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# AERODYNAMIC INVESTIGATION OF FOUR-VANE CASCADE DESIGNED FOR TURBINE COOLING STUDIES

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16. Abstract

An aerodynamic study was made of an annular-sector four-vane cascade designed for cooled-turbine thermodynamic studies. Static and total pressures at the vane cascade exit were measured as well as the vane surface static pressures at three radial sections. The vane surface static pressure distribution was of particular interest since it directly affects the determination of vane metal temperatures in later testing. Tests were conducted primarily with low pressure unheated air at vane mean radius exit Mach numbers of 0.73, 0.85 (design), and 0.93. Acceptable aerodynamic characteristics were found to exist.

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## SUMMARY

An experimental investigation was made to determine the aerodynamic characteristics of a four-vane annular-sector cascade designed for cooled-turbine thermodynamic studies. Characteristics considered were exit total pressure loss contours, exit circumferential and radial static pressure gradients, and vane surface static pressure distributions. The latter characteristic was of particular importance since it directly affects the determination of vane metal temperatures in later testing. Tests were conducted primarily with low pressure unheated air at vane mean radius exit Mach numbers of 0.73, 0.85 (design), and 0.93.

The surface static pressure distributions obtained for the two test vanes were found to be similar at each of the three radial sections investigated. These distributions further indicated that the flow accelerated relatively smoothly from vane inlet to exit. Furthermore, testing at temperatures up to $1700^{\circ}$ R (944 K) and pressures up to 85.5 psia (58.9 $N/cm^2$) produced negligible differences in these pressure distributions. Analytical results from two separate computer programs (CTTD and TSONIC) compared favorably with experimental pressure distributions over most of the vane surface.

Exit total pressure surveys showed that the pressure loss contours were uniform in thickness, relatively thin across each wake, and that no flow separation occurred on any of the vane surfaces. The boundary layers formed at the hub and tip radii were no thicker than 0.35 inch (0.89 cm) and consequently did not interfere with the instrumented sections on the vanes. The gradient in exit static pressure, both circumferential and radial, was different from that indicated by design. In particular, the radial gradient in the center channel was approximately 50 percent of that expected for three-dimensional flow. Extension of an end wall to provide additional flow guidance did not improve these pressure gradients significantly. Despite a reduced radial exit static pressure gradient, the overall aerodynamic characteristics of this cascade facility were considered acceptable for future heat-transfer investigations.

## INTRODUCTION

An experimental investigation was conducted to determine the aerodynamic characteristics of an annular-sector cascade of four turbine stator vanes. Of particular interest was the determination of static pressure distributions over the vane surface. Other characteristics considered important were the total pressure loss contours and the circumferential and radial static pressure distribution at the cascade exit.

In the future, high temperature heat-transfer studies (up to $2960^{\circ}$ R (1644 K)) will be conducted with this cascade to evaluate various internal air-cooling concepts and fabrication techniques for turbine vanes having the same outside profile. The development of techniques for the prediction of vane metal temperatures is of real importance and involves the use of outside heat-transfer coefficients which depend, in part, on the accuracy to which the local gas velocities are known over the vane surface. Therefore, an objective of this investigation was to establish the distribution in vane surface static pressure from which the surface velocities can be computed.

In general, there are two areas related to the areodynamic characteristics of a cascade that could have a detrimental effect on the thermodynamic performance of a vane - namely, the excessive accumulation of boundary layer flow and flow separation. Briefly, boundary layers that develop on the pressure and suction surfaces of the vanes can exert a strong influence in altering the effective flow area in the vane channel and, therefore, on the pressure and velocity distribution around the vane. Under certain conditions, the boundary layer formed on the vane surface may actually separate somewhere in advance of the vane trailing edge. This displacement would alter the flow within the vane channel. Excessive buildup of a boundary layer on the inlet ducting and at the vane hub and tip radii could also be of some concern when locating instrumentation sections on the vanes for thermodynamic studies.

In the present investigation, vane exit total pressure surveys and exit static pressure measurements were obtained just downstream of the cascade of vanes to determine if a nonuniform flow condition existed. The vane surface pressure distributions obtained at three radial locations were compared with analytically determined distributions. Tests were conducted primarily with low temperature air (~$535^{\circ}$ R (297 K)) at low pressure (~21 psia (14.5 $N/cm^2$)) for the vane mean radius design exit Mach number of 0.85. Additional data were obtained at off-design exit Mach number conditions, and some testing was conducted at elevated temperature and pressures. Data were also obtained with an extended end wall - the purpose of which was to provide additional flow guidance downstream of the vane cascade.

The turbine stator vane design incorporated a twisted profile and had a nominal 4-inch (10.2-cm) span, a 2.5-inch (6.35-cm) actual chord, and a solidity of 2.05. The use of cooling air to the vanes was purposely omitted to obtain basic aerodynamic information without secondary flow injection into the main gas stream.

# SYMBOLS

| | |
|---|---|
| d | surface distance from leading edge stagnation point |
| L | surface distance from leading edge to trailing edge for either pressure or suction surface |
| LE | leading edge |
| M | exit Mach number |
| p | absolute pressure |
| R | radius, in. (cm) |
| T | temperature |
| TE | trailing edge |
| X | horizontal coordinate |
| Y | vertical coordinate |
| Z | stacking point for vane airfoil sections |
| $\theta$ | angle between axis of rotation and vane chord line, deg |

Subscripts:

| | |
|---|---|
| le | leading edge |
| m | mean radius |
| ps | pressure surface |
| s | vane surface |
| ss | suction surface |
| te | trailing edge |
| 1 | station at inlet to cascade |
| 2 | station at cascade exit, 1/8 in. (0.32 cm) from vane hub trailing edge |
| 3 | station at cascade exit, 1/4 in. (0.64 cm) from vane hub trailing edge |

Superscript:

| | |
|---|---|
| $'$ | total state condition |

# APPARATUS AND INSTRUMENTATION

## Description of Cascade Facility

The cascade facility (fig. 1) was designed and fabricated as a tool for conducting

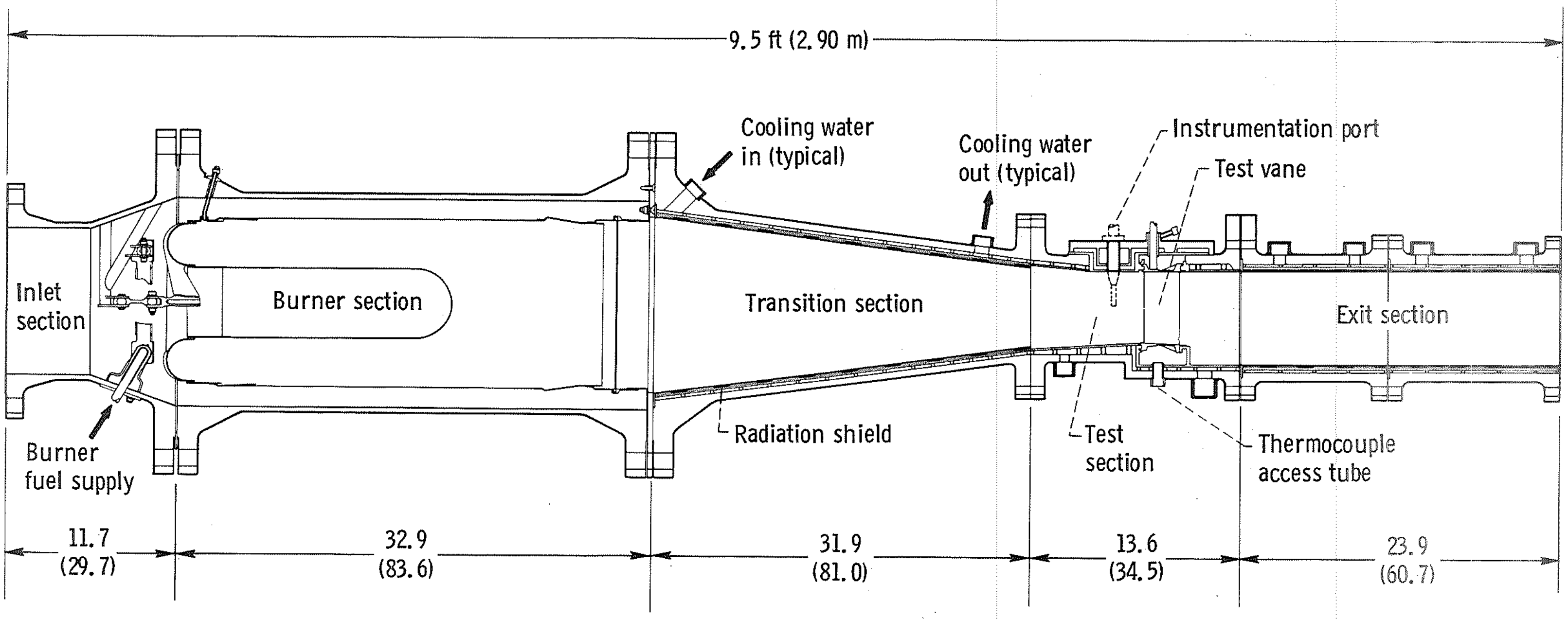



Figure 1. - Schematic cross sectional view of static cascade facility. All dimensions are in inches (cm) except where noted.

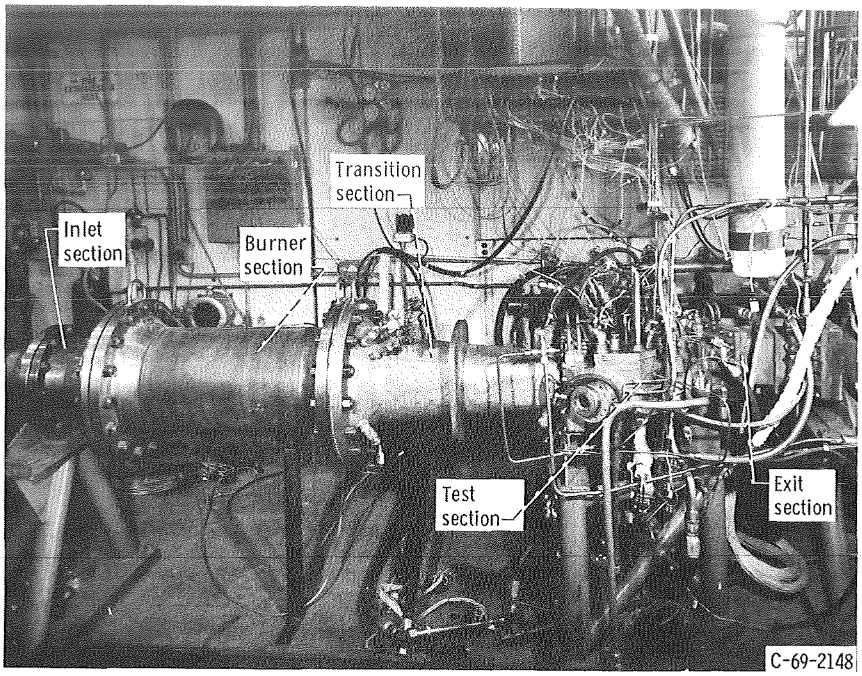


Figure 2. - Cascade facility installed in test cell.

high temperature (up to 2960° R (1644 K)) heat-transfer investigations of cooled-turbine stator vanes. It consisted of five components: (1) an inlet section, (2) a burner section, (3) a transition section, (4) a test section, and (5) an exit section. The cascade facility as installed in a test cell is shown in figure 2. For a detailed description of both the facility and the test cell see reference 1.

A laboratory combustion air system provided pressurized air up to about 120 psia (82.7 $N/cm^2$) to the inlet section of this facility. The burner section housed a can-annular type burner liner, which was actually an extended version of a production model; the extra length was incorporated to promote mixing of the combustion gas and to achieve a more uniform temperature profile at the cascade inlet. A hexagonal array of fuel nozzles was used to inject ASTM A-1 fuel into the burner section to attain elevated temperatures at the inlet to the cascade. The burner had the capability of operating at temperatures up to 2960° R (1644 K), but for this investigation, the burner was seldom ignited and then only to attain temperatures as high as 1700° R (944 K). The transition section was shaped to provide a smooth transition of the gas flow from a circular cross section to an annular sector cross section. The circular section at the burner exit had a 12-inch (30.5-cm) inside diameter, and the height of the annular sector at the test section interface was approximately 4 inches (10.2 cm). All sections downstream of the burner section were of double wall construction and incorporated baffles to provide passages for water cooling of the internal wall. In addition, the transition section utilized a thermal radiation shield and the test section and exit section had a ceramic-like coating on the inner surfaces to inhibit the flow of heat to the cooled walls.

The test section contained four vanes, which had a twisted profile, in an annular sector that simulated a portion of a turbine stator ring. Pertinent information concerning the vane design and operating criteria are as follows:

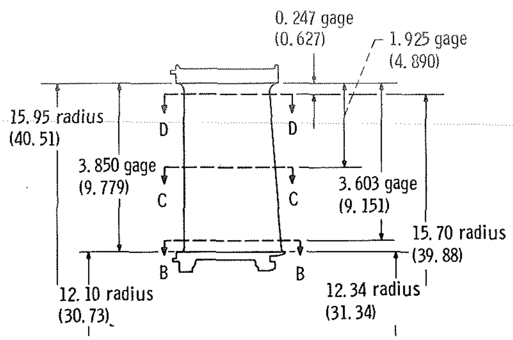
| | |
|---|---|
| Tip radius, in. (cm) | 15.95 (40.50) |
| Hub radius, in. (cm) | 12.10 (30.72) |
| Hub-to-tip radius ratio | 0.76 |
| Vane height, in. (cm) | 3.85 (9.78) |
| Vane chord (mean radius), in. (cm) | 2.47 (6.28) |
| Vane solidity (mean radius) | 2.05 |
| Aspect ratio | 1.54 |
| Design inlet Mach number | 0.23 |
| Design exit Mach number: | |
| Hub | 0.96 |
| Mean | 0.85 |
| Tip | 0.76 |

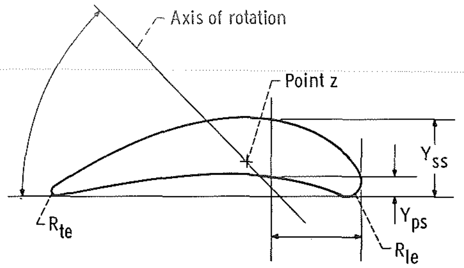
The actual vane profile is defined by the coordinates and dimensional information presented in table I. Coordinates are given for three radial sections - namely, B-B, C-C, and D-D. The X-Y coordinate system used for describing the vane section profiles is also shown. The vane profile is the same as that which will be used in future cooled-turbine-vane investigations. The vanes used in this investigation were uncooled, and consequently there was no cooling air being ejected through the vane surface to disturb the main gas stream. When heat-transfer tests are conducted with vane designs which incorporate cooling air being ejected through the vane surface, additional testing may be required to verify surface static pressure distributions.

Figure 3(a), a schematic top view of the test section, shows four vanes and, with the two end walls, five flow channels. (This view approximates the cross section at the vane mean radius.) The end walls at the inlet to the cascade were radial planes whose intersection was 12.1 inches (30.7 cm) below the hub platform and 15.95 inches (40.5 cm) below the tip platform. The direction of flow at the inlet to the cascade is indicated by the flow vector just upstream of the cascade. The flow is seen to be axial - that is, normal to the plane of the vane leading edges. The design free-stream exit flow angle at the vane mean radius is noted in the figure by the flow vector just downstream of the cascade. The flow has been turned by an angle of $64^{\circ}$ and, therefore, is at an angle of $26^{\circ}$ with respect to the plane of the vane trailing edges. As indicated by the dimensions, the angle of the end walls just downstream of the cascade was similar to the design exit flow angle. The exit end wall, which helps guide the flow down-

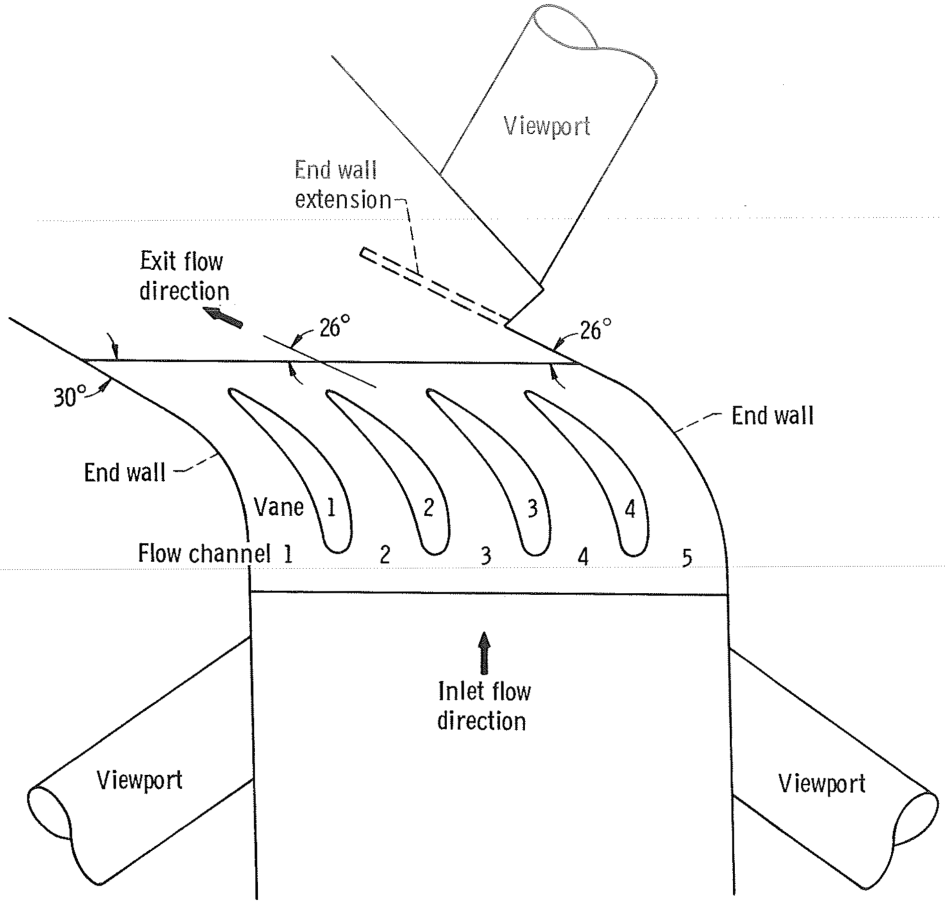
TABLE I. - VANE SECTION DATA

All dimensions are in inches (cm) unless otherwise indicated.

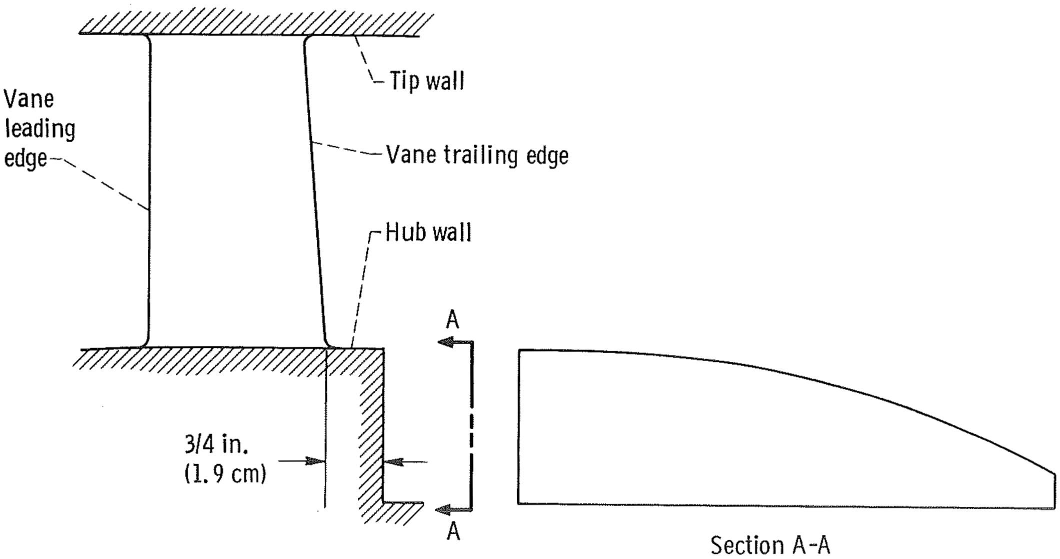



| Section | B-B | | C-C | | D-D | |
|---|---|---|---|---|---|---|
| Point Z, X | 1. 039 | | 1. 028 | | 1. 012 | |
| Point Z, Y | 0. 261 | | 0. 333 | | 0. 404 | |
| $\theta$ | $28^{\circ}46'$ | | $33^{\circ}33'$ | | $38^{\circ}20'$ | |
| $R_{le}$ | 0. 160 | | 0. 160 | | 0. 160 | |
| $R_{te}$ | 0. 035 | | 0. 034 | | 0. 033 | |
| X | $Y_{ps}$ | $Y_{ss}$ | $Y_{ps}$ | $Y_{ss}$ | $Y_{ps}$ | $Y_{ss}$ |
| 0. 000 | 0. 160 | 0. 160 | 0. 160 | 0. 160 | 0. 160 | 0. 160 |
| . 100 | ----- | . 319 | ----- | . 323 | ----- | . 337 |
| . 200 | . 005 | . 390 | . 006 | . 408 | . 006 | . 429 |
| . 300 | . 043 | . 450 | . 050 | . 473 | . 057 | . 495 |
| . 400 | . 077 | . 497 | . 093 | . 523 | . 108 | . 543 |
| . 500 | . 105 | . 536 | . 127 | . 560 | . 148 | . 576 |
| . 600 | . 132 | . 566 | . 156 | . 587 | . 177 | . 601 |
| . 700 | . 156 | . 587 | . 180 | . 606 | . 199 | . 619 |
| . 800 | . 177 | . 601 | . 197 | . 619 | . 214 | . 630 |
| . 900 | . 194 | . 610 | . 211 | . 624 | . 227 | . 633 |
| 1. 000 | . 207 | . 611 | . 222 | . 624 | . 235 | . 631 |
| 1. 100 | . 216 | . 606 | . 231 | . 619 | . 240 | . 624 |
| 1. 200 | . 221 | . 535 | . 235 | . 608 | . 243 | . 612 |
| 1. 300 | . 224 | . 580 | . 236 | . 590 | . 242 | . 584 |
| 1. 400 | . 223 | . 560 | . 233 | . 568 | . 238 | . 571 |
| 1. 500 | . 220 | . 534 | . 227 | . 541 | . 228 | . 542 |
| 1. 600 | . 212 | . 503 | . 217 | . 508 | . 217 | . 507 |
| 1. 700 | . 201 | . 467 | . 205 | . 472 | . 202 | . 470 |
| 1. 800 | . 186 | . 426 | . 188 | . 431 | . 183 | . 427 |
| 1. 900 | . 167 | . 382 | . 168 | . 334 | . 161 | . 380 |
| 2. 000 | . 144 | . 334 | . 144 | . 334 | . 137 | . 328 |
| 2. 100 | . 118 | . 283 | . 115 | . 280 | . 110 | . 274 |
| 2. 200 | . 087 | . 229 | . 083 | . 223 | . 081 | . 215 |
| 2. 300 | . 055 | . 171 | . 048 | . 162 | . 046 | . 155 |
| 2. 400 | . 020 | . 112 | . 012 | . 098 | . 009 | . 091 |
| 2. 460 | ----- | ----- | ----- | ----- | . 033 | . 033 |
| 2. 470 | ----- | ----- | . 034 | . 034 | ----- | ----- |
| 2. 493 | . 035 | . 035 | ----- | ----- | ----- | ----- |




(a) Top view.




(b) Side view.

Figure 3. - Schematic views of vane test section.

stream of channel 5, was somewhat abbreviated to allow the installation of a viewport in this region. The viewports shown in the figure are described in a subsequent section on instrumentation. The dashed lines represent a temporary modification made to the end wall contour downstream of channel 5. In effect, the original wall was extended by the installation of an aluminum plate, which covered the downstream viewport. Additional testing was then done to investigate the effect of the original abbreviated wall and existing viewport.

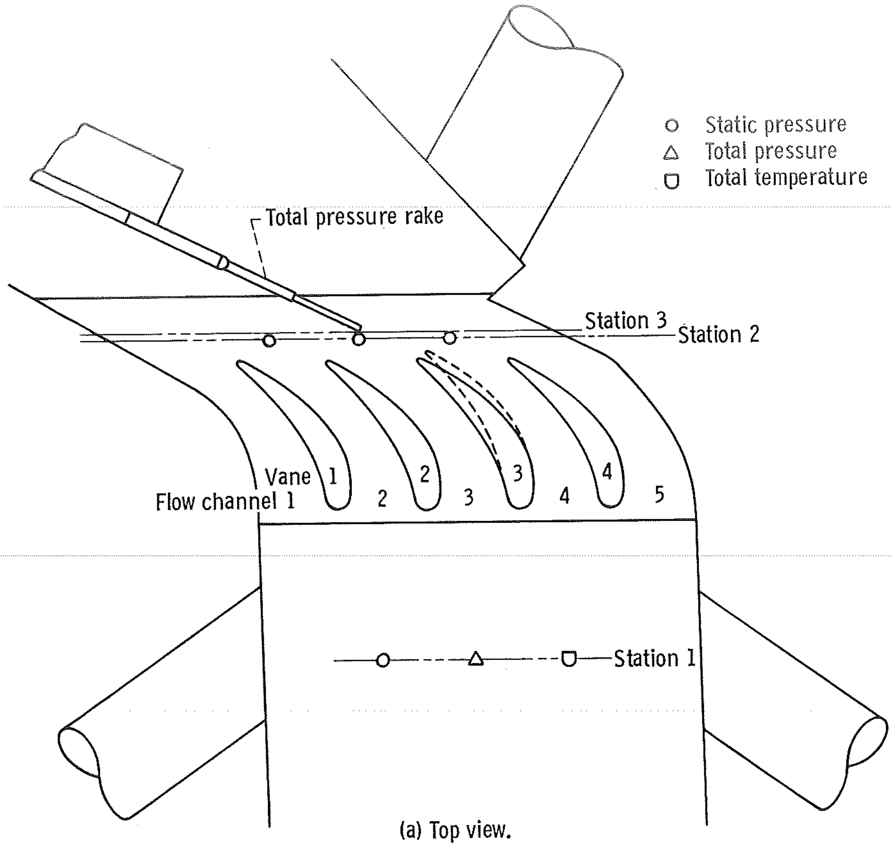
Figure 3(b) shows a schematic side view of the cascade and the wall contour at the hub and tip radius immediately downstream of the cascade exit. As can be seen, the hub wall drops off abruptly at a point approximately 3/4 inch (1.9 cm) beyond the vane hub trailing edge. The view of section A-A to the right shows that this dropoff is not constant across the cascade exit.

The exit section of the facility was connected to the laboratory exhaust system which had the capability of operating at either atmospheric pressure or at altitude conditions. For obtaining exit total pressure surveys in this investigation, however, the exit section was removed and the flow discharged to the room to permit the installation of a traversing total pressure rake just downstream of the cascade. (The total pressure rake is described in the next section.)

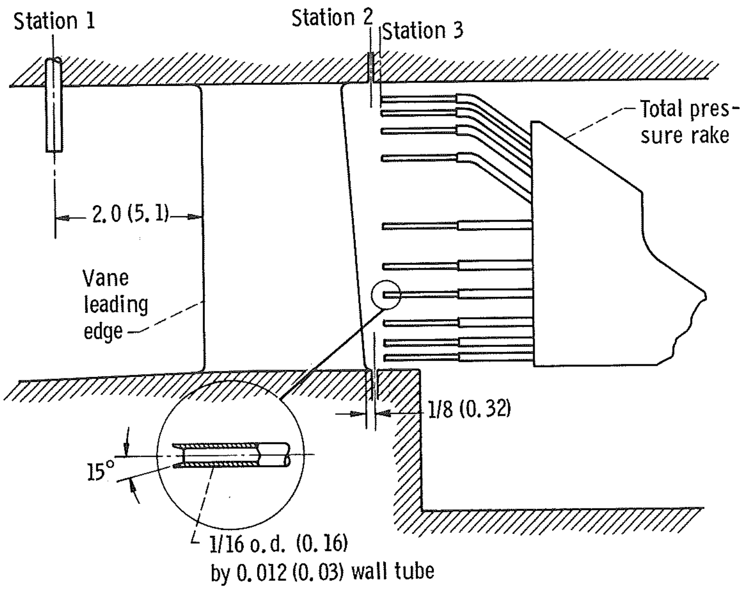
## Instrumentation

Figure 4 illustrates the location of instrumentation incorporated upstream and downstream of the cascade. At station 1, a radial traversing total pressure probe was installed in front of channel 3 and a traversing total temperature probe was installed in front of channel 4. These probes were used to obtain representative average inlet air conditions to the cascade. Static pressures were measured both upstream and downstream of the cascade at stations 1 and 2. A single static pressure was measured at the hub wall of station 1, which was located 2 inches (5.08 cm) upstream of the vane leading edge. Six static pressures were measured downstream of the vanes in the middle of channels 2, 3, and 4 at both the hub and tip radii of station 2. Station 2 was approximately 1/8 inch (0.32 cm) axially downstream of the hub trailing edge, as shown in figure 4. (The profile of vane 3 at the hub radius is shown in phantom.)

A circumferentially traversing total pressure rake consisting of 10 sensing probes was located downstream of the cascade at station 3, which is located approximately 1/8 inch (0.32 cm) downstream of station 2 (see fig. 4(b)). The tips of the pressure tubes were in a radial line, and the probes were set at the design exit free-stream flow angle for the vane mean radius. The cross-sectional area surveyed by the total pres-




(a) Top view.




(b) Side view. All dimensions are in inches (cm) except where noted otherwise.

Figure 4. - Schematics of vane test section showing pertinent instrumentation.

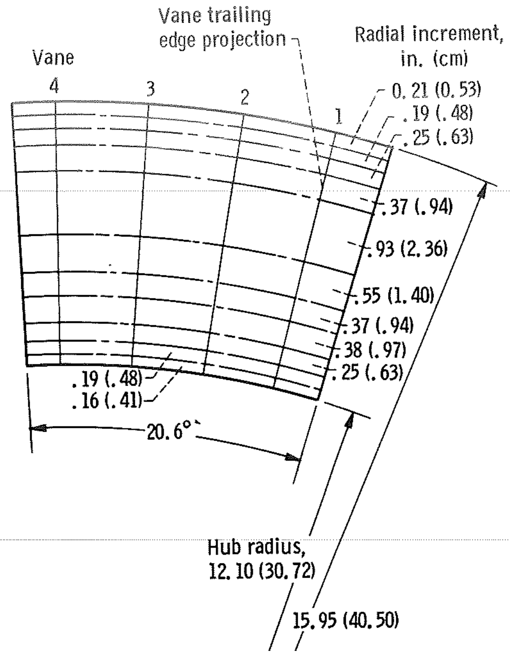



Figure 5. - Cross-sectional area surveyed by total pressure rake

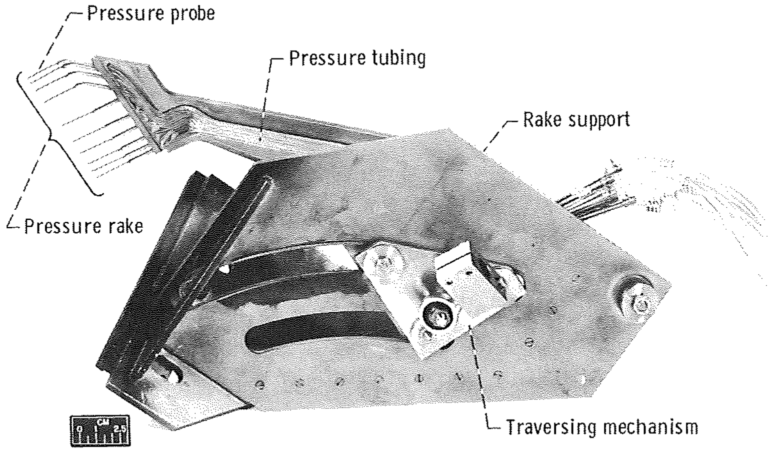



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Figure 6. - Exit total pressure rake and associated traversing guide mechanism.

sure rake is indicated in figure 5. Radial locations of the individual probes are indicated and the trailing edge projection of the four vanes is shown. Figure 6 shows the traversing rake and its associated guide mechanism, while figure 7 shows the rake and its motor-drive actuator installed in the aft end of the test section.

Of the four vanes in the cascade, only vanes 2 and 3 were instrumented for test purposes. Each of these test vanes was instrumented with a total of 30 static pressure taps to measure vane surface static pressures. Sixteen taps were located at the vane mean radius and seven each were located at sections 5/8 inch (1.6 cm) from the vane hub

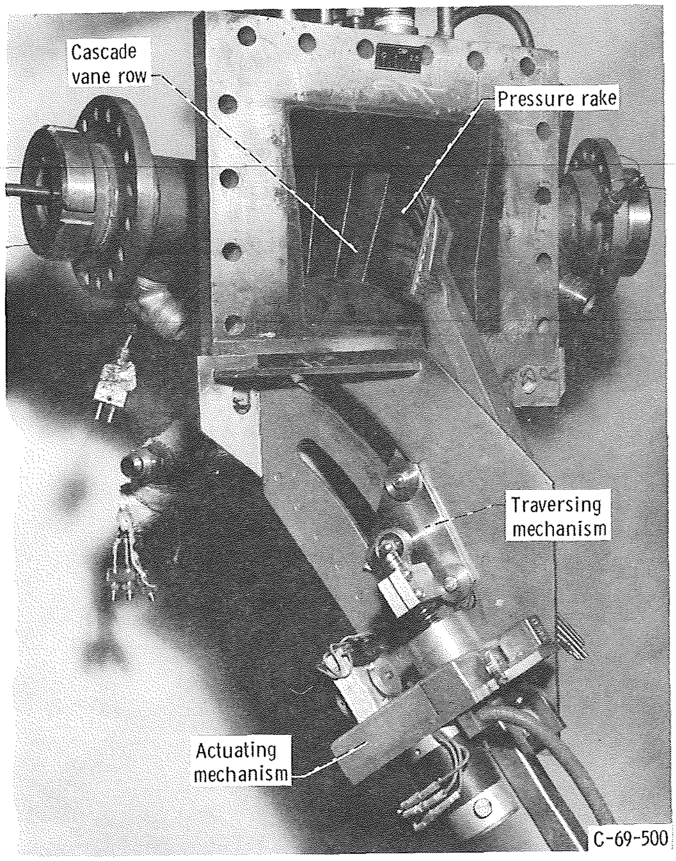
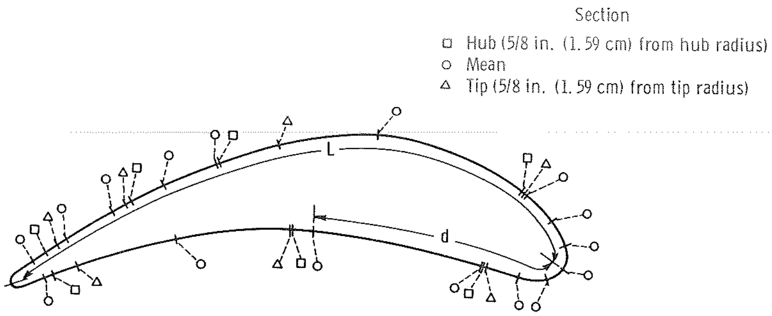



Figure 7. - Total pressure rake installed in exit of test section.

and tip platforms. For discussion purposes these latter two locations are referred to, respectively, as hub and tip sections. Table II gives the location of the pressure taps, and the accompanying sketch shows the relative position of these taps on each test vane. Figure 8 shows the pressure taps installed on the suction surface of one of the test vanes. Grooves approximately 0.032 inch (0.081 cm) wide and deep were machined into the vane surface for installing pressure tube leads. After the installation of the pressure tubing,

TABLE II. - STATIC PRESSURE TAP LOCATIONS ON TEST VANES




| Surface distance, d, in. (cm) | Dimensionless surface distance, d/L | Surface distance, d, in. (cm) | Dimensionless surface distance, d/L |
|---|---|---|---|
| Suction surface | | Pressure surface | |
| Hub section | | | |
| Vane surface distance from leading edge to trailing edge, L = 2.859 in. (7.26 cm) | | Vane surface distance from leading edge to trailing edge, L = 2.591 in. (6.58 cm) | |
| 0.401 (1.02) | 0.140 | 0.374 (0.095) | 0.144 |
| 1.777 (4.51) | .622 | 1.241 (3.15) | .479 |
| 2.201 (5.59) | .770 | 2.339 (5.44) | .903 |
| 2.634 (6.69) | .921 | ----- ------ | ----- |
| Mean section | | | |
| Vane surface distance from leading edge to trailing edge, L = 2.861 in. (7.27 cm) | | Vane surface distance from leading edge to trailing edge, L = 2.571 in. (6.53 cm) | |
| 0 (0) | 0 | 0.094 (0.239) | 0.037 |
| .101 ( .257) | .035 | .219 ( .556) | .085 |
| .218 ( .554) | .076 | .391 ( .993) | .152 |
| .370 ( .940) | .129 | 1.151 (2.922) | .450 |
| 1.089 (2.767) | .381 | 1.777 (4.514) | .691 |
| 1.796 (4.562) | .628 | 2.389 (6.090) | .932 |
| 2.046 (5.195) | .715 | ------------ | ----- |
| 2.296 (5.830) | .802 | ------------ | ----- |
| 2.521 (6.405) | .882 | ------------ | ----- |
| 2.696 (6.845) | .943 | ------------ | ----- |
| Tip section | | | |
| Vane surface distance from leading edge to trailing edge, L = 2.872 in. (7.30 cm) | | Vane surface distance from leading edge to trailing edge, L = 2.563 in. (6.51 cm) | |
| 0.370 (0.940) | 0.129 | 0.370 (0.940) | 0.144 |
| 1.499 (3.808) | .522 | 1.264 (3.210) | .494 |
| 2.219 (5.635) | .798 | 2.237 (5.680) | .873 |
| 2.565 (6.515) | .893 | ------------ | ----- |

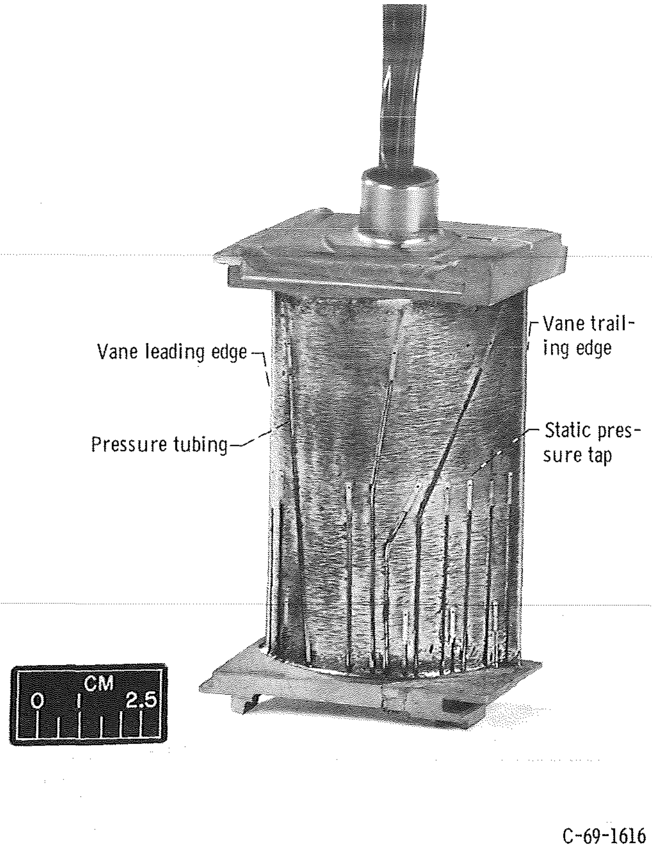



Figure 8. - Instrumented test vane (suction surface shown).

the groove was filled and faired to the contour of the vane surface. The actual diameter of the static taps was 0.16 inch (0.041 cm).

## PROCEDURE

The tests were conducted with combustion air from a laboratory source, and conditions were set by controlling the inlet and, in some cases, the exit pressure. In general, the testing was done with unheated air, but the burner was ignited to provide elevated temperatures for selected runs.

The vane exit design Mach number at the mean radius was approximately 0.85. Correspondingly, the vane exit design Mach numbers at the inner radius and outer radius were listed as 0.96 and 0.76, respectively. Preliminary tests, however, indicated that the radial static pressure gradient at the vane exit was not as great as design nor was the circumferential static pressure constant across the cascade exit as could be expected in a full annular vane assembly. The middle channel (channel 3) exit conditions were therefore used for setting test conditions. For determining exit Mach number, the total pressure at the exit was assumed equal to the total pressure at the inlet to the cascade, that is, no total pressure loss across the cascade. Then, with a linear radial pressure gradient assumed at the exit of channel 3, inlet pressure was adjusted to obtain hub and tip exit static-to-inlet total pressure ratios ($p_2/p_1'$), which resulted in the desired mean radius exit Mach number. Consequently, the vane tip exit Mach number was actually somewhat high than design, while the vane hub exit Mach number was somewhat lower than design. A similar technique was also used for setting test conditions at off-design vane exit Mach numbers. A summary of conditions for the aerodynamic tests conducted in this investigation is presented in table III. Data obtained from these tests are pre-

TABLE III. - OPERATING CONDITIONS FOR AERODYNAMIC TESTS

| Inlet total temperature, $T_1'$, $^{\circ}R$ (K) | Inlet total pressure, $p_1'$, psia ($N/cm^2$) | Vane exit Mach number (mean radius), $M_{m,2}$ |
|---|---|---|
| 540 (300) | 22.0 (15.2) | 0.85 |
| 522 (290) | 19.2 (13.2) | .73 |
| 503 (280) | 23.6 (16.3) | .93 |
| 547 (304) | 45.5 (31.4) | .83 |
| 1700 (944) | 44.8 (30.9) | .84 |
| 1310 (728) | 85.5 (58.9) | .83 |
| [a]512 (285) | 21.5 (14.8) | .85 |

[a]Extended wall test.

sented in the form of an exit total pressure survey, vane surface static pressure distributions, and exit static pressure distributions at the hub and tip radii.

## Exit Total Pressure Surveys

To obtain exit total pressure surveys, the facility's exit section was removed to accommodate the traversing total pressure rake. With the aft-end of the test section exposed, the static pressure at the vane trailing edge was at or near atmospheric pressure. Unheated combustion air of about 500° to 550° R (278 to 306 K) was supplied to the inlet of the cascade from the laboratory's air system. For these tests, pressures at the inlet to the cascade were manually controlled through upstream valving in the piping system to obtain the desired exit static-to-inlet total pressure ratio.

Exit total pressure surveys were obtained at the following vane mean radius exit Mach number conditions: 0.73, 0.85 (design), and 0.93. Data for these surveys were obtained by actuating the traversing pressure rake in equal angular steps across the cascade. Angular steps of approximately 0.003 radian were used to obtain surveys at the design exit Mach number of 0.85, and angular steps of about 0.012 radian were used for the off-design conditions. All pressures were measured through individually calibrated transducers. The electrical outputs from these transducers were recorded on magnetic tape in a central date recording facility.

## Vane Surface Pressure Distribution

Experimental distribution. - Concurrent with the exit total pressure surveys (unheated air flow), static pressures around the vane surface were obtained at the three instrumented sections (hub, mean, and tip). In addition to these tests, the facility was operated at elevated temperatures and pressures with the exit section in place (total pressure rake removed) to obtain additional surface static pressure distributions for comparative purposes. Inlet pressures as high as 85.5 psia (58.9 $N/cm^2$) and temperatures up to $1700^{0}$ R (944 K) were investigated. The burner section was operated to obtain the temperatures required for these tests. A valve in the exhaust ducting downstream of the exit section was used to control exit static pressures to obtain the approximate desired vane mean radius exit design Mach number of 0.85. Inlet pressure conditions were controlled in the same manner as for the exit total pressure surveys. Vane surface static pressures were measured by means of pressure capsules, and the electrical signals from these were recorded on magnetic tape at the control facility.

Analytical distribution. - Comparing experimentally obtained static pressure distribution data for the vane surface with that determined through analytical techniques was also of interest. Two computer programs were used to make these comparisons. The first was a quasi-three-dimensional compressible flow (subsonic) program known as CTTD, which is described in detail in reference 2. A drawback of the CTTD program was that it only provided a reliable solution for guided channel flow. Portions of the vane surface, however, were not within a guided channel so that solutions obtained were of limited value. A guided channel was considered to include only those points on the vane surface from which an orthogonal line could be drawn to an adjacent vane. Figure 9 presents a section layout of adjacent vanes and shows the guided and unguided portions of the channel as applied to this program. The limits of the guided portion are represented by the two orthogonal surfaces shown. The unguided areas are the leading edge region and the vane suction surface beyond the throat region. To obtain a solution for the latter region, the program was adjusted by assuming that a "guided" channel existed. This was done by supposing that an imaginary surface extended from the trailing edge stagnation point parallel to the uncovered suction surface of the adjacent vane.

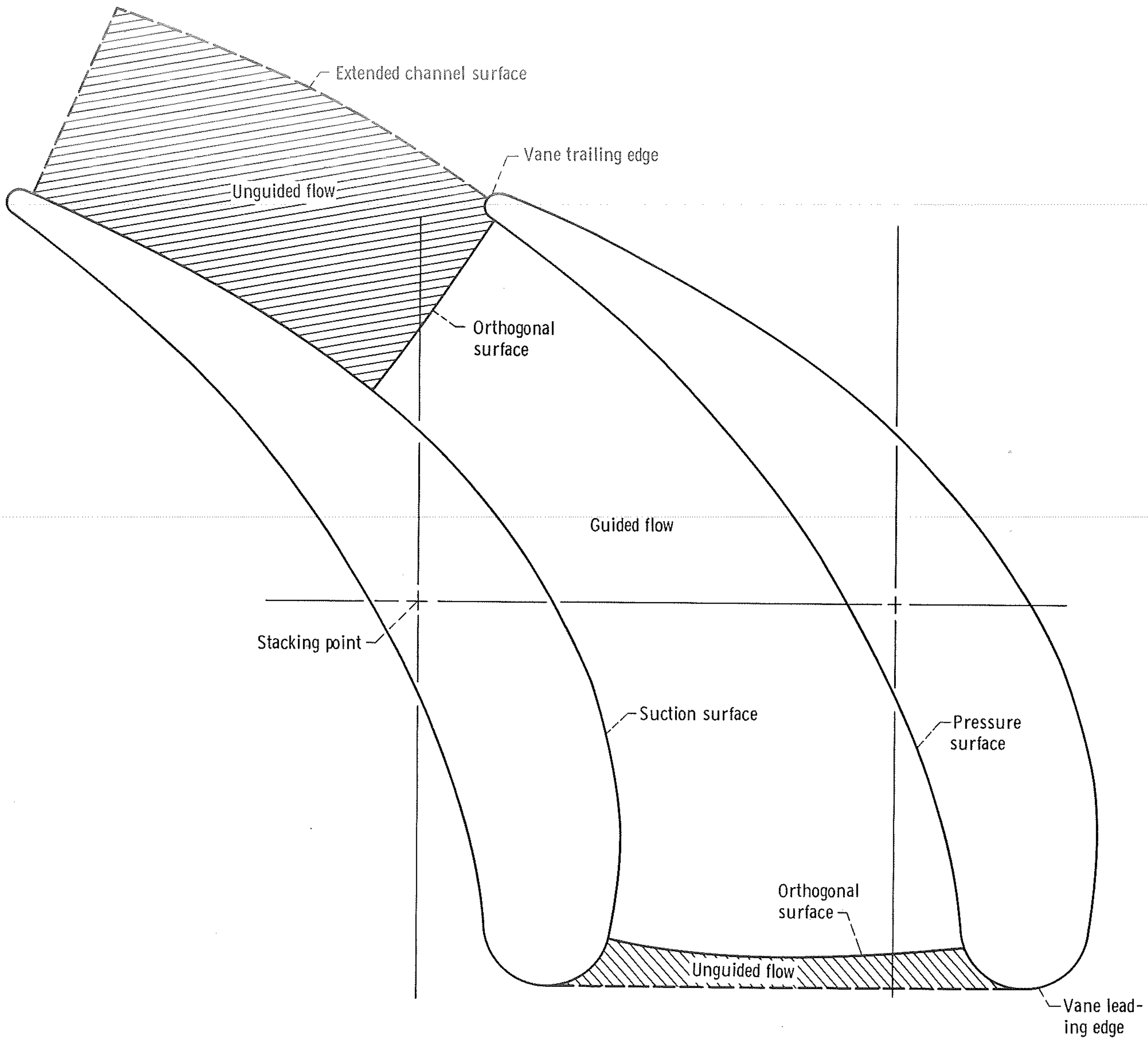



Figure 9. - Guided and unguided portions of flow channel for CTTD computer program.

Pressure distributions for the leading edge region were obtained from a potential flow solution around a cylinder. This solution is described in reference 3.

The second computer program used was a two-dimensional compressible flow program known as TSONIC, which is described in detail in reference 4. This program utilizes the velocity-gradient (stream filament) method and the finite-difference solution of the stream-function equation to obtain transonic solutions. Figure 10 shows a typical layout of adjacent vanes and the coordinate system used with this program.

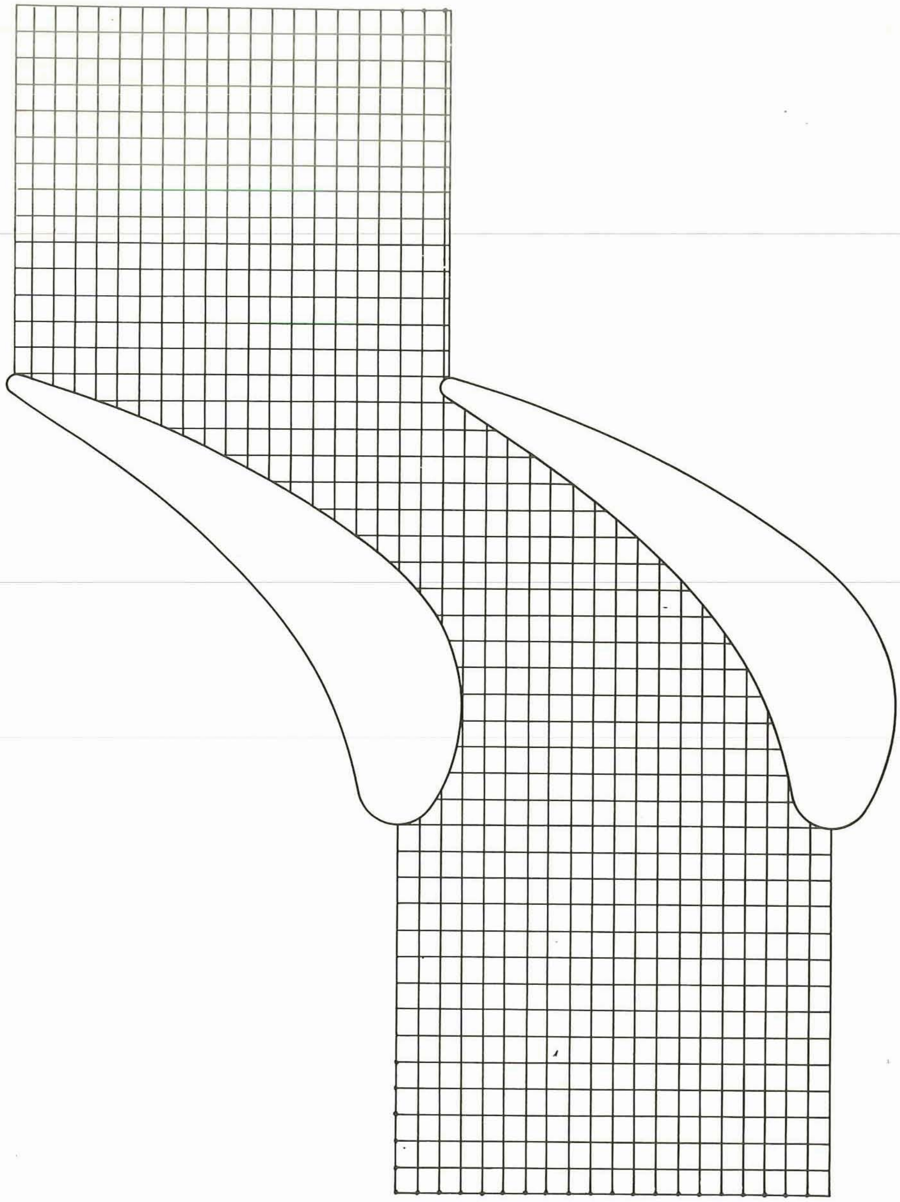


Figure 10. - Typical coordinate system used in TSONIC computer program.

## RESULTS AND DISCUSSION

The results are presented in the next three sections. The first section presents cascade performance data in the form of exit static pressure gradients, exit total pressure loss contours, and vane surface static pressure distributions. Data for the latter are provided not only for the vane exit design Mach number, but for two off-design Mach numbers as well. The second section presents the comparative results for data obtained with the extended wall downstream of channel 5. The third section compares experimental vane surface static pressure distributions with analytical results.

## Cascade Performance

A radial total pressure survey in front of channel 3 at station 1 was made prior to each data run to determine a representative average inlet total pressure $p_1'$. The pressure profile at this location was flat (excluding the hub and tip wall boundary layer) and never varied more than ±0.5 percent.

Exit static pressure gradients. - Figure 11 presents the exit static-to-inlet total pressure ratios obtained at station 2 for the design operating condition of $M_{m,2} = 0.85$ in

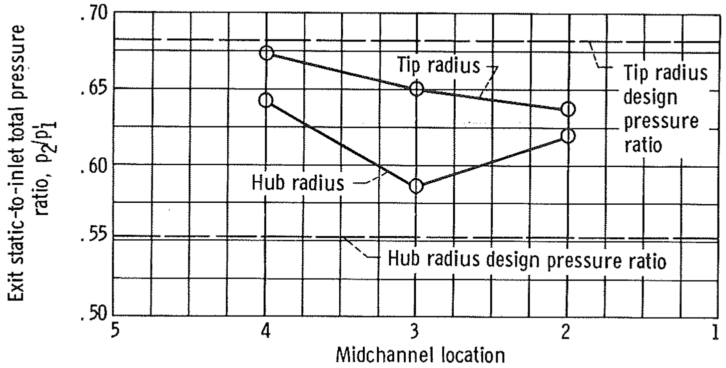



Figure 11. - Distribution of static pressure at cascade exit (station 2) for Mach number $M_{m,2} = 0.85$.

channel 3. The dashed lines represent the hub and tip radius design pressure ratios for a full annulus of vanes having a radius ratio of 0.76. Rather than a constant circumferential pressure for the mid channel positions, there was a variation in pressure ratio at both the hub and tip radius. In addition, the difference in static pressure between the hub and tip walls was about half of the design difference, with circulation particularly lacking close to the end walls. This reduction in the radial static pressure gradient resulted in the hub and tip sections operating at a somewhat lower and higher level of reaction, respectively, than design. The figure shows that for channel 3 the experimental pressure ratios are 0.586 and 0.650 at the hub and tip radii, respectively. When a linear variation is assumed in the exit static pressure from hub to tip, a pressure ratio of 0.618 would be obtained at the mean radius. This is equivalent to an ideal exit Mach number of 0.858, which compares favorably to the design value of 0.85. The exit Mach number based on experimental data at the hub radius is 0.908 compared to a design value of 0.96. The Mach number at the tip radius is 0.809 compared to design value of 0.76. This condition indicates that this cascade was operating more like a two-dimensional than a three-dimensional cascade which infers that a pseudo radius ratio, which approached 1.0, existed for this four-vane cascade.

Exit total pressure survey. - A map of loss total pressure ratio is presented in figure 12 for the exit total pressure survey made at the mean radius design exit Mach number. The data are presented as contours of percent loss total pressure ratio. Inspection of the figure indicates that a maximum loss in total pressure of 10 to 20 percent

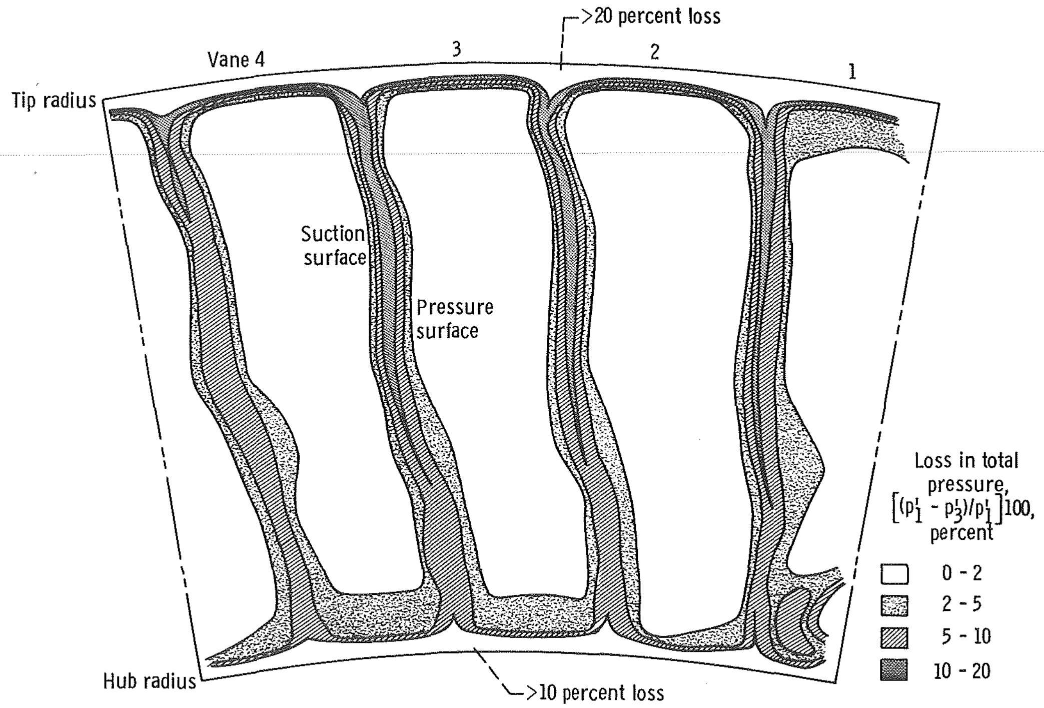



Figure 12. - Percentage loss of total pressure represented by contour lines, $[(p_1' - p_3')/p_1']\,100$, for Mach number $M_{m,2} = 0.85$.

occurred behind each vane. The wake behind each vane was of a fairly uniform size and shape, particularly for the test vanes. The thickness of the wake behind both test vanes was relatively thin, and the distribution of the pressure loss was almost identical. This condition would suggest that both vanes were performing in a similar manner. Because of the absence of large pressure loss cores anywhere across the cascade, with the possible exception of near the hub radius of channel 1, it was concluded that flow separation did not occur.

The boundary layer at the hub and tip radii was assumed to include a pressure loss of 2 percent or greater. Inspection of figure 12 shows the hub radius boundary layer was about 0.35 inch (0.89 cm) thick and the tip radius boundary layer was about 0.2 inch

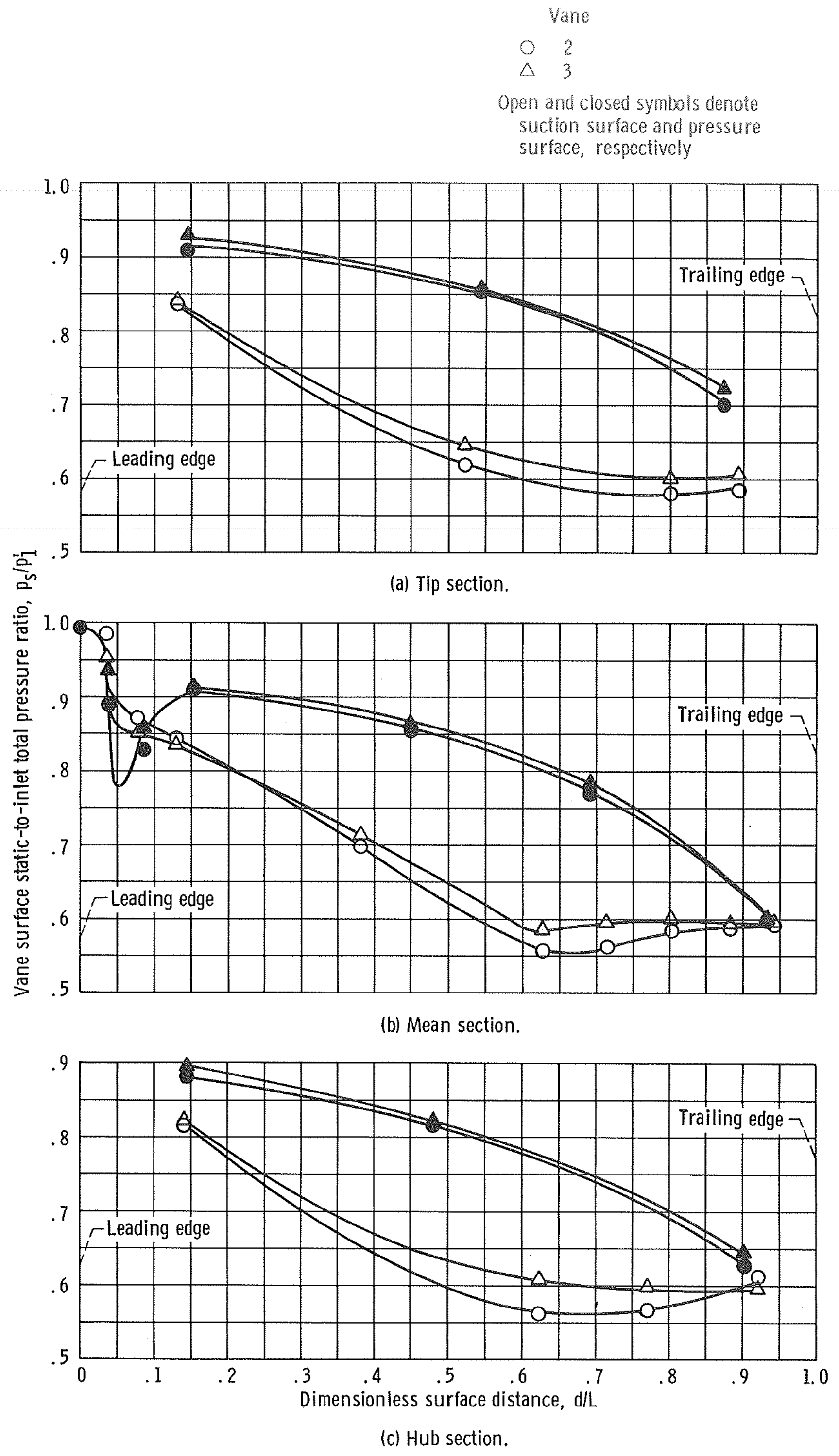



Figure 13. - Experimental distribution of vane surface pressure ratio at Mach number $M_{m,2} = 0.85$.

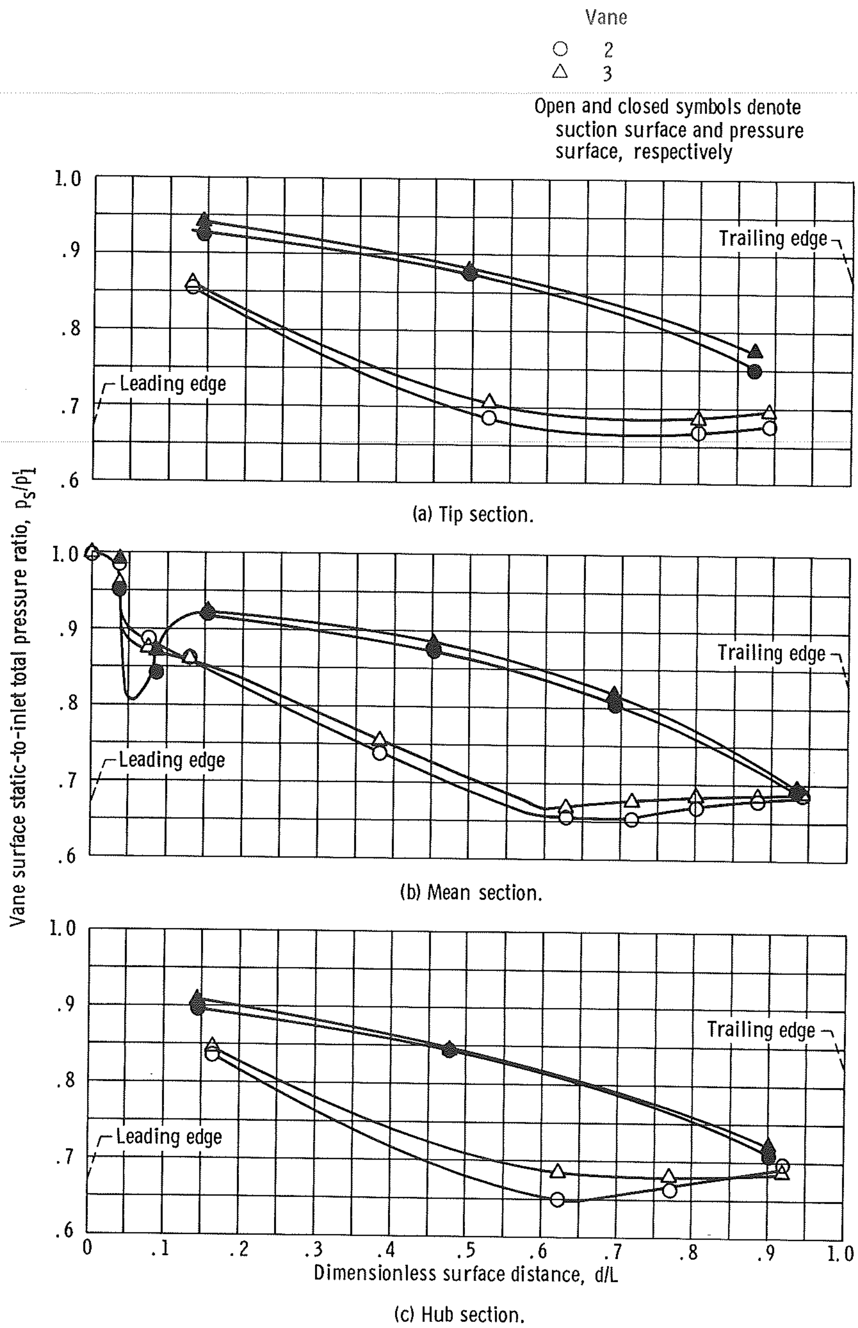



Figure 14. - Experimental distribution of vane surface pressure ratio at Mach number $M_{m,2} = 0.73$.

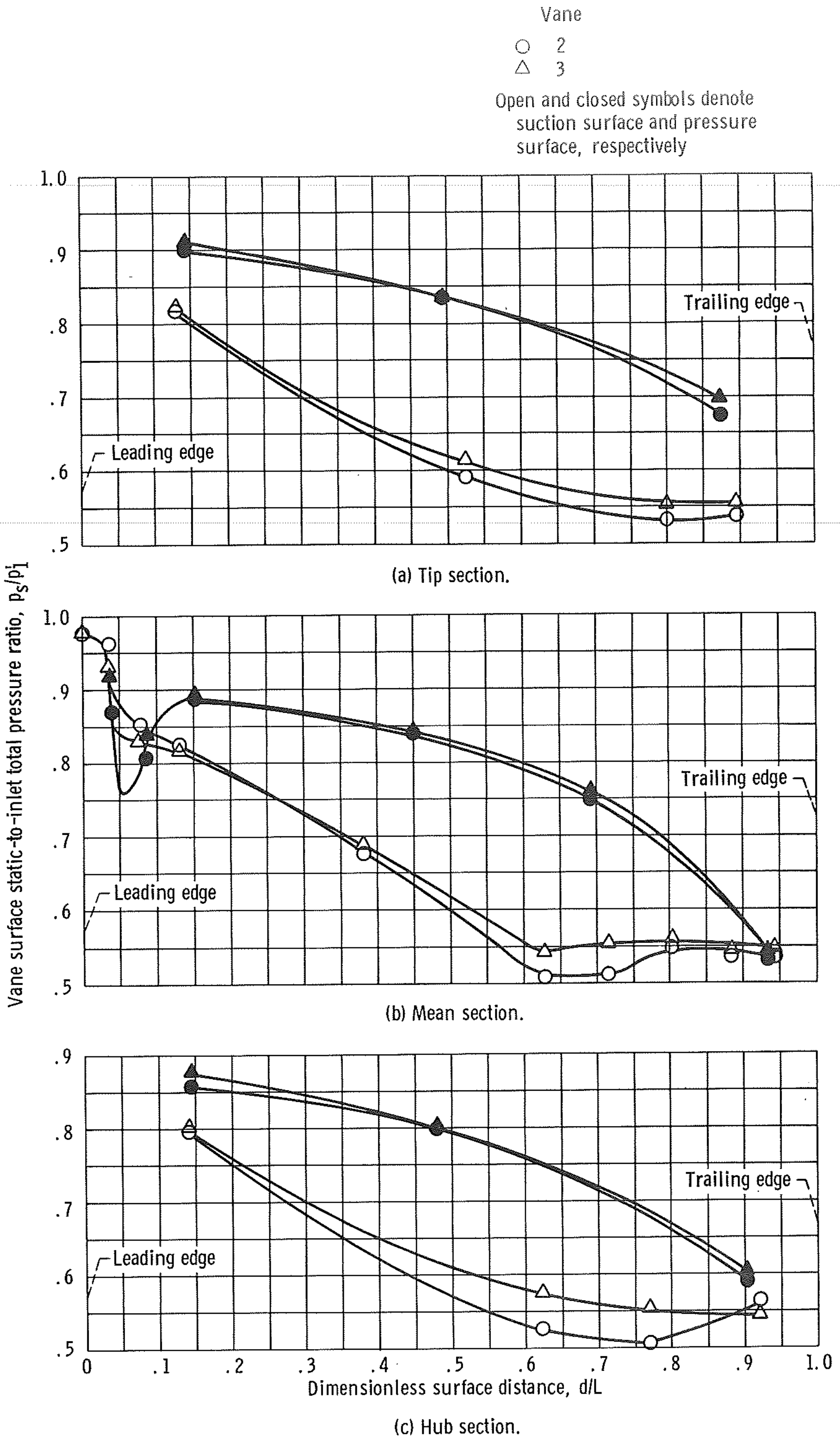
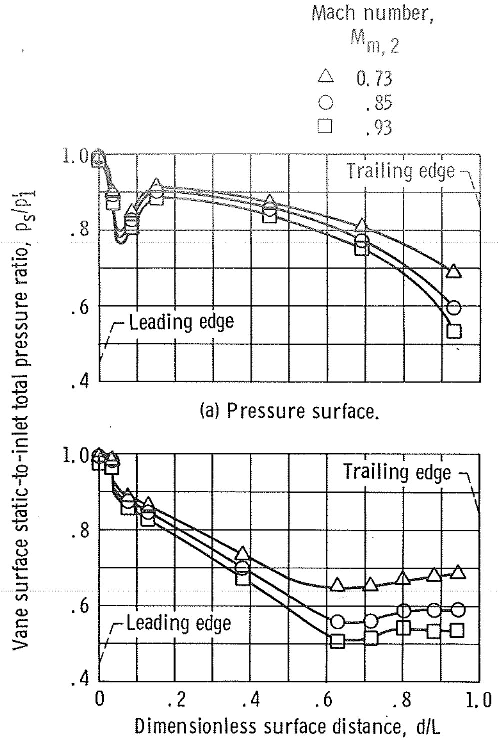



Figure 15. - Experimental distribution of vane surface pressure ratio at Mach number $M_{m,2} = 0.93$.




(a) Pressure surface.

(b) Suction surface.

Figure 16. - Comparison of mean section surface pressure distributions for vane 2 over a range of Mach numbers.

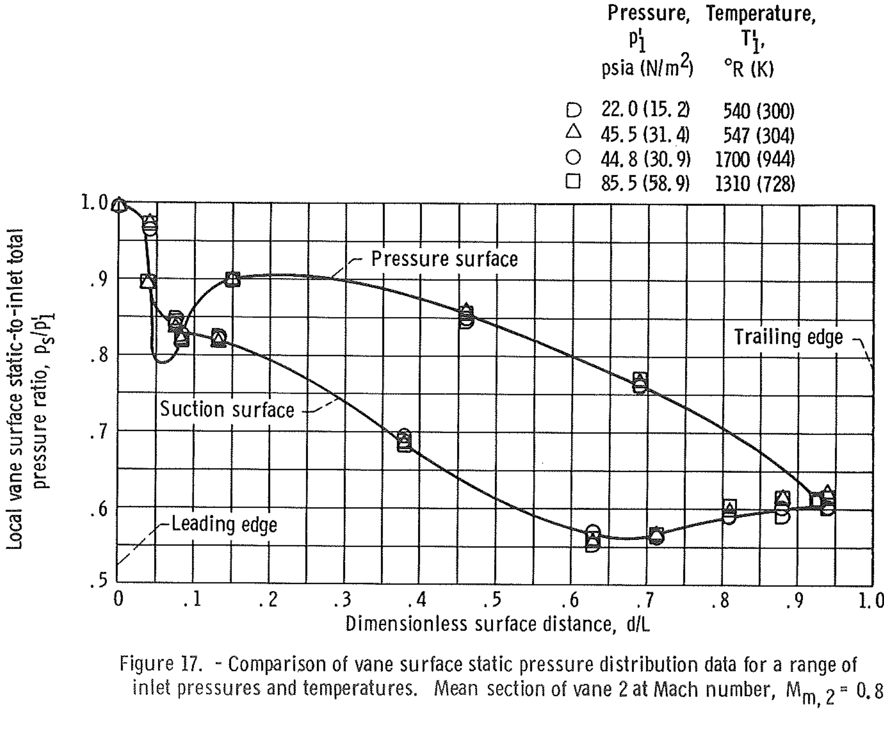



Figure 17. - Comparison of vane surface static pressure distribution data for a range of inlet pressures and temperatures. Mean section of vane 2 at Mach number, $M_{m,2} = 0.85$.

(0.5 cm) thick. This thickness was not sufficient to interfere with the vane instrumentation sections near the hub and tip radius. In all, the characteristics determined from the exit total pressure surveys indicated that the cascade performance was acceptable for its intended purpose.

Surface static pressure distribution. - Comparisons of the surface static pressure distributions for the two test vanes at the tip, mean, and hub sections are shown in figure 13. These data are for the design mean radius exit Mach number. The data are presented as a surface static-to-inlet total pressure ratio, $p_s/p_1'$, and are plotted as a function of the dimensionless surface distance, d/L. In general, the agreement of the pressure distribution curves between the two vanes was considered good. The maximum deviation in pressure distribution between vanes occurred on the suction surface of the hub section and was approximately 9 percent.

Surface static pressure distributions for off-design condition are presented in figures 14 ($M_{m,2} = 0.73$) and 15 ($M_{m,2} = 0.93$) for the three instrumented sections. Here again the maximum deviation in pressure ratio between vanes occurred on the suction surface at the hub section and was approximately 5 and 9 percent, respectively, for the low and high Mach number tests.

Figure 16 shows a comparison of the pressure distribution at the mean section for the three exit Mach numbers investigated. These data are for vane 2 only and merely indicate the trend of surface static pressure distributions with variation in exit Mach number.

Surface static pressure distributions were also recorded at elevated temperatures and pressures at the mean radius design exit Mach number. These data were obtained for inlet total temperatures of $540^\circ$ to $1700^\circ$ R (300 to 944 K) and at total inlet pressures of 22.0 to 85.5 psia (15.2 to 58.9 N/cm$^2$). Figure 17 shows the comparison of these data plotted for vane 2. The agreement is very good for all conditions tested. The only apparent deviation in the data is attributed to the variation in the actual Mach number of each setting. From these observations it was concluded that operation at elevated temperatures and pressures had little or no effect on the surface static pressure distribution.

## Extended Wall

Because of the reduced exit radial static pressure gradient and the nonuniform circumferential static pressures at the hub and tip radii noted in the previous testing, the abbreviated end wall downstream of channel 5 was extended (see fig. 3(a)) in an attempt to improve these exit static pressure conditions. The extended wall covered the viewport opening and provided additional guidance to the flow. The data for the extended wall were taken at design Mach number only and are plotted in the same format as before.

The results of these tests are described in the following two sections.

Exit static pressure gradient. - The circumferential variation in exit static pressure at the tip radius was nearly constant as shown by figure 18. However, the variation in circumferential static pressure ratio at the hub radius showed about the same pattern as before; namely, a nonuniform distribution. It was also obvious that the radial pressure gradient was still only about one-half that of the anticipated hub-to-tip radius design value. The pressure ratios at the hub and tip radii for channel 3 were 0.593 and 0.661, respectively, which gave a mean radius pressure ratio of 0.627 ($M_{m,2}$ = 0.845).

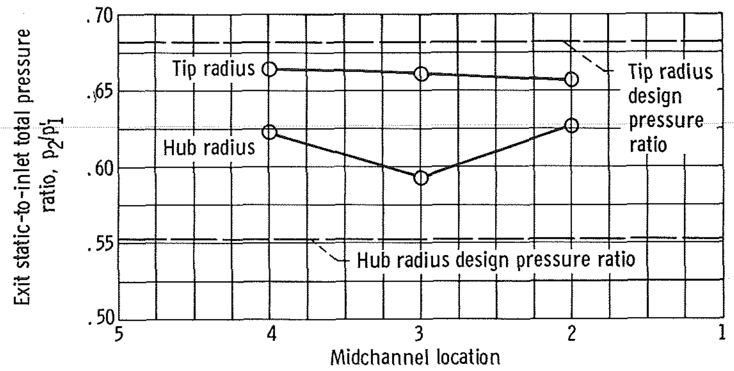
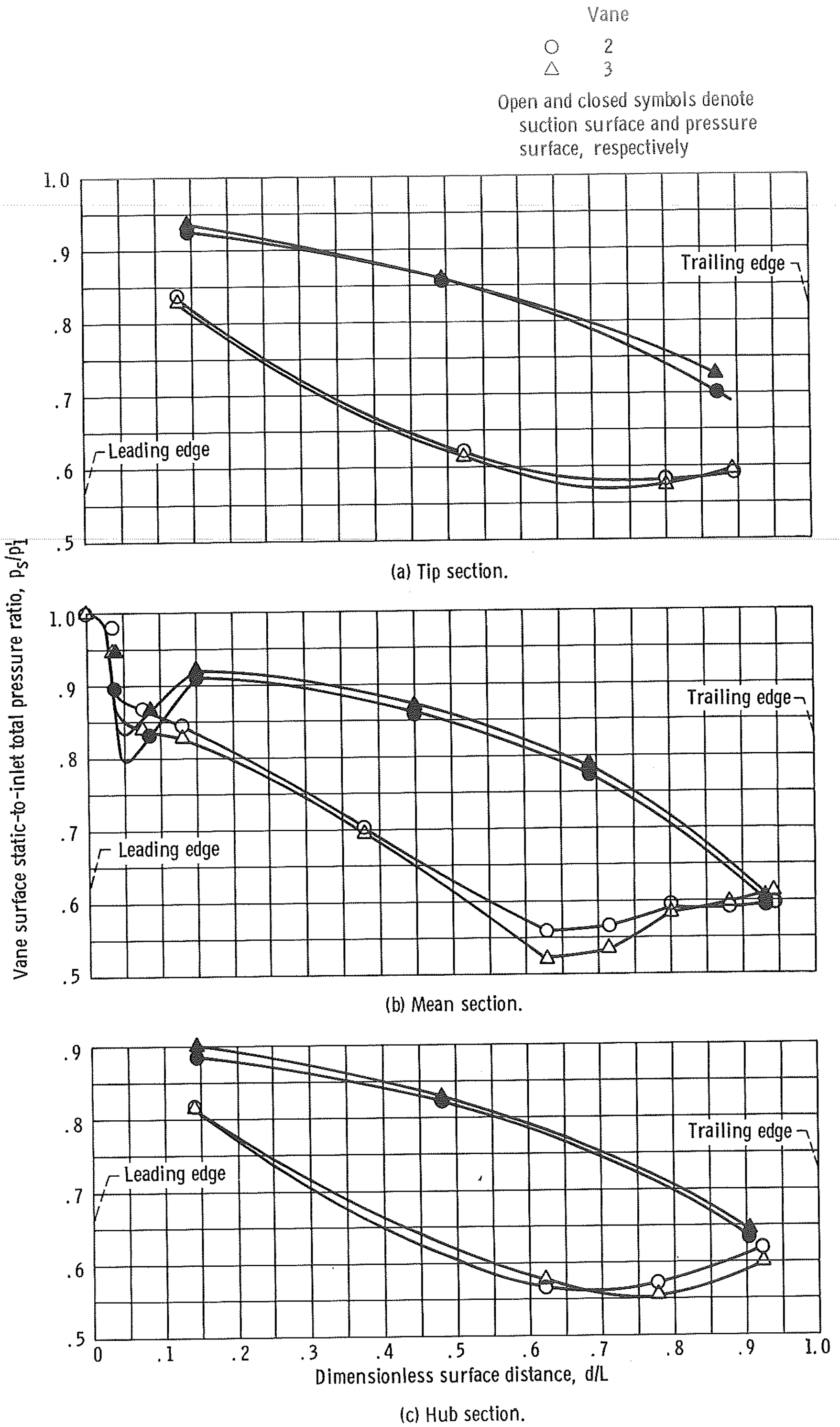



Figure 18. - Distribution of static pressure at cascade exit using extended end wall adjacent to channel 5. Station 2 Mach number, $M_{m,2}$ = 0.85.

The small improvement in distribution of exit static pressure did not justify the loss of the viewport. Despite discrepancies in the circumferential and radial exit static pressure distribution between experimental data and design values, this was not considered a serious restriction for conducting heat-transfer studies.

Surface static pressure distribution. - The vane surface static pressure distributions for the extended wall configuration are shown in figure 19. This figure compares the two test vanes at design operating conditions and includes the tip, mean, and hub sections. As noted, the comparison of the two vanes for the extended wall configuration is quite similar to that for the configuration without the extended wall (see fig. 13). The good agreement of pressure distributions between test runs indicates that the additional guidance provided by the wall extension did not significantly alter the cascade performance.




(c) Hub section.

Figure 19. - Experimental distribution of vane surface pressure ratio for the extended wall. Mach number, $M_{m,2} = 0.85$.

## Analytical and Experimental Data Comparison

The ability to predict vane surface static pressures (and hence velocities) accurately over the entire surface of the vane is of importance for the subsequent heat-transfer investigations to be conducted in this cascade. The fact that this cascade did not perform as expected from design information for an annulus of vanes (as evident from the reduced radial gradient in exit static pressure) had to be considered when using the available analytical programs. The experimental pressure distribution data for the mean radius design conditions are compared with the analytical results of the three-dimensional CTTD program and the two-dimensional TSONIC program.

CTTD quasi-three-dimensional program. - The comparison of analytical and experimental pressure distributions at the tip, mean, and hub sections is shown in figure 20. The input to this program describes the vane geometry and the inlet gas flow conditions. The actual hub-to-tip radius ratio, however, was not used because of the reduced exit static pressure gradient. A radius ratio of 0.91 was used instead of the actual value of 0.76, and it was based on the exit static pressures obtained experimentally at the hub and tip radii. As noted in the figure, relatively good agreement was obtained over most of the vane surface (dashed line near the leading edge represents a faired curve between a potential flow solution and the CTTD solution). The areas of major deviation were at the hub suction surface near the vane throat ($d/L \approx 0.6$) and also at the tip suction surface near the leading edge. These deviations were approximately 14 and 9 percent, respectively.

TSONIC, a two-dimensional program. - Since this program is two-dimensional, just the mean radius data was used to demonstrate the validity of the program. Experimental pressure distributions and calculated results for the design exit Mach number of 0.85 are compared in figure 21. Five solutions were obtained for various exit flow angles and inlet mass flow rates. The exit flow angles considered were $64^{\circ}$, $60^{\circ}$, and $62.5^{\circ}$, but results are only presented for the latter two angles. Since the exact exit flow angle was not measured, the design angle of $64^{\circ}$ was used to obtain the initial solution. An incremental flow rate of 0.0541 pound mass per second (0.0245 kg/sec) was obtained by using an area ratio of the stream-sheet size to the total throat area of the cascade multiplied by the measured inlet mass flow rate. The initial solution resulted in choked flow near the trailing edge. This implied either excessive mass flow or an incorrect exit flow angle. In figure 3(a) the end wall forming channel 1 implied an exit flow angle of $60^{\circ}$ instead of $64^{\circ}$. This value was investigated as well as a value of $62.5^{\circ}$ in an attempt to bracket the true angle. With a reduced exit flow angle a 2-percent increase in inlet mass flow rate was considered.

As shown in the figure, the solid curves A and B are for an exit angle of $60^{\circ}$ and an inlet mass flow rate of 0.0541 and 0.0552 pound mass per second (0.0245 and 0.0250

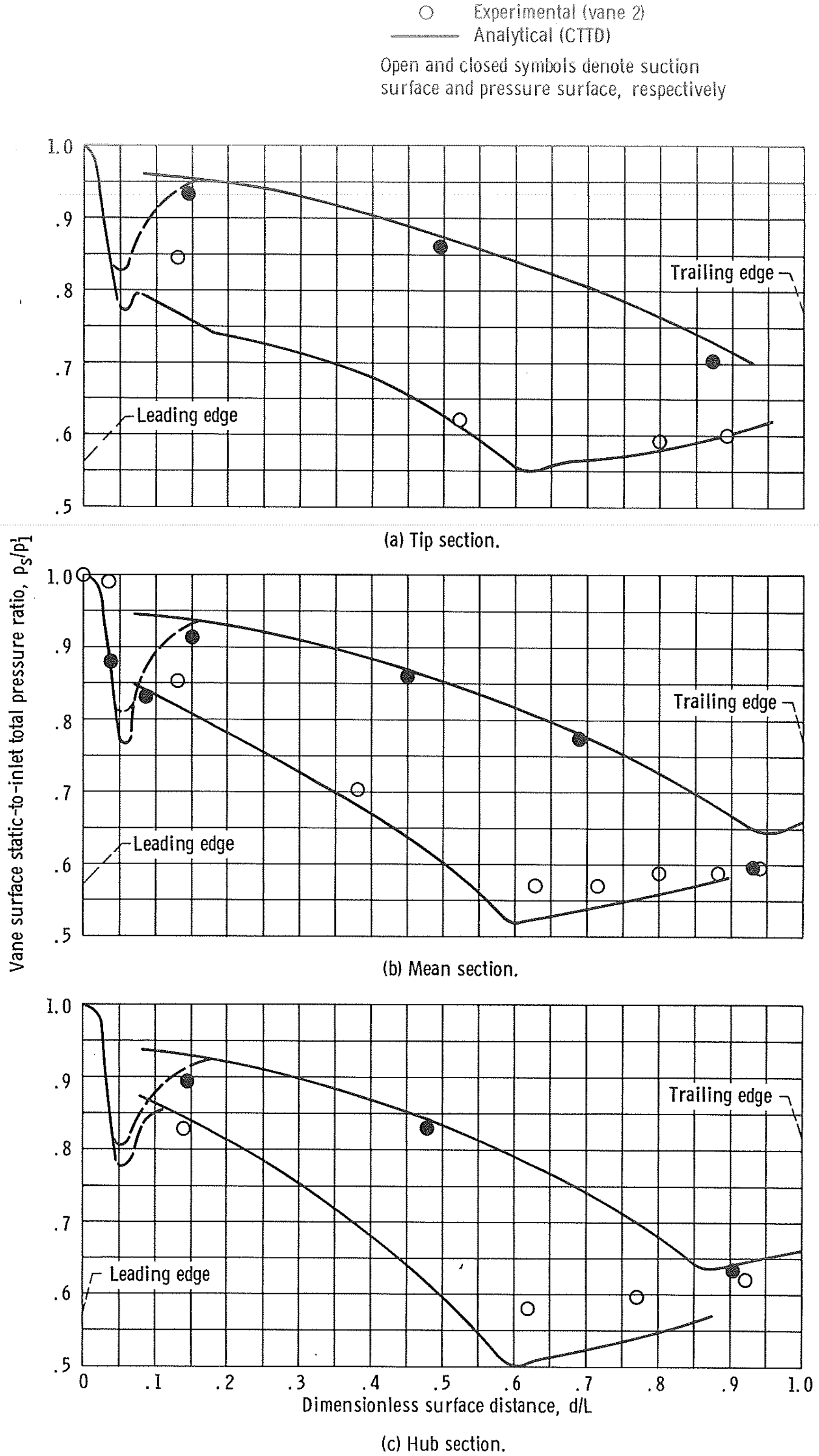



Figure 20. - Comparison of experimental and analytical (CTTD program) surface pressure ratio distribution for Mach number $M_{m,2} = 0.85$.

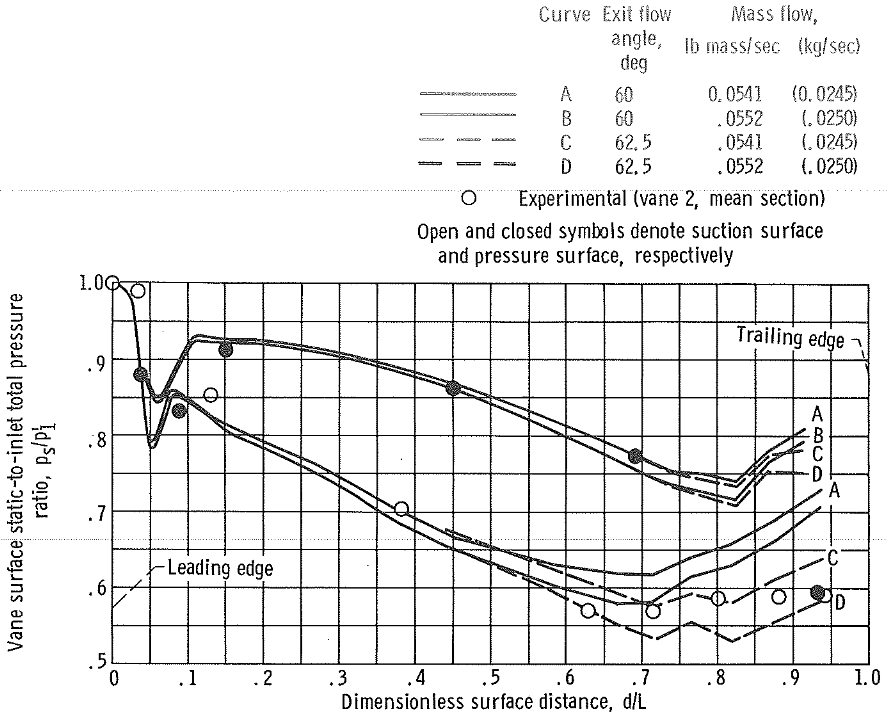



Figure 21. - Comparison of experimental and two-dimensional analytical (TSONIC program) surface pressure ratio distribution for Mach number $M_{m,2} = 0.85$.

kg/sec), respectively. Curve A fits the experimental data quite well over approximately 50 percent of the suction surface and over approximately 75 percent of the pressure surface. Curve B fits the experimental data reasonably well over 70 percent of the suction surface and approximately 80 percent of the pressure surface. Increasing the exit flow angle to 62.5° has the effect of further separating the trailing edge pressure and suction surface results, but, as shown by curve C, the comparison obtained was quite good over the entire suction surface. The predicted static-to-inlet total pressure ratio for the pressure surface, however, indicated agreement over 85 percent of the surface. Curve D represents the theoretical results for an increased flow rate of 2 percent and the same flow angle as before. There was no significant improvement for the pressure surface over the results shown in curve C. Also, the results of the suction surface of curve D did not compare as well as the results of curve C. The best overall agreement between experimental and analytical pressure distribution was demonstrated with curve C.

## SUMMARY OF RESULTS

An experimental investigation was made to determine the general aerodynamic characteristics of an annular-sector four-vane cascade to be used for heat-transfer studies.

Of particular interest was the static pressure distribution over the vane surfaces. Other characteristics of interest were contours of loss total pressure ratio and hub and tip radii static pressure distributions at the cascade exit. The analytical prediction of vane surface pressure distributions and their comparison with experimental data were also considered. The results of this investigation are summarized as follows:

1. The surface static pressure distributions were similar for the two center test vanes and indicated a relatively smooth and uniform acceleration of the flow from vane inlet to exit.

2. Contours of loss total pressure ratio derived from exit total pressure surveys indicated that the vane wakes were relatively thin and fairly uniform in thickness both radially and circumferentially across the cascade with no flow separation occurring on any of the vane surfaces. At the design mean-radius exit Mach number of 0.85, the contours showed the boundary layer thickness on the hub and tip walls to be about 0.2 and 0.35 inch (0.5 and 0.89 cm), respectively. It was concluded that this boundary layer would not interfere with the intended instrumentation sections located on the two test vanes 5/8 inch (1.6 cm) from the vane hub and tip walls.

3. The radial gradient in exit static pressure was smaller than the design value, with little radial distribution existing near the end walls. In addition, the circumferential distribution in exit static pressure was not constant, as could be expected in a complete annulus of vanes.

4. The analytically predicted distribution in vane surface static pressure computed with the CTTD program (a quasi-three-dimensional program) compared closely with the experimental data over most of the vane surface. Notable exceptions were at the leading edge region of the suction surface at the tip section and near the throat area of the suction surface at the hub section. Maximum deviation, however, was only 14 percent.

5. Analytical pressure distribution data obtained from the TSONIC computer program (a two-dimensional program) compare quite favorably with the experimental data when the measured mass flow rate was used with an exit flow angle of $62.5^{\circ}$. The suction surface analytical and experimental pressure ratio data agree quite well over the entire surface, whereas the agreement of the analytical and experimental pressure data was limited to approximately 85 percent of the pressure surface.

6. Extension of the end wall to provide additional flow guidance did not significantly improve the radial or circumferential static pressure gradients at the cascade exit.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 1, 1969,
720-03.

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