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COLD-AIR ANNULAR-CASCADE INVESTIGATION OF AERODYNAMIC PERFORMANCE OF CORE-ENGINE-COOLED TURBINE VANES

II - Pressure Surface Trailing Edge Ejection and Split Trailing Edge Ejection

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16. Abstract

The aerodynamic performance of two trailing edge ejection cooling configurations of a core-engine stator vane were experimentally determined in an ambient inlet-air full-annular cascade where three-dimensional effects could be obtained. The tests were conducted at the design mean-radius ideal aftermixed critical velocity ratio of 0.778. Overall vane aftermixed thermodynamic and primary efficiencies were obtained over a range of coolant flows to about 10 percent of the primary flow at a primary to coolant total temperature ratio of 1.0. The radial variation in efficiency and the circumferential and radial variations in vane-exit total pressure were determined. Comparisons are made with the solid (uncooled) vane.

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COLD-AIR ANNULAR-CASCADE INVESTIGATION OF AERODYNAMIC PERFORMANCE OF CORE-ENGINE-COOLED TURBINE VANES II - PRESSURE SURFACE TRAILING EDGE EJECTION AND SPLIT TRAILING EDGE EJECTION

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SUMMARY

A cold-air experimental investigation was conducted in a full-annular cascade to determine the effect of different trailing edge cooling configurations on the aerodynamic performance of a core-turbine stator vane. The two configurations investigated were (1) trailing edge ejection from the pressure surface and (2) split trailing edge ejection. This investigation was conducted at the design pressure ratio, which corresponds to a mean-radius ideal aftermixed critical velocity ratio of 0.778. Performance data were taken and calculations were made to obtain overall vane performance, radial variations in vane efficiencies, and radial and circumferential variations in the vane-exit total pressure for selected coolant flow rates. In addition, coolant slot discharge coefficients and Reynolds numbers were determined.

The overall aftermixed thermodynamic efficiencies for the two cooled configurations are nearly the same and constant for coolant flow rates up to 4.5 percent of the primary flow. As coolant flow increased above 4.5 percent, the thermodynamic efficiency decreased for both configurations. However, the thermodynamic efficiency of the split trailing edge ejection vane is greater than that of the pressure surface trailing edge ejection vane. The overall aftermixed thermodynamic efficiency at a coolant flow rate of 4 percent, which corresponds to a coolant to primary total pressure ratio of approximately 1.0, was about 0.953 for both configurations. The coolant slot discharge coefficients were the same for the two cooled configurations and increased with increasing coolant to primary total pressure ratio. The discharge coefficient at a coolant to primary total pressure ratio of 1.0 was 0.77.

INTRODUCTION

Research studies are being conducted at the NASA Lewis Research Center to investigate the performance of air-cooled blading for high-temperature core-engine turbines. As part of this effort, the performance of a solid (uncooled) core turbine (half scale) has been obtained and reported in reference 1. These results will form the basis for comparison with the cooled versions of the core turbine. The performance of the solid core turbine stator vanes (full size), tested in a two-dimensional cascade, has been reported in reference 2. These results, although indicative of the vane performance at the mean section, do not include end-wall or secondary flow losses. Because of the high radius ratio (hub radius to tip radius of 0.85) and the low aspect ratio (vane height to vane axial chord of 1.0), both of these losses may be significant.

Consequently, an investigation was undertaken wherein the core turbine stator vane (full size and same aerodynamic profile as the vanes of refs. 1 and 2) would be studied in a full-annular cascade where three-dimensional effects could be obtained with and without coolant flows. The annular cascade was designed primarily for cold-air studies at a primary to coolant total temperature ratio of 1.0. It was felt that a valid comparison of vane cooling configurations could be made at this low temperature ratio since the total temperature ratio affects the level of efficiency but not the basic trends. The first phase of the study obtained the three-dimensional performance of the solid (uncooled) vane (reported in ref. 3). Subsequent studies are being conducted to determine the performance of different cooling schemes for comparison with the full-annular solid vane results. This report presents the experimental results of an investigation of two cooled vane configurations: (1) trailing edge ejection from the pressure surface and (2) split trailing edge ejection.

The cold-air studies of this report were made with ambient conditions at the cascade inlet. Investigations of the trailing edge ejection cooling configurations were conducted at the design pressure ratio, which corresponds to a mean-radius ideal aftermixed critical velocity ratio of 0.778. Circumferential data surveys were taken downstream of the annular vane ring, in the test section, over a range of radii from hub to tip. Aerodynamic performance data were obtained over a range of coolant flow rates from 2.5 to 9.7 percent of the primary flow. This range of coolant flows corresponds to coolant to primary total pressure ratios from 0.83 to 1.86.

This report includes a description of the two trailing edge ejection cooling configurations tested and the results obtained. Overall aftermixed thermodynamic and primary efficiencies are given over the range of coolant flow rates tested. The radial variations in vane aftermixed efficiencies are shown. The circumferential and radial variations of vane exit total pressure are also shown. The results obtained are compared with the solid (uncooled) vane results of reference 3.

SYMBOLS

$C_{D,s}$	coolant slot discharge coefficient, $\bar{\bar{m}}_c/(\rho V)_{c,id,ave}Lw$
g	force-mass conversion constant, 32.174 lbm-ft/lbf-sec^2
L	slot length, m (ft)
$\bar{\bar{m}}$	total mass flow per passage, kg/sec (lbm/sec)
$\bar{\bar{m}}_c$	coolant mass flow per passage, kg/sec (lbm/sec)
N	number of coolant slots per vane
p	pressure, N/m^2 (lbf/ft^2)
R	gas constant, J/kg-K (ft-lbf/lbm-$^{\circ}$R)
Re_s	coolant slot Reynolds number, $4R_h(\rho V)_{c,id,ave}/\mu$
R_h	slot hydraulic radius, $wL/2(w + L)$, m (ft)
r	radial position, m (ft)
T	temperature, K ($^{\circ}$R)
V	velocity, m/sec (ft/sec)
w	slot width, m (ft)
y	ratio of coolant flow to primary flow
y_c	ratio of coolant flow to total flow
y_p	ratio of primary flow to total flow
γ	ratio of specific heats
$\bar{\eta}$	efficiency at radius r based on kinetic energy
$\bar{\bar{\eta}}$	overall efficiency based on kinetic energy
Θ	vane angular spacing, rad (deg)
θ	circumferential position, rad (deg)
μ	viscosity, N-sec/m^2 (lbm/ft-sec)
ρ	density, kg/m^3 (lbm/ft^3)

Subscripts:

ave	average quantity
c	coolant flow
cr	flow condition at Mach 1

h hub

i survey position closest to hub wall

id ideal or isentropic process

o survey position closest to tip wall

P primary

p primary flow

T thermodynamic

t tip

z axial direction

0 station at inlet plane of cascade bellmouth, fig. 2

1 station one axial chord length upstream of vane leading edge, fig. 2

2 station at vane trailing edge, fig. 2

3 station downstream of vane trailing edge where survey measurements were taken, fig. 2

3M station downstream of vane trailing edge where flow was assumed to be circumferentially mixed (uniform), fig. 2

Superscript:

total-state condition

APPARATUS AND PROCEDURE

Cascade Facility

The full-annular cascade facility consists primarily of an inlet section, a test section, and an exit section. The actual facility and a cross-sectional view of the facility are shown in figures 1 and 2, respectively. In operation, primary air is drawn from the test cell through the inlet section, blading, and exit section. Coolant air is supplied at 27.58 newtons per square centimeter (40 psig) by the laboratory combustion air system and is routed to the vane tip as shown in figures 1 and 2.

Inlet section. - The inlet, consisting of a bellmouth and a short straight section, was designed to accelerate the flow to uniform axial flow at the vane inlet. The bellmouth profile was designed to provide a smooth transition to the straight section.

Test section. - The test section consists of a sector of 5 vanes which are part of the full-annular ring of 36 vanes. The vanes pass through a hollow ring allowing laboratory combustion air to be supplied to both the vanes and the end walls (see fig. 2). For these trailing edge ejection vane tests, laboratory combustion air was supplied to the vane tip coolant supply only, where it enters the hollow vanes and exits through the trailing edge slots. For the pressure surface trailing edge ejection cooling configuration, the full test section of five cooled vanes was used. However, for the split trailing edge ejection cooling configuration, only three cooled test vanes were used. In both cases, results are presented for the middle cooled vane. The performance of the middle vane should not be significantly affected by the number of cooled test vanes used in this investigation.

Exit section. - The exit section consists primarily of a diffusing section and a flow straightening section (see fig. 2). The diffusing section decelerates the flow downstream of the 3M station. The flow straightening section turns the swirling flow back to the axial direction prior to its entering the laboratory exhaust system. The straightener consists of a bundle of short tubes with centerlines parallel to the cascade axis.

Cooling Configurations

The two trailing edge ejection cooling configurations tested herein have the same aerodynamic profile as the solid (uncooled) vanes of reference 3. The untwisted vanes, of constant profile from hub to tip, have a height of 3.81 centimeters (1.50 in.), an axial chord of 3.823 centimeters (1.505 in.), and a trailing edge radius of 0.089 centimeter (0.035 in.). The vane aspect ratio and the solidity at the mean section are 1.00 and 0.93, respectively (based on axial chord). The stator hub-to-tip radius ratio is 0.85 and the mean radius is 23.50 centimeters (9.25 in.).

The cooled test vanes were hollow with a wall thickness of 0.102 centimeter (0.040 in.). The hub and tip ends of the vanes extend through the vane ring into the hub and tip coolant supply cavities (see fig. 2). For the tests reported herein, the tip ends of the test vanes were open to the vane tip coolant supply cavity. The hub ends were sealed. The two end slots (one each at hub and tip) were sealed for both configurations to prevent coolant leakage into the end wall coolant supply cavities.

The pressure surface trailing edge ejection vane is shown in figure 3. A schematic of the slot configuration is also shown. Each test vane has 19 open slots. The slots were measured to be, on the average, 0.122 centimeter (0.048 in.) in height and 0.124 centimeter (0.049 in.) in width. The slot ribs are 0.069 centimeter (0.027 in.) in height. The slot openings are located on the pressure surface at approximately 90 percent of the vane axial chord.

The split trailing edge ejection vane is shown in figure 4. A schematic of the slot configuration is also shown. Each test vane has 9 open slots. The slots were measured to be, on the average, 0.329 centimeter (0.130 in.) in height and 0.108 centimeter (0.042 in.) in width. The slot ribs are 0.052 centimeter (0.020 in.) in height.

The trailing edge ejection configurations were designed to have the same exit slot area per vane. During fabrication, however, machining errors resulted in the split trailing edge configuration having a 10 percent greater slot area per vane than the pressure surface trailing edge configuration. This had some effect on the coolant supply pressure required by the two configurations to obtain a specified coolant flow rate.

Instrumentation

Instrumentation was provided to measure inlet total temperature and pressure, wall static pressures upstream and downstream of the test section, survey data of vane exit total pressure, and coolant supply conditions. All pressures were measured using calibrated strain gage transducers, and all temperatures were measured using copper-constantan thermocouples.

Inlet total conditions. - The total temperature of the inlet primary air was measured by four thermocouples located 90° apart circumferentially at the bellmouth inlet (station 0). The ambient pressure was measured by a calibrated strain gage transducer located near the cascade inlet.

Wall-static pressure. - Static pressures were measured at various locations in the cascade by pressure taps located on both the hub and tip walls. At a distance of one axial chord length upstream of the vane inlet (station 1), four taps were located 90° apart circumferentially. These static pressures were used to ascertain the uniformity of the flow entering the vanes as well as to provide information for estimating the incoming primary air flow rate. At the exit survey plane (station 3), eight taps each at hub and tip spanned the test section and were spaced circumferentially as shown in figure 5. These pressures were used to determine a linear static pressure distribution, from hub to tip, for use in the performance calculations. Two static taps, one each at the hub and tip walls, were located 10.2 centimeters (4.0 in.) axially downstream of the vane exit where it was felt the flow would be mixed to relatively uniform conditions (station 3M). The hub wall aftermixed static pressure was used to set the primary air flow conditions in the cascade.

Survey probe. - Vane performance data were obtained using a two-element total pressure probe (shown in fig. 6). This type of probe allows survey data to be taken near both hub and tip end walls. The lower probe element (fig. 5) was used for measurements from near the hub wall to 75 percent of the vane span. The upper probe element was then used in the remaining tip region. The probe was set at the design flow angle of 67°. Survey data were taken over three vane wakes with the probe tips at station 3, which is 1.3 centimeters (0.5 in.) axially downstream of the vane trailing edge (see fig. 5). The probe tips were made of stainless steel tubing with an outside diameter of 0.051 centimeter (0.020 in.) and an inside diameter of 0.038 centimeter (0.015 in.). The total pressure tubes had an inside bevel of 30°.

Coolant flow conditions. - The coolant rate was measured using calibrated venturi meters of various sizes. The venturi meters and runs conformed with ASME specifications and were calibrated prior to use. The total pressure and temperature of the coolant were measured prior to coolant entry into the vane tip supply cavity (see fig. 1).

Test Procedure

To operate the cascade facility, atmospheric air from the test cell was drawn through the cascade and exhausted into the laboratory exhaust system. The primary air flow conditions were set by controlling the pressure ratio across the stator ring with a throttle valve located in the exhaust system. The hub static pressure tap located at station 3M downstream of the vane exit was used to set this pressure ratio.

Vane cooling air at room temperature was supplied at 27.58 newtons per square centimeter (40 psig) by the laboratory combustion air system. The desired coolant flow rate was obtained by setting the pressure upstream of the venturi with a pressure regulator and controlling the venturi pressure ratio with a throttling valve located downstream of the venturi run.

The two trailing edge ejection configurations were tested at an overall pressure ratio corresponding to the design mean radius ideal aftermixed critical velocity ratio of 0.778. Coolant flow rates up to 9.7 percent of the primary flow were investigated. At a given flow condition, probe survey data were obtained at a number of different radii from hub to tip. At a fixed radius, the probe was moved circumferentially in a continuous manner behind the middle three vanes of the five-vane test section with survey data being taken at 0.04° increments (see fig. 5). The vane spacing Θ was 10°. The output signals of the thermocouples and pressure transducers were digitized and recorded on magnetic tape.

Data Reduction

The cooled vane performance presented herein was calculated from probe position, the probe survey measurement of total pressure, and wall static pressures at the survey plane (station 3). Data from the middle wake (of the three vane wakes that were measured) were used in these calculations. It was assumed that no loss in total pressure occurred between the bellmouth inlet (station 0) and the vane inlet. Also, total temperature was assumed constant from the bellmouth inlet to the probe survey plane (station 3). Since only total pressure was measured for these tests, additional assumptions were necessary for data reduction purposes:

(1) The static pressure at station 3 is constant circumferentially and varies linearly with radius. The hub and tip wall static pressures, at station 3, were used to linearly interpolate this variation in pressure.

(2) The exit flow angle (station 3) is constant circumferentially and radially. The design value of 67° was used for the performance data presented herein.

A comparison of calculated vane performance was made in reference 3 with data obtained from a total pressure probe (similar to the one used in this report) using the previous assumptions and from a combination probe (measuring total and static pressure and flow angle). The results indicated excellent agreement in the radial variation of aftermixed efficiency for the two probe types.

The calculation of the vane efficiencies is based on the determination of a hypothetical state where it is assumed that the flow has mixed to a circumferentially uniform condition. The application of the conservation equations to an annular-sector control volume to obtain this aftermixed state, at each radius, has been described fully in reference 4. The aftermixed vane efficiency is used herein because it is theoretically independent of the axial location of the survey measurement plane. It should be noted that the aftermixed efficiency contains not only the vane profile and end wall losses, but also the mixing loss.

For cooled vane performance, both the thermodynamic and primary efficiencies are in general use. Thermodynamic efficiency is defined as the ratio of the actual aftermixed kinetic energy to the sum of the ideal aftermixed kinetic energies of both the primary and coolant flows. Primary efficiency is defined as the ratio of the actual aftermixed kinetic energy to the ideal aftermixed kinetic energy of the primary flow only. The thermodynamic efficiencies at a given radius $\bar{\eta}_{3M,T}(r)$ and for the total passage $\bar{\bar{\eta}}_{3M,T}$ are given by

$$\bar{\eta}_{3M,T}(r) = \frac{V_{3M}^2(r)}{y_p(r)\left[V_{3M,id}^2(r)\right]_p + y_c(r)\left[V_{3M,id}^2(r)\right]_c} \tag{1}$$

$$\bar{\bar{\eta}}_{3M,T} = \frac{\int_{r_i}^{r_o} \left[\rho_{3M}(r) V_{3M,z}(r) V_{3M}^2(r)\right] r\, dr}{\int_{r_i}^{r_o} \rho_{3M}(r) V_{3M,z}(r) \left\{ y_p(r) \left[V_{3M,id}^2(r)\right]_p + y_c(r) \left[V_{3M,id}^2(r)\right]_c \right\} r\, dr} \tag{2}$$

where the ideal velocities of the primary $\left[V_{3M,id}(r)\right]_p$ and coolant flows $\left[V_{3M,id}(r)\right]_c$ are given by

$$\left[V_{3M,id}(r)\right]_p = \sqrt{\left(\frac{2\gamma}{\gamma - 1}\right) gRT_i' \left\{1 - \left[\frac{p_{3M}(r)}{p_i'}\right]^{(\gamma-1)/\gamma}\right\}} \tag{3}$$

$$\left[V_{3M,id}(r)\right]_c = \sqrt{\left(\frac{2\gamma}{\gamma - 1}\right) gRT_c' \left\{1 - \left[\frac{p_{3M}(r)}{p_c'}\right]^{(\gamma-1)/\gamma}\right\}} \tag{4}$$

The fraction of coolant flow to total flow $y_c(r)$ is assumed to be independent of radius r and to equal

$$y_c = \frac{\bar{\bar{m}}_c}{\bar{\bar{m}}} = 1 - y_p = \text{Constant} \tag{5}$$

(for a given survey) where $\bar{\bar{m}}_c$ is the measured coolant flow rate per passage and $\bar{\bar{m}}$ the total flow rate per passage given by

$$\bar{\bar{m}} = \int_{r_h}^{r_t} \int_0^{\Theta} \rho_3(r, \theta) V_{3,z}(r, \theta) r\, d\theta\, dr \tag{6}$$

The primary efficiencies at a given radius $\bar{\eta}_{3M,P}(r)$ and for the total passage $\bar{\bar{\eta}}_{3M,P}$ are given by

$$\bar{\eta}_{3M,P}(r) = \frac{V_{3M}^2(r)}{y_p \left[V_{3M,id}^2(r)\right]_p} \tag{7}$$

$$\bar{\bar{\eta}}_{3M,P} = \frac{\int_{r_i}^{r_o} \left[\rho_{3M}(r)V_{3M,z}(r)V_{3M}^2(r)\right] r\, dr}{\int_{r_i}^{r_o} \left\{y_p \rho_{3M}(r)V_{3M,z}(r)\left[V_{3M,id}^2(r)\right]_p\right\} r\, dr} \tag{8}$$

RESULTS AND DISCUSSION

Presented in this section are the experimentally determined overall vane aerodynamic performance, radial variations in vane efficiencies, and radial and circumferential variations in vane exit total pressure for selected coolant flow rates. Comparisons are made between the two cooled configurations, a similarly configured high aspect ratio vane, and the solid (uncooled) core turbine stator vane. The effect of coolant slot area on coolant flow rate will be discussed. Coolant slot discharge coefficients and Reynolds numbers will be presented.

Overall Aerodynamic Performance

Figure 7 shows the cooled vane primary and thermodynamic efficiencies as functions of coolant flow rate (percent of primary flow). The overall aftermixed efficiency of the solid (uncooled) vane of reference 3, which has the same aerodynamic profile as the two cooled configurations, is also shown in this figure.

As shown in figure 7, for increasing coolant flows the primary efficiency increases above the solid (uncooled) vane efficiency. The primary efficiency increase occurs because coolant flow contributes to the vane output and the ideal coolant kinetic energy is not accounted for in this definition of efficiency. The primary efficiencies are the same at a given coolant flow rate for the two cooling configurations tested. At a coolant rate of 4.0 percent of the primary flow, which corresponds approximately to a coolant to primary total pressure ratio of 1.0 for both configurations, the overall aftermixed primary efficiency is about 0.991. Compared to the solid vane efficiency of 0.960, the increase in primary efficiency indicates that about 80 percent of the coolant ideal energy was utilized at this particular coolant flow condition.

The overall aftermixed thermodynamic efficiency is also shown in figure 7. The thermodynamic efficiencies for the two cooled configurations are less than for the solid (uncooled) vane for all coolant flow rates tested. For coolant flow rates from 2.5 to 4.5 percent of the primary flow, the efficiency levels of the two cooled configurations are approximately the same and nearly constant. At a coolant flow rate of 4.0 percent, which corresponds to a coolant to primary total pressure ratio of approximately 1.0, the thermodynamic efficiency was about 0.953 for both configurations. For coolant flow rates greater than 4.5 percent of the primary flow, both configurations have decreasing thermodynamic efficiencies but the split trailing edge ejection vane has a higher efficiency than the pressure surface trailing edge ejection vane at a given coolant flow rate.

For comparison, the variations in overall aftermixed thermodynamic efficiency for the split trailing edge ejection cooled vane of reference 5 are shown in figure 7. These test results are for a primary to coolant total temperature ratio of 1.0. The aerodynamic profile of this vane is similar to the core-turbine stator vane but the axial aspect ratio is 2.4 times as great. The efficiency differences shown in figure 7 are due, in large part, to the additional losses incurred because of the low aspect ratio (high relative end wall and secondary flow losses) of the core-turbine stator vane.

Radial Variations in Vane Performance

Efficiency. - The radial variations of aftermixed thermodynamic and primary efficiency for the two cooled configurations are presented in figures 8(a) and (b) for two selected coolant flow rates. Also shown are the solid (uncooled) vane results from reference 3. At the low coolant flow rate (about 4.2 percent of the primary flow) shown in figure 8(a), the trends in efficiency are similar to those of the solid (uncooled) vane. The vortex core loss regions are apparent at 10 and 80 percent of the vane height. The overall levels of primary and thermodynamic efficiency are approximately the same for both cooling configurations for the 4.2 percent coolant flow case.

For the high coolant flow rate case (about 8.6 percent of the primary flow) shown in figure 8(b), the depression in efficiency in the 10-percent span vortex core region appears to have been decreased. The 80-percent span region loss deficit is still present at this high coolant flow condition. It should be noted that the level of primary efficiency is similar for the two cooled configurations. The thermodynamic efficiency level is generally higher for the split trailing edge ejection configuration. The effect of the coolant slot ribs can be seen from the irregular behavior of the data points in the midspan region.

Total pressure. - The probe total pressure data obtained from circumferential surveys, at a number of radii from hub to tip, were used to obtain a computer developed contour map of total pressure ratio (vane exit to vane inlet) downstream of the vane exit (station 3). These contour maps are used to better visualize the effect coolant ejection from trailing edge slots has on the vane exit flow characteristics, as well as show the differences between the exit flow characteristics of the two trailing edge configurations of this report. The middle vane wake, of the three survey wakes, was used for the contour maps shown herein.

The solid (uncooled) vane total pressure ratio contour map is shown in figure 9(a). The vortex core regions of high loss at 10 and 80 percent of the vane height are readily apparent in this figure. Pressure surface and split trailing edge ejection cooled vane contour maps are shown in figures 9(b) and (c), respectively, for the 4.2 percent coolant flow case. This coolant flow rate corresponds to coolant to primary total pressure ratios of 1.06 and 1.00 for the pressure surface and split trailing edge ejection configurations, respectively. The pressure surface trailing edge ejection vane contour is similar to that of the solid vane (fig. 9(a)). The split trailing edge ejection vane contour, however, shows a thinner wake with higher total pressure losses not only in the vortex core regions but all through the middle of the vane wake region. The mixing of coolant and primary flows between the slot exit and the survey plane (station 3) appears greater for the pressure surface trailing edge ejection cooling configuration.

Pressure surface and split trailing edge ejection configuration contour maps are shown in figures 9(d) and (e), respectively, for the 8.6 percent coolant flow case. The corresponding coolant to primary total pressure ratios are 1.82 and 1.69 for the pressure surface and split trailing edge ejection configurations, respectively. For this high coolant flow condition, both cooled vane configurations have a large increase in total pressure in the wake region. However, small regions of total pressure loss can still be seen for both configurations on the suction surface side of the wakes in the 10- and 80-percent span regions. The vortex core regions of higher loss are still apparent at this high coolant flow condition. The maximum total pressure increase in the wakes due to coolant ejected from the trailing edge is much greater for the split trailing edge ejection vane. The circumferential thickness of the split trailing edge ejection vane wake is again thinner than the wake of the pressure surface trailing edge ejection vane. The mixing of coolant and primary flows between the vane slot exit and the survey plane (station 3) is greater for the pressure surface trailing edge ejection cooling configuration. This phenomena is due in part to the greater flow path length (from slot exit to station 3) of the pressure surface cooling configuration. Also, the pressure surface cooling configuration ejects the coolant in an area of high shear flow ahead of the trailing edge whereas the split cooling configuration ejects coolant into the middle of the trailing edge wake region.

Coolant Slot Performance

The split trailing edge ejection vane has approximately a 10 percent larger slot area than the pressure surface trailing edge ejection vane, as mentioned previously. The difference in coolant flow rates, as shown in figure 10(a), reflects this difference in vane slot flow area at the higher coolant flow rates, where the coolant slots are choked. At low coolant flows, the slots are not choked and so the coolant flow rate also depends on slot exit static pressure. The two cooled vane configurations have different slot locations and different static pressure distributions at slot exit, with the pressure surface slot exit static pressure being higher. This results in larger differences in coolant flow at the low coolant flow conditions.

Coolant slot discharge coefficients and Reynolds numbers (as described in ref. 6) were computed from the test data. An estimate of the coolant slot exit static pressure distribution from hub to tip was required to compute the coolant ideal flow conditions. The design radial distribution of vane exit static pressure was used for the split trailing edge ejection cooling configuration. The solid (uncooled) vane surface static tap data from reference 3 was used to estimate the radial distribution of slot exit static pressure for the pressure surface trailing edge ejection cooling configuration.

The resulting coolant slot discharge coefficients are shown in figure 10(b) over the range of coolant to primary total pressure ratios investigated. The discharge coefficients are the same for the two configurations at a given pressure ratio over the entire range of pressure ratios tested. The discharge coefficient increases with increasing total pressure ratio. At a coolant to primary total pressure ratio of 1.0 the discharge coefficient is 0.77. The Reynolds number is shown in figure 10(c) for the range of pressure ratios investigated. The differences shown in figure 10(c) between the two configurations are due primarily to differences in slot geometry and the static pressure distribution at the slot exit.

SUMMARY OF RESULTS

A cold-air experimental investigation was conducted in a full-annular cascade to determine the effect of different trailing edge cooling configurations on the aerodynamic performance of a core-turbine stator vane. The two configurations tested were (1) trailing edge ejection from the pressure surface and (2) split trailing edge ejection. This investigation was made at the design pressure ratio, which corresponds to a mean-radius ideal aftermixed critical velocity ratio of 0.778. Performance data were taken and calculations were made to obtain overall vane performance, radial variations in vane efficiencies, and radial and circumferential variations in the vane exit total pressure for selected coolant flow rates. Coolant slot discharge coefficients and Reynolds numbers were also determined. The pertinent results are as follows:

1. The overall aftermixed primary efficiencies for the two configurations are the same at a given coolant flow rate and increase with increasing coolant flow. At a coolant flow rate of 4.0 percent (coolant to primary total pressure ratio of approximately

1.0), the primary efficiency was 0.991. Approximately 80 percent of the coolant ideal energy is utilized at this condition.

2. The overall aftermixed thermodynamic efficiencies are nearly the same for the two cooled configurations and constant for coolant flow rates from 2.5 to 4.5 percent of the primary flow. At a coolant flow rate of 4.0 percent, the thermodynamic efficiency was about 0.953 for both the pressure surface and split trailing edge ejection vanes.

The overall aftermixed thermodynamic efficiencies decrease with increasing coolant flow for coolant flow rates greater than 4.5 percent. The split trailing edge ejection vane efficiency is higher than the pressure surface trailing edge ejection vane efficiency in this higher coolant flow region.

3. The coolant slot discharge coefficients for both cooled configurations are the same at a given coolant to primary total pressure ratio and increase with increasing total pressure ratio. At a total pressure ratio of 1.0, the coolant slot discharge coefficient is 0.77.

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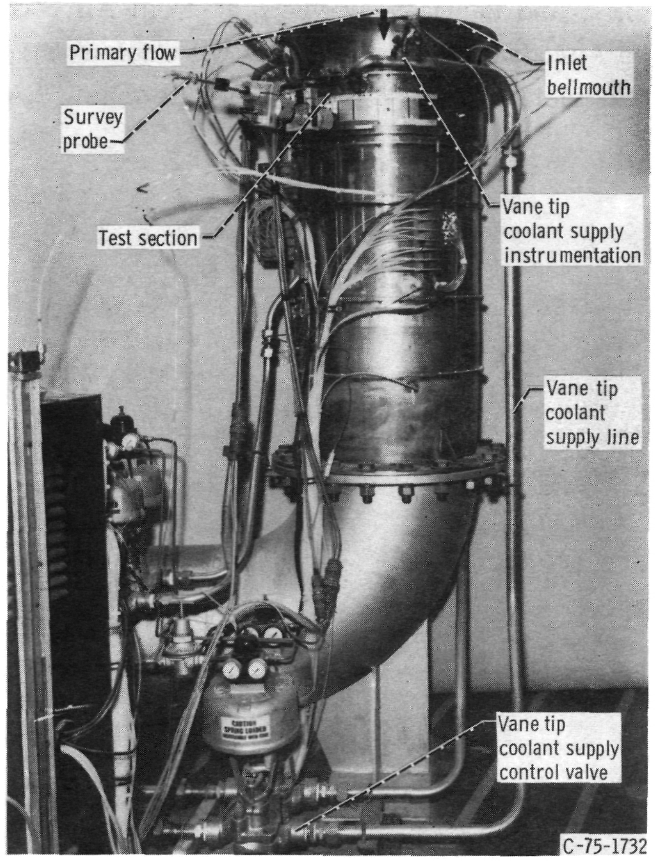


Figure 1. - Core turbine stator annular cascade.

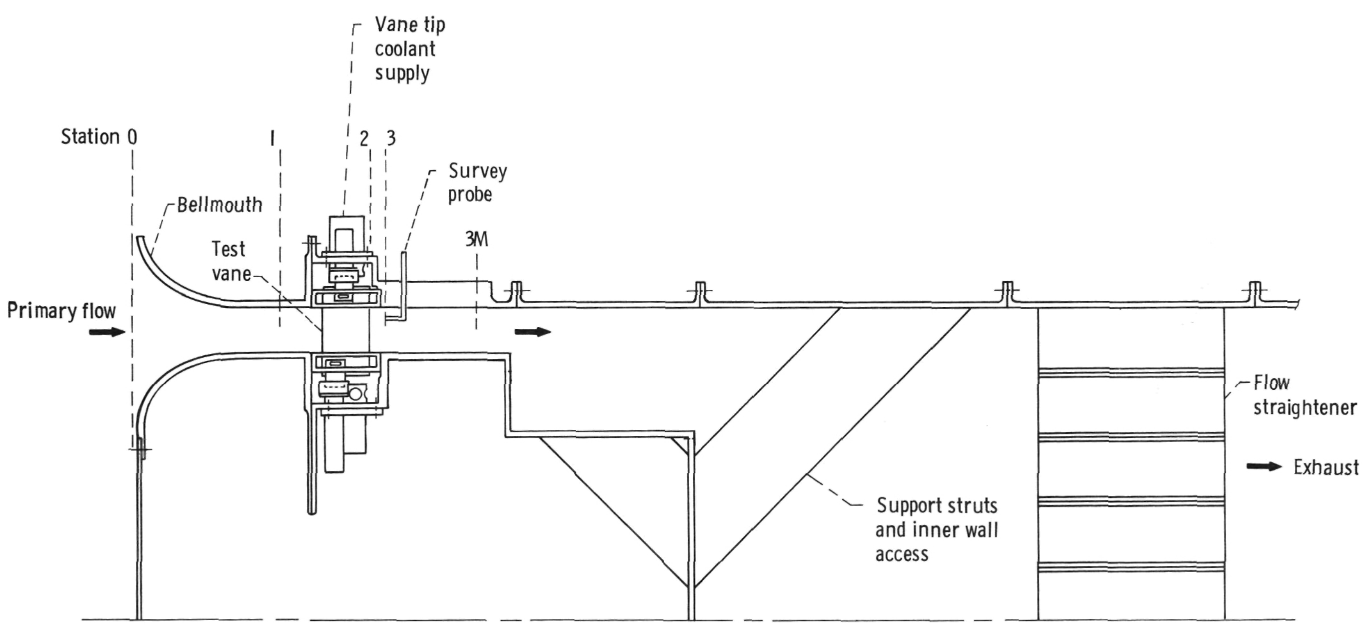
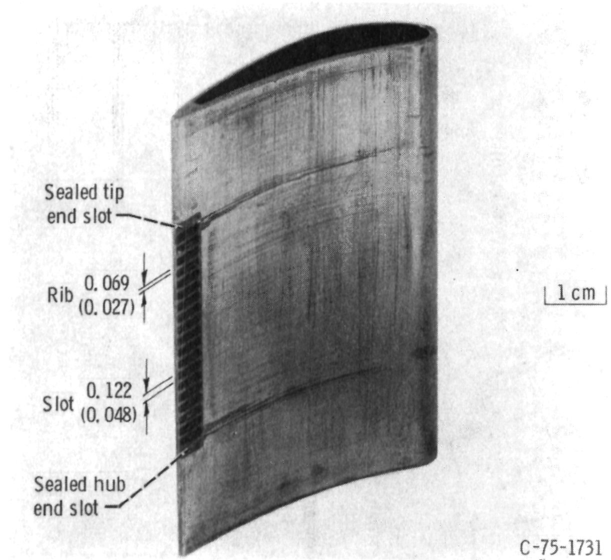
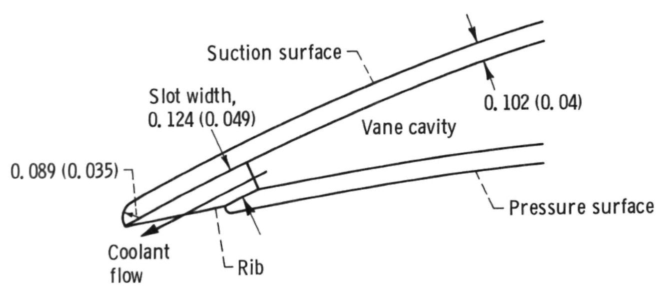


Figure 2. - Schematic cross-sectional view of core turbine stator cascade.

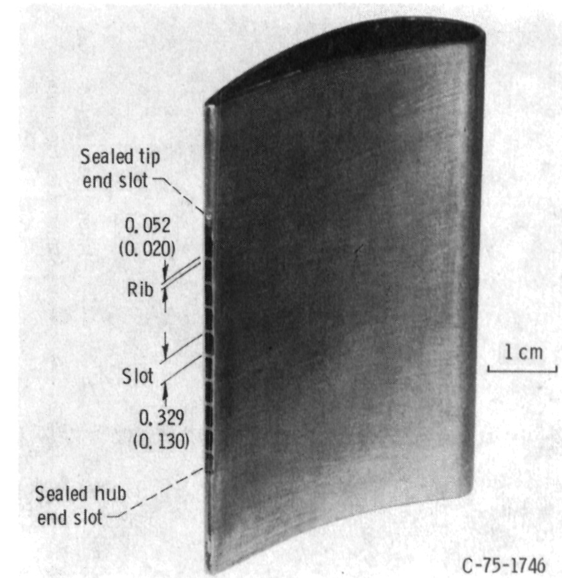


(a) Test vane.

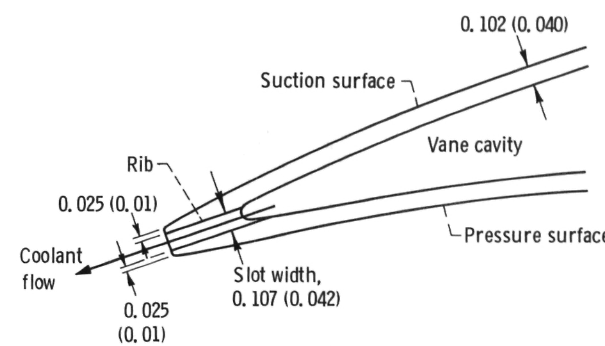


(b) Cross-sectional view of slot.

Figure 3. - Pressure surface trailing edge ejection cooling configuration. All dimensions are in centimeters (in.).



(a) Test vane.



(b) Cross-sectional view of slot.

Figure 4. - Split trailing edge ejection cooling configuration. All dimensions are in centimeters (in.).

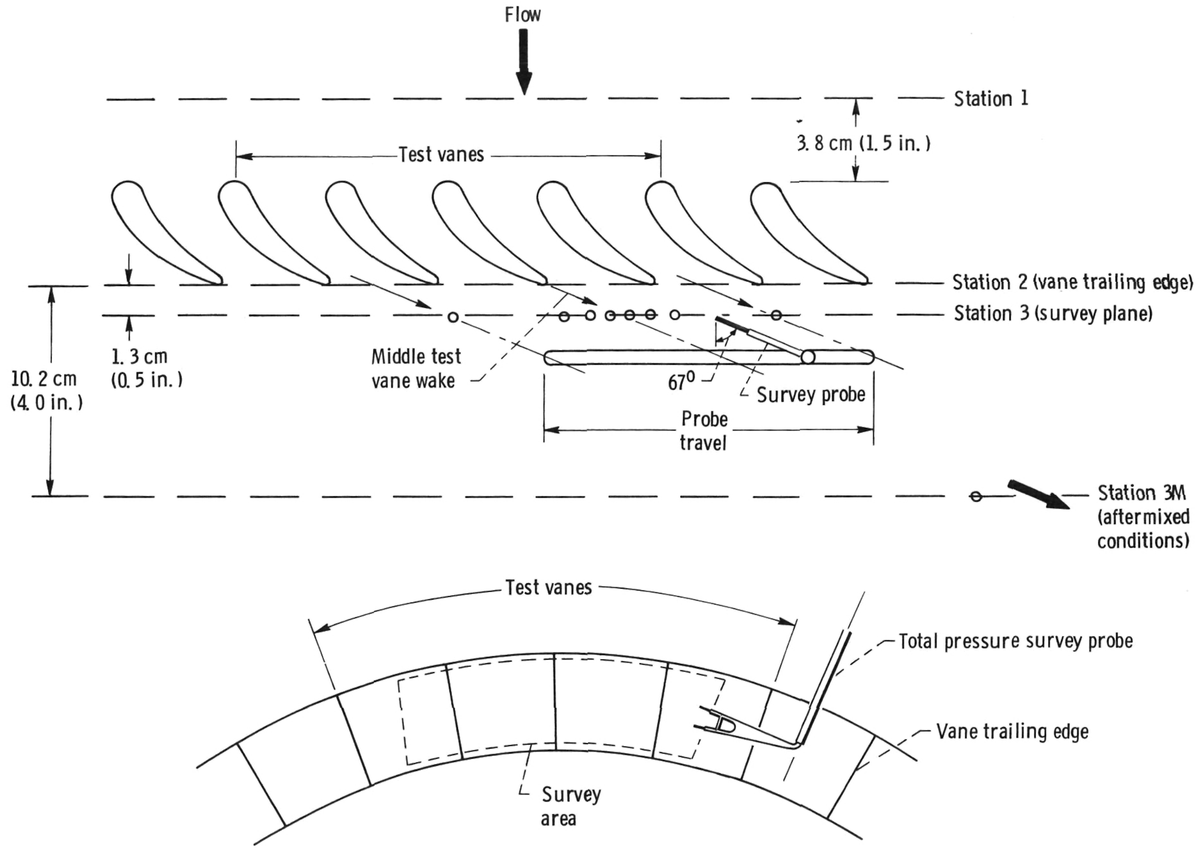


Figure 5. - Schematic of instrumentation for survey data.

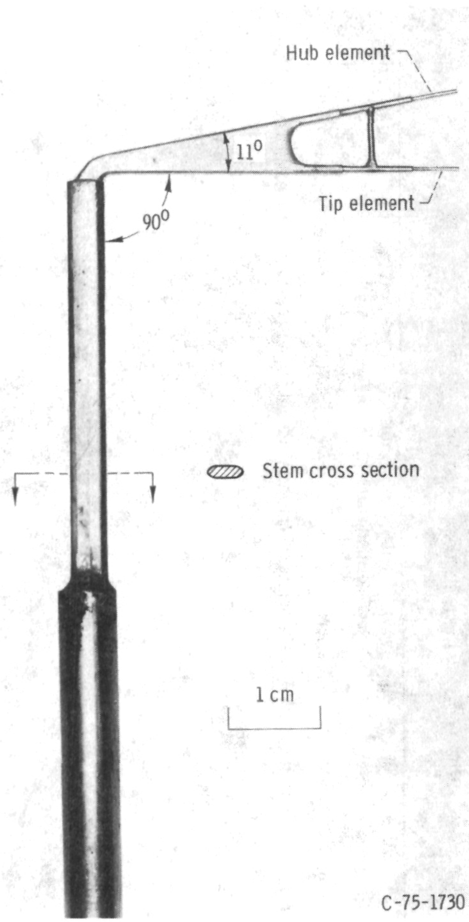


Figure 6. - Total pressure survey probe.

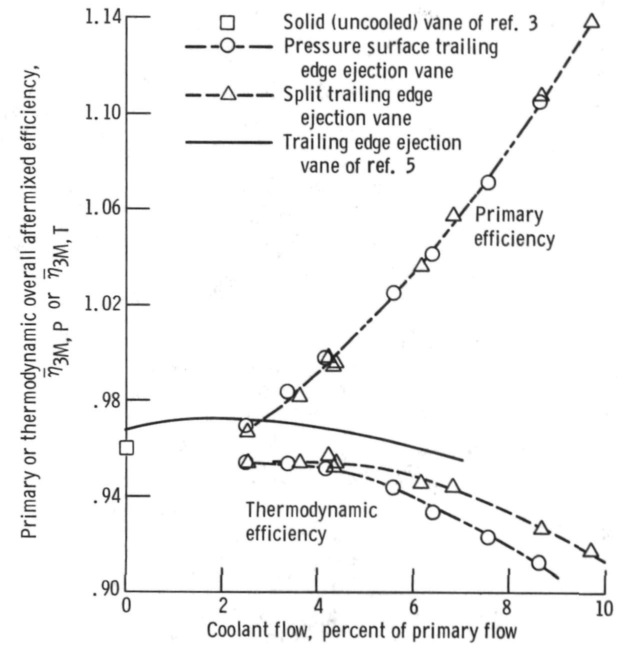
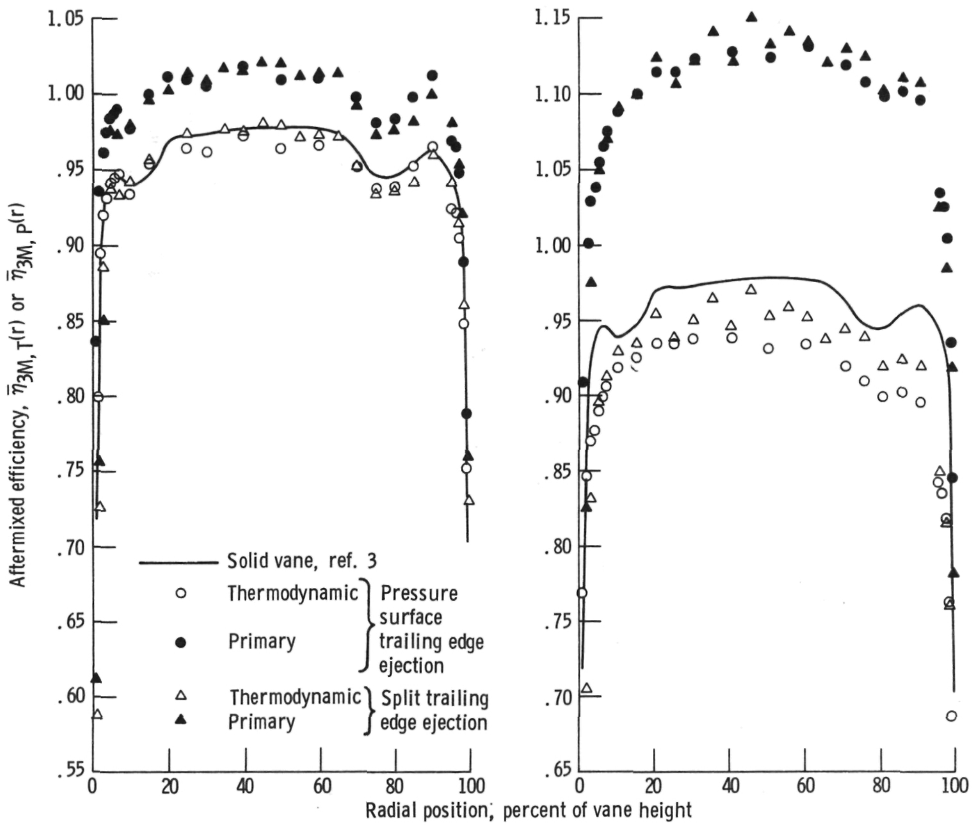


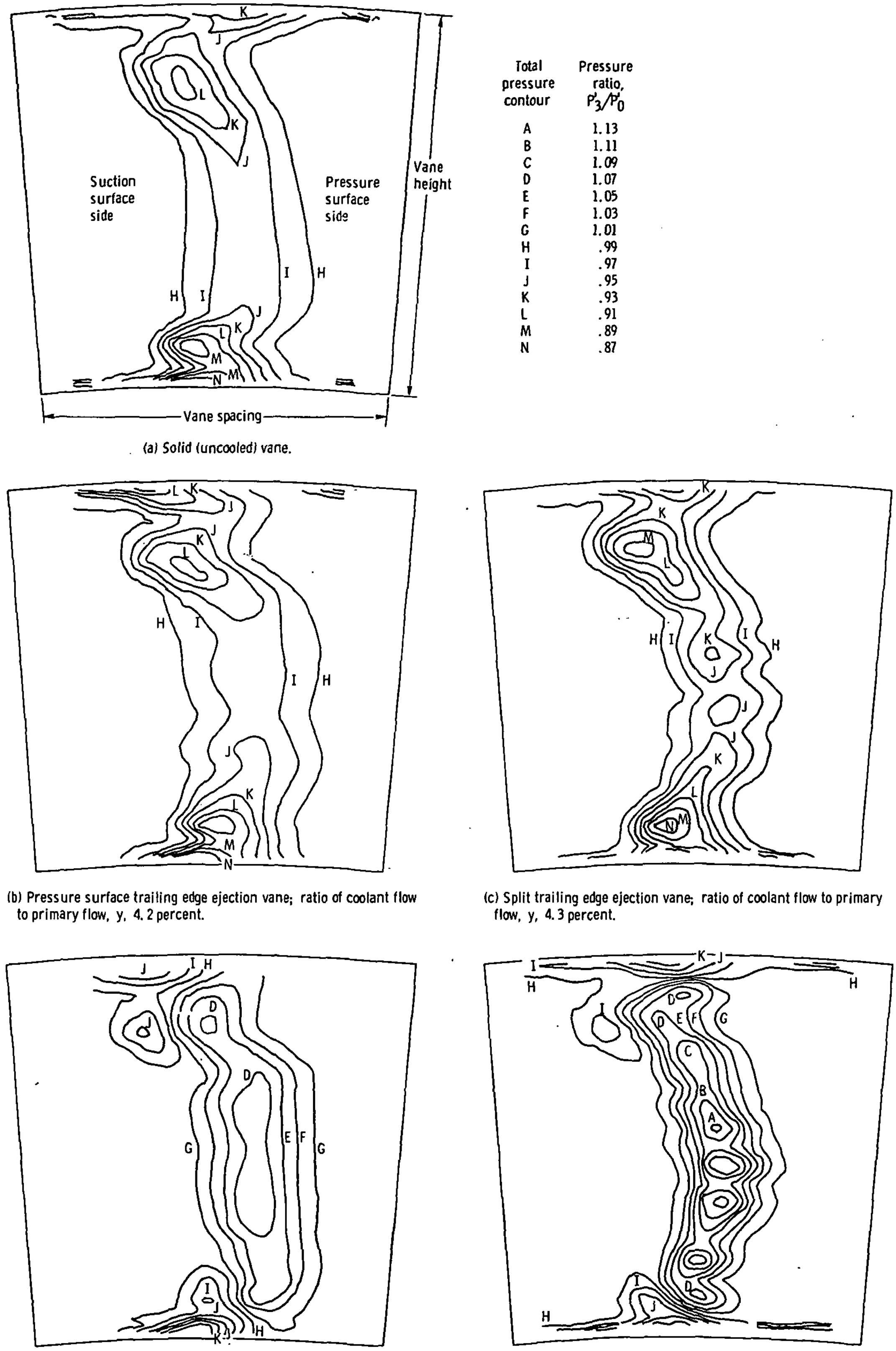
Figure 7. - Variation of overall aftermixed efficiency with coolant flow rate.



(a) Coolant flow rate, y, 4.2 percent.

(b) Coolant flow rate, y, 8.6 percent.

Figure 8. - Radial variation of aftermixed thermodynamic and primary efficiency for selected coolant flow rates.



Total pressure contour	Pressure ratio, P'_3/P'_0
A	1.13
B	1.11
C	1.09
D	1.07
E	1.05
F	1.03
G	1.01
H	.99
I	.97
J	.95
K	.93
L	.91
M	.89
N	.87

(a) Solid (uncooled) vane.

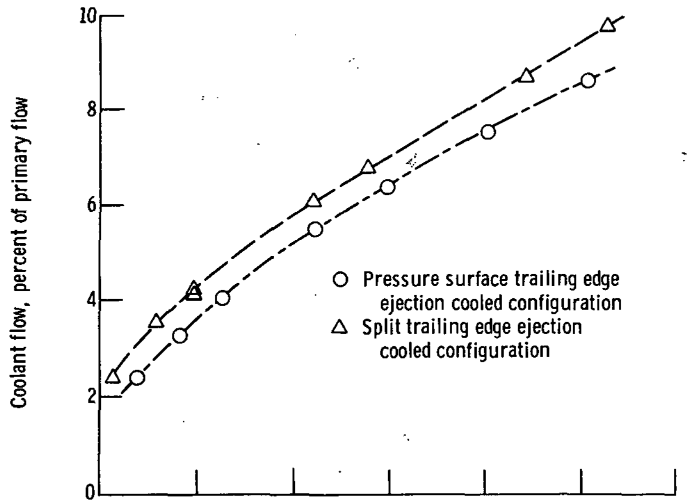
(b) Pressure surface trailing edge ejection vane; ratio of coolant flow to primary flow, y, 4.2 percent.

(c) Split trailing edge ejection vane; ratio of coolant flow to primary flow, y, 4.3 percent.

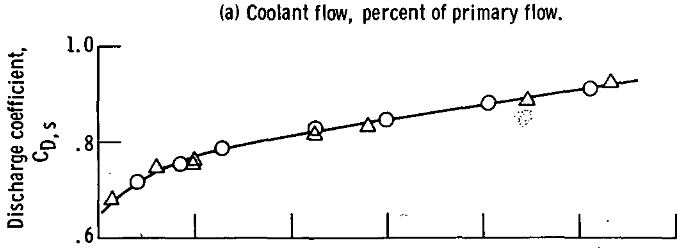
(d) Pressure surface trailing edge ejection vane; ratio of coolant flow to primary flow, y, 8.6 percent.

(e) Split trailing edge ejection vane; ratio of coolant flow to primary flow, y, 8.6 percent.

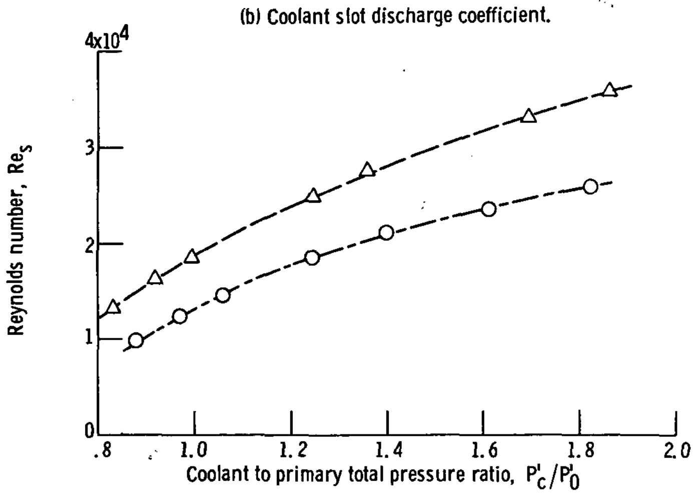
Figure 9. - Survey plane total pressure ratio contour plots.



(a) Coolant flow, percent of primary flow.



(b) Coolant slot discharge coefficient.



(c) Coolant slot Reynolds number.

Figure 10. - Coolant slot performance as function of coolant to primary total pressure ratio.

NASA-Langley, 1976 E-8566

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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