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RESEARCH MEMORANDUM

VISUALIZATION OF ROTOR TIP SECONDARY FLOWS WITH BLADE TIP AIR DISCHARGE AND SUCTION IN A LOW-SPEED TURBINE

By Milton G. Kofskey and Hubert W. Allen

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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VISUALIZATION OF ROTOR TIP SECONDARY FLOWS WITH BLADE TIP AIR DISCHARGE AND SUCTION IN A LOW-SPEED TURBINE

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SUMMARY

Smoke was used to visualize the effects of turbine rotor blade tip air discharge and suction on the rotor tip secondary-flow patterns. These patterns consisted of a tip-leakage vortex at low rotor speeds and a scraping vortex of opposite rotation at higher rotor speeds. A region of transition (no definite vortex pattern) existed between the tip-leakage and scraping vortex regions and visually appeared to indicate a condition of reduced disturbance in the main flow at the rotor blade tip.

Tip air discharge had the effect of energizing a portion of the outer-wall boundary layer in the direction of rotor motion and resulted in a shift of required rotor speed for each secondary-flow pattern to a higher value. The effect on the secondary-flow pattern was increased by guiding the tip air discharge in the direction of rotor motion and decreased by guiding it opposite to rotor motion. For any specific quantity of tip air discharge, a decrease in the blade tip opening area resulted in an increase in the rotor tip speed required for a scraping pattern. However, there was a greater increase in the tip speed required for scraping, for a given reduction in blade tip opening area, if the length rather than width of the opening was reduced. Tip air discharge appeared to shift the low-momentum air away from the blade suction surface. Altering the secondary-flow phenomena by tip air discharge may be a method of shifting the scraping pattern away from the conventional rotor operating speeds.

Suction weight flow required for complete elimination of the scraping pattern appeared to be considerably greater than the weight flow of the outer-wall boundary layer (computed on the basis of an equivalent flat-plate length between nozzle and rotor blade rows). However, in high-speed turbines complete elimination of the secondary-flow pattern might not be necessary for minimizing flow disturbances caused by secondary-flow phenomena.

INTRODUCTION

As a part of the basic program of determining the sources and significance of losses within turbines, studies of secondary-flow patterns in blade rows have been made in a number of earlier investigations (refs. 1 to 4).

Flow phenomena in the rotor blade tip region where rotor tip clearance space exists are discussed in reference 4. Smoke flow patterns for a low-speed turbine indicated that the clearance space gave rise to a tip-leakage vortex at low rotor speeds, and when the relative motion between blade tip and casing was of sufficient magnitude, a scraping vortex of opposite rotation was produced. A region of rotor speeds with no definite vortex pattern existed between the tip-leakage and the scraping vortex regions. This region of transition appeared visually to represent a condition of reduced disturbance in the main flow at the rotor blade tip. Preliminary comparison of the results at low speed with actual turbine operating data indicated that turbines may normally be operating in the region where the scraping effect would be expected.

If turbines normally operate in the region of scraping and if operation in transition is desirable, some means must be employed to effect a change in the secondary-flow pattern at the rotor blade tip. Since the trend of present day jet engine development is toward higher turbine-inlet temperatures, turbine blade cooling may become an engine requisite. The turbine rotor blade cooling method of passing cooling air through hollow blades and discharging it at the blade tip may be one of the most feasible methods of changing the secondary-flow pattern. Therefore, as an extension of the fundamental investigation of secondary flows in rotor blade tip regions, current smoke flow techniques were used to determine the effect of blade tip air discharge on the secondary-flow patterns observed.

In addition, an investigation was made of the effects of blade tip suction on secondary-flow patterns and these results are included.

In the present investigation, photographs and visual observations of the effect of air discharge and suction through the rotor blade tip were made at the NACA Lewis laboratory by independently varying the direction and quantity of tip air discharge and suction and varying tip clearance, and mainstream airspeed. In addition, the cross-sectional area of the hollow blade discharge opening was varied for the case of tip air discharge.

APPARATUS AND PROCEDURE

Test Unit

A schematic view of the test unit used in the investigation is shown in figure 1. The outer casing was constructed of Lucite to facilitate the use of a light which was synchronized with the blades for visual inspection and photography of the smoke pattern through the turbine. The supply of air to the hollow rotor blades was made by an air commutator chamber that was attached to the rotor shaft by sealed ball bearings. Pressurized air to the commutator was controlled by regulating valves and was measured by use of a rotameter. 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 pressurized-air system and was discharged directly into the room. The axial air velocity was determined through the use of an electronic manometer, which was previously calibrated against a thin-plate orifice.

Introduction of smoke used for observation of the secondary-flow behavior was made through the Lucite casing at an axial location slightly upstream of the rotor blade midchord. Smoke was produced by burning oil-soaked cigars in a forced draft of air. In order to avoid disturbing the main flow, the rate of smoke production and injection into the air stream was carefully controlled by a pressure regulator in an effort to match closely the velocity and pressure of the air stream.

Nozzle Blades

A set of 48 airfoil-shaped nozzle blades with a hub-tip radius ratio of 0.730 and a tip diameter of 16.25 inches was used for the investigation. These blades were designed for a constant discharge angle of 30.2° from tangential. A complete description of the blades with profile coordinates is given in reference 2 (blades designated type B therein).

Rotor Blades

The rotor initially consisted of 29 sheet-metal circular arc blades (blade C, ref. 4) having a chord length of 1.87 inches and a tip solidity of 1.07. By soldering 0.010-inch sheet metal along the leading and trailing edges of the pressure surface of the original blade, 24 of these blades were modified into hollow blades. Spacers, consisting of strips of sheet metal placed at midchord and running radially between the pressure surface of the original blade and the 0.010-inch sheet metal, were provided to ensure similar blade tip areas for the hollow blades. The length of the spacers was approximately 0.5 inch shorter than the height of the blade to ensure tip air discharge over the entire blade tip opening. This modification of the original blade to a hollow blade gave the blade a camber angle of 53.2°. Photographs of the original rotor blade and the hollow blade types are shown in figure 2. Six blades of each of the three basic types (A, B, and C) of hollow blade configurations were investigated. For blade type A, the pressure-surface height was shortened by 0.040 inch; for type B, both surfaces were of the same height; and for type C, the suction surface height was shortened by 0.040 inch. With these configurations investigations of the effect of tip air discharge from the pressure surface, top, and suction surface of the blade could be made.

To investigate the effect of changing the shape of the blade tip opening, blade type C (shortened suction surface) was further modified by blocking the tip opening to approximately one-half of the area of the original tip opening (designated type D, fig. 2). In addition, the effect of the width of the blade tip opening at midchord was also investigated. Three blades had 0.125-inch-wide openings (type E), and three blades had 0.031-inch-wide openings (type F). For all other blade configurations, types A to D, the width of the tip opening was 0.065 inch.

Observational Procedure

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

Because of limitations in photographic techniques, visual observations were more dependable and much less time consuming. Under many conditions, however, even visual observation was difficult. Values of rotor speed required for any given smoke pattern were not well defined because of slowness of variation in pattern with the rotor speed. Therefore, determination of rotor speed depended on establishing arbitrary standards for the shape of the pattern. Measurements were subjective in nature, because memory of the reference-pattern shape was required for comparison of rotor speeds observed under different conditions. Mainstream air speed, tip clearance, amount and direction of tip air discharge affected the definition of the pattern. Hence, much care was required in finding similar identifying characteristics for all variations in appearance of the reference pattern, and the individual values of rotor speed obtained were limited in accuracy. Although there is much scatter of data, the results show definite trends.

The scraping pattern was chosen as the reference pattern, because it was more clearly defined than the others and occurred closer to the normal operating values of the ratio of rotor tip speed to axial air speed U/V_x. All symbols used in the report are defined in appendix A.

RESULTS AND DISCUSSION

General Description of Rotor Tip Air Discharge Effects

Change in tip secondary-flow pattern appearance with rotor speed constant. - The type of scraping pattern observed at a large tip clearance such that the blade tips were in free-stream air is shown in figure 3(a). Figure 3 shows the shortened-suction-surface blade type as an example of blade types that produce the same effect. These photographs were made looking axially upstream into the rotor exit with the line of sight nearly parallel with the inner surface of the Lucite outer wall. Nozzle blades appear in the background. The tachometer indicates rotor speed multiplied by a gearing ratio (approximately 16). Since mainstream axial air speeds were very low, 2.5 to 8 feet per second, the outer-wall boundary layer was considered laminar for all the conditions of the investigation. For all photographs, the boundary-layer thickness was about 0.07 inch. This boundary-layer thickness was computed on the basis of an equivalent flat-plate length from nozzle trailing edge to rotor blade leading edge. For figure 3(a) smoke entered through an orifice in the outer wall and was scraped ahead of a layer of mainstream air which spilled over the blade tip. The smoke did not outline a vortex, but curvature at the end of the more dense portion of the smoke indicated the beginning of a clockwise rotation. This is characteristic of the smoke pattern observed when the scraping effect enhances the passage vortex.

For figure 3(b) all conditions, including rotor speed, were the same as for figure 3(a), except that air was being discharged from the blade tip. The ratio of discharge air weight flow to mainstream air weight flow was 5.3 percent. The result was a pattern at the outer wall indicating that in figure 3(b) the secondary flow had characteristics of the tip-leakage type (ref. 4) even though the rotor speed was the same as that for figure 3(a) showing scraping. This tip leakage pattern of counterclockwise rotation normally occurred at lower rotor speeds. The blade tip air discharge increased the rotor speed required for each type of pattern.

The comparison in figure 3, therefore, shows that tip air discharge disrupted outer-wall boundary-layer flows. Also, the tip air discharge seemed to have the effect of adding tangential momentum in the direction of rotor motion to the already existing boundary-layer tangential momentum. This added tangential momentum may have consisted of two tangential components, both involving the weight flow of the tip discharge air. One of these components would have been due to the blade tip speed since the discharge air had this tangential speed at the instant of discharge from the tip of the blade. The other component would have appeared when the discharge air, because of its radial component, encountered the outer wall or outer-wall flows. Then the radial motion of the discharge air would have resolved into axial and tangential components. This tangential component as well as that due to blade tip speed would have been added to the boundary-layer tangential momentum already existing with the resulting shift in the secondary-flow pattern shown in figure 3.

The transition rotor speed showed (visually) a condition of minimum flow disturbance between the tip leakage pattern and the scraping pattern. It appeared visually to be a less undesirable secondary-flow situation than scraping, where it is thought most turbines operate. It appears that the amount of tip air discharge can be adjusted to change the secondary-flow pattern at the blade tip from the scraping pattern at a given rotor speed to transition. Thus, tip air discharge may be useful in altering the secondary-flow phenomena in order to reduce flow disturbance.

Change in rotor speed required to maintain a fixed secondary-flow pattern. - Approximately the same point in development of the scraping pattern (not necessarily minimum rotor speed required for scraping) is shown in all the photographs of figure 4. These patterns were photographed for only the shortened-suction-surface blade (type C), but the same effects were observed for blade types A and B. There is a difference in the appearance of the patterns in figure 4 due to a difference in tip clearance. For figures 4(a) to (d) the blade tip was in the outer-wall boundary layer, and for figures 4(e) to (h) it was in mainstream air. These figures show that for either of these tip clearances increases in rotor speed were required to obtain this pattern for increasing amounts of tip air discharge. They also show that with discharge the pattern was shifted slightly away from the blade suction surface. Thus, where increase in rotor speed enabled a fixed type of secondary-flow pattern to be maintained, the discharge air appeared to displace the low-momentum air at the blade tip suction surface.

Effect of direction of rotor tip air discharge. - The three basic types of hollow blade described previously were made in order to study the effect of changing the direction of rotor tip air discharge (fig. 2). Tip discharge air from the blade with shortened suction surface was expected to take the direction of rotor motion, and that from the blade with shortened pressure surface was expected to take the direction opposite to rotor motion. It was thought that the full-height surfaces would result in no preferential guidance.

The effect on required rotor speed, when a quantity of air amounting to 5.3 percent of mainstream air flow was discharged from the three types of blade tip, is shown in figure 5. Figures 5(a) to (c) show the effect with the blade tip in the boundary layer, and figures 5(d) to (f) show the effect with the blade tip in mainstream air. For all three blade types, tip discharge air caused an increase in the rotor speed (over the value for no tip air discharge, $U/V_x \approx 0.79$) required to produce this development of the scraping pattern. This indicated that, regardless of the type of blade tip opening, the tip discharge air always energized the outer-wall boundary layer in the direction of rotor motion with only the magnitude of the effect depending on the tip opening type. Thus, the directional effects of hollow blades with these types of tip opening did not appear to be the primary factors in determining the direction of the reaction on the boundary layer. Rather, they were superimposed on a more influential factor which in all three cases caused the tip discharge air to increase the tangential momentum of the boundary-layer air in the direction of rotor motion. This means that, for all three types of blade, as the air was discharged toward the outer wall the pressure gradient from pressure to suction side over the blade tip in the direction of rotor motion, acted on the discharge air. The amount of tangential momentum resulting from this action when the discharge air encountered the outer wall (the second added component mentioned previously in discussing fig. 3) depended on which of the three basic types of blades was in use. At tip clearances greater than boundary-layer thickness, the pressure gradient from pressure to the suction side of the blade was reduced. However, the momentum of mainstream spillage over the blade tip may have aided in driving the discharge air in the direction of rotor motion.

Measurements of Rotor Tip Air Discharge Effects

Figure 6 shows data plots that indicate the combined effects of several factors on the rotor tip speed required to produce a given development of the scraping pattern. The effects of mainstream air speed, tip clearance, tip air discharge weight flow, and blade tip opening type were studied. The graphs show the ratio of rotor tip speed to axial air speed U_{sc}/V_x, which is required to produce the chosen scraping pattern, plotted against the ratio of tip clearance to outer-wall boundary-layer thickness s/δ. As stated previously, boundary-layer thicknesses were computed on the basis of an equivalent flat-plate length from nozzle trailing edge to rotor leading edge.

For each plot a horizontal line was drawn at the average ordinate for the nine points representing tip clearances so that the blade tip was in or very near the free-stream air (s/δ, approximately 1.0). In this region, tip clearance appeared to have no effect on the results. Hence, this average ordinate was thought to be the best basis available for comparing results.

One of the effects of tip air discharge seemed to be an increased general turbulence in the flow patterns near the outer wall. Thus, the scatter of data points for figure 6 became greater when the tip air discharge increased to large values. This was due to the increasing difficulty of observation as the increased discharge caused dissipation of the smoke in the pattern.

Effect of discharge on required rotor speed. - The ordinate of figure 6 includes the effect of rotor speed on angle of incidence. After correction to zero angle of incidence using the data of reference 4, the average values of the ratio of rotor tip speed to axial air speed U_{sc}/V_x were plotted as shown in figure 7. The vertical band through each data point represents the average deviation from the mean of the nine observations averaged for each point. It is thus considered possible to represent the data with straight lines, within the accuracy indicated.

Figure 7 shows that the shortened-suction-surface type of blade was more effective in changing tip flow conditions than the other types. A description of a possible mechanism by which tip discharge affects a given smoke pattern is given in appendix B.

Use of a tip-leakage pattern as the reference pattern gave approximately the same changes in rotor tip speed for a given change in tip air discharge as did use of the scraping pattern. It follows that transition would give similar results. By using tip air discharge, then, it should be possible to raise the rotor speed at which transition would appear to a value approaching that at which turbines normally operate (e.g., $U/V_x = 1.0$). For example, data of reference 4 without discharge air and current observations with discharge air indicate a difference in the value of U/V_x for transition and for the beginning of scraping amounting to approximately 0.15 to 0.20. Therefore, to have transition at a value of $U/V_x = 1.0$, the scraping pattern would begin at a value of $U/V_x = 1.15$ to 1.20. Data in figure 7 for blade type C (shortened suction surface) show that a tip discharge weight flow of approximately 4 percent of mainstream weight flow would be required to obtain transition at a $U/V_x \approxeq 1.0$.

Effect of shape of blade tip opening. - The effects of changes in the width and length of the blade tip opening on the rotor speed required for the scraping pattern were studied using blade types D, E, and F together with type C as a standard for comparison purposes (see fig. 2). The shortened-suction-surface type was chosen as the standard for this study rather than the full-length-surface type B or the shortened-pressure-surface type A, because the rotor tip speed required for scraping was more sensitive to discharge from this blade type. Results are shown in figure 8. These data were not corrected for angle of incidence, because in some cases the angles of incidence had such high negative values that correction data were not available. At the time these data were taken, conditions were such that only discharge weight flows greater than 5 percent were available. For blade type C, data included in figure 6 were added to figure 8. An approximate calculation of boundary-layer thickness inside the blade air passage indicated that the flows inside the hollow blades were fully developed for the 0.065- and 0.031-inch-wide, full-length blade openings (type C and F blades, respectively, fig. 2), but not for the other two blades.

For a given discharge weight flow, decreasing the discharge opening area increased the rotor tip speed required for scraping (fig. 8). Shortening the discharge opening length shortened the axial length of the outer-wall boundary layer which was affected by the discharge air, and increased the required tip speed for scraping as observed in the region of the blade tip opening. Comparison of the results for blade types D and F, which had approximately equal tip opening areas, with data for type C, having twice the area, shows that for a given reduction in tip opening area a greater increase in tip speed required for scraping can be obtained by reducing the length of the tip opening rather than by reducing the width of the opening. Reducing the length of the opening is thought to reduce the amount of boundary layer affected by the discharge thus concentrating the discharge and further increasing the effect in a restricted region.

A more detailed discussion of figure 8 is presented with the equations of appendix B.

General Description of Blade Tip Suction Effects

The effects of suction on rotor tip secondary flows were studied with the presently available blades as a means of obtaining a rough indication of what might be done with suction and of the amount of air involved in these secondary flows. The method was not intended as a recommended means of reducing rotor tip secondary-flow effects in an actual turbine.

The photographs of figure 9 show the effect at two tip clearances of withdrawing air from the outer-wall region through a hollow blade of the type having a shortened suction surface. The photographic evidence of figures 9(a) to (d) indicates that a suction weight flow of about 3.6 percent of mainstream weight flow was sufficient to remove the scraping pattern, but about 7 percent was required to remove all the smoke which had entered the boundary layer. To compare with this, visual observations at the same mainstream air flow rate showed that the scraping pattern began to be less extensive, more diffuse, and erratic at suction weight flows of about 3 percent, and that it was necessary to use about 7 percent in order to eliminate the pattern completely with no momentary recurrences. However, it might be that complete elimination of the pattern would not be necessary in order to reduce to a minimum the undesirable effects of the rotor tip secondary flow in a turbine.

Measurements of Rotor Tip Suction Effects

The results of measurements of suction weight flow required to eliminate the scraping pattern completely for different mainstream weight flows are shown in figure 10. The required suction was observed at two tip clearances for the blades with full-length surfaces and shortened suction surface. Under the conditions of the investigation, no appreciable effect of tip clearance and no difference between these two types of blade tip opening could be observed. However, for the blades with shortened pressure surface, the available suction was not sufficient to remove the pattern even at the lowest mainstream air flows. Presumably, this was because of the necessity of drawing the low-momentum air through the clearance space from the suction side of the blade to the opening on the pressure side.

The lower curve in figure 10 represents a calculated value of the suction weight flow which would be required if only the boundary layer at the rotor inlet (computed, as before, on the basis of an equivalent flat-plate length between blade rows) was removed. A comparison of this calculated curve with the actual observed data indicates that complete elimination of the scraping pattern by blade tip suction requires removal of several times as much air as that in outer-wall boundary-layer flow with the flat-plate assumption. Thus, it appears from these data that suction through the tips of hollow blades may be an inefficient means of removing rotor tip secondary flows. Even if this is true, however, the suction required to reduce the undesirable effects of the secondary flows to an acceptable value may be less than this.

SUMMARY OF RESULTS

The investigation consisted essentially in determining the effects of rotor blade tip air discharge and suction on the rotor tip secondary-flow patterns. The results of these effects were measured in terms of tip speed required to maintain a fixed development of the secondary-flow pattern formed under scraping conditions, or in the case of suction, in terms of quantity of air required to remove the scraping pattern. Rotor blade tip suction experiments were intended only as a means of obtaining information on suction effects and on the amount of air involved in secondary flows, and not as a recommended means of reducing secondary-flow effects in a turbine.

The following results were obtained:

1. Tip air discharge disrupted outer-wall boundary-layer flows and had the effect of energizing a portion of the boundary layer in the direction of rotor motion. This caused all secondary-flow phenomena to appear at higher rotor speeds, depending on the momentum of the tip air

discharge. Thus, tip air discharge may be useful in altering secondary-flow phenomena in order to shift the scraping pattern away from operating rotor speeds. For example, under the conditions of this investigation and for the shortened-suction-surface blade type, a tip air discharge of about 4 percent of mainstream weight flow would be required to raise the rotor speed needed for transition to a ratio of rotor tip speed to axial air speed approaching that at which turbines normally operate.

2. Rotor tip air discharge appeared to shift the low momentum air in the secondary-flow pattern away from the blade suction surface.

3. Of the three basic blade types tested, the type with the tip opening formed by a shortened suction surface showed the greatest effect of tip air discharge on the secondary-flow pattern, and that with tip opening formed by a shortened pressure surface showed the least effect.

4. For any specific quantity of tip discharge air, decreasing the blade tip opening area resulted in an increase in tip speed required for the scraping pattern. However, for a given reduction in blade tip opening area, reducing the length of the opening rather than the width resulted in a greater increase in tip speed required for the scraping pattern.

5. Complete elimination of the scraping pattern by rotor blade tip suction required removal of several times as much air as that in the outer wall boundary-layer flow (computed on the basis of an equivalent flat-plate length between nozzle and rotor blade rows). However, complete elimination of the secondary-flow pattern may not be necessary in order to minimize resulting flow disturbances.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 17, 1956

APPENDIX A

SYMBOLS

A_1	cross-sectional area of tip-leakage flow, sq ft
A_2	cross-sectional area of cross-channel flow, sq ft
A_d	area of rotor blade tip opening, sq ft
A_x	cross-sectional area of mainstream flow in the axial direction, sq ft
k	constant, nondimensional
k_1	boundary-layer momentum ratio, $\frac{A_2V_2(V_2 + U_{sc})}{A_1V_1(V_1 + U_{sc})}$
k_2	ratio of added boundary-layer momentum to radial momentum of blade tip air discharge
k_3	ratio of increase in $U_{sc,d}/V_x$ to increase in w_d^2/w_{ms}^2
s	rotor blade tip clearance, in.
U	rotor blade tip speed, ft/sec
V_1	tangential boundary-layer velocity of tip-leakage flow, ft/sec
V_2	tangential boundary-layer velocity of cross-channel flow, ft/sec
V_d	effective discharge velocity at rotor-blade tip opening, ft/sec
V_x	mainstream axial air velocity, ft/sec
w	weight flow, lb/min
δ	computed boundary-layer thickness, in.
ρ	air density, lb/cu ft

Subscripts:

d	discharge

ms	mainstream
s	suction
sc	scraping
δ	boundary layer

APPENDIX B

MECHANISM BY WHICH TIP DISCHARGE AFFECTS SMOKE PATTERN

The following reasoning may explain the results shown in figures 7 and 8 in a qualitative manner. The assumption is made that the ratio of the relative tangential momentum of cross-channel boundary-layer flow to the relative tangential momentum of tip-leakage boundary-layer flow is a constant for a given smoke pattern with no air discharge from the blade tip. If this assumption is made, an equation results which is in agreement with the data plotted in these two figures. This momentum ratio increases as the smoke pattern changes because of increasing rotor speed. At the low pressure differences involved, air density was essentially the same everywhere in the turbine and for all the flow conditions of this investigation. The assumption for the scraping pattern which gave the data of figures 7 and 8 may be expressed as follows:

$$\rho A_2 V_2 (V_2 + U_{sc}) = k_1 \rho A_1 V_1 (V_1 - U_{sc})$$

If air is discharged from the blade tip, its momentum is $\rho A_d V_d^2$ and this has a radial direction relative to the blade. At the outer wall a portion of this momentum $k_2 \rho A_d V_d^2$ becomes a net addition to the tangential momentum of tip-leakage flow. The value of k_2 depends upon the type of blade tip opening used, whether shortened suction surface, shortened pressure surface, or full-length surfaces. With this tip air discharge, the rotor tip speed is increased from U_{sc} to $U_{sc,d}$ to maintain the same scraping pattern development. Then,

$$\rho A_2 V_2 (V_2 + U_{sc,d}) = k_1 \rho A_1 V_1 (V_1 - U_{sc,d}) + k_2 \rho A_d V_d^2$$

To put this equation in a form for comparison with the data as plotted in figures 7 and 8, both sides are multiplied by $A_d/\rho A_x^2 V_x^2$ and the equation is then rearranged. For the data of figures 7 and 8 it is noted that ρ and A_x were constant; A_1 and A_2 were effectively equal to each other; and V_1 and V_2 were proportional to V_x for a fixed secondary-flow pattern. For a given blade modification type, A_d was a constant. Therefore,

$$\frac{U_{sc,d} - U_{sc}}{V_x} = k_3 \frac{w_d^2}{w_{ms}^2}$$

where

$$U_{sc} = \frac{k_1 V_1^2 - V_2^2}{k_1 V_1 + V_2}$$

and

$$k_3 = \frac{k_2 A_x^2 V_x}{A_d A_1 (kV_1 + V_2)}$$

which shows that a straight line would be expected when $U_{sc,d}/V_x$ is plotted against w_d^2/w_{ms}^2 for a given blade modification. This type of plot is shown in both figure 7 and 8. The slope of the line k_3 depends upon which of the three basic types of blade modification was used, since k_3 is proportional to k_2. This effect is shown in figure 7. The equation also shows that the slope would be increased when either the area of the discharge opening at the blade tip A_d or the area of the boundary layer affected by the discharge, A_1 or A_2, is diminished. These effects are shown by the data plotted in figure 8, where lines representing three values of A_d (the three lowest straight lines) and two values of the boundary-layer area (the two highest straight lines) are plotted.

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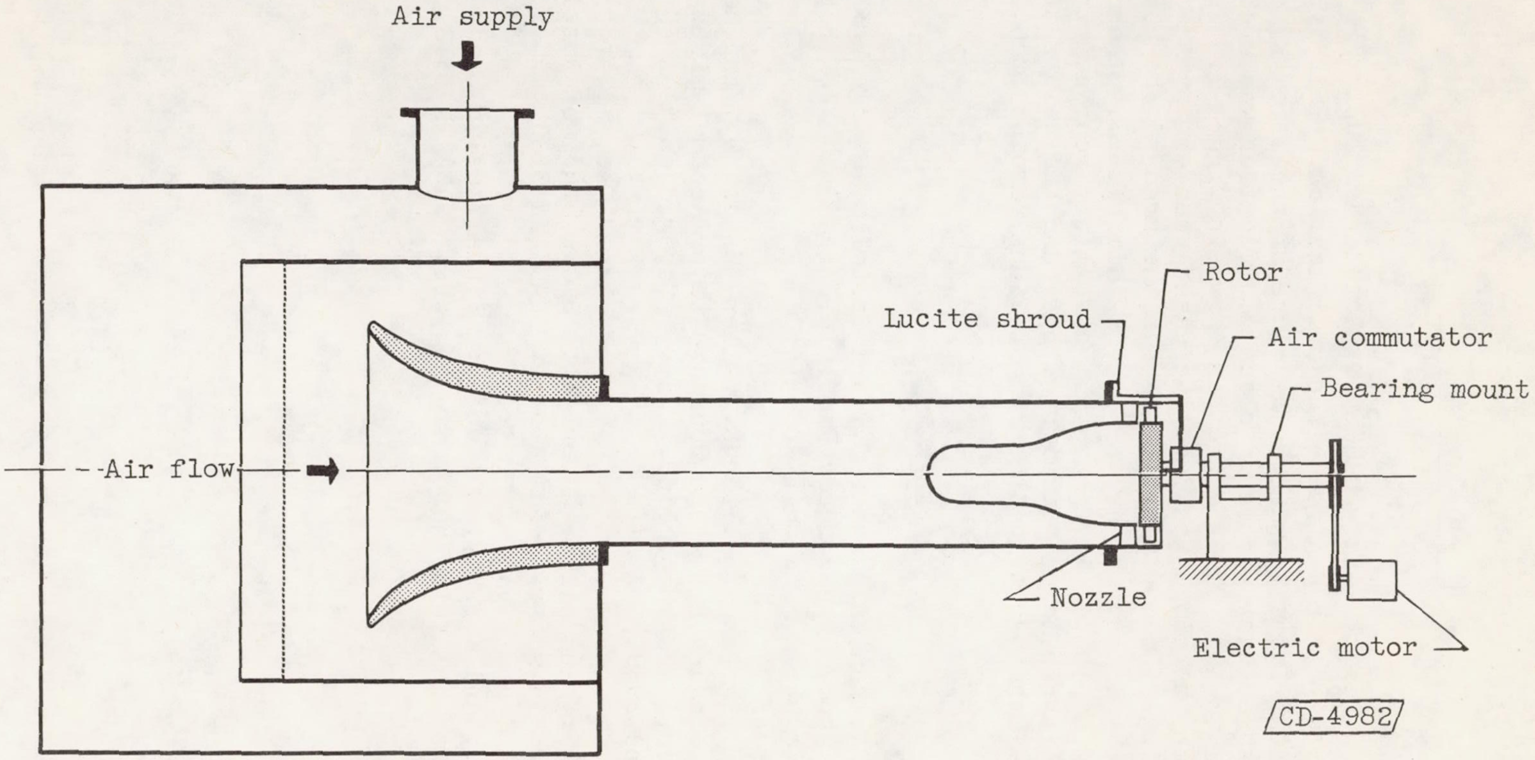

Figure 1. - Schematic view of low-speed turbine.

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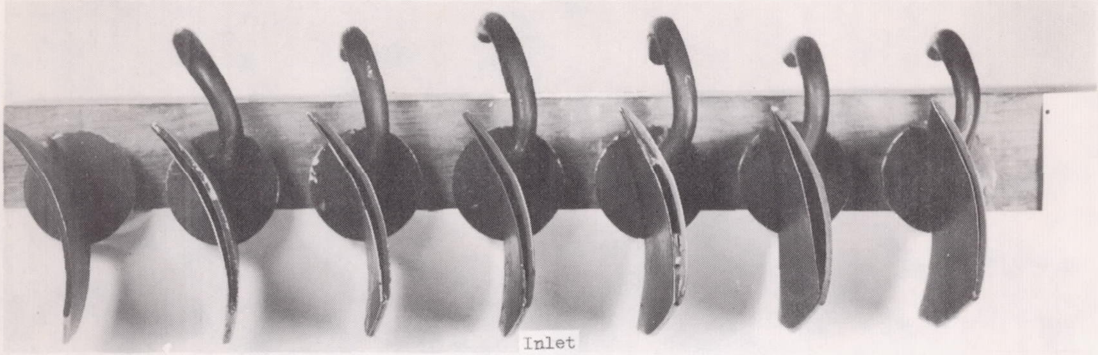
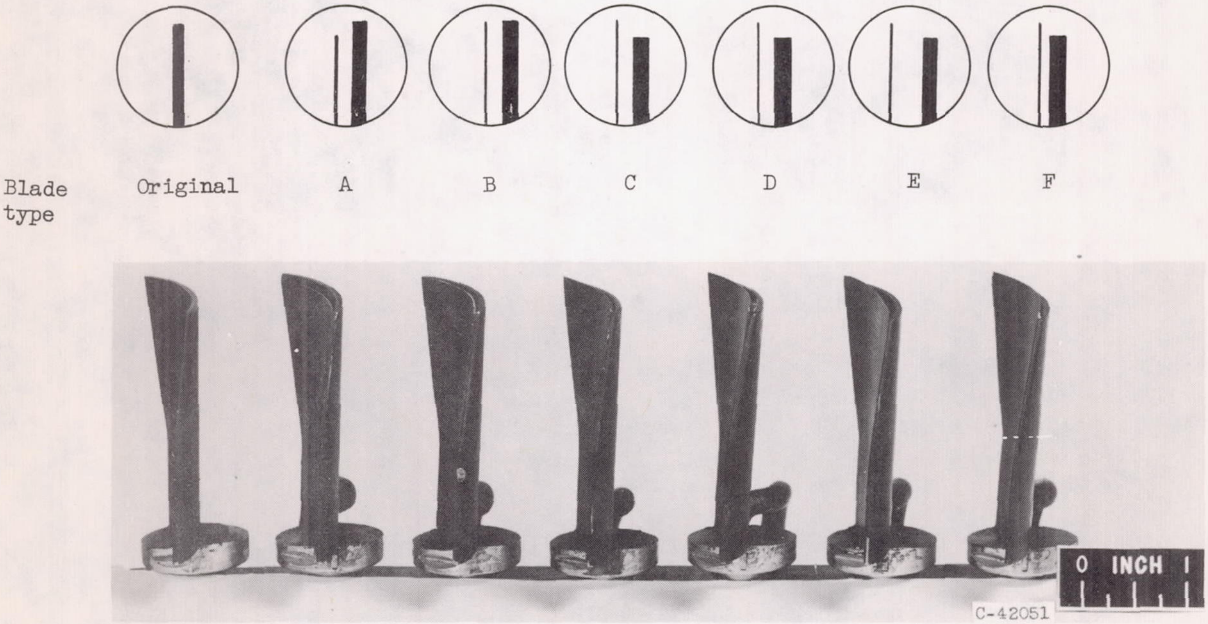
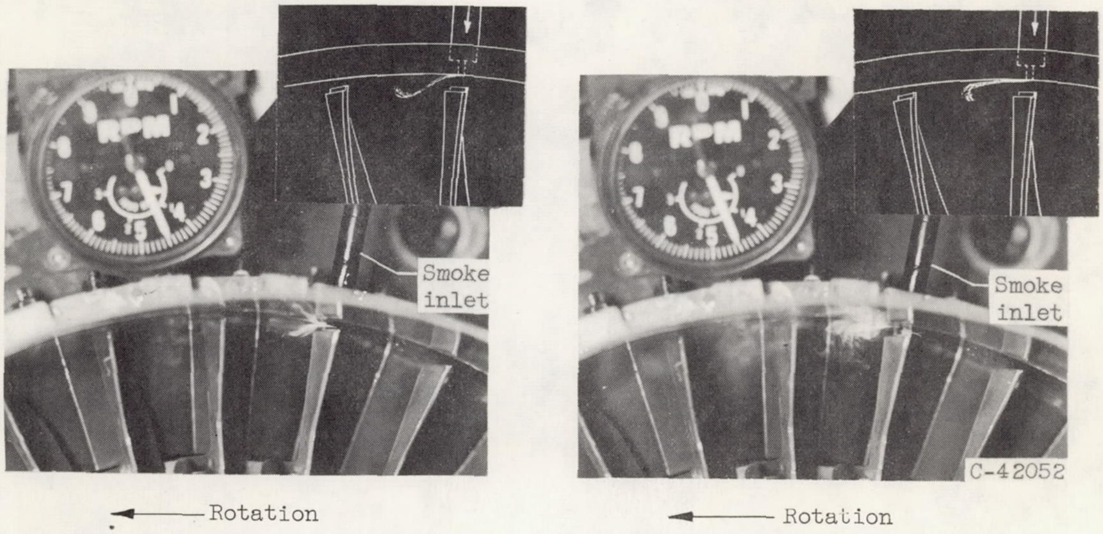


(a) Radial view.



(b) Upstream view.

Figure 2. - Rotor blade configurations.



(a) No air discharge.

(b) Air discharge, 5.3 percent.

Figure 3. - Effect of tip air discharge on scraping pattern with smoke through outer wall. Blade type, C (shortened suction surface); tip clearance, 0.095 inch; main-stream axial air velocity, 2.7 feet per second; ratio of rotor tip speed to axial air speed, 0.74.

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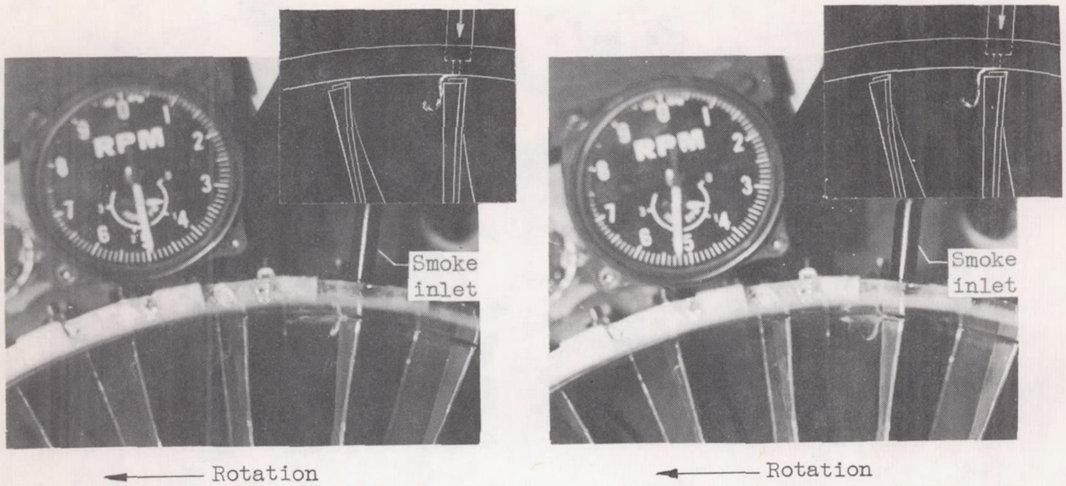
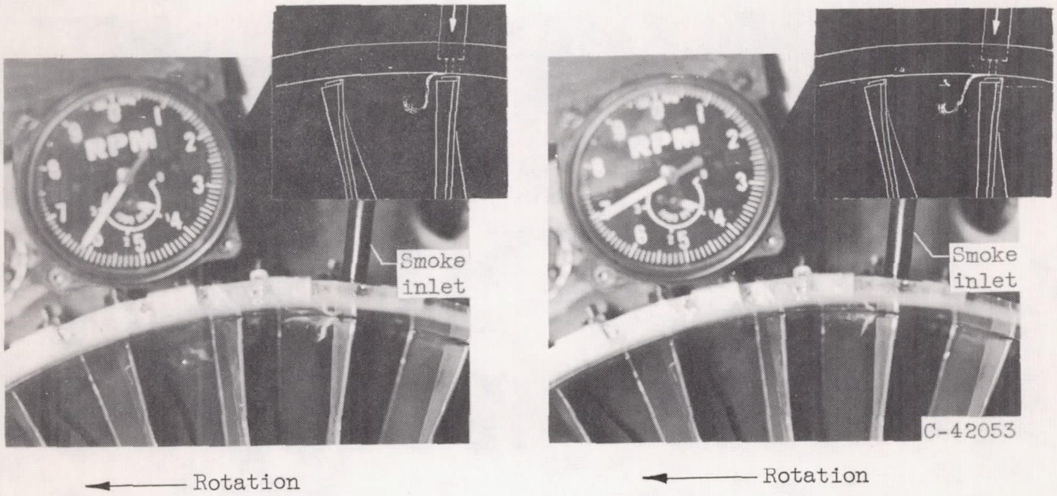
CR-3 back



(a) No air discharge; ratio of rotor tip speed to axial air speed, 0.79; tip clearance, 0.023 inch.

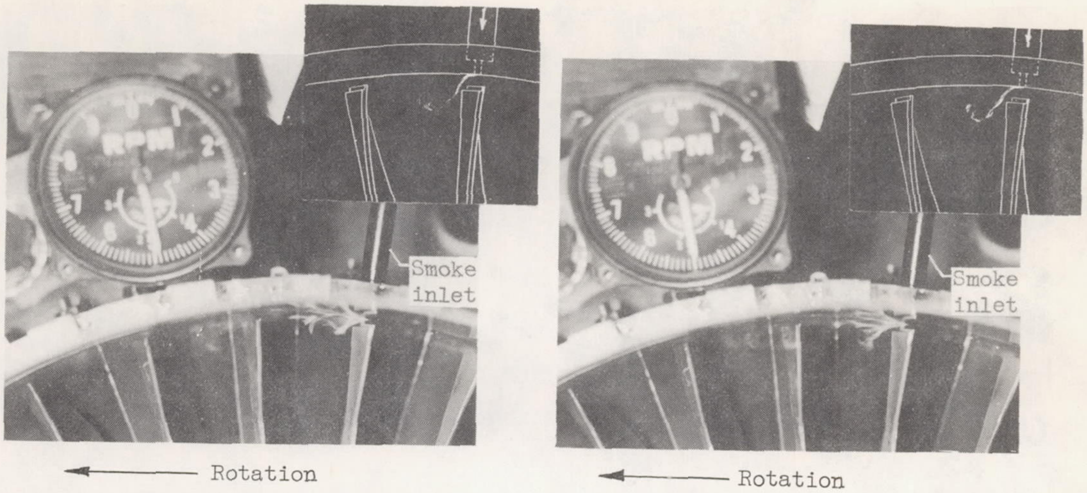
(b) Air discharge, 1.6 percent; ratio of rotor tip speed to axial air speed, 0.85; tip clearance, 0.023 inch.



(c) Air discharge, 3.2 percent; ratio of rotor tip speed to axial air speed, 1.00; tip clearance, 0.023 inch.

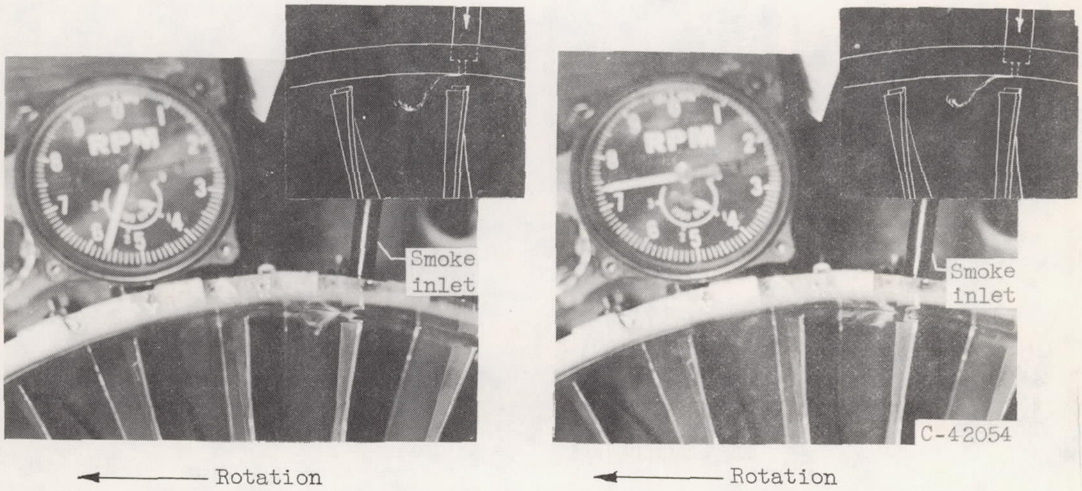
(d) Air discharge, 5.3 percent; ratio of rotor tip speed to axial air speed, 1.12; tip clearance, 0.023 inch.

Figure 4. - Effect of changing magnitude of tip air discharge on rotor speed required for scraping pattern. Blade type C (shortened suction surface); mainstream axial air velocity, 2.7 feet per second.



(e) No air discharge; ratio of rotor tip speed to axial air speed, 0.79; tip clearance, 0.095 inch.

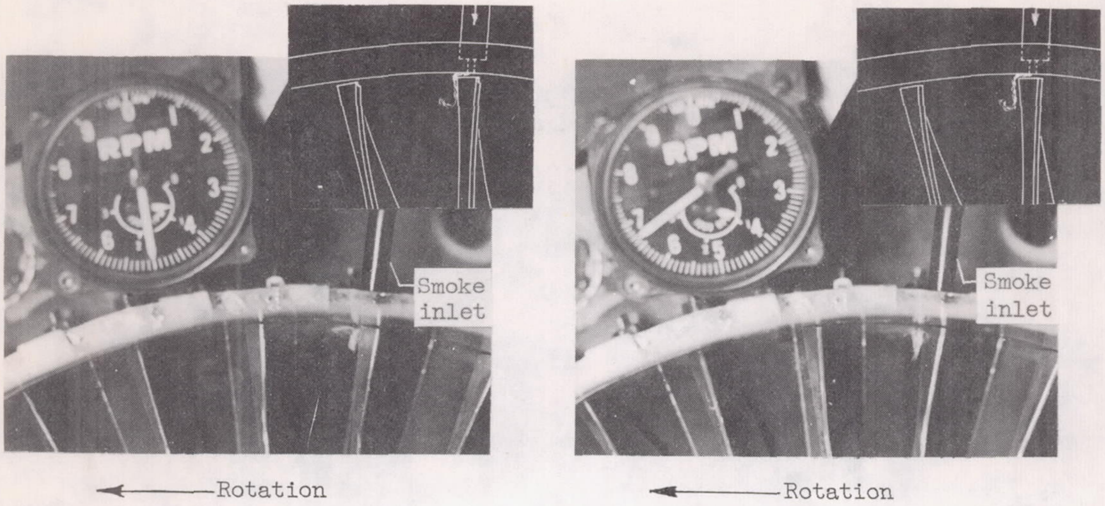
(f) Air discharge, 1.6 percent; ratio of rotor tip speed to axial air speed, 0.81; tip clearance, 0.095 inch.



(g) Air discharge, 3.2 percent; ratio of rotor tip speed to axial air speed, 0.93; tip clearance, 0.095 inch.

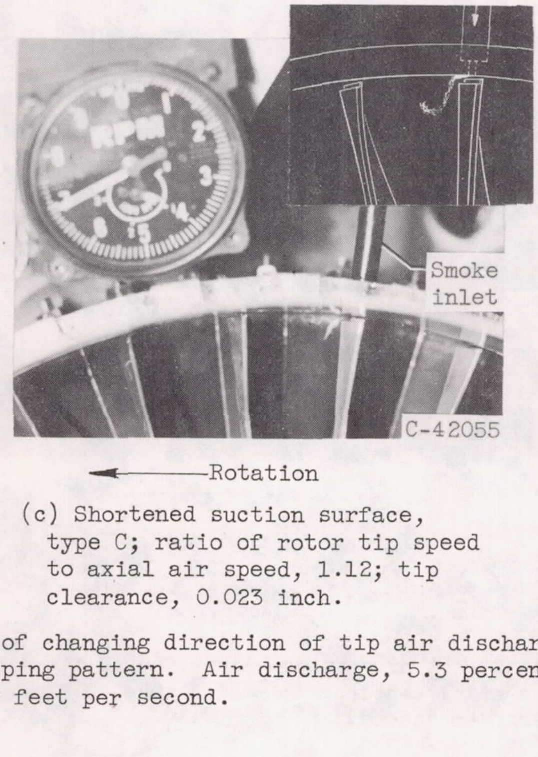
(h) Air discharge, 5.3 percent; ratio of rotor tip speed to axial air speed, 1.19; tip clearance, 0.095 inch.

Figure 4. - Concluded. Effect of changing magnitude of tip air discharge on rotor speed required for scraping pattern. Blade type C (shortened suction surface); mainstream axial air velocity, 2.7 feet per second.



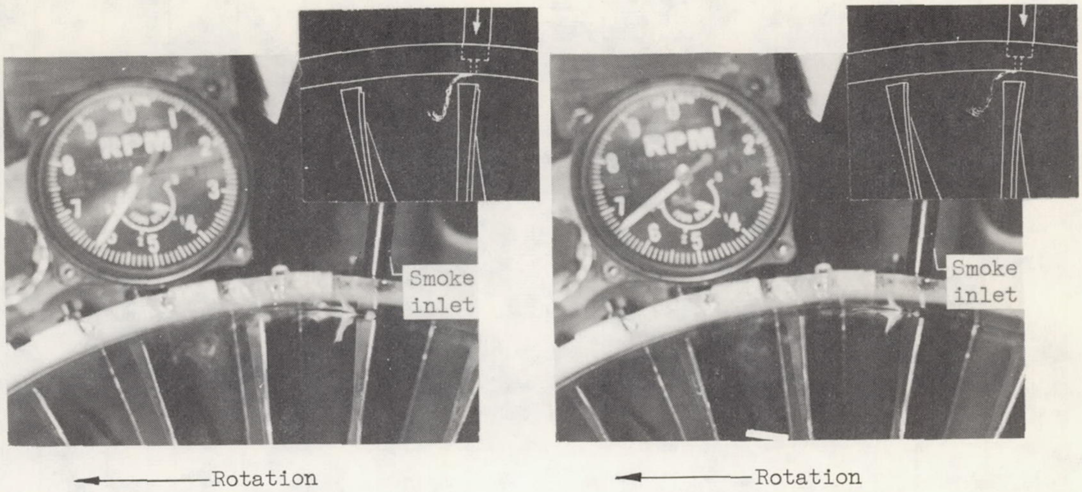
(a) Shortened pressure surface, type A; ratio of rotor tip speed to axial air speed, 0.81; tip clearance, 0.023 inch.

(b) Full length surfaces, type B; ratio of rotor tip speed to axial air speed, 1.08; tip clearance, 0.023 inch.



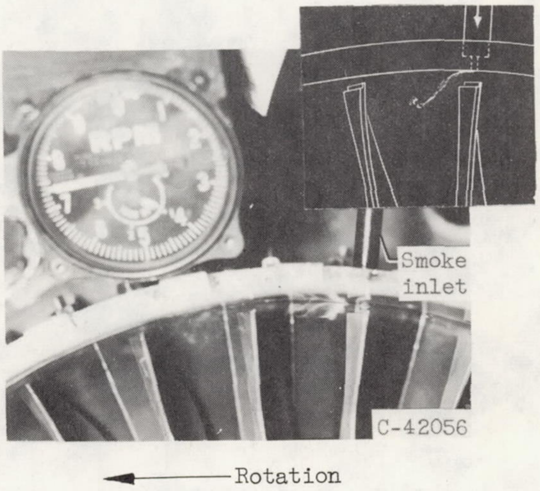
(c) Shortened suction surface, type C; ratio of rotor tip speed to axial air speed, 1.12; tip clearance, 0.023 inch.

Figure 5. - Effect of changing direction of tip air discharge on rotor speed required for scraping pattern. Air discharge, 5.3 percent; mainstream axial air velocity, 2.7 feet per second.



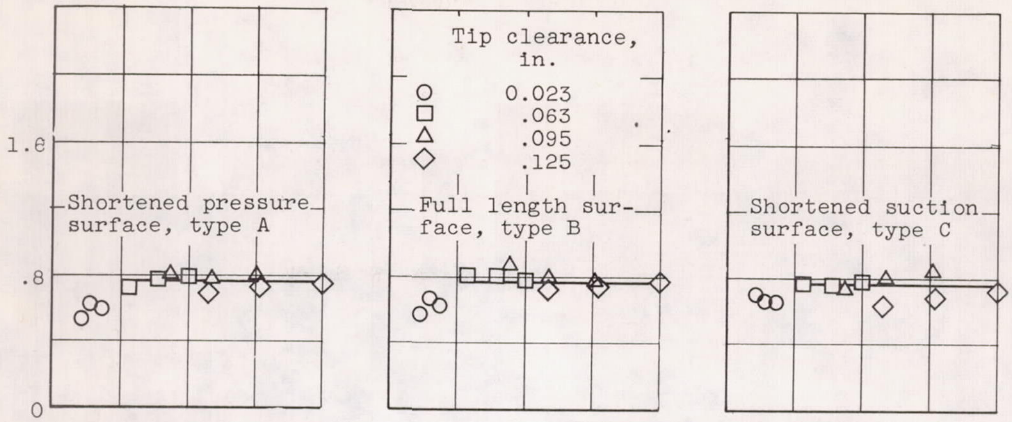
(d) Shortened pressure surface, type A; ratio of rotor tip speed to axial air speed, 0.99; tip clearance, 0.095 inch.

(e) Full length surfaces, type B; ratio of rotor tip speed to axial air speed, 1.05; tip clearance, 0.095 inch.

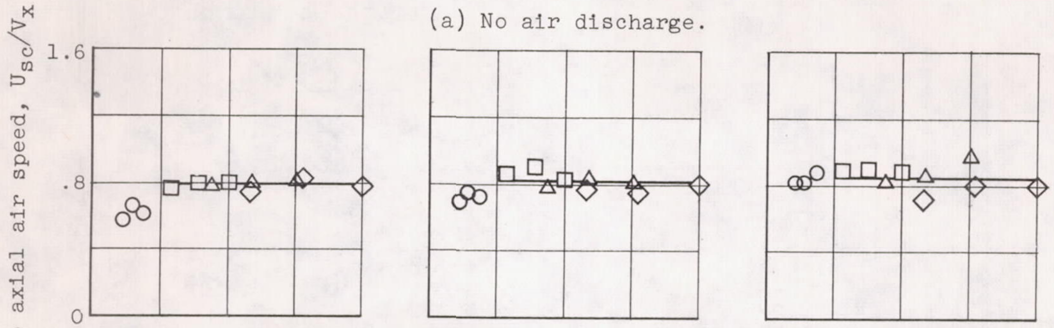


(f) Shortened suction surface, type C; ratio of rotor tip speed to axial air speed, 1.19; tip clearance, 0.095 inch.

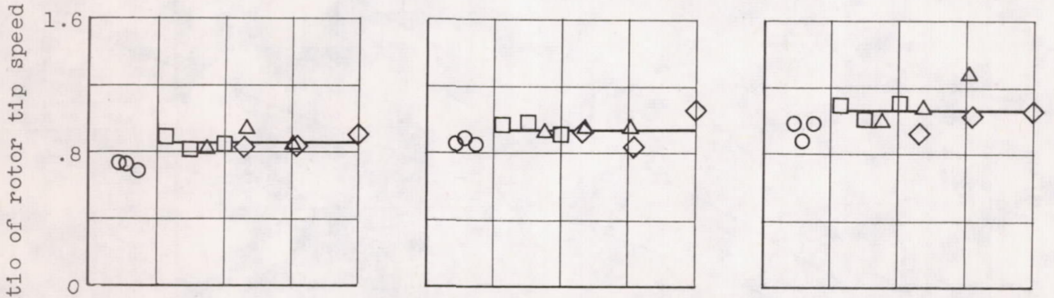
Figure 5. - Concluded. Effect of changing direction of tip air discharge on rotor speed required for scraping pattern. Air discharge, 5.3 percent; mainstream axial air velocity, 2.7 feet per second.



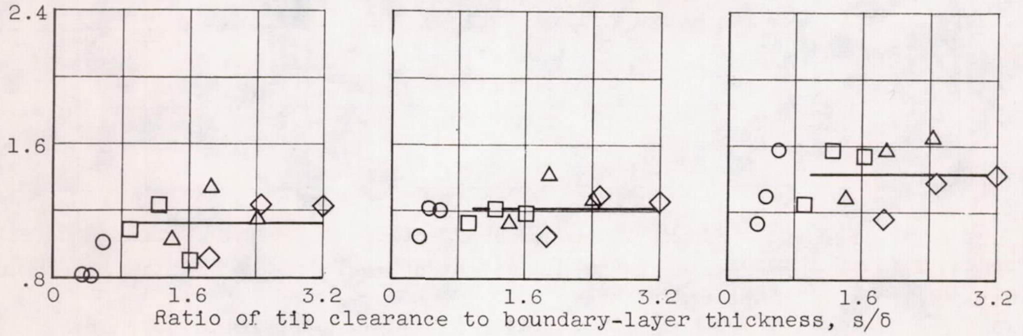
(a) No air discharge.



(b) Air discharge, 1.6 percent.



(c) Air discharge, 3.2 percent.



(d) Air discharge, 5.3 percent.

Figure 6. - Effect of tip clearance and air discharge on rotor speed required for scraping pattern for three hollow blade types.

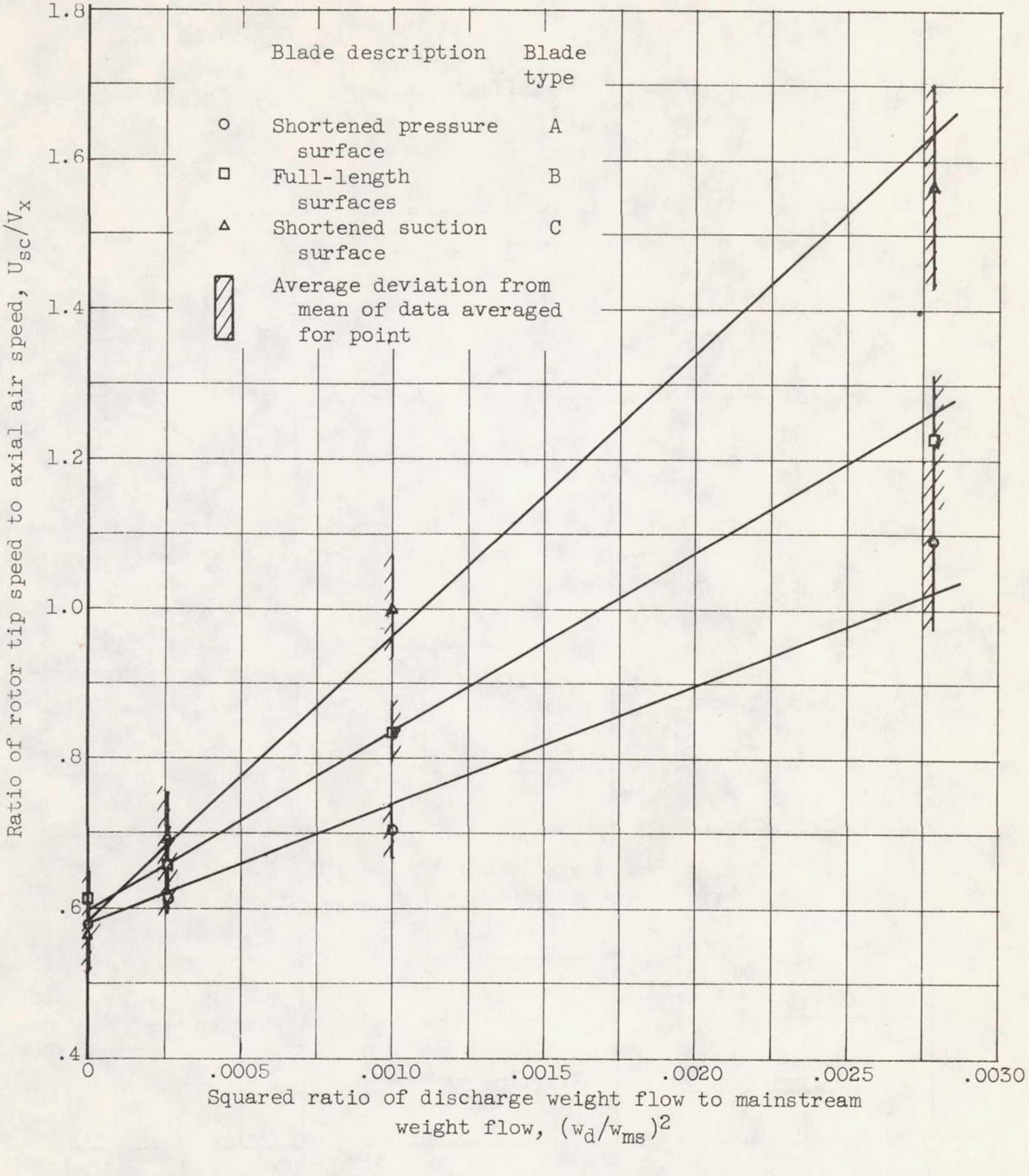
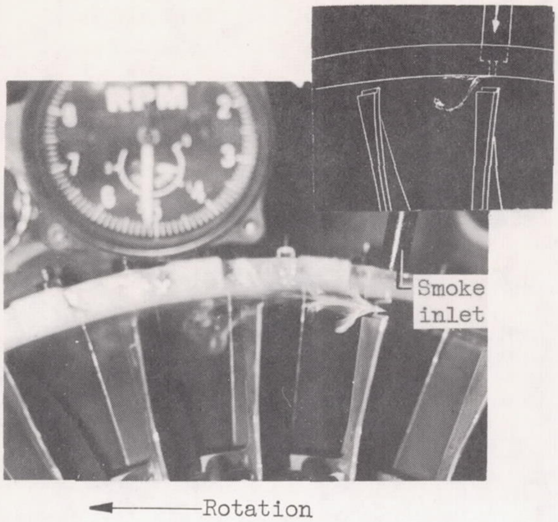
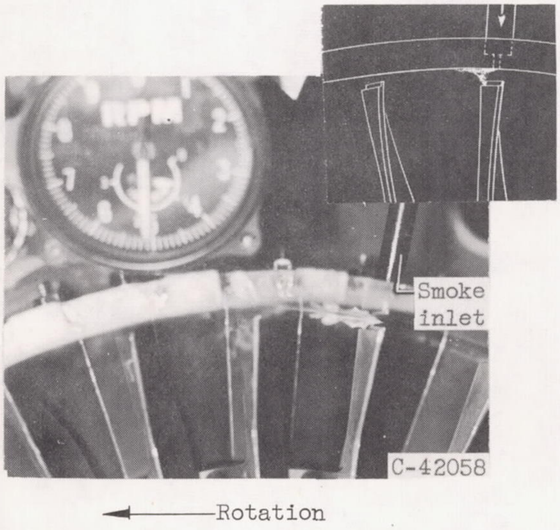


Figure 7. - Averaged effect of tip air discharge on rotor speed required for scraping.



(e) No suction; ratio of rotor tip speed to axial air speed, 0.84; tip clearance, 0.095 inch.



(f) 5.2 Percent suction; ratio of rotor tip speed to axial air speed, 0.84; tip clearance, 0.095 inch.

Figure 9. - Concluded. Effect of tip suction on scraping pattern. Blade type C (shortened suction surface); mainstream axial air velocity, 2.7 feet per second.

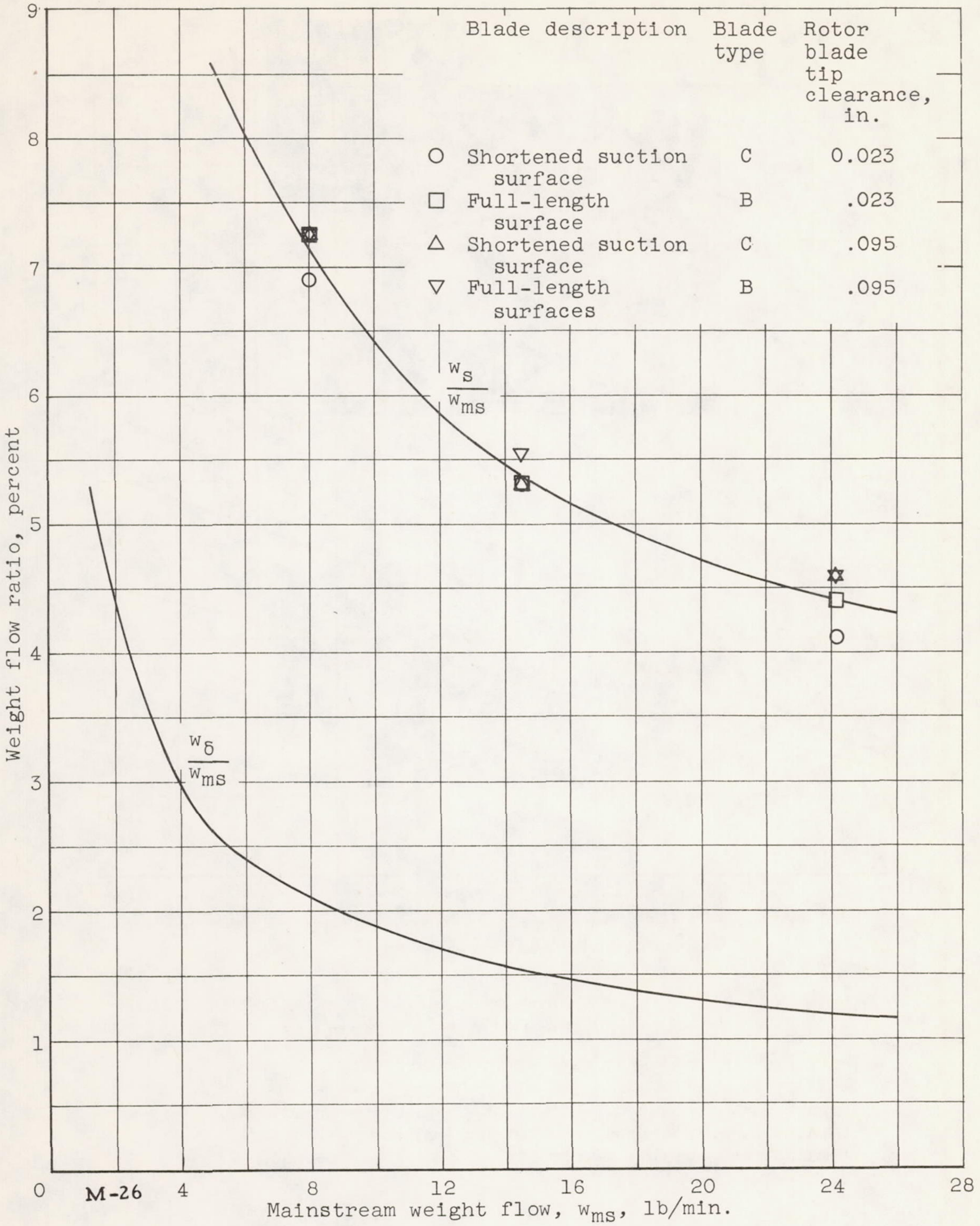


Figure 10. - Suction required for elimination of scraping pattern.

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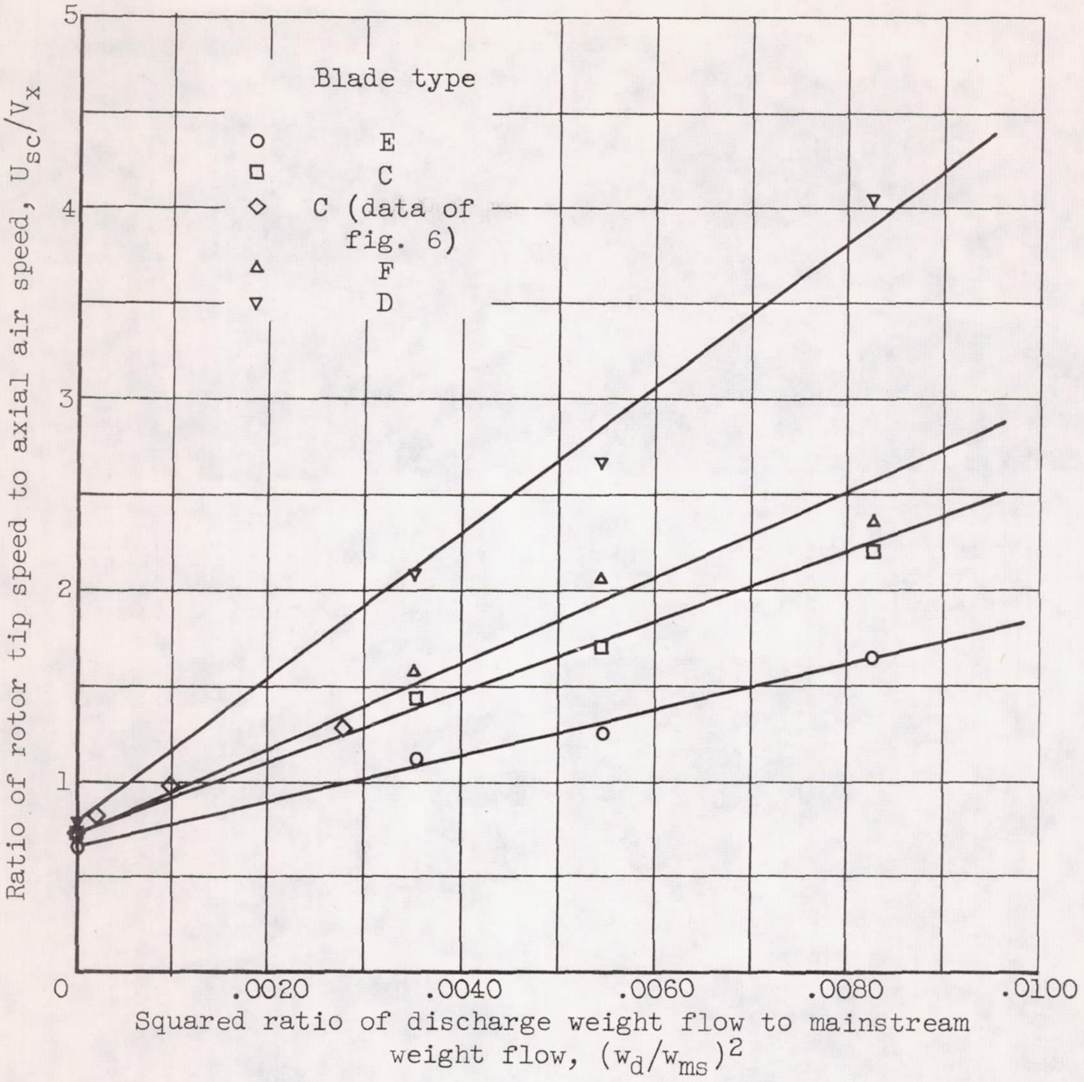
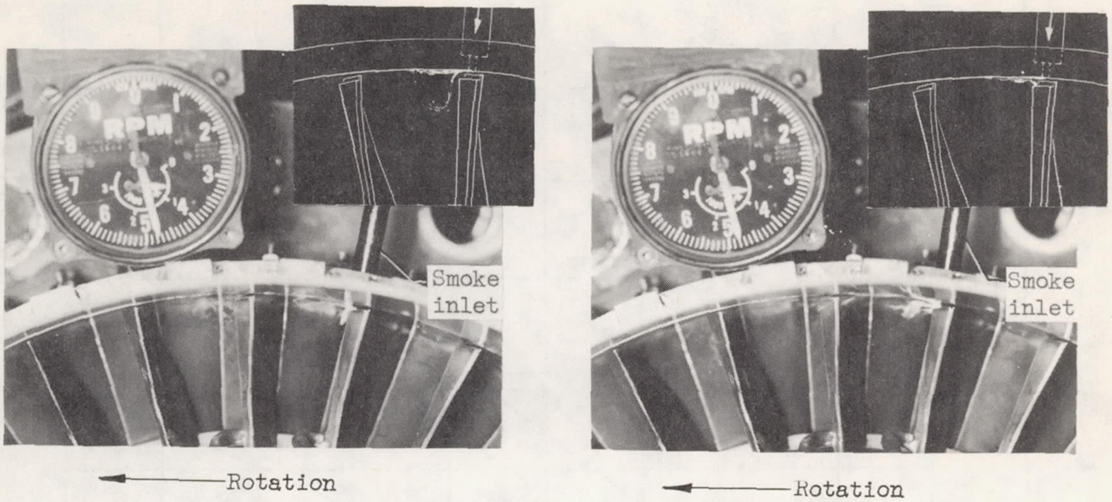
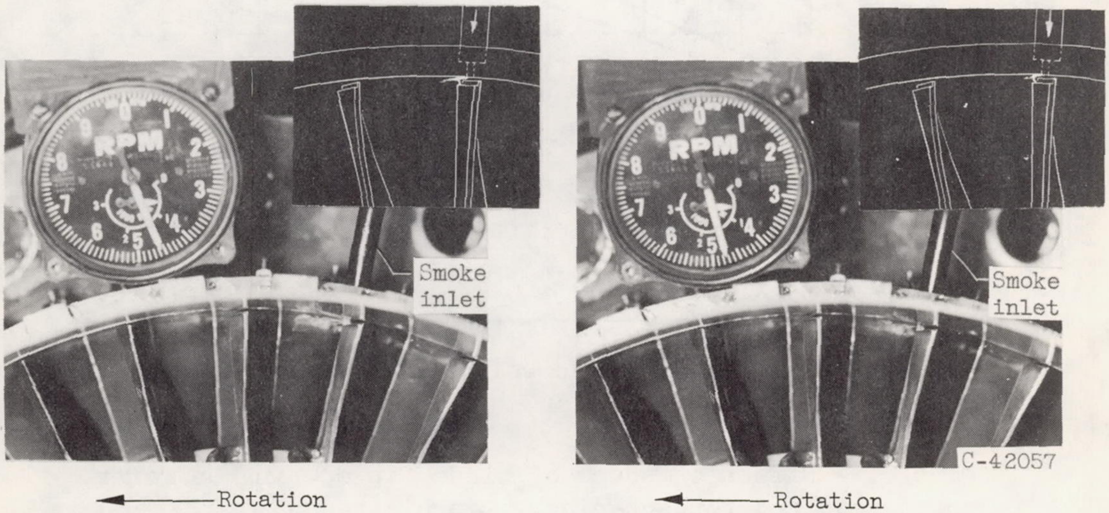


Figure 8. - Effect of shape of blade tip opening on rotor speed required for scraping. Tip clearance, 0.095 inch; shortened-suction-surface blades.



(a) No suction; ratio of rotor tip speed to axial air speed, 0.78; tip clearance, 0.023 inch.

(b) 3.6 Percent suction; ratio of rotor tip speed to axial air speed, 0.78; tip clearance, 0.023 inch.



(c) 5.3 Percent suction; ratio of rotor tip speed to axial air speed, 0.75; tip clearance, 0.023 inch.

(d) 7.1 Percent suction; ratio of rotor tip speed to axial air speed, 0.78; tip clearance, 0.023 inch.

Figure 9. - Effect of tip suction on scraping pattern. Blade type C (shortened suction surface); mainstream axial air velocity, 2.7 feet per second.