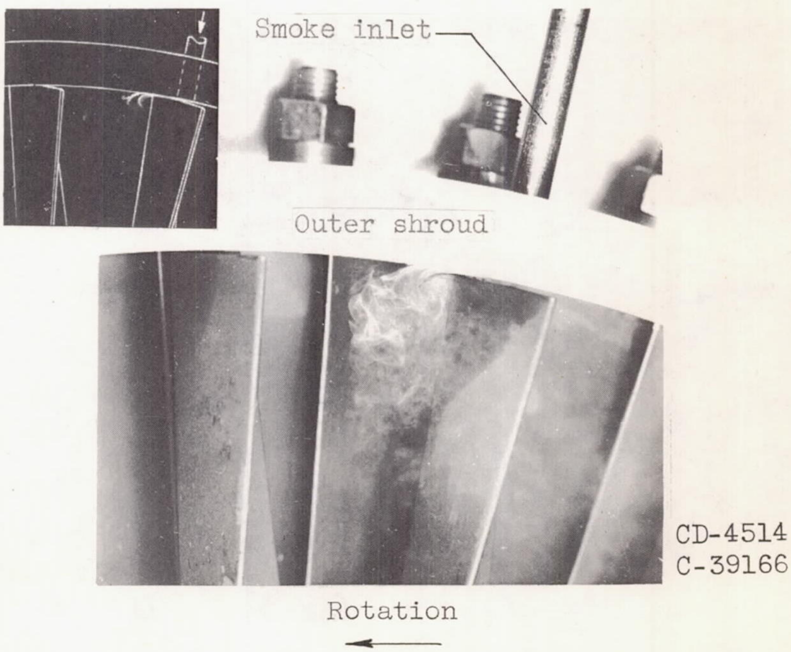
(b) Tip-leakage vortex. Configuration D_4; U/V_x, 0.20; tip clearance, 0.095 inch.

Figure 8. - Downstream views of passage vortex and tip-leakage vortex.



(a) Tip clearance, 0.023 inch; U/V_x, 0.05.



(b) Tip clearance, 0.023 inch, U/V_x, 0.15.

Figure 9. - Effect of rotor speed on tip-leakage smoke pattern. Downstream view; configuration A_2.

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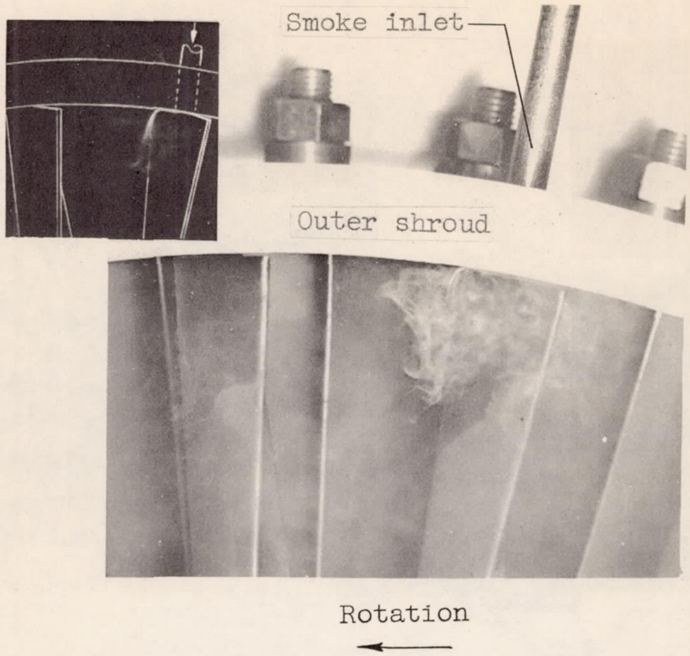
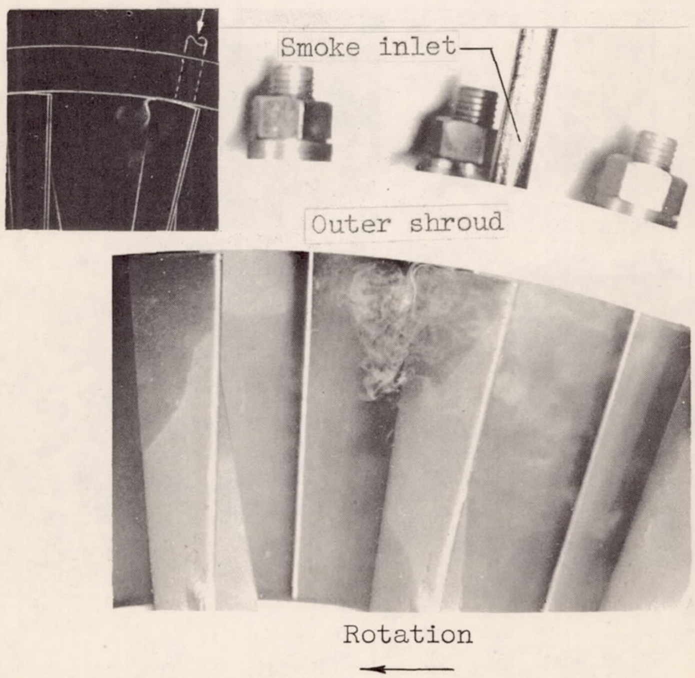
CO-4, back



(a) Tip clearance, 0.023 inch; U/V_x, 0.30.



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(b) Tip clearance, 0.023 inch; U/V_x, 0.45.

Figure 10. - Transition rotor-speed region. Downstream view; configuration A_2.

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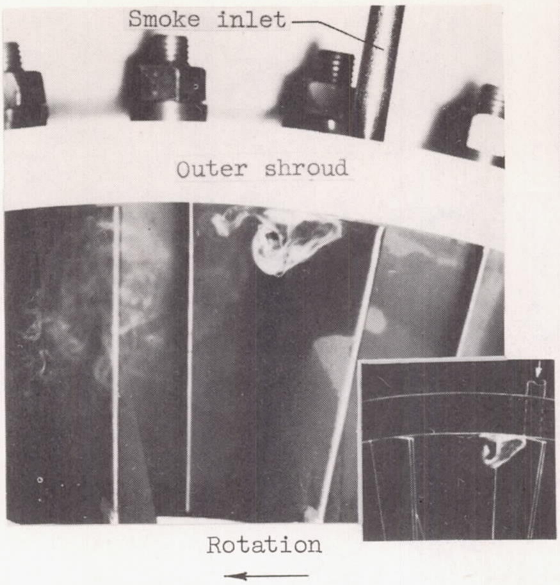
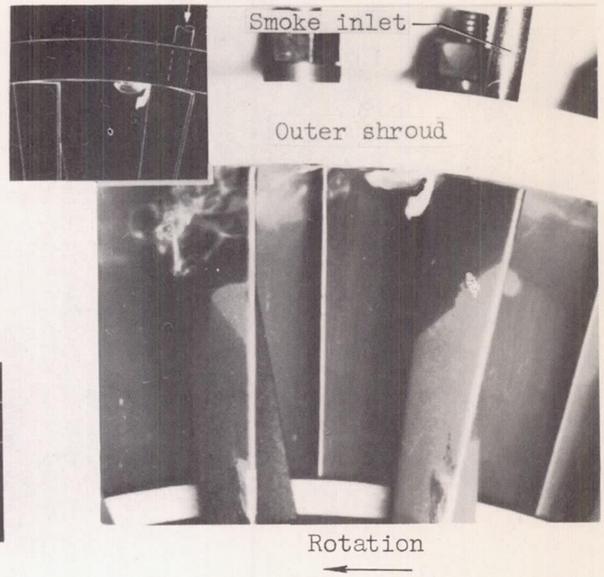
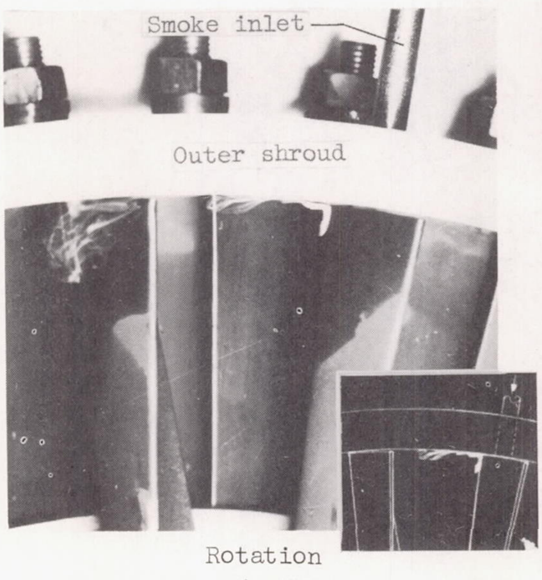


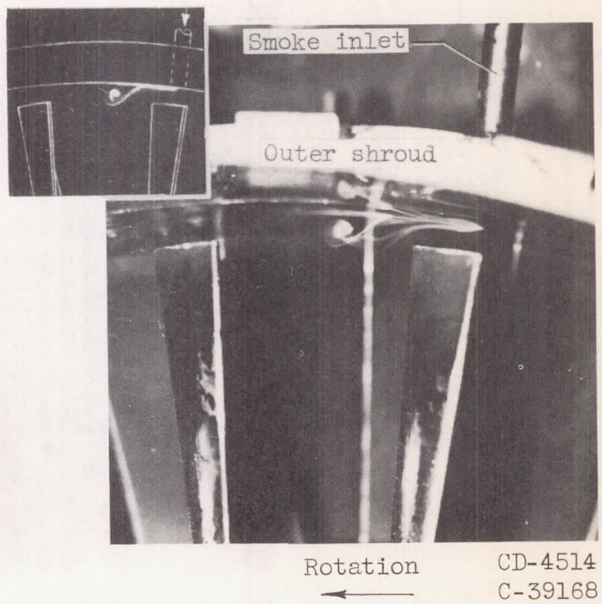
(a) Tip clearance, 0.023 inch; U/V_x, 0.60.



(b) Tip clearance, 0.023 inch; U/V_x, 0.90.



(c) Tip clearance, 0.023 inch; U/V_x, 1.25.



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(d) Tip clearance, 0.200 inch; U/V_x, 0.90.

Figure 11. - Effect of rotor speed and tip clearance on scraping smoke pattern. Downstream view; configuration A_2.

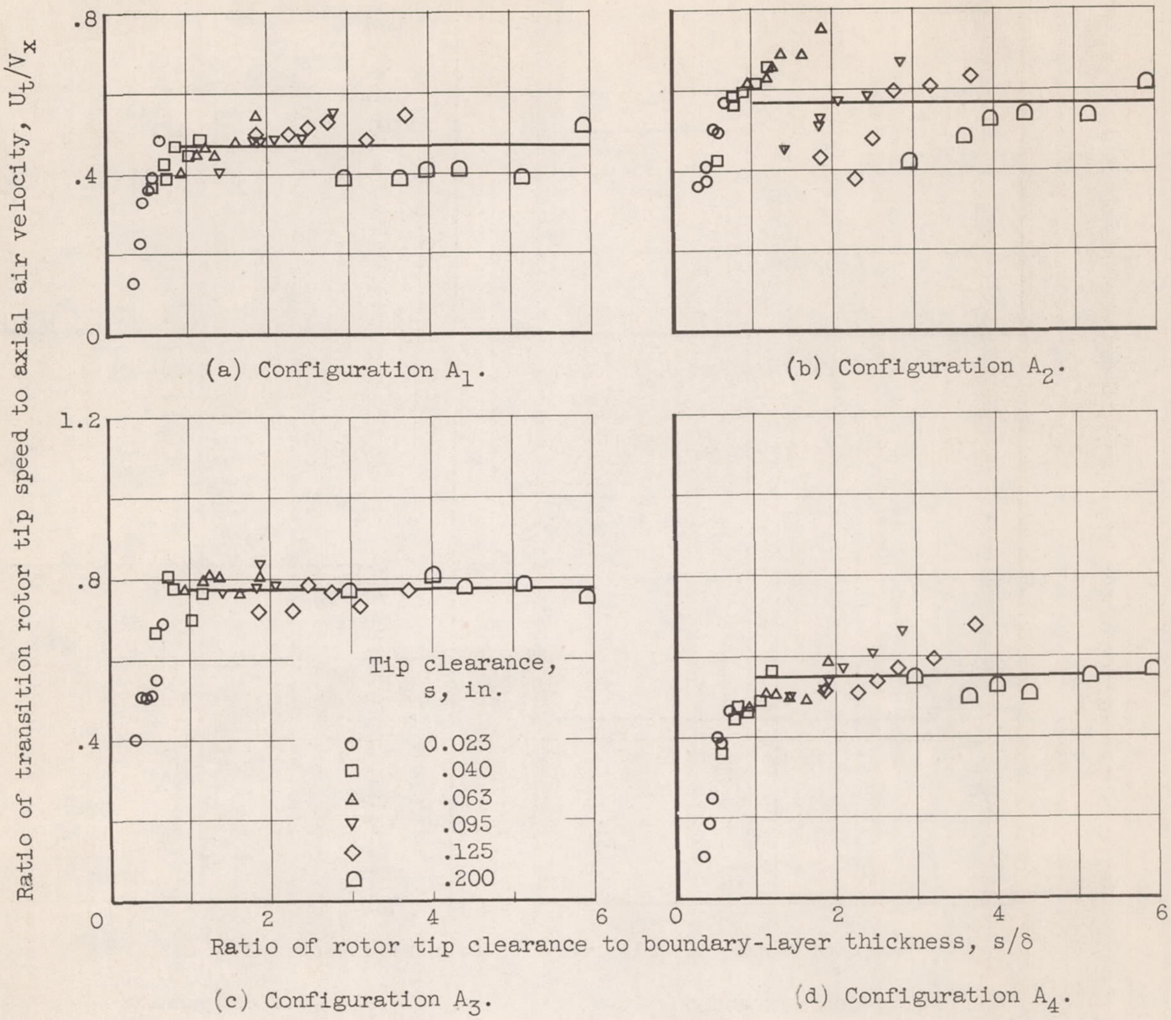


Figure 12. - Effect of tip clearance on rotor tip speed required for transition.

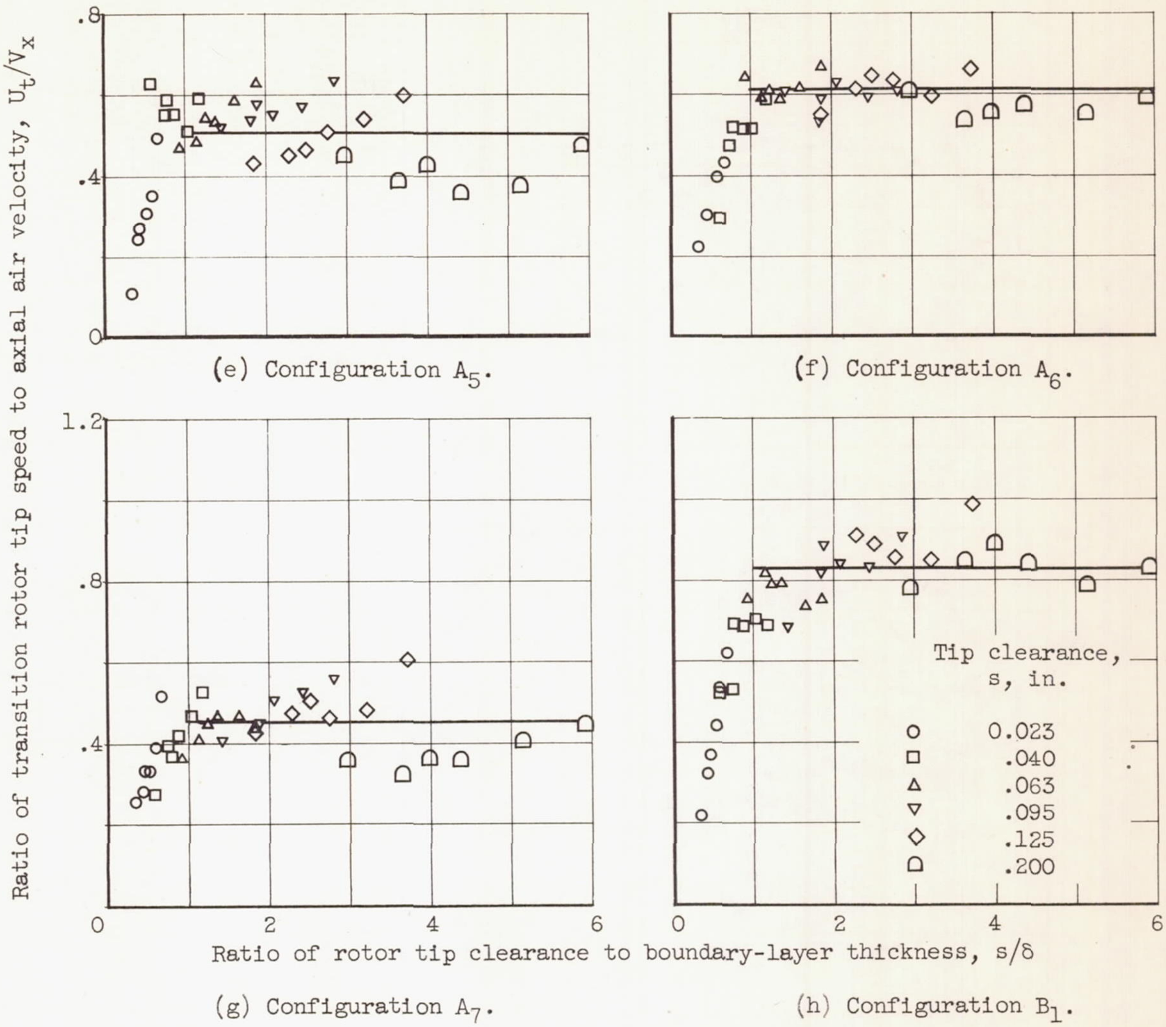
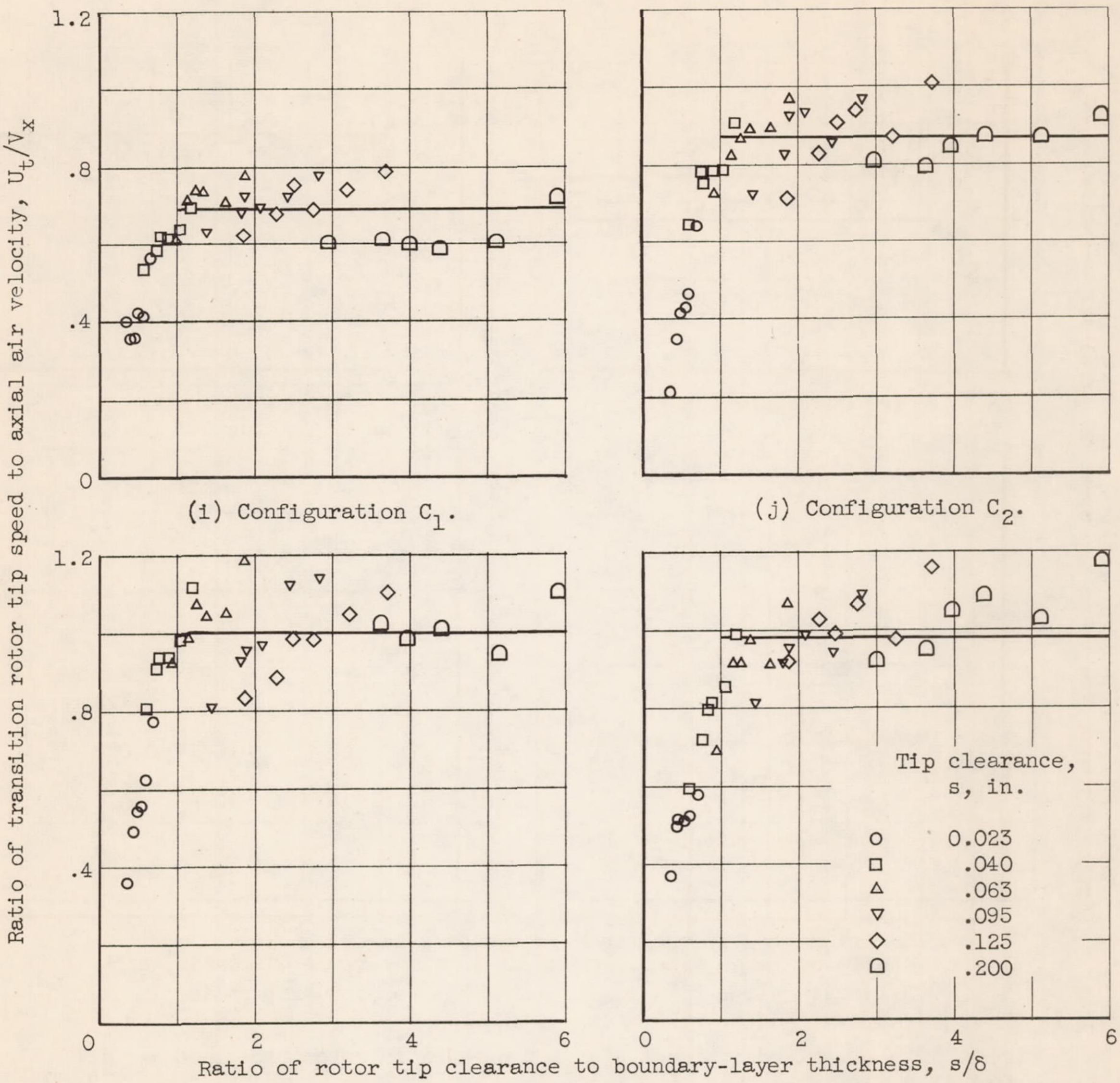


Figure 12. - Continued. Effect of tip clearance on rotor tip speed required for transition.



(i) Configuration C_1.

(j) Configuration C_2.

(k) Configuration C_3.

(l) Configuration D_1.

Figure 12. - Continued. Effect of tip clearance on rotor tip speed required for transition.

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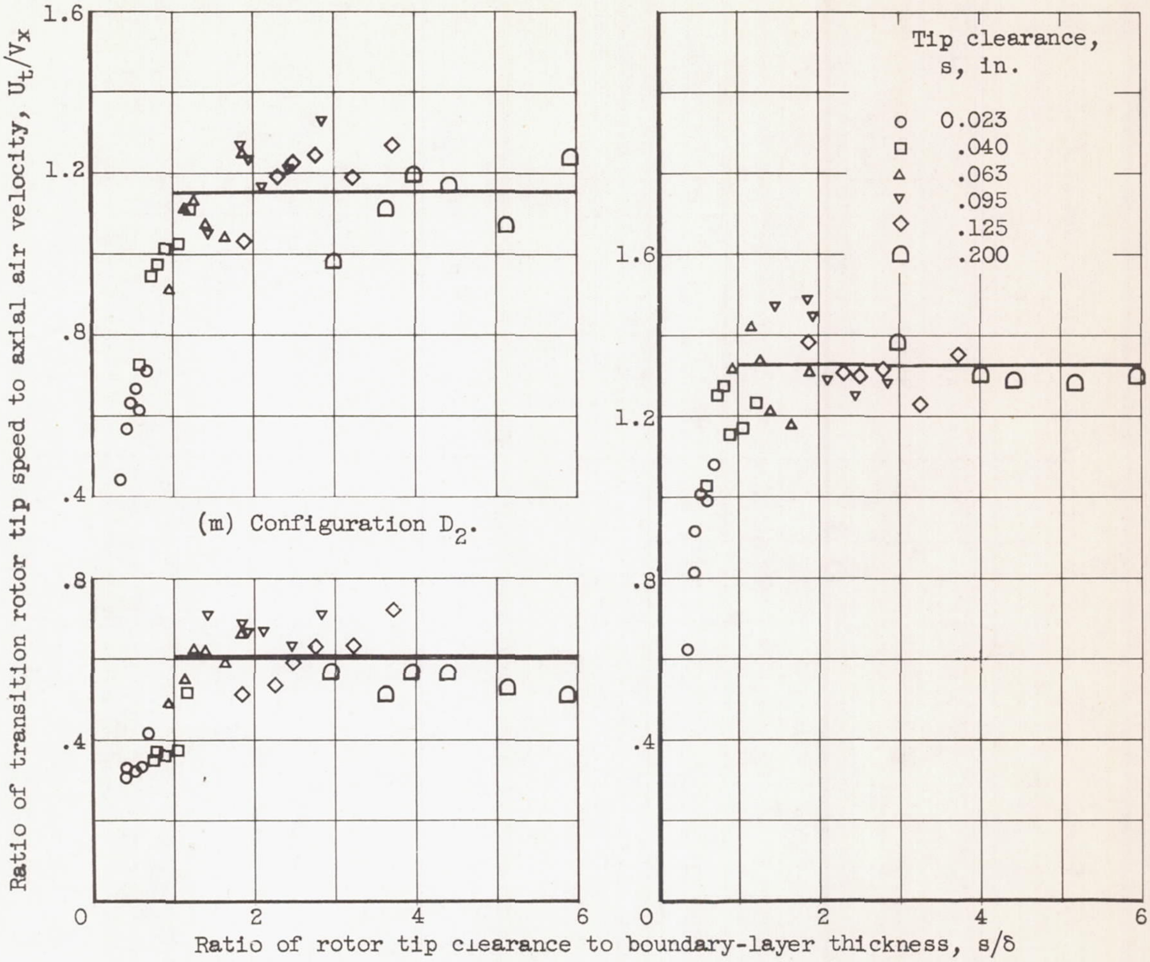

(o) Configuration D_4.

(n) Configuration D_3.

Figure 12. - Concluded. Effect of tip clearance on rotor tip speed required for transition.

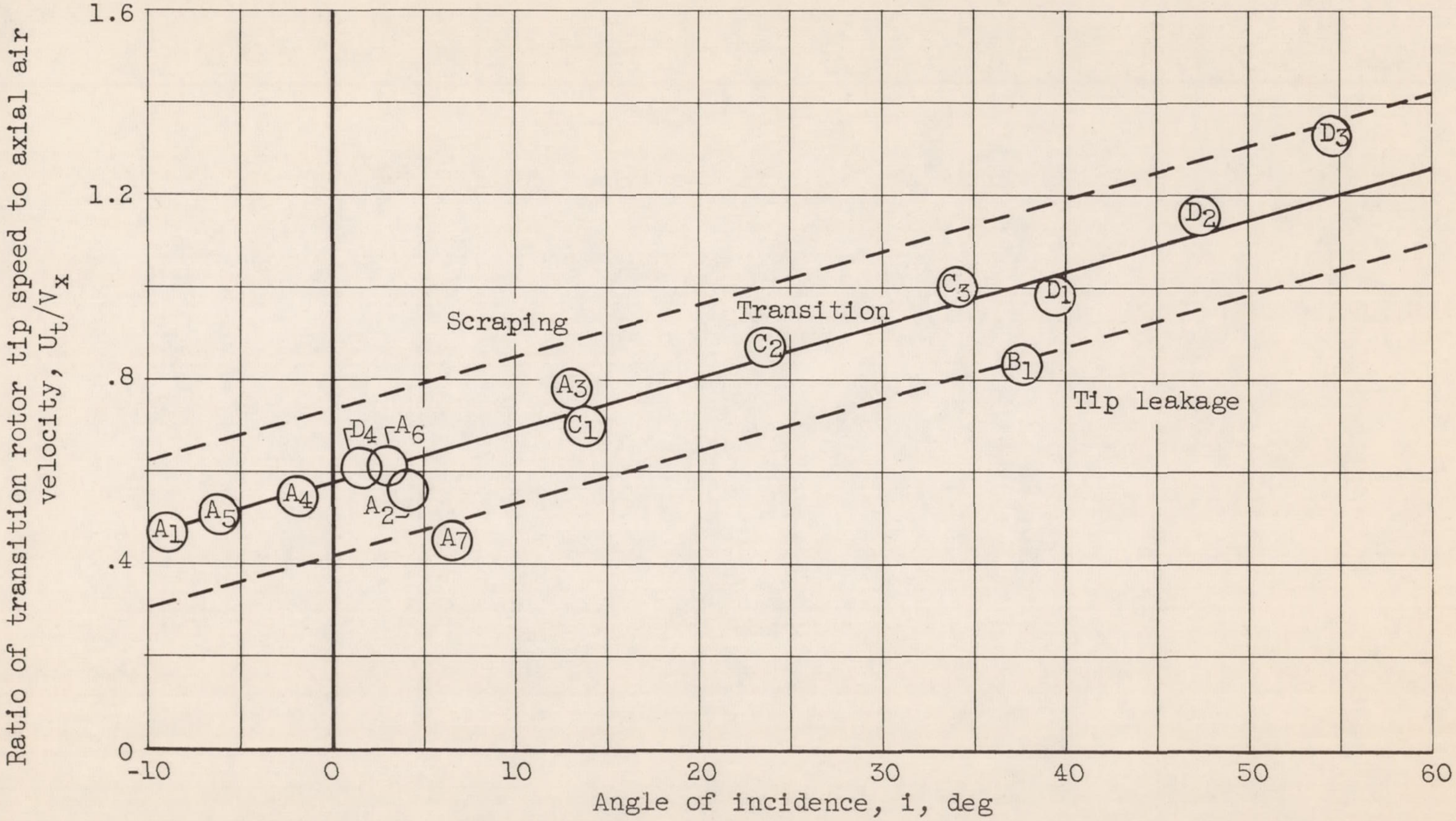

Figure 13. - Effect of rotor-blade angle of incidence on transition rotor tip speed ($s/\delta > 1.0$).

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