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METAL TEMPERATURES AND COOLANT FLOW IN A WIRE-CLOTH TRANSPIRATION-COOLED TURBINE VANE

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16. Abstract

An experimental heat-transfer investigation was conducted on an air-cooled turbine vane made from wire-wound cloth material and supported by a central strut. Vane temperature data obtained during this investigation were compared with temperature data from two full-coverage film-cooled vanes made of different laminated construction. Measured porous-airfoil temperatures were compared with predicted temperatures.

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METAL TEMPERATURES AND COOLANT FLOW IN A WIRE-CLOTH TRANSPIRATION-COOLED TURBINE VANE

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SUMMARY

Transpiration-cooled strut-supported turbine vanes made from wire-wound cloth were tested in a four-vane cascade to determine their heat-transfer and coolant flow characteristics. Experimental temperature data from this investigation were compared with temperature data from two full-coverage film-cooled vanes made of different laminated construction. The transpiration-cooled vane compared favorably with the full-coverage film-cooled vanes. The measured airfoil temperatures also compared favorably with predicted temperatures except at the forward portion of the suction surface. A laminar boundary layer on the suction surface, which had been predicted from the gas conditions, was apparently tripped to a turbulent regime by the injection of the cooling air, and as a result the experimentally measured temperatures were higher than predicted. This vane was designed for a gas temperature and pressure of 1640 K and 3 atmospheres, respectively, a coolant temperature of 920 K, and a maximum wall temperature of 1200 K.

INTRODUCTION

An experimental investigation of the heat transfer and flow characteristics of a strut-supported wire-cloth turbine vane was made in a four-vane cascade. Experimental temperatures are presented in this report and compared with analytical values.

It has been known for some time that transpiration cooling is the most efficient means of tolerating the high gas temperatures expected in future gas turbine engines. The relative merits of transpiration cooling, film cooling, full-coverage film cooling, and convection cooling have been examined and are reported in references 1 to 3. From a heat-transfer viewpoint, transpiration cooling is superior to any other means of cooling. But there are a number of offsetting disadvantages associated with conventional porous materials, such as fabrication problems, susceptibility to foreign object damage, and susceptibility to plugging of the airflow passages by oxidation and contaminated coolant. Also, reference 4 shows that the aerodynamic losses due to roughness and blowing are greater for a transpiration-cooled vane than for a convection-cooled vane. Many of the porous materials (wire-wound cloth woven-wire cloth, or sintered powered metal) are generally of low strength and require some type of supporting strut, which adds to the airfoil weight and the fabrication complexity. The oxidation characteristics of two wire-wound porous materials and a full-coverage film-cooled material are discussed in reference 2. These materials show promise of reducing the severity of the oxidation and strength problems.

The purpose of the investigation described in this report was to evaluate the heat-transfer characteristics of the transpiration-cooled vane design approach discussed in reference 5 and to determine if predicted surface temperature distributions could be verified by experiment. Dimensionless experimental temperatures were obtained and compared with similar data from two full-coverage film-cooled vanes made of different laminated construction. Experimental and predicted airfoil temperatures were also compared.

The transpiration-cooled vane investigated had a porous wire-wound airfoil attached to a central supporting strut. The coolant pressure and airflow distribution of this vane were investigated in detail, and the results are presented in reference 6. The design gas conditions were a temperature and pressure of 1640 K and 3 atmospheres, respectively, a coolant temperature of 920 K, and a maximum airfoil temperature of 1200 K. Experimental temperature data for this vane were generated in a four-vane cascade over a range of test conditions. These conditions were gas temperatures of 1090 to 1370 K, gas pressures of 2 and 4 atmospheres, and coolant temperatures of about 800 K. Data were also taken at two points representative of a high-temperature core turbine (2200 K and 20 atm). These similarity state data were taken at gas temperatures of 540 and 760 K and gas pressures of 4 and 6 atmospheres. The experimental coolant temperature was ambient.

SYMBOLS

A to J	coolant passages
P	pressure
R	local wall temperature parameter
$\bar{R}$	average wall temperature parameter
T	temperature

$\bar{T}$ average temperature

$\dot{w}$ flow rate

Subscripts:

c coolant

g gas

H hub

i inlet

J coolant passage J

M midspan

o outlet

T tip

APPARATUS

Vane Description

A midspan cross-sectional schematic of the strut-supported wire-cloth vane is shown in figure 1. The vane had a span of about 10 centimeters and a chord of about 6.4 centimeters. The porous wire-cloth airfoil was fabricated from Poroloy, a wire-wound porous material. The Poroloy was wound from Driver-Harris 242 wire to a thickness of 0.061 centimeter. Additional design information is given in reference 5. The airfoil coordinates corresponded to the first-stage vane of a modified J-75 turbojet engine used at the Lewis Research Center for heat-transfer studies. Views of the vane both before and after the porous shell was welded to the strut are shown in figure 2.

The strut, a casting of Udimet 700, essentially carried the gas bending loads on the airfoil and provided compartments within the interior of the airfoil to distribute cooling air. The pressures in each compartment were controlled by orifices drilled in the tip of the strut casting (fig. 1). There were 10 lands or attachment regions on the strut, each land being approximately 2.54 millimeters wide. The airfoil was attached to the strut at each land with a continuous spanwise electron-beam weld. The attachment of the airfoil to the strut defined 10 individual internal compartments. However, compartments D and E (fig. 1) were supplied at a common plenum pressure with air passages cast through the strut dividing these two compartments. The primary purpose of the strut in this region was to stiffen the airfoil against excessive deflection caused by gas pressure forces.

Compartments I and J were also supplied at a common plenum pressure, in a similar manner to compartments D and E.

The strut design was guided primarily by considerations related to ease of casting and efficient heat transfer. The relatively thick land sections aided in the transfer of heat from the weld regions to the coolant channels. In addition, the wide land sections were necessary to obtain a reliable electron-beam weld of the airfoil to the strut. The coolant channels were also made as large as possible in cross section to reduce pressure loss in the spanwise direction in the compartments. Stress analysis of the strut relative to gas bending loads showed that it would operate well within allowable stress limits at the design condition.

Cooling air was supplied to the vane through a tube attached to the tip platform. The air impinged on a baffle plate, entered a plenum chamber in the platform, and was distributed to the 10 spanwise coolant passages (A to J) through the metering orifices.

Cascade Description

A detailed description of the four-vane cascade facility is given in reference 7. The test section was a 23° annular sector of a vane row and contained four vanes and five flow channels. A plan view of the test section showing the central two test vanes, the outer slave vanes, and selected instrumentation is presented in figure 3. The outer slave vanes completed the flow channels for the two center test vanes and also served as radiation shields between the test vanes and the water-cooled walls of the test section.

The vane cooling air was supplied to the four vanes from a single manifold. The flow was measured by a venturi flowmeter. The cooling air was filtered by a 5-micrometer sintered-element filter ahead of the manifold.

The test section was equipped with three view ports in the side walls so that a portion of the test vane surface could be observed with optical temperature measuring devices. The view-port extension tubes were of double wall construction to permit water cooling of the tubes. The flanged end of each extension tube accommodated a 1.3-centimeter-thick quartz disk for viewing purposes. View ports 1 and 2 permitted observation of portions of the pressure and suction surfaces near the leading edges of vanes 2 and 3 (see fig. 3). View port 3 permitted observation of portions of the trailing edge suction surfaces of vanes 2 and 3. The space between the dashed lines in figure 3 indicates the approximate chordwise surface distances on the vanes that could be observed from the view ports. The lines of sight from the three view ports were in a horizontal plane which passed through the midspan region of the two central vanes.

Instrumentation

Vane temperature data presented in this report are divided into two sets that are a function of the number of thermocouples and their location, which are discussed in this section. Gas conditions were measured by radially traversing total-temperature and pressure probes and by inlet and outlet static-pressure taps. These and other operating instrumentation are discussed in reference 7.

Figure 4(a) is a schematic showing typical midspan vane thermocouple locations for the first set of data. Each of the four vanes in the vane pack had nine strut thermocouple locations: five at the midspan, two near the tip platform, and two near the hub platform. In addition, there were two airfoil thermocouples on vane 2 (one on the web near the leading edge of the suction surface and one near the trailing edge of the suction surface) and one airfoil thermocouple on vane 3 (near the trailing edge of the suction surface). All thermocouples were made from 0.51-millimeter-diameter sheathed Chromel-Alumel wire. Because the airfoil was made from a wire-wound cloth, which could not be slotted to provide a smooth airfoil after the thermocouple was installed, the thermocouple lead was laid along a strut web on the vane surface to the point of interest and the junction was then located midway between webs on the airfoil surface.

In addition to data from the thermocouple instrumentation, infrared radiometry data were obtained from the leading edge suction and pressure surfaces and from the trailing edge suction surface. Because of geometry limitations, these data were restricted to the midspan of vanes 2 and 3.

The second set of data was obtained with the addition of thermocouples on the suction surface of vane 2 and the pressure surface of vane 3. A schematic representation of this instrumentation layout is shown in figure 4(b). The strut thermocouples were retained in vanes 2 and 3 only. Each thermocouple lead was attached to the gas-side surface of a strut web, while the junction was located on the airfoil surface midway between webs.

The instrumentation for the second data set also included five gas-side surface static-pressure taps near the tip platform. These static taps were embedded in the strut web to provide a smooth airfoil surface. Three static taps were located on the suction surface of vane 2, and two static taps were located on the pressure surface of vane 3, as shown in figure 4(c).

Strut thermocouple installation. - In order to avoid damage to the strut thermocouples, slots and guide tubes were provided so that the thermocouples could be slid into position in the strut after the airfoil was attached. The thermocouple junction was not directly grounded to the strut by this method. Therefore, the indicated strut temperatures could be several degrees below the actual strut temperatures.

Airfoil thermocouple installation. - The leads for the thermocouples used to measure the airfoil surface temperature were laid along a strut web to a point near the midspan and then routed perpendicular to the web to the midpoint between adjacent webs.

Routing the leads along a web reduced to a minimum the amount of coolant flow blockage. In order to reduce the effect of each thermocouple lead on succeeding measurements, the plane of thermocouple junctions was skewed from leading edge to trailing edge with respect to the midspan chord line. This is depicted in figure 4(c).

Infrared radiometer. - An infrared spot radiometer was used to measure airfoil temperatures in the leading and trailing edge regions. The radiometer was mounted on a movable table so that chordwise scans could be made of the field of view through the viewport. The instrument was sensitive to radiation energy in the 2.0- to 2.6-micrometer wavelength band, and, to obtain reliable temperatures, the instrument was calibrated to the vane airfoil emissivity in this wavelength band. These temperatures were estimated to be accurate within ±5 K. The output of the radiometer was recorded on a strip chart.

TEST PROCEDURE

Prior to the heat-transfer tests, the vanes were preoxidized in a furnace at 1030 K to obtain a stabilized oxide layer on the wire cloth surface. This oxidized surface had the relatively constant emissivity needed for infrared radiometry measurements.

The vane cooling airflow was checked before and after each heat-transfer test run to determine the extent to which oxidation of the wire cloth reduced the total flow.

The heat-transfer tests were made in such a way that the lowest airfoil temperature data were taken first and the highest airfoil temperature data were taken last. For early tests, the maximum measured airfoil temperature was limited to 1030 K to limit the oxidation rate of the wire cloth. The vane design conditions were a gas temperature and pressure of 1640 K and 3 atmospheres, respectively, a coolant temperature of 920 K, and a maximum airfoil temperature of 1200 K. The predicted coolant- to gas-flow ratio for the design point was 0.053. The test conditions investigated were gas temperatures of 1090, 1140, 1255, 1370, and 1480 K; gas pressures of 2 and 4 atmospheres; a coolant temperature of about 800 K; and coolant- to gas-flow ratios of 0.0165 to 0.0635. The gas stream midspan midchannel exit Mach number was maintained at about 0.85.

Data were taken at two additional gas conditions which represented a similarity state for a high-temperature core turbine (2200 K and 20 atm). These similarity conditions were 540 K at 4 atmospheres and 760 K at 6 atmospheres with a coolant temperature of 290 K. These conditions were derived from similarity constraints discussed in reference 8 which allow high-temperature and -pressure environments to be experimentally investigated at reduced temperatures and pressures.

RESULTS AND DISCUSSION

The experimental temperature data from the porous wire-cloth (Poroloy) vane are presented and compared with temperature data previously reported for two full-coverage film-cooled vanes. Table I shows all the temperature data generated by this investigation. Listed in the table are the gas and coolant inlet conditions, the strut temperatures, the thermocouple and infrared airfoil temperatures where applicable, and the measured coolant temperatures at the hub and tip ends of passage J.

Local Wall Temperature Parameter and Comparisons

The following relation between the vane wall temperature parameter R and the total coolant- to gas-flow ratio is often used for defining and comparing vane performances:

$$R = \frac{T_w - T_{c,J,i}}{T_{g,M} - T_{c,J,i}} \qquad (1)$$

For a local value of R, a local airfoil wall temperature T_w is used along with the inlet coolant temperature in passage J $T_{c,J,i}$ and the mainstream total temperature $T_{g,M}$ at the midspan position. The local R values for the Poroloy vane are shown in figure 5. Figure 5 is composed primarily of thermocouple temperature data from data sets 1 and 2, however, some infrared radiometry temperature data are also included. In general, the data curves follow the expected trends. That is, the airfoil temperature decreases as the coolant flow increases.

A closer examination of the data shows that the infrared measured airfoil temperatures were about 20 K less than those indicated by the thermocouples in the leading edge region. The reverse was true in the trailing edge region, probably because a combination of effects resulting from the sheathed thermocouple lying on the vane surface and extending into the gas stream boundary layer. For the thermocouples near the leading edge, the relatively thin boundary layer and some local blockage of the coolant flow through the porous airfoil could create a situation where the indicated temperature would be between the gas total and the airfoil temperature. Near the trailing edge, because of the buildup of the coolant film in a relatively thick boundary layer, the thermocouples could indicate a temperature between the coolant discharge and the airfoil temperature.

The maximum and minimum design point airfoil temperatures were found from the data of figure 5 by substituting the design gas and coolant temperatures in equation (1) and finding the value of R at the design coolant- to gas-flow ratio (0.053). These temperatures were determined to be 1120 and 1040 K, respectively.

Local R values are also shown in figure 5 for selected regions of a full-coverage film-cooled vane fabricated from a laminated sheet material (Lamiloy). These data are from reference 9. Figures 5(a) and (b) show that the leading edge temperature of the Lamiloy vane was higher (by about 55 K) than the temperature of the Poroloy vane of this investigation. However, the trailing edge suction surface temperatures of these two vanes were similar (fig. 5(c)).

Local R values for a full-coverage film-cooled vane made from laminated platelets (a wafer vane) are also shown in figure 5. These data, taken from reference 10, show that the temperature of this vane was generally higher at all thermocouple positions than the temperature of the Poroloy vane.

Average Wall Temperature Parameter

Average values of R for the Poroloy vane are presented in figure 6. An average airfoil temperature $\bar{T}_w$ was used in equation (1) in place of the local airfoil temperature T_w. These data are based on a weighted average of the thermocouple temperatures of data set 2 and represent the average temperature at the midpoint between struts. These average data also follow the expected trend over the range of gas temperatures investigated. Also shown in figure 6 are average R values for the wafer vane of reference 10. Insufficient data were available for the Lamiloy vane to obtain an $\bar{R}$ for comparison. The average temperature of the wafer vane was about 30 K higher than that of the Poroloy vane for the same gas and coolant temperatures. The average temperature of the Poroloy vane was about 1080 K at design gas and coolant conditions and a coolant- to gas-flow ratio of 0.046.

Two additional data points for the Poroloy vane are included in figure 6 and represent a similarity state where the gas temperature would be 2200 K and the pressure would be 20 atmospheres. These data were taken at gas temperatures of 540 and 760 K and gas pressures of 4 and 6 atmospheres. Ambient temperature cooling air was utilized for both data points. At these conditions, which would be representative of a core turbine engine, and a coolant- to gas-flow ratio of 0.046, the average Poroloy airfoil temperature would be about 1220 K.

Oxidation Effects on Cooling Airflow

The oxidation of transpiration-cooled vanes is of particular concern because it can reduce the cooling airflow and result in failure of the vane. The airflow to the four vanes tested was measured before and after each heat-transfer test run to indicate the progress of the oxide formation and flow blockage. These flow data are shown in figure 7. After about 26 hours of testing at airfoil temperatures between 750 and 1060 K, there was approximately a 15-percent reduction in the total cooling airflow. The coolant pressure and airflow characteristics of this vane are discussed in detail in reference 5.

Surface Static-Pressure Distribution

Gas-side static pressures near the tip platform were measured during the final series of tests. These data were compared with surface static pressures measured on solid vane airfoils tested in the same cascade facility. Within the experimental accuracy, there was no notable difference in these static-pressure distributions.

Experimental and Predicted Temperature Distributions

The analytical model of the Poroloy vane discussed in reference 5 was used to predicted airfoil temperatures. A comparison of experimental and predicted airfoil temperatures was made and is shown in figure 8 for run 23. The experimental and predicted temperatures compared reasonably well except on the forward portion of the suction surface. The predicted temperatures in this region were based on laminar boundary layer heat-transfer coefficients which were predicted from the gas side test conditions. Apparently, injection of the cooling air tripped the boundary layer into a transition or turbulent regime. The installation of the airfoil thermocouples did not contribute to tripping the boundary layer; this was verified by the fact that infrared temperature data taken before and after installation did not show any effect of the thermocouple installation. The comparison shown in figure 8 was made for a gas temperature and pressure of 1380 K and 31 newtons per square centimeter, respectively, a coolant temperature of 800 K, and a coolant- to gas-flow ratio of 0.043.

The coolant temperature rise in passage J predicted by the analytical program was about 33 K. This was about one-fourth the temperature rise measured in passage J of vane 2 (136 K). This experimental result was similar to the trend found in the work of reference 11, where, for transpiration cooling, the heat-transfer coefficient in a coolant passage was about five times that predicted by simple tube flow heat transfer.

SUMMARY OF RESULTS

Experimental temperature distributions and coolant flow pressure losses of a strut-supported wire-cloth turbine vane (Poroloy) were obtained in a four-vane cascade. The following results were obtained:

1. A substantial reduction in the vane airfoil temperature (520 to 600 K) below the gas temperature was attained at the design coolant- to gas-flow ratio. In general, the

data followed the expected trend of decreasing airfoil temperature with increasing coolant-flow rate.

2. Based on the experimental correlations, the average airfoil temperature was determined to be about 1080 K, with chordwise variations from 1120 to 1040 K, at gas and coolant temperature of 1640 and 920 K, a pressure of 3 atmospheres, and 4.6 percent coolant flow. Based on similarity state tests, the average airfoil temperature was determined to be about 1220 K at gas and coolant temperatures of 2200 and 920 K, a pressure of 20 atmospheres, and 4.6 percent coolant flow.

3. The cooling performance of this vane was slightly better than that of two other full-coverage film-cooled vanes of different laminated construction (Lamiloy and wafer vanes).

4. The coolant temperature rise in the spanwise channel, which ducted cooling air to the porous material, was about four times that predicted by simple tube flow heat transfer.

5. The coolant flow through the vane was reduced by about 15 percent after 26 hours of testing at airfoil temperatures between 750 and 1060 K, apparently by restrictions caused by oxidation of the wire-cloth material.

6. The airfoil temperatures were predicted reasonably well with the exception of those at the forward portion of the suction surface, where the predicted temperatures were lower than the experimental temperatures. The analytical program assumed a laminar gas-side boundary layer in this region, but, the boundary layer was apparently tripped to the turbulent regime by the injected air.

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505-04.

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TABLE I. - EXPERIMENTAL DATA

(a) Gas temperatures, pressures, and flow rates

Run	Inlet gas total temperature, K			Inlet gas total pressure, P_g, N/cm^2	Gas flow per vane, w_g, kg/sec	Coolant-to gas-flow ratio	Manifold coolant temperature, $T_{c,i}$, K	Vane							
								1		2		3		4	
								Coolant temperature in passage J, K							
	At hub, $T_{g,H}$	At midspan, $T_{g,M}$	At tip, $T_{g,T}$					$T_{c,o}$	$T_{c,i}$	$T_{c,o}$	$T_{c,i}$	$T_{c,o}$	$T_{c,i}$	$T_{c,o}$	$T_{c,i}$
Data set 1															
1	1082.7	1146.1	1096.6	31.1	0.5164	0.0291	819.3	828.5	741.1	864.1	777.7	851.9	766.2	847.5	744.1
2	1087.6	1157.5	1110.4	31.2	.4830	.0261	812.8	839.9	744.0	879.9	781.0	870.0	764.3	864.2	735.7
3	1086.7	1157.2	1108.3	31.2	.4855	.0235	808.5	842.4	754.5	885.9	787.8	880.0	764.2	871.1	735.1
4	1213.8	1274.2	1192.4	31.2	.4552	.0628	813.6	854.1	756.2	854.6	777.9	846.4	775.9	850.7	767.1
5	1215.4	1274.0	1191.4	30.6	.4523	.0348	818.6	893.7	747.9	919.3	783.4	898.4	771.0	899.5	754.2
6	1214.4	1274.4	1189.9	30.5	.4638	.0279	814.4	905.3	752.1	938.9	788.2	916.9	771.7	920.3	745.9
7	1318.8	1391.6	1295.6	31.3	.4169	.0639	824.9	900.5	740.4	895.7	791.4	887.6	790.1	896.8	782.6
8	1264.8	1357.3	1277.6	31.2	.4260	.0371	821.7	915.3	761.2	937.7	797.1	928.2	784.3	927.5	773.2
9	1403.4	1483.3	1377.8	30.9	.4116	.0553	826.9	943.7	773.1	939.2	797.9	928.2	797.9	932.0	789.9
10	1113.5	1154.3	1065.1	62.9	.9235	.0296	814.9	863.8	758.3	882.4	790.2	900.4	781.0	860.6	769.0
11	1092.3	1150.9	1064.7	63.4	.9323	.0328	775.0	836.1	734.3	845.6	758.4	867.6	748.5	841.5	744.4
12	1089.0	1124.3	1049.2	64.1	.9333	.0299	814.3	868.8	759.7	876.3	787.8	880.7	781.1	841.2	770.5
13	1196.0	1283.6	1164.1	63.0	.8573	.0337	817.8	841.0	772.8	926.2	799.6	914.9	785.8	878.6	793.6
Data set 2															
14	1050.7	1105.4	980.9	31.2	0.5169	0.0382	812.6	829.3	750.7	836.7	769.6	818.9	-----	797.4	756.4
15	1053.8	1110.3	978.9	31.0	.5156	.0286	807.9	843.4	740.2	857.0	765.8	831.3	-----	802.7	741.2
16	1053.2	1104.4	975.1	31.1	.5177	.0222	809.0	851.9	747.3	874.7	767.9	846.2	-----	809.6	729.8
17	1054.9	1106.3	975.2	30.9	.5299	.0165	805.9	867.1	728.0	899.9	780.3	872.4	-----	826.9	749.4
18	1096.6	1167.4	1036.7	31.1	.5014	.0374	816.7	856.5	755.6	861.3	777.7	840.6	-----	818.4	762.4
19	1097.4	1160.8	1032.4	31.1	.5138	.0266	806.9	869.3	744.4	886.0	772.8	856.5	-----	827.2	744.9
20	1091.8	1159.8	1035.4	30.8	.5237	.0199	812.3	884.3	771.4	911.0	786.9	882.8	-----	844.9	747.4
21	1195.9	1274.9	1128.5	30.9	.4888	.0438	812.7	891.1	765.7	884	783.8	868.7	-----	850.7	773.7
22	1206.9	1280.9	1148.7	31.1	.4922	.0299	811.4	933.8	762.1	935.6	791.2	909.7	-----	883.6	767.9
23	1294.7	1383.9	1242.9	31.0	.4717	.0429	813.4	948.7	774.2	930.3	794.1	903.8	-----	889.8	784.0
24	538.2	540.8	535.9	40.9	.8597	.0462	297.8	-----	-----	-----	-----	-----	-----	-----	-----
25	743.2	760.8	704.6	62.3	1.122	.0454	303.7	-----	-----	-----	-----	-----	-----	-----	-----

TABLE I. -

(b) Strut and air foi

Run	Vane 1					Vane 2													
	Thermocouple																		
	21	22	23	24	25	21	22	23	24	25	6	[a]6	5a	5	4	3	2	[a]2	1
	Strut temperature, K					Strut temperature, K					Airfoil temperature, K								
	Data set 1																		
1	830.1	839.9	823.9	818.8	834.0	872.7	868.1	865.3	852.9	882.4	------	893	884.4	-----	-----	-----	868.4	855	-----
2	840.4	854.6	832.8	825.2	842.7	888.0	886.4	880.7	863.3	895.5	------	911	898.4	-----	-----	-----	882.0	867	-----
3	840.1	860.0	835.8	826.1	844.1	906.2	893.6	886.1	866.7	900.8	------	928	920.7	-----	-----	-----	886.7	872	-----
4	892.9	827.3	817.1	814.2	832.5	838.0	837.3	840.0	836.3	860.0	------	872	867.6	-----	-----	-----	844.5	848	-----
5	909.8	817.0	853.6	847.5	874.0	903.1	899.1	894.8	882.2	923.3	------	922	919.3	-----	-----	-----	905.2	894	-----
6	912.5	892.7	865.7	857.1	884.2	916.1	919.5	914.0	896.7	940.7	------	900	930.8	-----	-----	-----	924.5	911	-----
7	940.6	861.7	845.2	841.4	869.9	871.3	868.8	870.3	865.4	900.8	------	894	905.0	-----	-----	-----	881.4	880	-----
8	923.6	909.3	880.6	871.8	906.9	931.7	927.7	920.8	903.8	955.3	------	950	947.0	-----	-----	-----	934.2	924	-----
9	978.1	900.8	875.7	870.4	911.7	911.7	904.9	903.3	895.2	947.6	------	944	949.3	-----	-----	-----	922.3	918	-----
10	891.1	840.4	823.1	820.8	836.0	890.4	861.9	858.6	844.6	877.2	------	922	931.2	-----	-----	-----	868.0	872	-----
11	868.4	810.9	794.2	781.5	811.4	850.5	826.9	823.6	809.8	848.9	------	894	891.3	-----	-----	-----	838.8	844	-----
12	897.3	837.8	821.2	819.1	835.7	883.5	856.9	854.4	841.8	875.3	------	911	924.4	-----	-----	-----	866.3	878	-----
13	993.3	882.8	857.0	853.7	887.0	922.3	891.8	887.5	872.3	923.9	------	955	975.6	-----	-----	-----	911.6	944	-----
	Data set 2																		
14	-----	-----	-----	-----	-----	838.7	833.4	839.4	-----	-----	884.7	889	-----	878.4	858.9	847.5	818.6	850	786.3
15	-----	-----	-----	-----	-----	863.8	855.1	858.6	-----	-----	913.5	903	-----	905.8	879.8	861.6	832.6	867	795.3
16	-----	-----	-----	-----	-----	880.8	877.4	876.6	-----	-----	964.3	975	-----	918.1	902.6	874.3	847.6	883	804.3
17	-----	-----	-----	-----	-----	947.0	909.7	901.6	-----	-----	1040.2	1033	-----	955.8	922.6	887.8	857.3	903	812.1
18	-----	-----	-----	-----	-----	863.3	855.6	860.8	-----	-----	913.9	911	-----	908.4	887.1	870.5	840.3	872	803.7
19	-----	-----	-----	-----	-----	889.3	881.8	882.7	-----	-----	953.9	953	-----	939.1	910.2	882.7	856.1	892	811.9
20	-----	-----	-----	-----	-----	927.3	913.4	909.0	-----	-----	1022.2	1033	-----	954.9	942.0	903.6	874.2	917	824.5
21	-----	-----	-----	-----	-----	874.3	866.3	872.3	-----	-----	937.4	950	-----	930.3	905.4	886.6	856.7	889	815.9
22	-----	-----	-----	-----	-----	927.8	919.1	920.0	-----	-----	998.9	997	-----	991.3	957.9	924.8	894.2	936	846.9
23	-----	-----	-----	-----	-----	912.1	901.1	906.3	-----	-----	981.8	992	-----	980.9	949.6	922.2	890.5	936	844.6
24	-----	-----	-----	-----	-----	342.0	331.0	327.2	-----	-----	384.4	----	-----	367.0	344.0	336.6	329.7	---	324.4
25	-----	-----	-----	-----	-----	382.0	357.3	356.2	-----	-----	463.3	----	-----	429.2	384.7	374.5	358.1	---	350.9

[a]Infrared radiometer data.

Concluded.

temperatures.

Vane 3													Vane 4				
Thermocouple																	
21	22	23	24	25	1	7	a7	8	9	10	11	12	21	22	23	24	25
Strut temperature, K					Airfoil temperature, K								Strut temperature, K				
Data set 1																	
855.2	858.0	858.5	847.8	868.4	850.1	------	911	------	------	-----	-----	-----	812.5	820.4	819.7	809.8	816.1
866.2	878.3	873.3	858.6	882.7	863.8	------	955	------	------	-----	-----	-----	822.9	836.4	830.6	815.9	822.3
882.1	890.0	879.7	861.8	886.8	865.9	------	989	------	------	-----	-----	-----	835.4	886.3	837.0	818.4	825.9
833.6	835.0	839.5	833.3	854.2	837.8	------	879	------	------	-----	-----	-----	809.4	814.4	816.6	812.1	821.8
883.0	987.8	887.1	874.7	906.2	888.2	------	950	------	------	-----	-----	-----	846.8	856.6	852.8	840.3	856.3
889.4	910.7	906.6	869.8	922.7	905.2	------	994	------	------	-----	-----	-----	856.7	877.3	868.0	850.5	866.6
866.0	867.7	871.3	863.0	895.0	876.0	------	917	------	------	-----	-----	-----	846.1	850.1	850.6	843.7	862.7
911.0	917.7	914.2	898.4	938.1	918.6	------	983	------	------	-----	-----	-----	882.3	891.3	886.9	869.5	889.5
897.1	899.3	901.5	890.6	934.2	916.8	------	961	------	------	-----	-----	-----	882.2	885.5	884.0	872.8	900.3
882.0	864.9	861.4	847.1	876.1	873.7	------	884	------	------	-----	-----	-----	853.6	845.1	845.5	828.8	830.8
842.5	829.9	826.5	812.6	847.0	846.6	------	855	------	------	-----	-----	-----	821.1	816.8	817.3	800.2	808.6
875.4	859.4	856.0	842.9	872.3	872.2	------	900	------	------	-----	-----	-----	851.8	843.6	844.4	827.6	832.4
912.7	896.0	889.4	873.4	919.5	924.8	------	928	------	------	-----	-----	-----	900.5	890.9	889.2	865.8	880.8
Data set 2																	
829.4	827.9	834.0	830.4	854.2	-----	880.0	883	873.6	895.3	875.1	861.6	809.7	-----	-----	-----	-----	-----
850.2	846.9	848.4	842.1	871.9	-----	920.2	900	916.2	922.9	896.4	878.6	818.3	-----	-----	-----	-----	-----
865.3	869.6	865.7	855.3	890.1	-----	984.6	978	981.7	961.8	924.8	902.3	832.1	-----	-----	-----	-----	-----
925.9	910.1	892.5	871.1	910.1	-----	1053.8	1033	1051.1	1010.8	956.0	925.6	844.4	-----	-----	-----	-----	-----
849.6	846.3	851.3	847.5	878.2	-----	908.3	900	901.3	924.3	899.3	888.3	828.2	-----	-----	-----	-----	-----
871.1	870.9	870.3	861.1	898.9	-----	967.0	953	960.1	961.5	925.3	908.6	840.1	-----	-----	-----	-----	-----
903.1	907.8	898.2	882.5	924.6	-----	1046.5	1033	1040.1	1013.1	964.9	940.7	859.3	-----	-----	-----	-----	-----
860.5	858.3	862.6	857.7	897.6	-----	927.4	964	910.6	942.7	915.7	908.6	842.2	-----	-----	-----	-----	-----
905.4	905.2	903.2	893.3	944.6	-----	1011.5	989	1004.2	1010.3	969.1	958.1	876.6	-----	-----	-----	-----	-----
891.2	888.2	890.7	885.2	939.8	-----	973.8	983	956.7	989.9	955.7	950.9	872.6	-----	-----	-----	-----	-----
339.6	331.5	325.3	323.5	353.3	-----	385.4	----	361.7	372.6	361.7	377.5	339.3	-----	-----	-----	-----	-----
378.5	362.6	349.7	345.9	402.9	-----	475.2	----	431.3	448.7	425.6	453.7	374.3	-----	-----	-----	-----	-----

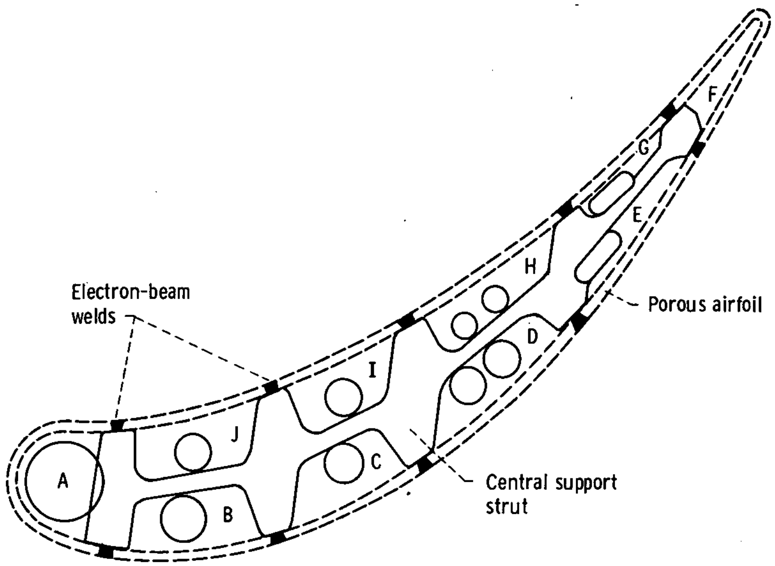
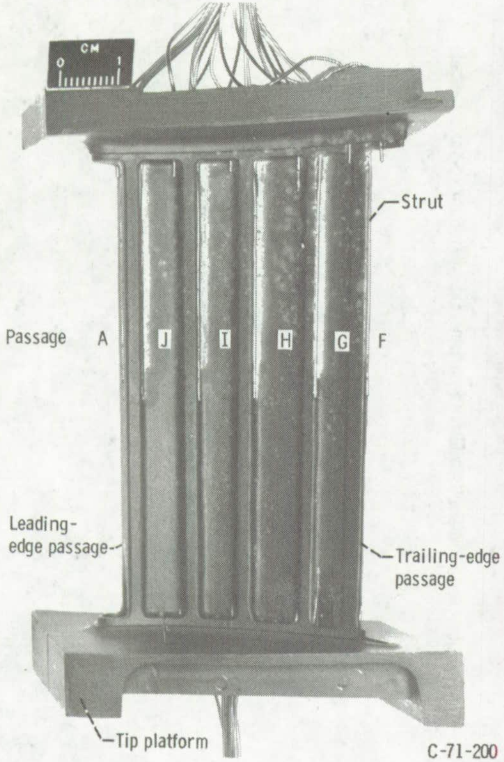
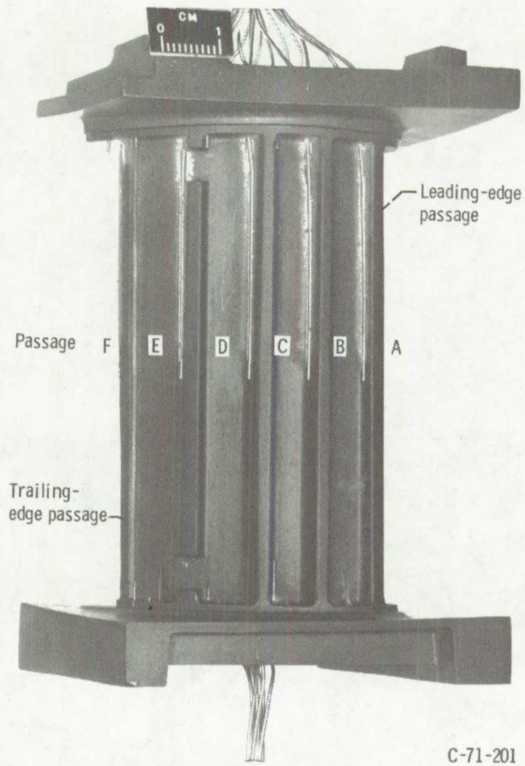


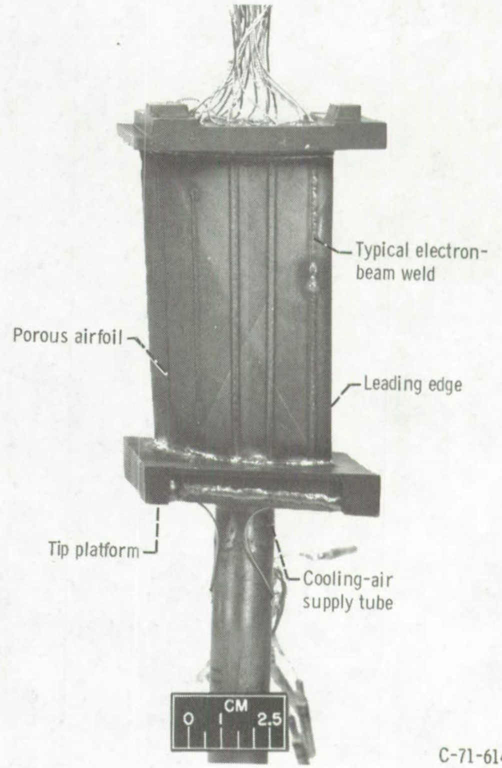
Figure 1. - Cross-sectional schematic of poroloy vane. Spanwise coolant passages and their associated metering orifices are indicated by letters A to J.



(a) Before porous airfoil was welded to strut; pressure side.



(b) Before porous airfoil was welded to strut; suction side.



(c) After porous airfoil was welded to strut; suction side.

Figure 2. - Transpiration-cooled vane.

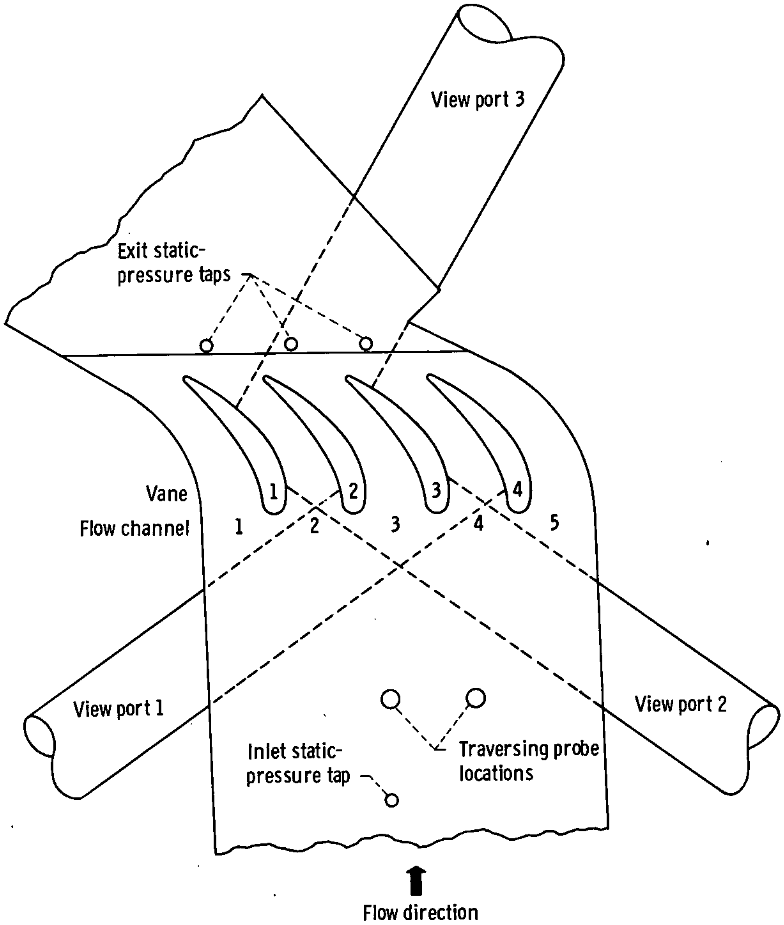
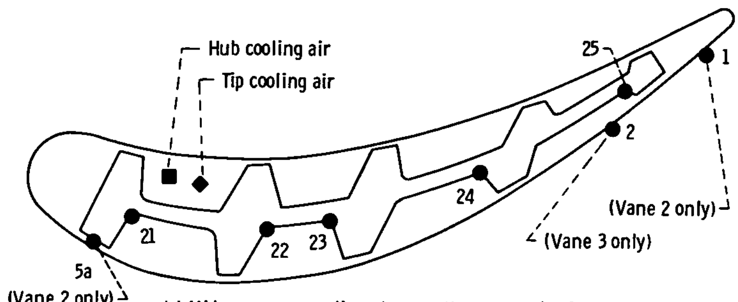
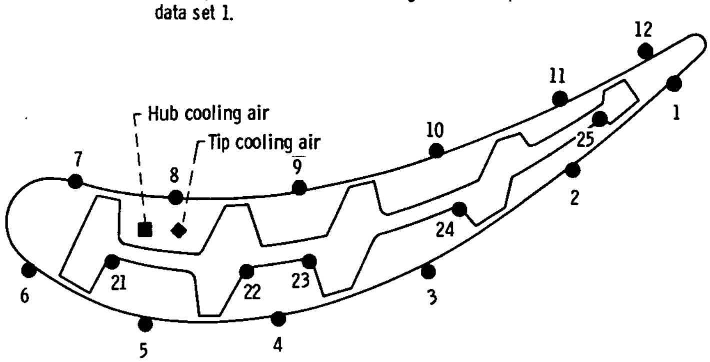


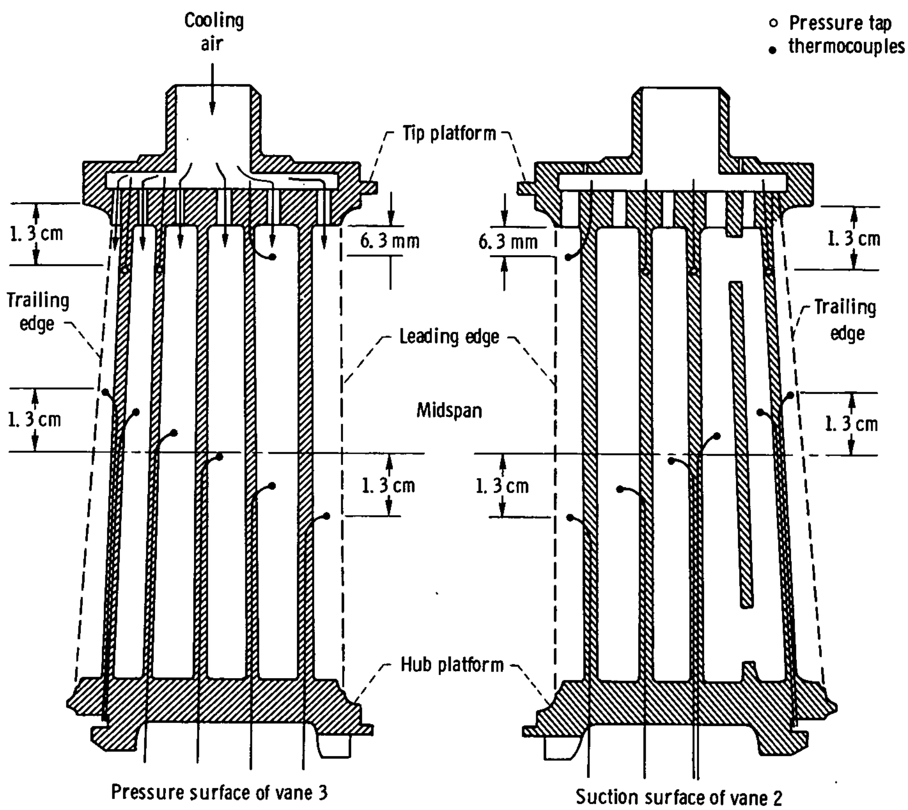
Figure 3. - Schematic of vane row and location of instrumentation stations in static cascade test section.



(a) Midspan cross section showing thermocouples for data set 1.



(b) Midspan cross section showing composite of vane 2 and 3 thermocouples for data set 2. Suction surface airfoil thermocouples on vane 2; pressure surface airfoil thermocouples on vane 3.



(c) View showing relative locations of thermocouples and pressure taps for vanes 2 and 3.

Figure 4. - Schematics showing vane instrumentation.

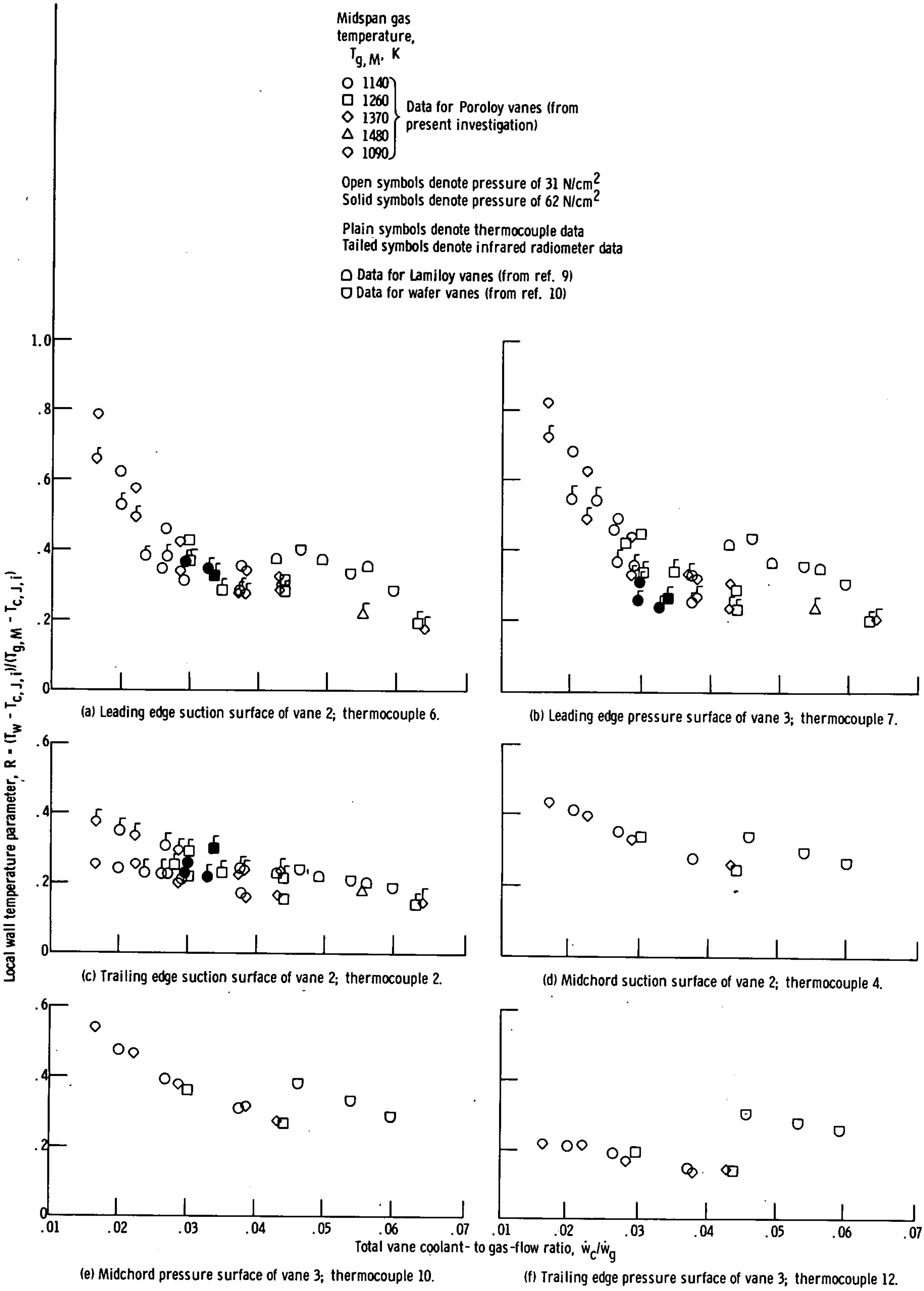


Figure 5. - Comparison of local wall temperature parameter at selected regions of Poroloy, Lamiloy, and wafer vanes.

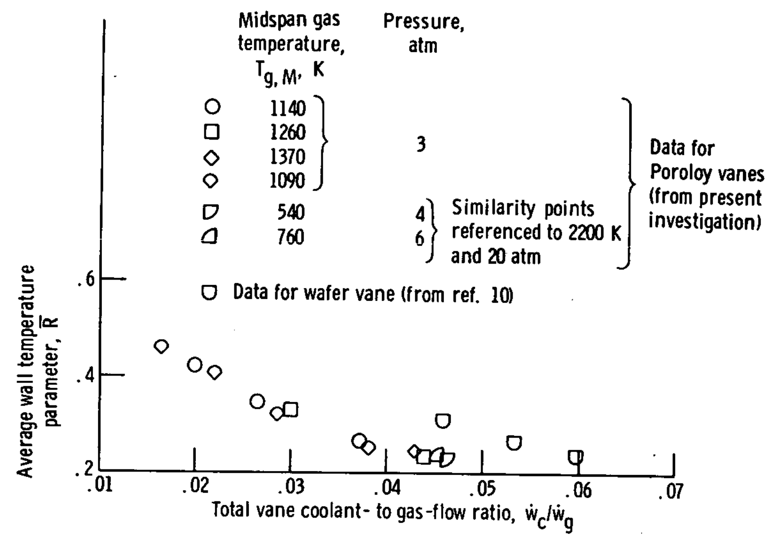


Figure 6. - Comparison of average wall temperature parameter for Poroloy and wafer vanes.

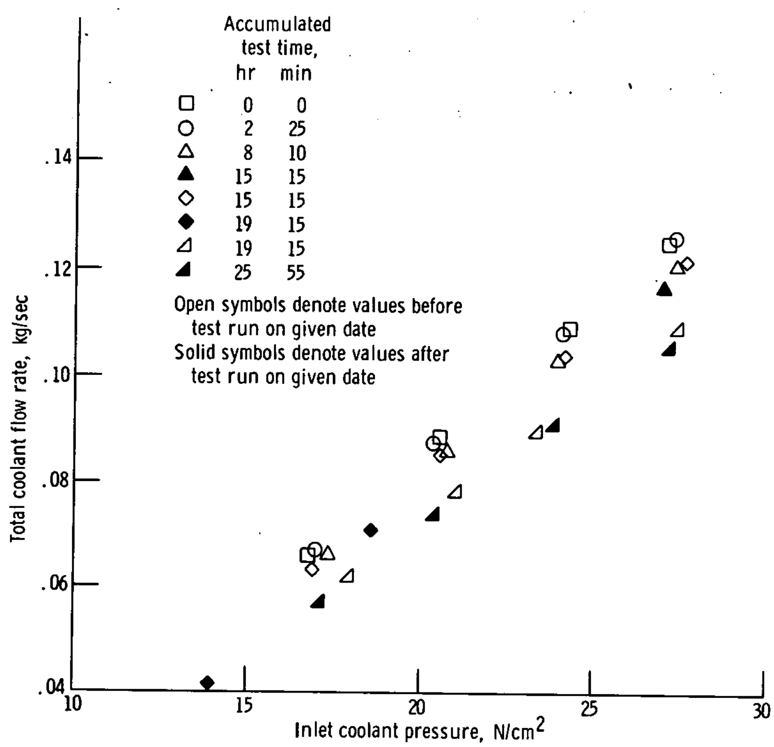


Figure 7. - Total coolant flow to four vanes as function of inlet coolant pressure with ambient exit pressure.

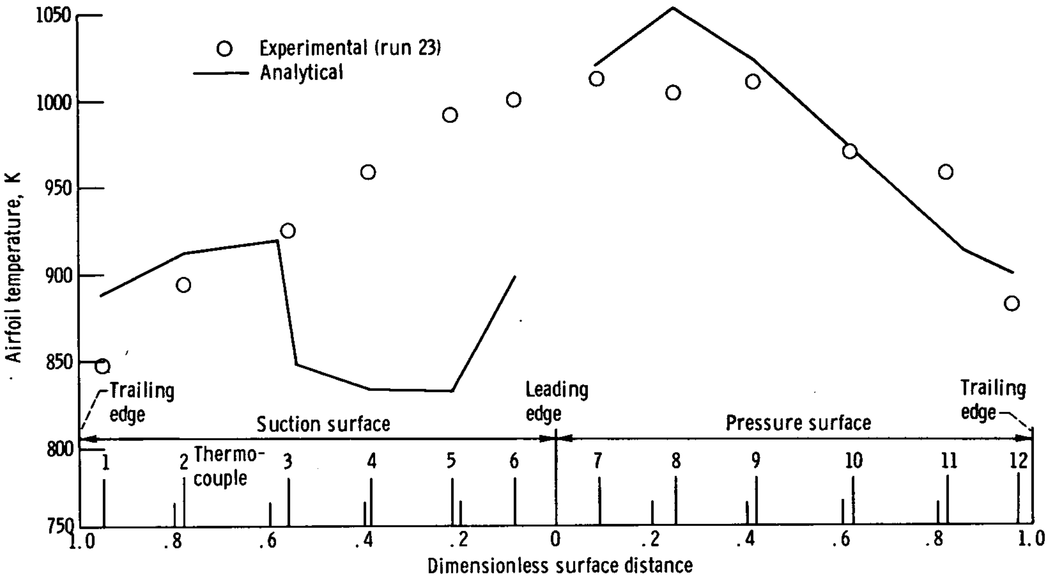


Figure 8. - Comparison of experimental and analytical airfoil temperatures. Gas temperature, 1380 K; gas pressure, 31 newtons per square centimeter; coolant temperature, 800 K; coolant- to gas-flow ratio, 0.043.

NASA-Langley, 1975 E-8249

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