RESEARCH MEMORANDUM

A TWO-DIMENSIONAL CASCADE STUDY OF THE AERODYNAMIC CHARACTERISTICS OF A TURBINE-ROTOR BLADE SUITABLE FOR AIR COOLING

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SUMMARY

An experimental investigation of the aerodynamic problems associated with turbine blades having relatively low solidity and thick profiles, thereby making them suitable for use in air-cooled turbines, was made in a two-dimensional cascade. The nature of the flow in the channel formed by adjacent blades and at the exit of the blade row was investigated by static-pressure measurements and schlieren photographs. Flow conditions at the exit of the blade row were evaluated from the static-pressure measurements by the conservation-of-momentum principle.

At total-to-static pressure ratios less than that for which maximum blade loading was obtained, separation of the flow from the suction surface of the blade occurred near the trailing edge of the blade. At low pressure ratios, this separation caused the flow to underturn as much as 9° from the minimum value of the exit flow angle, which was obtained when the blade was fully loaded. As the pressure ratio was increased, the region of separated flow decreased until maximum blade loading was obtained at a pressure ratio of 1.86, where the flow was completely attached. For this pressure ratio, the flow was turned through an angle of 77.3° to an exit angle of 48.9° as measured from the tangential direction. Relatively little variation occurred in the velocity coefficient, defined as the ratio of the actual velocity to the isentropic velocity as measured at the exit of the blade row. The value of the velocity coefficient for the condition of maximum blade loading was 0.972.

This investigation of a turbine-rotor-blade design suitable for cooling because of its relatively low solidity and thick trailing edge indicates that supersonic velocities may be obtained over the greater portion of the blade suction surface, resulting in high blade loading without an appreciable decrease in efficiency from that obtained using blades with lower velocities.

INTRODUCTION

In the design of gas turbines having air-cooled blades for application to aircraft propulsion, the aerodynamic blade design may have to be compromised to accomodate the blade-cooling requirements. For example, air-cooled turbines require blade profiles thick enough to accomodate the coolant passages over the whole blade chord. The use of low-solidity blading is also desirable in order to reduce the amount of coolant required, reduce the turbine-wheel weight, and simplify the mechanical design of the rotor.

In order to obtain low blade solidity, the power output of each blade must be increased, or in other words, the blades must be more highly loaded. This high blade loading requires a greater difference between the average velocity over the suction surface and the average velocity on the pressure surface of the blades and, in general, for contemporary turbines, supersonic velocities will be obtained over at least part of the suction surface.

In order to meet the thick-blade-profile requirements of air-cooled turbines, the profile near the trailing edge of the blade must be tapered to a blunt edge. This tapered-trailing-edge requirement can be met through the use of convex profile curvature on the suction surface of the blade near the trailing edge. Curving the suction surface of the blade profile downstream of the guided channel, however, increases the possibility of flow separation over this region, particularly for subsonic exit velocities. This separation would result in a reduction of blade loading and increased profile losses. With supersonic expansion on the suction surface near the exit of the blade row, the favorable pressure gradient may delay this separation and thereby reduce the associated losses. Therefore, in order to determine whether these supersonic velocities can be obtained over the trailing-edge portion of the blade with the resulting high blade loading, a knowledge of the mechanism of the flow at the exit of blades of this type must be obtained.

The results of an experimental investigation of the mechanism of the flow and the losses involved in the operation of several turbine-blade profiles having supersonic velocities on a portion of the blade suction surface and downstream of the blade row are given in reference 1. The blades investigated, however, were of comparatively high solidity and had trailing-edge profiles unsuitable for cooling. The method used in the analysis of the experimental cascade data of reference 1 is applicable to the present problem.

As the initial phase of a program to investigate these aerodynamic problems associated with air-cooled turbine blades, an experimental investigation of a blade configuration suitable for air cooling has been made in a two-dimensional cascade at NACA Lewis laboratory. The solidity of the blade configuration investigated is representative of the lower values being used in current aircraft gas turbines, whereas the blade profile is sufficiently thick to provide adequate space for the coolant passages. The results of this investigation are reported herein. The results of the static-pressure surveys made in the cascade using blade and wall static-pressure taps include the blade-profile velocity distribution, the mass-averaged velocity at the exit of the blade row, and the losses at the exit of the cascade. Schlieren photographs are also presented to indicate qualitatively the shock and separation losses encountered in this design, and to give an insight into the mechanism of the flow. The blade profile used in this investigation has a solidity of 1.38, based on the axial width. All the experimental studies were carried out for an inlet temperature of 600° R, an inlet pressure within 5 percent of 22.0 pounds per square inch, and total-to-static pressure ratios from 1.46 to as high as 3.66.

SYMBOLS

The following symbols were used in this report:

K	frictional drag force, (lb)
m	mass flow, (slug/sec)
P	pressure force, (lb)
p	pressure, (lb/sq ft)
W	relative velocity, (ft/sec)
β	angle of flow measured from tangential direction, (deg)

Subscripts:

cr	critical
q	pressure surface of blade downstream of station 2
s	suction surface of blade downstream of station 2
u	tangential component
x	axial component
1	inlet to cascade

2 station in blade passage (fig. 1)

3 station downstream of blade row where exit flow is evaluated

Superscripts:

' stagnation state

THEORETICAL ANALYSIS

Experimental Method for Obtaining Flow Conditions at Cascade Exit

The flow conditions at the blade-row exit were evaluated experimentally by the conservation-of-momentum principle in a manner similar to that presented in reference 1. The equations of momentum may be applied to the fluid enclosed by the area ABCDEFA shown in figure 1. The components of momentum are resolved in the axial and tangential directions to give the corresponding velocity components as follows:

$$W_{x,3} = W_{x,2} + \frac{P_2 + P_{x,s} - K_{x,s} - P_{x,q} - K_{x,q} - P_3}{m} \qquad (1a)$$

$$W_{u,3} = \frac{P_{u,q} - K_{u,q} - P_{u,s} - K_{u,s}}{m} \qquad (1b)$$

For the blade profile investigated, the velocity at station 2 can be assumed to be in the axial direction. This assumption was verified by an analysis of the flow through the passage by the stream-filament method (reference 2). The magnitude of the average velocity at station 2 and on the blade surfaces AF and BC can be determined from the static-pressure distribution assuming isentropic flow relations. The mass flow was calculated at this station using the measured pressure distribution and isentropic-flow relations. A flow coefficient of 1 was assumed. The pressure forces P_2, P_q, P_s, and P_3 can be determined experimentally by integrating the static-pressure distribution over the corresponding areas. The frictional forces K_s and K_q are comparatively small and can be calculated with sufficient accuracy by assuming the boundary layer to be turbulent from the leading edge and by using conventional relations for calculating the drag as in reference 1. The forces along the boundaries CD and EF are equal and opposite and therefore have no effect on the flow.

APPARATUS AND PROCEDURE

Blade Profile

The blade profile used in this investigation was the mean section of an air-cooled nontwisted rotor blade designed for a turbine that is applicable for use in contemporary jet engines and is shown in figure 2. The inlet-flow angle β_1 for all data presented was 53.8° measured from the tangential direction. This gave a critical velocity ratio of 0.710 at the blade-row inlet for all total-to-static pressure ratios equal to and greater than 1.6. The guided channel formed by adjacent blades was slightly convergent from the blade-row entrance to exit. Because of the wide throat section at the guided-passage exit, this blade design was able to pass a high mass flow per unit of annulus area. The solidity of the blade configuration investigated was 1.38 based on the axial width of the blade.

Equipment

Two experimental test sections were made for this investigation, one for making static-pressure surveys and another for obtaining schlieren photographs. The axial width of the blades used was 1.40 inches. Each test section had five blades and two end blocks forming six equal passages.

The static-pressure-survey test section had 22 static-pressure taps on the blade pressure surface and 28 taps on the suction surface in order to determine the velocity distribution of the profile. A total of 30 static-pressure taps on the blade profile downstream of station 2, 12 wall taps located at station 2, and 33 wall taps spaced approximately 1/10 inch apart located at station 3, 0.59 inch downstream of the blade row, were used to determine the pressure distribution at these stations in order to calculate the velocity at the exit of the blade row by the conservation-of-momentum principle (fig. 2). A total of 13 wall static-pressure taps evenly spaced across the width of the cascade at the inlet to the blade row were used to measure the static pressure at that point in order to determine the uniformity of the entering flow.

For the optical test section, the blades were held in place by pins fastened to four steel bars that were inlaid in the glass plates.

The inlet total pressure and temperature were measured in the surge tank just upstream of the cascade. The inlet total temperature was measured with a thermocouple and read on a potentiometer to within 3° F. The static pressures were read to an accuracy within 0.05 pound per square inch. Provision was made for drawing off the boundary-layer air from the horizontal walls $1\frac{5}{8}$ inches upstream of the cascade. The static pressure at a point in the ducting downstream of the test section was observed for both the static-pressure surveys and the optical tests in order to correlate the schlieren photographs with pressure-survey data.

Additional information about the experimental equipment is given in reference 1.

RESULTS AND DISCUSSION

The results of the static-pressure survey are shown in figure 3 and the schlieren photographs of the flow through the blade passages in figure 4.

The flow conditions at relatively low pressure ratios are shown in figures 4(a) and 4(b). A series of lambda shock waves on the suction surface that persist at all higher pressure ratios can be seen in figure 4(a). The loss through a series of such weak shock waves is so small that it probably has a negligible effect on turbine performance. The shock-wave pattern on the third profile from the top of the photograph differs from the others because of the disturbance caused by a series of lines parallel to the blade span that were scribed on this blade in order to make the Mach lines visible in the supersonic portion of the flow field. In figure 4(b), which was taken at the same pressure ratio but at a different schlieren knife-edge setting from that of figure 4(a), the region of flow separation on the trailing portion of the blade suction surface appears more clearly. Weak compression waves are seen to originate across the flow at the passage exit in this photograph.

The results of the static-pressure survey (fig. 3) indicate that at low pressure ratios the separation of the flow from the blade suction surface causes the flow to underturn as much as 9° from the minimum value of β_3 of 48.9°, which corresponds to a blade turning angle of 77.3°. As the pressure ratio is increased, the flow gradually becomes attached to the blade as can be seen in figures 4(c) to 4(e). The flow is completely attached to the blade when maximum blade loading is attained. The blade is fully loaded at pressure ratios above 1.86 where the tangential component of exit velocity ratio $(W_u/W_{cr})_3$ has reached its maximum value (fig. 3). Over the range of pressure ratios from 1.45 to 1.86, the rate of increase in the tangential velocity component is considerably greater than that of the axial component as shown in figure 3. This high rate of increase is reflected in the sharp decline in the exit flow angle β_3 over this range of pressure ratios.

As shown in figure 3, relatively little variation occurs in the velocity coefficient. There is a slight rise from 0.970 to 0.977 over the range of pressure ratios from 1.50 to 1.75 as the wake losses due to separation are decreased. Then, as the exit Mach number continues to increase the shock wave losses become appreciable. The total loss in the exit shock-wave pattern will continue to increase beyond a pressure ratio of 2.0. The velocity coefficient as measured at station 3, however, actually rises as these shock waves swing downstream of the survey station, as shown in figure 4(e). Operation of the actual turbine with pressure ratios greater than 1.86 across these rotor blades for which maximum blade loading is obtained would be undesirable. Utilizable energy is dissipated in these shock waves without any increase in turbine power.

The velocity distribution on the blade surface for the condition of maximum blade loading is shown in figure 5. The velocity on the suction surface becomes supersonic a short distance downstream of the leading edge. The lambda shock waves on the suction surface cause the variations in velocity at the midchord station.

Because the suction-surface velocities are supersonic over the greater portion of the blade profile while the pressure-surface velocities are relatively low, the loading obtained for this blade represents a substantial improvement over that obtained for the blades investigated in reference 1, which had supersonic velocities downstream of the guided passage only.

CONCLUSION

A two-dimensional cascade investigation of the aerodynamic characteristics of a turbine-rotor-blade design suitable for cooling by virtue of its relatively low solidity and thick profile indicates that supersonic velocities may be obtained over the greater portion of the blade suction surface, which results in high blade loading without an appreciable decrease in efficiency from that obtained using blades with lower velocities.

SUMMARY OF RESULTS

A turbine-rotor-blade profile suitable for air cooling was investigated in a two-dimensional cascade and the following results were obtained:

1. At total-to-static pressure ratios less than 1.86 for which maximum blade loading was obtained, separation of the flow from the

suction surface of the blade occurred near the trailing edge. As the pressure ratio was increased, the region of separated flow decreased until maximum blade loading was obtained when the flow was completely attached.

2. At the low pressure ratios, the separation of the flow from the suction surface caused the flow to underturn as much as 9° from the minimum value of an exit flow angle of 48.9° as measured from the tangential direction, corresponding to a blade turning angle of 77.3°, which is obtained when the blade is fully loaded.

3. Relatively little variation occurred in the measured velocity coefficient as the pressure ratio was increased to the point of maximum blade loading, where a value of 0.972 was obtained.

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REFERENCES

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2. Huppert, M. C., and MacGregor, Charles: Comparison between Predicted and Observed Performance of Gas-Turbine Stator Blade Designed for Free-Vortex Flow. NACA TN 1810, 1949.

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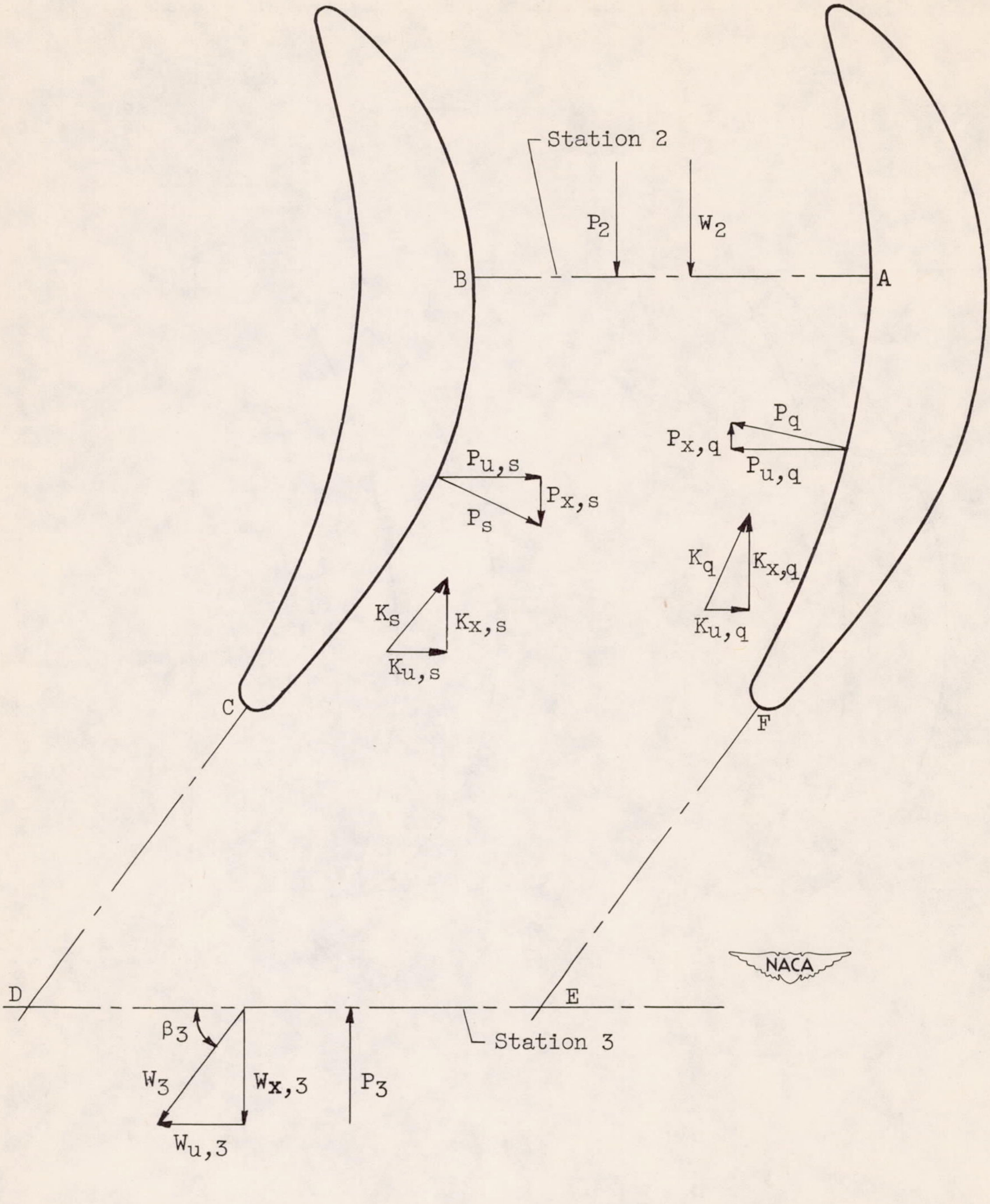

Figure 1. - Diagram of cascade flow conditions measured in static-pressure surveys for evaluation of exit flow by conservation-of-momentum principle.

Blade profile
coordinates

X	Y_U	Y_L
0	0.022	0.022
.033	.088	.002
.145	.209	.040
.383	.337	.119
.621	.384	.150
.859	.355	.138
1.097	.259	.095
1.336	.112	.010
1.383	.077	.000
1.412	.037	.037

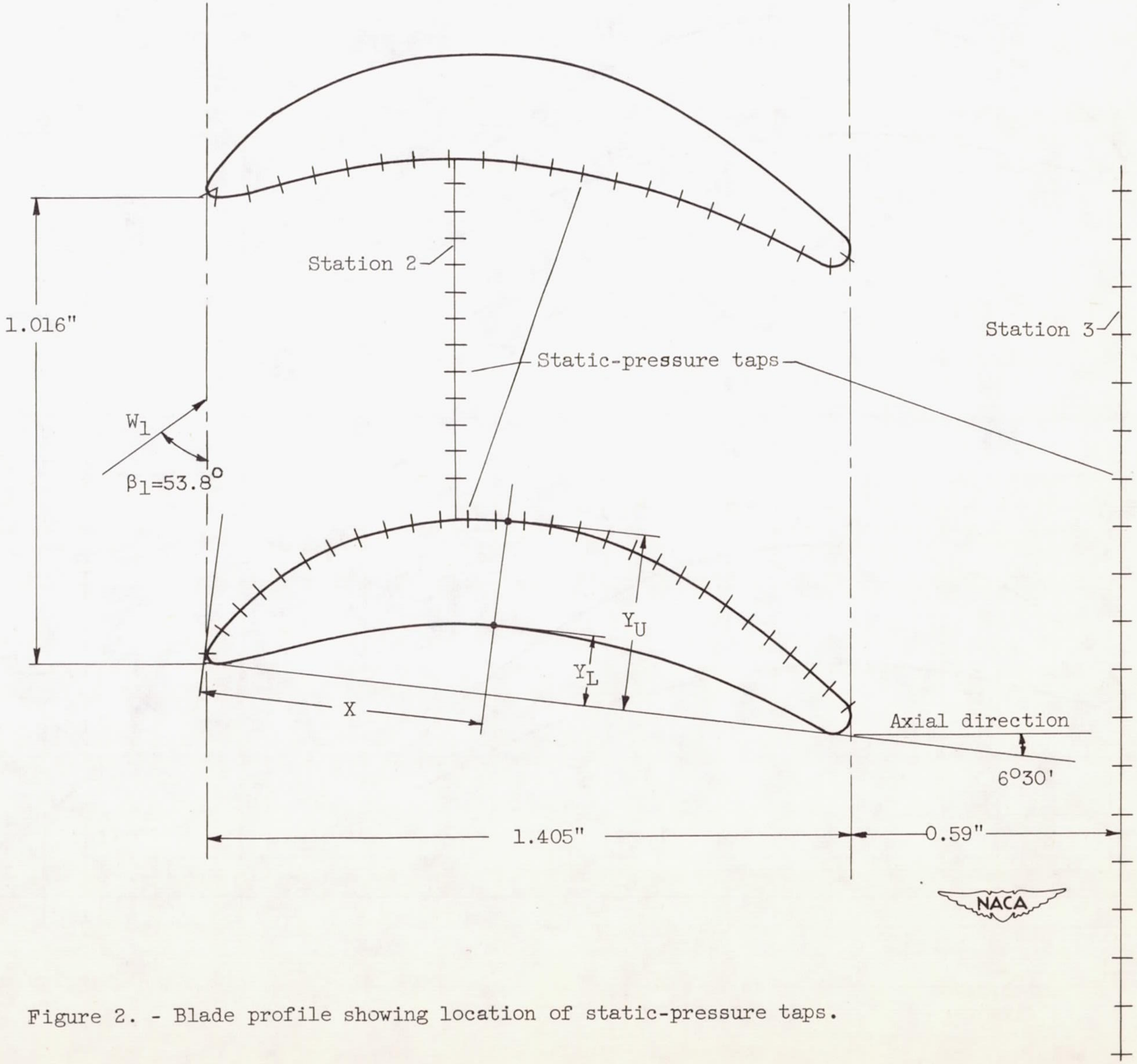

Figure 2. - Blade profile showing location of static-pressure taps.

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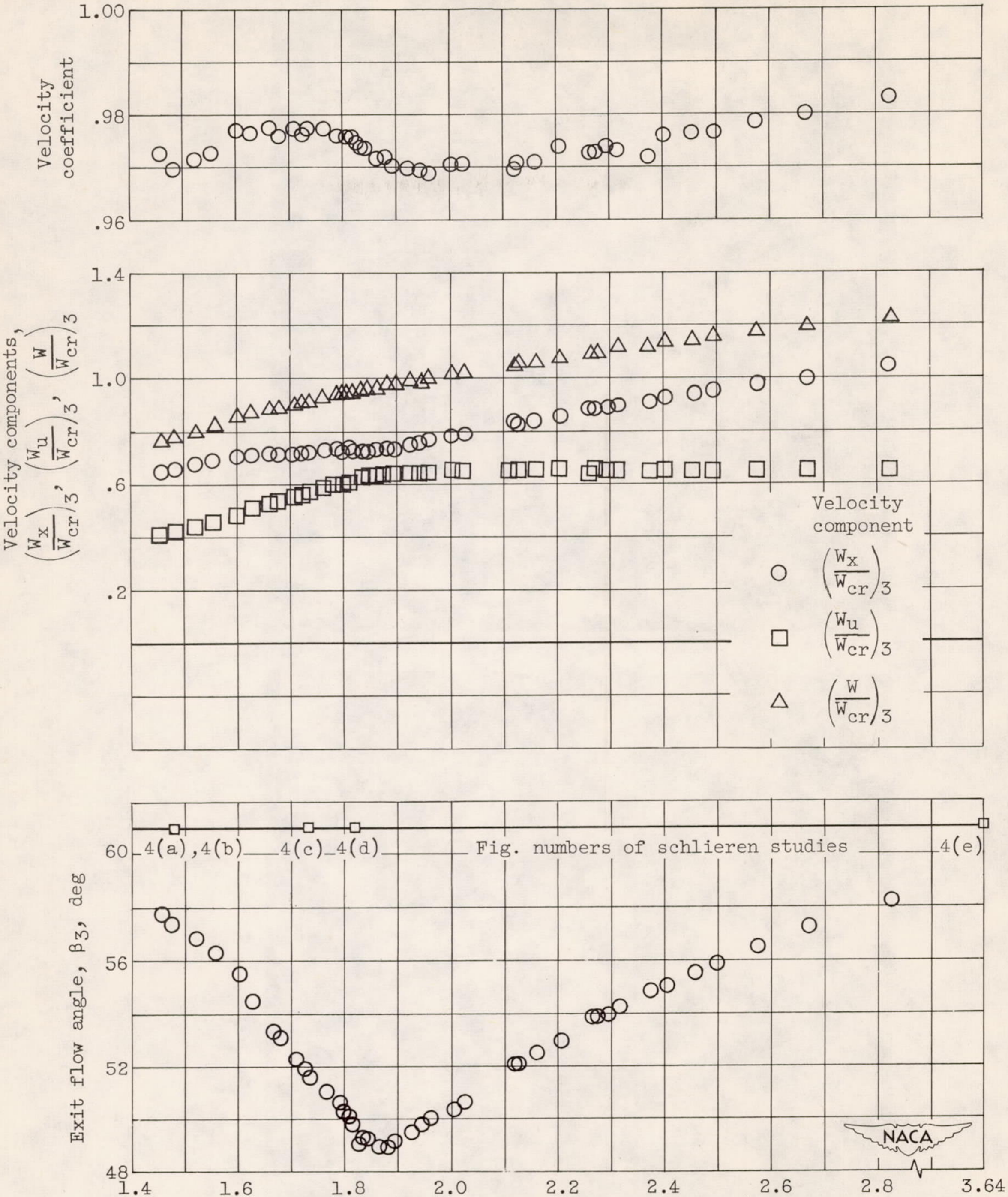
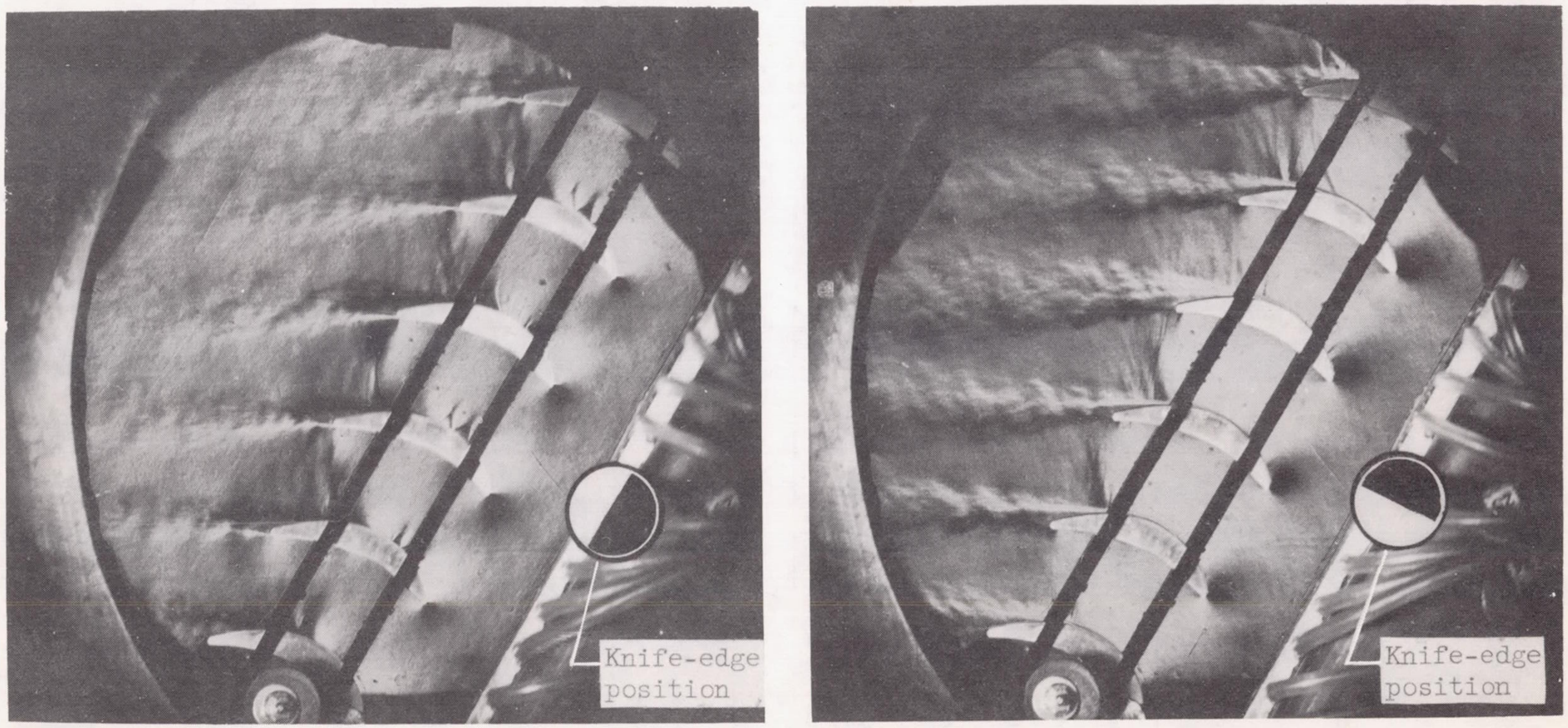


Figure 3. - Flow conditions at cascade exit (station 3) as determined from static-pressure surveys.



(a) Total-to-static pressure ratio, 1.48.

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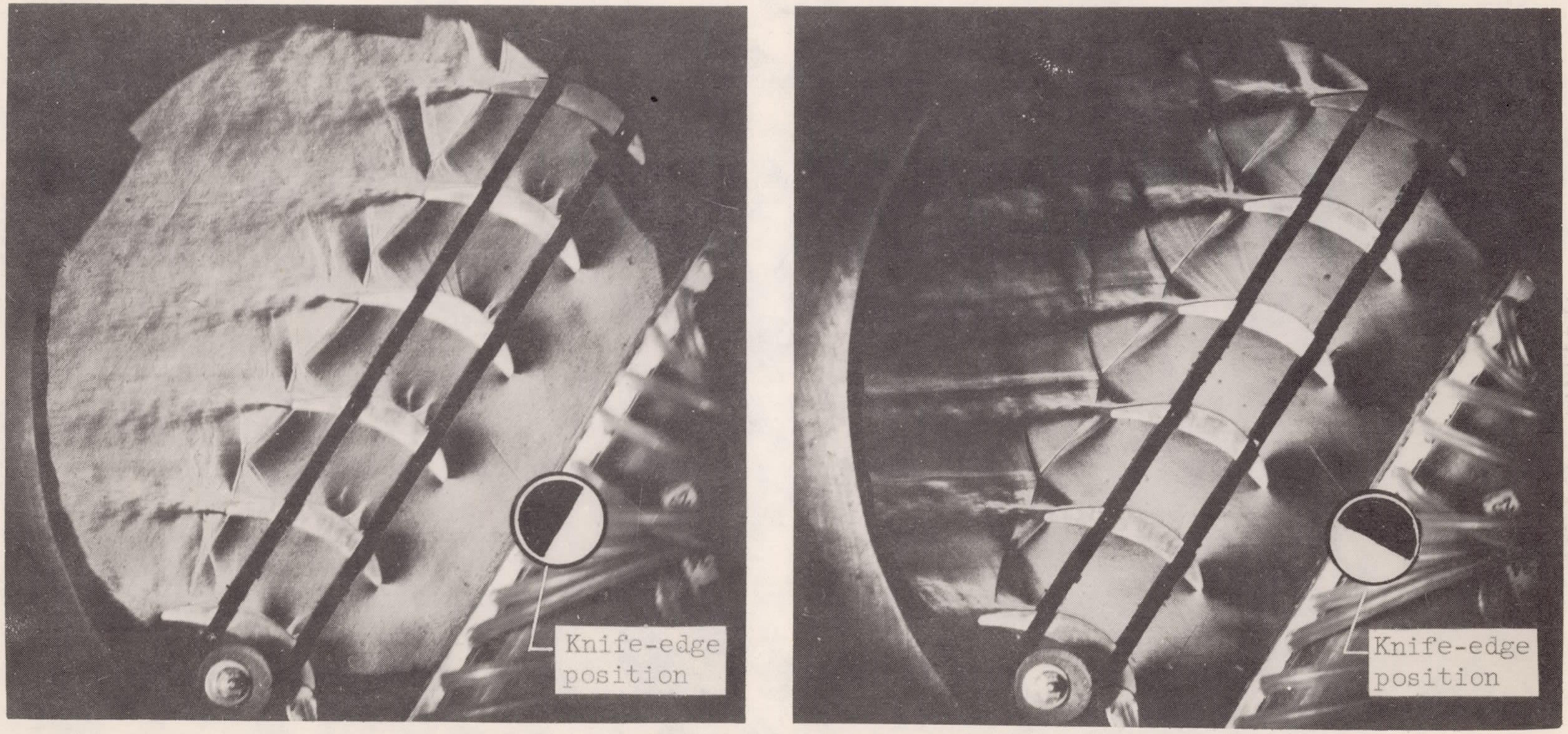
(b) Total-to-static pressure ratio, 1.48.

Figure 4. - Schlieren studies of flow through cascade.



(c) Total-to-static pressure ratio, 1.73.

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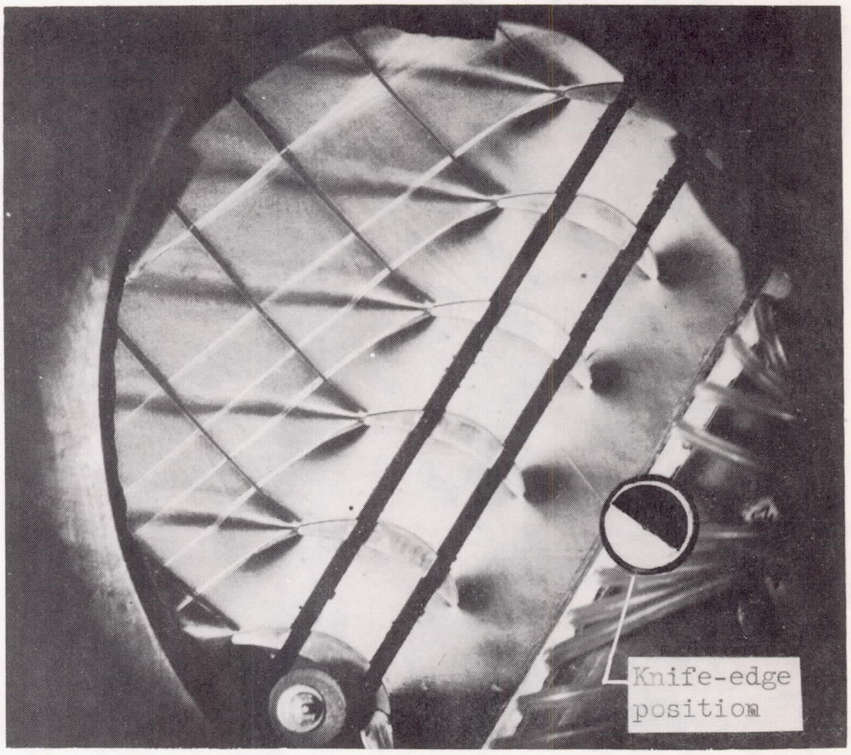
(d) Total-to-static pressure ratio, 1.82.

Figure 4. - Continued. Schlieren studies of flow through cascade.



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(e) Total-to-static pressure ratio, 3.64.

Figure 4. - Concluded. Schlieren studies of flow through cascade.

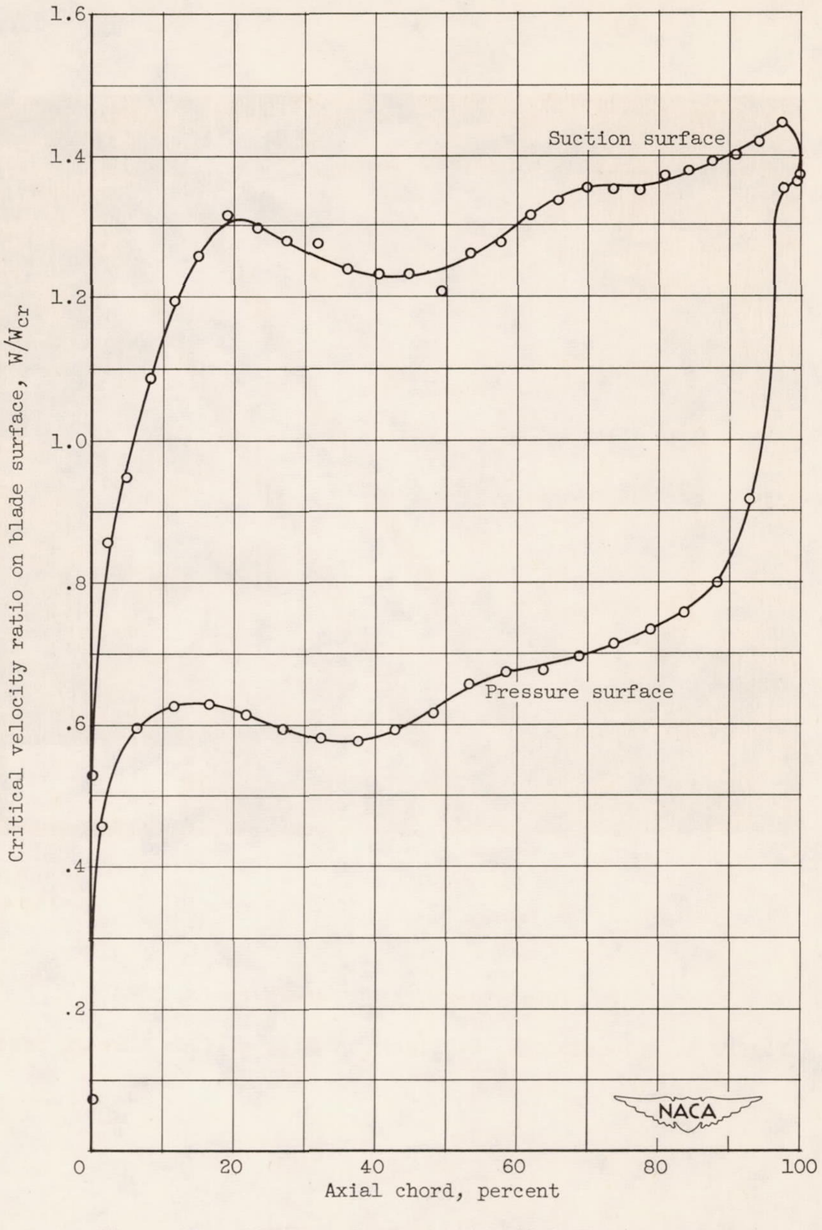

Figure 5. - Blade-surface velocity distribution at maximum blade loading.