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AERODYNAMIC PERFORMANCE OF A CERAMIC-COATED CORE TURBINE VANE TESTED WITH COLD AIR IN A TWO-DIMENSIONAL CASCADE

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16. Abstract

The aerodynamic performance of a core turbine vane with a ceramic coating was investigated experimentally in a two-dimensional cascade of 10 vanes. The vane was first tested with a rough coating and then retested after the coating had been smoothed. The test fluid was atmospheric air. The cascade tests covered a range of pressure ratios corresponding to ideal exit critical velocity ratios of 0.6 to 0.95. The principal measurements were cross-channel surveys of exit total pressure, static pressure, and flow angle. The results presented include exit survey results and overall performance in terms of flow angle, weight flow, and kinetic energy loss. The performance of the ceramic-coated vanes is compared with the performance of an uncoated vane having a similar profile.

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SUMMARY

The aerodynamic performance of a core turbine vane with a ceramic coating was investigated experimentally in a two-dimensional cascade of 10 vanes. The vane was first tested with a rough coating and then retested after the coating had been smoothed. The test fluid was atmospheric air. The cascade tests covered a range of ideal exit critical velocity ratios. The principal measurements were cross-channel surveys of exit total pressure, static pressure, and flow angle. The results of these tests were compared with the results of similar tests with an uncoated vane having a similar profile.

The kinetic energy loss for the rough ceramic-coated vane was more than twice as high as the loss for the uncoated vane. Smoothing the surface of the ceramic coating markedly reduced this loss. At approximately design exit critical velocity ratio, 0.8, the kinetic energy loss coefficients were 0.062, 0.031, and 0.023 for the rough-coated, smooth-coated, and uncoated vanes, respectively.

The difference in loss between the ceramic-coated vane with the smoothed surface and the uncoated vane was found to be caused almost entirely by the increased thickness of the trailing edge resulting from the ceramic coating.

INTRODUCTION

The use of higher turbine inlet temperatures in advanced aircraft engines has necessitated increasingly comprehensive and sophisticated turbine cooling schemes in order to maintain acceptable blading temperatures. Such cooling can adversely affect the aerodynamic performance of the turbine. A comprehensive research program is in progress at the NASA Lewis Research Center to investigate these effects. Some of the results of this program are reported in references 1 to 3.

Another approach to the problem of maintaining acceptable blading temperatures in very high-temperature turbines is the use of ceramic coatings. This approach is also being investigated. A ceramic coating applied to a high-strength metallic blade markedly reduces heat transfer and therefore the metal temperature of the blade. Blade internal cooling in conjunction with a ceramic coating may eliminate the need for film or transpiration cooling. The use of a ceramic coating would then reduce the cooling air requirements, the complexity of the blading, and the aerodynamic losses associated with the injection of cooling air into the primary flow stream.

However, some other aerodynamic losses may be incurred because of the ceramic coating. These are losses caused by surface roughness and increased trailing-edge thickness. One of the more promising methods of applying a ceramic coating is plasma spraying. In the as-sprayed condition the coating is very rough, averaging 7.6 to 10.2 micrometers deviation from zero roughness. Fortunately, this surface can be smoothed considerably by polishing with an appropriate abrasive. The trailing-edge thickness is largely determined by strength and internal cooling requirements. To this the thickness of the coating must be added. Consequently, the trailing edge of a ceramic-coated blade will be thicker than the trailing edge of an uncoated blade.

For the subject investigation, the effect of the ceramic coating on aerodynamic loss was investigated by testing coated and uncoated core turbine vanes in a simple two-dimensional cascade of 10 vanes. One of these 10 vanes, near the center of the cascade, was coated and the others were uncoated. The test fluid was atmospheric air. The cascade tests covered a range of pressure ratios corresponding to ideal exit critical velocity ratios from about 0.6 to 0.95. The principal measurements were cross-channel surveys of exit total pressure, static pressure, and flow angle. The ceramic-coated vane was tested in both the as-sprayed condition and the polished condition. The results of the investigation include exit survey results and overall performance in terms of flow angle, weight flow, and kinetic energy loss for both rough- and smooth-ceramic-coated vanes and an uncoated vane.

The testing was done in the U.S. customary system of units. Conversion to the International System of Units (SI) was for reporting purposes only.

SYMBOLS

a distance along axial chord from leading edge, cm

c_a vane axial chord, cm

$\bar{e}_3$ kinetic energy loss coefficient, $1 - (V_3/V_{id,3})^2$

p absolute pressure, N/cm^2

s vane spacing, cm

t tangential distance from vane trailing edge, cm

V velocity, m/sec

W flow rate per unit of vane span, kg/(sec)(cm)

α exit flow angle, deg from axial

δ ratio of inlet total pressure to U.S. standard sea-level atmospheric pressure, $p_1'/10.132\ N/cm^2$

$\sqrt{\theta_{cr}}$ ratio of inlet critical velocity to critical velocity of U.S. standard sea-level air, $V_{cr,1}/310.6$ m/sec

Subscripts:

cr flow conditions at Mach 1

id ideal or isentropic process

s vane surface

1 station at vane inlet

2 station at vane exit survey plane

3 station downstream of the vane exit where flow conditions are assumed to be uniform

Superscript:

' total state conditions

APPARATUS AND PROCEDURE

Test Vanes

A ceramic-coated test vane is shown in figure 1. The coating was applied to the core turbine vane tested for reference 3. The profile and coordinates of this vane are shown in figure 2. This figure also shows the position of the vanes relative to one another in the cascade, significant dimensions, and velocity diagrams. The vane surface was prepared for coating by abrasive blasting with dry aluminum oxide sand. Then a 0.051-millimeter-thick coating of nichrome was plasma (flame) sprayed onto the roughened surface. A ceramic coating of zirconium orthosilicate was plasma sprayed over the nichrome to complete the composite application. A solid piece of aluminum oxide was used to lightly polish and smooth the ceramic surface.

A profile plotting machine was used to draw smooth, continuous, 10-times-size cross sections of the rough-coated, smooth-coated, and uncoated vanes. The cross sections were then compared to determine the average coating thicknesses. These comparisons indicated a mean rough-coated ceramic composite thickness of 0.46 millimeter with a standard deviation of 0.05 millimeter and a mean smooth-coated composite thickness of 0.40 millimeter with a standard deviation of 0.06 millimeter.

The surface roughness of the rough-coated, smooth-coated, and uncoated vanes was measured with a commercial surface roughness indicator. The arithmetical average deviation of the surface from zero roughness was 7.6 to 10.2 micrometers for the rough-coated surface, 1.6 to 3.0 micrometers for the smooth-coated surface, and 0.15 to 0.18 micrometer for the uncoated base profile.

Cascade Tunnel

The vanes were tested in the simple two-dimensional cascade tunnel shown in figure 3. This cascade tunnel has 10 vanes with a span of 10.16 centimeters. Three different configurations were tested. One of these was with 10 uncoated vanes with the profile shown in figure 2. The other two tests were with the rough- and smooth-coated vanes. For these tests, only one coated vane was used. This single coated vane was inserted in place of one of the uncoated vanes near the center of the 10-vane cascade.

In operation, atmospheric air was drawn through the cascade tunnel, the vanes, and an exhaust control valve into the laboratory exhaust system. All three configurations were tested over a range of pressure ratios corresponding to ideal exit critical velocity ratios of about 0.6 to 0.95.

Instrumentation

In the uncoated vane configuration the two vanes that formed the center passage of the 10-vane cascade were instrumented at midspan with static pressure taps. The location of these taps is shown in figure 2. Vane surface pressure taps were not used on the coated vanes. The cascade tunnel also had wall static pressure taps in the exit section. These taps were used to set the exit static pressure. The vane surface and wall static pressures were measured with mercury-filled manometers. The pressure data were recorded by photographing the manometer board.

The vane-to-vane variation of exit total pressure, static pressure, and flow angle were surveyed simultaneously with the rake shown in figure 4. The total pressure was measured with a simple square-ended tubular probe. The static pressure was measured with a wedge probe that had an included angle of 15°. The angle probe was a two-tube type with the tube ends cut at 45°. The probe measures a differential pressure which is related to flow angle. Strain-gage transducers were used to measure these pressures.

The survey rake was installed in the cascade with the rake stem parallel to the vane trailing edges. The sensing elements of the rake were alined with the design flow angle and fixed. This angle was not changed during the surveys. The sensing elements were located at the midspan region of the vane with the element tips at the survey plane, station 2 in figure 2. Station 2 was located 16.6 percent of the vane axial chord axially downstream of the vane trailing edges. The rake was traversed tangentially over a distance of about two vane spaces behind the vane bounding the center channel of the 10-vane cascade. The traverse speed was about 2.5 centimeters per minute. An actuator-driven potentiometer was used to provide a signal proportional to rake position. The output signals of the three pressure transducers and the rake position potentiometer were recorded on magnetic tape. The recording rate was 20 words per second.

Data Reduction

Vane surface static pressures were taken from photographs of the manometer board. These data were used to calculate the vane surface velocity ratios. A computer was used to reduce the vane exit survey data recorded on magnetic tape. These flow angle and pressure data were used to calculate velocity, mass flow, and the tangential and axial components of momentum as a function of rake position. These quantities were then integrated numerically over a distance equal to one vane space to obtain overall values at the plane of the rake, station 2. The continuity and conservation of momentum and energy relations were then used to calculate the flow angle, velocity, and pressures at a hypothetical location where the flow conditions were assumed to be uniform. This location is designated station 3. For these calculations a constant-area process and conservation of the tangential component of momentum were assumed between stations 2 and 3. The details of these calculations are given in reference 4.

RESULTS AND DISCUSSION

The performance of ceramic-coated core turbine vanes with both rough and smoothed surfaces was determined in a two-dimensional cascade. The results of these tests are compared with the results of similar tests with uncoated vanes having similar profiles.

Survey Results

Typical exit total pressure survey data for the three test configurations are shown in figure 5. The total pressure wake for the ceramic-coated vane with the rough coating is shown in figure 5(a). This wake is very large, which indicates that the loss for this vane will also be large. Smoothing the ceramic coating by polishing with an abrasive reduced the size of the wake considerably. The wake for the smoothed-coated vane is shown in figure 5(b). This wake is only slightly larger than the wake for the uncoated vane, shown in figure 5(c). Only one ceramic-coated vane was used in the 10-vane cascade. This resulted in some distortion of the flow field. However, the pattern of the vane-to-vane variation of static pressure and flow angle repeated fairly well for the adjacent vanes. This implies that the data are valid.

The two vanes forming the center channel of the 10-vane cascade were instrumented with static pressure taps. These taps were installed on the uncoated vanes only. The vane surface velocity distribution, which was calculated from the static pressure measurements at near-design operating conditions, is shown in figure 6. This is a typical velocity distribution for a core turbine vane with moderately high loading. The Zweifel loading coefficient for incompressible flow is 0.789. The loading coefficient for compressible flow, which was calculated by integrating the vane surface static pressure distribution, is 0.654. The surface velocity distribution for the coated vanes was probably similar to that shown for the uncoated vane.

Overall Performance

The aftermix values of flow angle, equivalent weight flow, and kinetic energy loss coefficient are shown in figure 7 as a function of the ideal exit critical velocity ratio. The aftermix parameters were calculated from the exit survey measurements as explained in the section Data Reduction.

The flow angle data are shown in figure 7(a). The flow angle was about the same for all three test vanes and close to the design value of 67°. At exit velocity ratios higher than design, about 0.8, the flow angle for the rough-coated vane increased and diverged from the flow angles of the smooth-coated and uncoated vanes.

The equivalent flow data are shown in figure 7(b). The weight flows for the smooth-coated vane and the uncoated vane were very nearly the same. However, at the highest ideal exit velocity ratios investigated, the flow for the smooth-coated vane did fall off slightly. The flow for the rough-coated vane was significantly lower than that for the other two test vanes over the range of ideal exit critical velocity ratios investigated. At an ideal exit velocity ratio of 0.8, which is near design, the flow for the rough-coated vane was 3.4 percent less than the flow for either the uncoated or smooth-coated vane.

The kinetic energy loss coefficient for the three test vanes is shown in figure 7(c). The loss for the rough-coated vane was much larger than the loss for either the smooth-coated or uncoated vane. The loss for the rough-coated vane is comparable to the loss for a full-coverage film-cooled vane which had the same profile as the uncoated vane. This particular full-coverage film-cooled vane had very poor performance. The loss for the full-coverage film-cooled vane, which is taken from reference 3, is noted in figure 7(c). This high loss is also the principal reason for the low weight flow obtained with the rough-coated vane.

In the as-sprayed condition the ceramic coating had a surface roughness averaging 7.6 to 10.2 micrometers. Polishing smoothed the ceramic coating to a surface roughness averaging 1.6 to 3.0 micrometers. This smoothing reduced the loss to about one-half of the loss obtained with the rough coating. This result is in fairly good agreement with reference 5. The loss for the smooth-coated vane was higher than the loss for the uncoated vane. At an ideal exit critical velocity ratio of 0.8, which is near design, the kinetic energy loss coefficients were 0.062, 0.031, and 0.023 for the rough-coated, smooth-coated, and uncoated vanes, respectively.

Much of the difference in loss between the smooth-coated vane and the uncoated vane was found to be due to the difference in trailing-edge thickness. The trailing-edge thickness of the uncoated vane was 2.03 millimeters. The ceramic coating increased the trailing-edge thickness to 2.8 millimeters, an increase of 38 percent. The loss caused by the trailing edge alone was calculated according to the method of references 1 and 6. This method requires a known value of either the full boundary layer thickness or the profile loss up to the trailing edge. A representative value for the profile loss coefficient from reference 6 of 0.015 was used. The calculated difference in trailing-edge loss coefficients between the smooth-coated and uncoated vanes was 0.007. If this loss difference were superimposed on the data shown in figure 7(c), the loss of a smooth-ceramic-coated vane would be about the same as the loss of an uncoated vane having the same trailing-edge thickness for ideal exit critical velocity ratios to about 0.9.

SUMMARY OF RESULTS

The aerodynamic performance of a core turbine vane with rough and smoothed ceramic coatings was investigated experimentally in a two-dimensional cascade of 10 vanes. The coated vanes were tested over a range of ideal exit critical velocity ratios. The vane performance obtained from these tests was compared with the results of similar tests with an uncoated vane having a similar profile. The results of this investigation are summarized as follows:

1. The loss for the rough-ceramic-coated vane was more than twice the loss for the uncoated vane. Smoothing the surface of the ceramic coating markedly reduced this loss. At approximately design exit critical velocity ratio the kinetic energy loss coefficients were 0.062, 0.031, and 0.023 for the rough-coated, smooth-coated, and uncoated vanes, respectively.

2. The difference in loss between the ceramic-coated vane with the smoothed surface and the uncoated vane for ideal exit critical velocity ratios to about 0.9 was found to be almost entirely caused by the increased thickness of the trailing edge resulting from the ceramic coating.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 21, 1974,
505-04.

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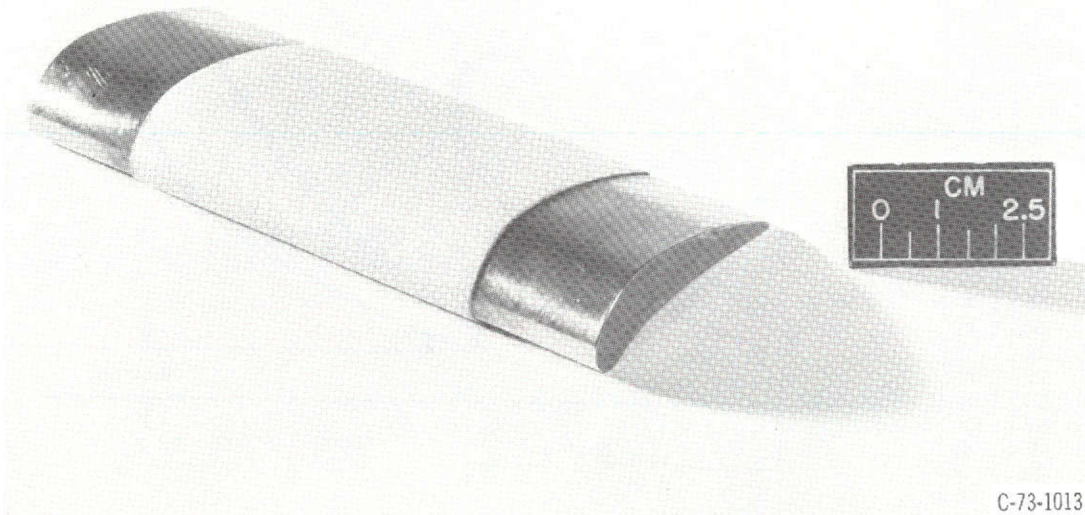


Figure 1. - Ceramic-coated core turbine test vane.

Vane coordinates		
X	Y_L	Y_U
0	0.508	0.508
.127	-----	.851
.254	-----	1.003
.381	-----	1.120
.508	-----	1.212
.635	-----	1.285
.762	.061	1.341
.889	.117	1.389
1.016	.163	1.425
1.143	.201	1.448
1.270	.236	1.463
1.397	.267	1.471
1.527	.292	1.476
1.778	.328	1.461
2.032	.358	1.427
2.286	.376	1.377
2.540	.384	1.321
2.794	.381	1.255
3.048	.368	1.191
3.302	.353	1.110
3.556	.328	1.026
3.810	.297	.942
4.064	.262	.848
4.318	.221	.747
4.572	.178	.635
4.826	.130	.521
5.080	.084	.399
5.334	.025	.267
5.552	.089	.089

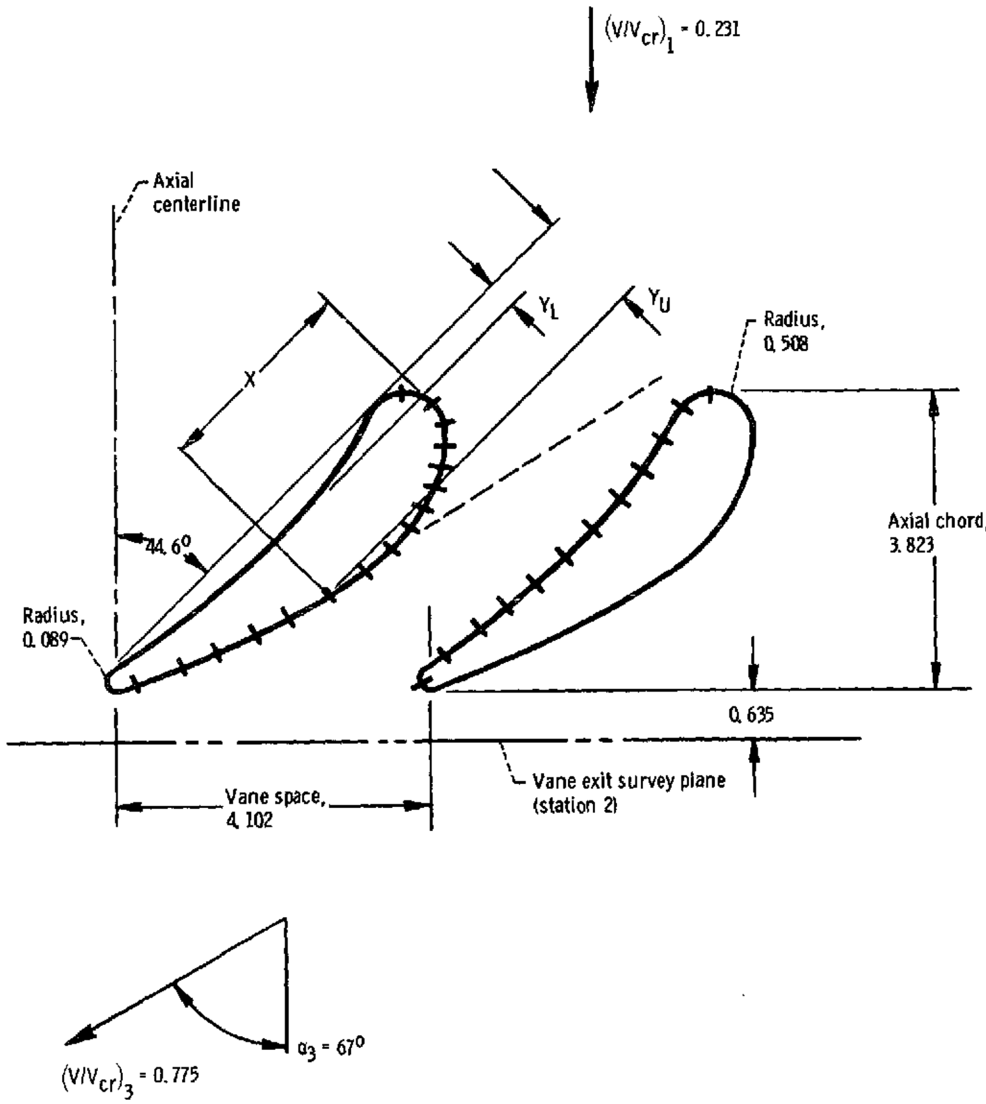


Figure 2. - Stator vane geometry. (Location of static taps is indicated by tic marks. All dimensions in cm. Coordinates are for uncoated vanes.)

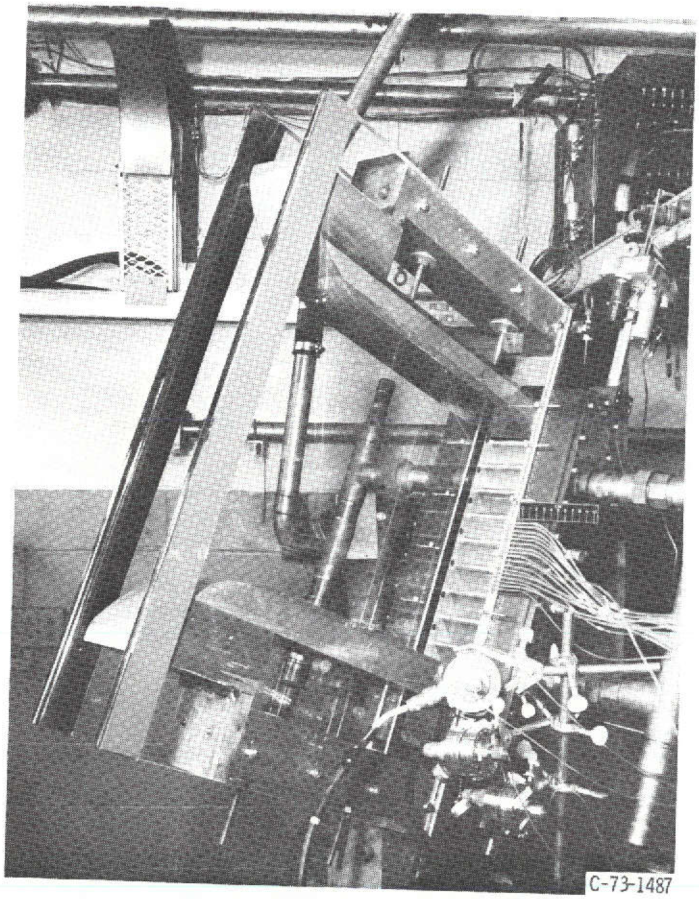


Figure 3. - Ten-vane cascade tunnel.

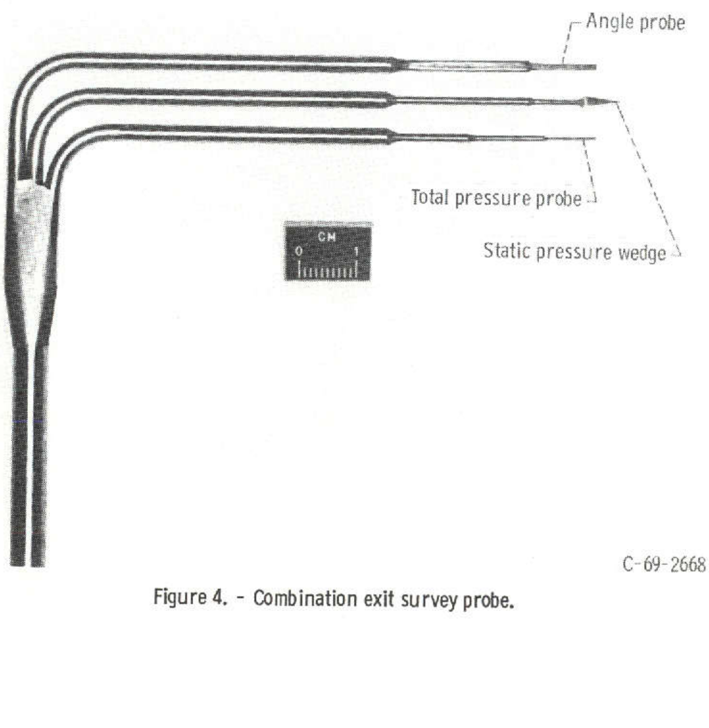


Figure 4. - Combination exit survey probe.

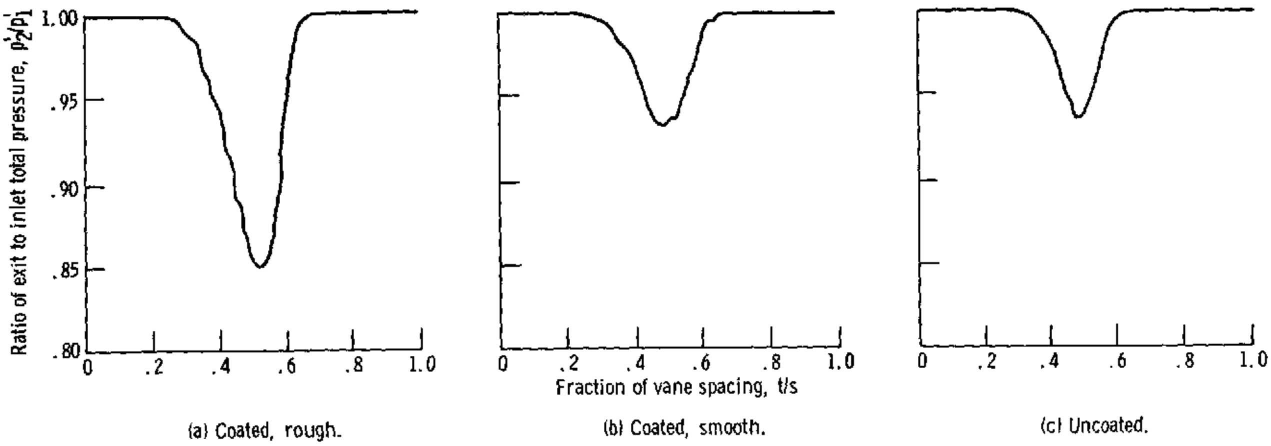


Figure 5. - Vane-to-vane variation in exit total pressure at station 2 for an ideal exit critical velocity ratio $(V/V_{cr})_{id,3}$ of about 0.8.

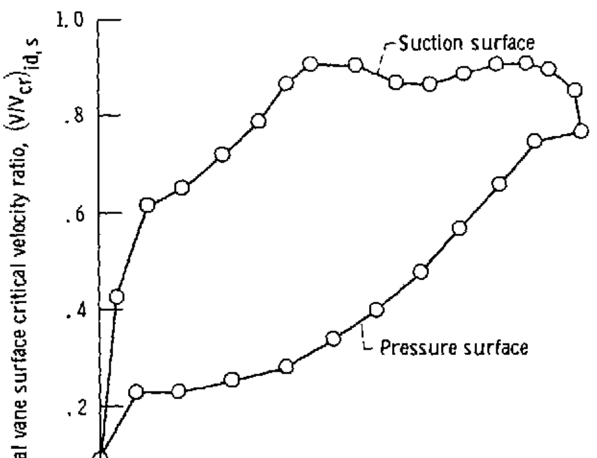
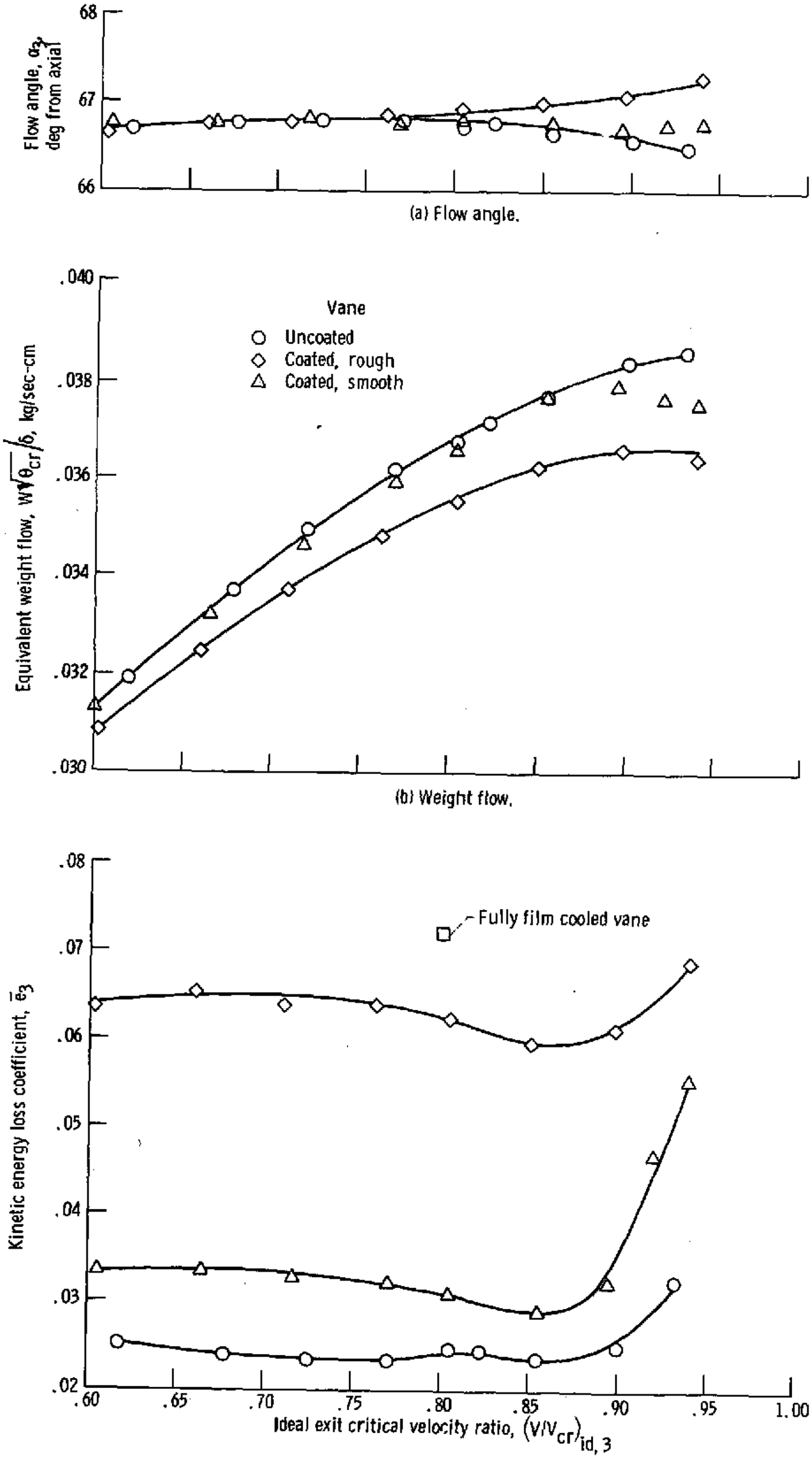


Figure 6. - Variation of ideal surface critical velocity ratio for solid, uncoated vanes at ideal exit critical velocity ratio $(V/V_{cr})_{id,3}$ of about 0.8.



(a) Flow angle.

(b) Weight flow.

(c) Kinetic energy loss coefficient.

Figure 7. - Overall performance.