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Peter L. Meitner
Propulsion Laboratory, AVRADCOM Research and Technology Laboratories
Lewis Research Center
Cleveland, Ohio

National Aeronautics
and Space Administration

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SUMMARY

The potential benefits of combining full-coverage film cooling with a thermal-barrier coating were investigated analytically for a turbine vane by calculating the metal and ceramic coating temperatures as functions of coating thickness and coolant flow. Calculations were performed for sections on the suction and pressure sides of the vane, with and without a thermal-barrier coating of plasma-sprayed, yttria-stabilized zirconia (Y_2O_3-ZrO_2) applied over a bond coating of nickel-chromium-aluminum-yttria (NiCrAlY). The assumed operating conditions were a main-stream-gas, hot-spot total temperature of 2550 K (4130° F) (corresponding to an average temperature of 2200 K (3500° F)) and an inlet total pressure of 38 atmospheres (385 N/cm^2, or 559 psia). The coolant temperature and pressure were assumed to be 811 K (1000° F) and 404 N/cm^2 (586 psia), respectively.

The addition of the thermal-barrier coating reduced the required coolant flows and metal temperatures significantly below those for an uncoated full-coverage-film-cooled vane. On the suction side, a 0.0127-centimeter- (0.005-in.-) thick coating halved the required coolant flow and simultaneously reduced the metal outer temperature by 133 K (240° F). On the pressure side, a 0.0127-centimeter- (0.005-in.-) thick coating with a comparable reduction in coolant flow reduced the metal outer temperature by 83 K (150° F). The thermal-barrier coating was more effective on the suction side than on the pressure side because the heat flux was higher on the uncoated suction side.

For comparison, metal temperatures and required coolant flows were calculated for the same suction- and pressure-side sections on a transpiration-cooled vane. Full-coverage film cooling of a coated vane required more coolant flow than did transpiration cooling (for equal metal outer temperatures and an assumed transpiration effectiveness of 0.8).

INTRODUCTION

NASA's research program to develop effective cooling schemes that use a minimum of coolant flow has included full-coverage film cooling as well as the use of a thermal-barrier coating. Full-coverage film cooling is compared with transpiration and convection cooling in reference 1. Although it is not as effective as transpiration cooling, full-coverage film cooling does not have the severe oxidation and flow blockage problems inherent with transpiration cooling. The use of a thermal-barrier coating has so far been limited to convectively cooled hardware. Reference 2, which analyzes the effects of a ceramic coating applied to such a vane, predicts substantially reduced metal temperatures or, alternatively, large reductions in required coolant flow. The predictions are substantiated by metal temperature measurements made on both uncoated and coated vanes in a turbojet engine.

In the vanes and blades coated to date, the coolant is ejected only through slots or holes in the trailing edges. Plasma spraying the thermal-barrier coating on airfoils with many holes in the outer shell could lead to coating adhesion problems or to blockage of the small cooling holes. However, if these potential application problems can be resolved, the use of a thermal-barrier coating with full-coverage film cooling offers the benefits of significantly reduced metal temperatures and/or reduced coolant flow rates - as have been demonstrated for coated, convectively cooled hardware.

This paper reports the potential benefits of combining full-coverage film cooling with a thermal-barrier coating on a high-temperature, high-pressure turbine vane. Calculations were performed for sections on the vane suction and pressure sides to establish metal and ceramic coating temperatures as functions of coating thickness and coolant flow. For comparison, metal temperatures and required coolant flows were calculated for the same sections on a transpiration-cooled vane.

SYMBOLS

A	area, m^2; ft^2
C_p	specific heat at constant pressure, J/(g·K); Btu/(lbm·°R)
h	heat-transfer coefficient, J/(m^2·hr·K); Btu/(ft^2·hr·°R)
T	temperature, K; °R
V	velocity, m/s; ft/s
$\dot{w}$	flow rate, kg/hr; lbm/hr
η	effectiveness
ρ	density, kg/m^3; lbm/ft^3

Subscripts:

c	coolant
ct	coating
g	main-stream gas
i	inner
m	metal

o	outer
tr	transpiration

Superscript:

'	total

ANALYSIS

Vane Geometry

Chambers on the suction and pressure sides of a full-coverage-film-cooled vane (figs. 1 and 2) were analyzed. The vane has a span of 3.81 centimeters (1.50 in.) and a chord of 5.552 centimeters (2.186 in.) and is designed for experimental use in a high-temperature, high-pressure turbine. The film-cooling holes are arranged in a staggered pattern 0.254 centimeter (0.100 in.) apart, as shown in figure 1. Impingement and film-cooling hole rows for the chosen suction- and pressure-side chambers are identified in figure 2, along with the hole sizes for the uncoated design. The vane material is MAR-M509 and the coating is 12-weight-percent-yttria-stabilized zirconia (Y_2O_3-ZrO_2) plasma sprayed over a bond coating of NiCrAlY (Ni-16Cr-6Al-0.5Y). The combined thickness of the metal shell and the plasma-sprayed bond coating is constant at 0.127 centimeter (0.050 in.).

Assumptions

In performing this analysis, the following assumptions were made:

(1) The operating conditions are a main-stream-gas, hot-spot total temperature of 2550 K (4130° F) (corresponding to an average inlet temperature of 2200 K (3500° F)) and an inlet total pressure of 38 atmospheres (385 N/cm^2, or 559 psia). Coolant temperature and pressure are 811 K (1000° F) and 404 N/cm^2 (586 psia), respectively.

(2) Thermal gas radiation is not accounted for in the analysis. For an uncoated vane at the chosen operating conditions, thermal gas radiation increases the heat flux by approximately 5 percent. For a coated vane, it increases the heat flux by approximately 1 percent because of the higher reflectance of the zirconia - 0.8 as compared with 0.2 for the base metal. Neglecting gas radiation thus results in a conservative estimate for the benefits of a ceramic coating.

(3) The coating is polished smooth, so that the main-stream-gas heat-transfer coefficients are not increased by surface roughness.

(4) The boundary layers over the vane suction and pressure sides are fully turbulent and are calculated by the computer program of reference 3, which was modified to include the discrete-hole blowing model of reference 4.

(5) The temperature calculations for the ceramic-coated vane are performed with a two-layer model (metal plus coating), which does not account for the 0.0076- to 0.0102-centimeter- (0.003- to 0.004-in.-) thick bond coating (NiCrAlY) between the base metal and the ceramic. The two-layer model combines the thin bond coating with the base metal since the thermal conductivity of each is much greater than that of the ceramic coating. This model introduces little error into the analysis.

(6) For full-coverage film cooling of a ceramic-coated vane, all coolant flow reductions are calculated on the basis of reduced hole sizes, since any significant drop in coolant supply pressure to the vane would lead to main-stream-gas inflow at the leading edge. The film-cooling holes of this design are spaced in a staggered pattern 0.254 centimeter (0.100 in.) apart, and the heat-transfer calculations of this analysis are based on data taken with film-cooling-hole spacing-to-diameter ratios of 10 or less. Film-cooling holes smaller than 0.0254 centimeter (0.010 in.) in diameter lie outside this range. Thus, the smallest film-cooling holes used are 0.0254 centimeter (0.010 in.) in diameter, which is consistent with manufacturing considerations.

Calculation Procedure

Full-coverage film cooling with and without coating. - Calculations were performed with the computer program of reference 5. This program calculates the coolant flow and metal temperatures of a full-coverage-film-cooled vane or blade. Coolant flow is treated as one-dimensional and compressible, and the heat-transfer from impingement on the shell inner wall and from convection in the film-cooling holes is calculated. Film-cooling heat-transfer calculations are one-dimensional and are based on a porous-wall model. Vane or blade inner and outer metal temperatures are calculated for the shell area associated with each film-cooling hole row. If a thermal-barrier coating is specified, the outer temperature of the ceramic coating is also calculated. The program input includes the chamber geometry (hole sizes, spacings, etc.); coolant temperature and pressure; and main-stream-gas-side temperature, pressure, velocity, and heat-transfer coefficient distributions.

Transpiration cooling. - The required coolant flow rates for a chosen metal outer temperature $T_{m,o}$ were calculated by using the following rearranged formula from reference 1:

$$\dot{w}_c = \frac{h_g A}{C_{p,g}} \ln \left[\frac{C_{p,g}}{\eta_{tr} C_{p,c}} \left(\frac{T'_g - T_{m,o}}{T_{m,o} - T_c}\right) + 1\right]$$

The transpiration effectiveness defined by

$$\eta_{tr} = \frac{T_{c,o} - T_{c,i}}{T_{m,o} - T_{c,i}}$$

was assumed to be 0.8, and the heat-transfer coefficient h_g was taken as the average over the chordwise length of the chamber.

RESULTS AND DISCUSSION

All the calculated wall temperatures discussed are average values for the chambers shown in figure 2.

Full-Coverage Film Cooling with Coating

Figure 3 shows the coating outer temperatures $T_{ct,o}$, the metal outer temperatures $T_{m,o}$, and the metal inner temperatures $T_{m,i}$ for various coating thicknesses at the uncoated-design coolant flow. Also shown are the uncoated-design metal outer temperatures. Calculations were carried out for coating thicknesses from 0.0127 to 0.076 centimeter (0.005 to 0.030 in.). Even thin coatings reduced the metal outer temperatures significantly from the uncoated-design temperatures. For example, a 0.0127-centimeter- (0.005-in.-) thick coating reduced the metal outer temperature by 189 and 150 K (340° and 270° F) for the suction- and pressure-side chambers, respectively.

Figure 4 shows the coating outer temperatures $T_{ct,o}$ and the metal outer temperatures $T_{m,o}$ for various coating thicknesses as a function of coolant flow for the suction- and pressure-side chambers, respectively. Coolant flows were reduced by decreasing the hole sizes while maintaining a constant coolant- to main-stream-gas mass-flux ratio $(\rho V)_c/(\rho V)_g$. The thermal-barrier coating significantly reduced metal temperature and/or coolant flow. Metal outer temperatures were more sensitive to coating thickness than to coolant flow. For example, using a 0.0127-centimeter- (0.005-in.-) thick coating and half the uncoated-design coolant flow reduced suction- and pressure-side metal outer temperatures by 133 and 83 K (240° and 150° F), respectively, from the uncoated-design temperatures. At twice this coolant flow (design), these reductions were 189 and 150 K (340° and 270° F), respectively. Doubling the coating thickness from 0.0127 to 0.0254 centimeter (0.005 to 0.010 in.) at half the uncoated-design coolant flow reduced the suction- and pressure-side metal outer temperatures by 228 and 178 K (410° and 320° F), respectively, below those of the uncoated design.

Figure 5 shows the required coating thicknesses for the suction- and pressure-side chambers, respectively, versus metal outer temperature at various coolant flows. Achieving the same reductions in metal outer temperature on the suction and pressure sides (at equal coolant flow reductions) required a thicker coating on the pressure side than on the suction side. For example, at half the uncoated-design coolant flow, the suction-side metal outer temperature could be reduced 133 K (240° F) below that of the uncoated design by a 0.0127-centimeter- (0.005-in.-) thick coating, but a 0.0178-centimeter- (0.007-in.-) thick coating was required for a comparable temperature reduction on the pressure side. The thermal-barrier coating is more effective on the suction side because of the higher heat flux on the uncoated suction side. (Reference 2 points out that the benefits of a thermal-barrier coating are directly related to the level of heat flux through the uncoated hardware.)

Transpiration Cooling

Figure 6 shows the calculated coolant flows required for the transpiration-cooled suction- and pressure-side sections. A comparison of figures 4 to 6 shows that, for the range of temperatures explored, the calculated transpiration-cooling flows are less than the calculated full-coverage-film-cooling flows for a coated vane. As an example, for a metal outer temperature of 1200 K (1700° F), the required fractions of transpiration coolant flow are 0.275 and 0.230 for the suction and pressure sides, respectively. These coolant flows are 50 to 60 percent of the minimum coolant flows calculated for full-coverage film cooling of a coated vane. However, transpiration cooling has severe flow blockage problems due to oxidation and dirt particles in the main-stream gas and coolant. These problems are not so severe for full-coverage film cooling.

CONCLUDING REMARKS

Although NASA has demonstrated good adherence of plasma-sprayed thermal-barrier coatings on convection-cooled vanes (ref. 2), no coated full-coverage-film-cooled hardware has yet been manufactured. Plasma spraying over large numbers of small, closely spaced holes needs to be investigated to determine coating adhesion and the extent of hole plugging by the coating. Laser drilling of holes through previously coated vane or blade shells is another method that has been considered. Research is needed to develop an acceptable manufacturing technique for coated full-coverage-film-cooled hardware.

SUMMARY OF RESULTS

The potential benefits of combining full-coverage film cooling with a thermal-barrier coating were investigated for a high-temperature, high-pressure turbine vane by calculating the metal and ceramic coating temperatures as functions of coating thickness and coolant flow. Calculations were performed for sections on the suction and pressure sides of the vane, with and without a thermal-barrier coating of plasma-sprayed, yttria-stabilized zirconia (Y_2O_3-ZrO_2) applied over a bond coating of nickel-chromium-aluminum-yttria (NiCrAlY). The assumed operating conditions were a main-stream-gas, hot-spot total temperature of 2550 K (4130° F) (corresponding to an average temperature of 2200 K (3500° F)) and a pressure of 38 atmospheres (385 N/cm^2, or 559 psia). Coolant temperature and pressure were assumed to be 811 K (1000° F) and 404 N/cm^2 (586 psia), respectively. For comparison, metal temperatures and required coolant flows were calculated for the same suction- and pressure-side sections on a transpiration-cooled vane.

The results of the analytical investigation are as follows:

1. Combining full-coverage film cooling with a thermal-barrier coating significantly reduced coolant flow or metal temperature, or combinations of both, from the uncoated design. For example, on the suction side, a 0.0127-centimeter- (0.005-in.-) thick coating halved the required coolant flow and simultaneously reduced the metal outer temperature by 133 K (240° F). On the pressure side, a 0.0127-centimeter- (0.005-in.-) thick coating with a comparable reduction in coolant flow reduced the metal outer temperature by 83 K (150° F). The thermal-barrier coating was more effective on the suction side than on the pressure side because of the higher heat-flux levels on the uncoated suction side.

2. For full-coverage film cooling of a coated vane, the metal outer temperature was more sensitive to coating thickness than to coolant flow. With a 0.0127-centimeter- (0.005-in.-) thick coating and half the uncoated-design coolant flow, suction- and pressure-side metal outer temperatures were reduced 133 and 83 K (240° and 150° F)), respectively, below those for the uncoated design. At the uncoated-design coolant flow, these reductions were 189 and 150 K (340° and 270° F), respectively. Doubling the coating thickness from 0.0217 to 0.0254 centimeter (0.005 to 0.010 in.) (at half the uncoated-design coolant flow) reduced the suction- and pressure-side metal outer temperatures by 228 and 178 K (410° and 320° F), respectively, below those for the uncoated design.

3. Full-coverage film cooling of a coated vane required more coolant flow than did transpiration cooling (for equal metal outer temperatures). For a metal outer temperature of 1200 K (1700° F), the required transpiration cooling flows were 50 to 60 percent of the minimum for full-coverage film cooling.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 7, 1978,
505-04.

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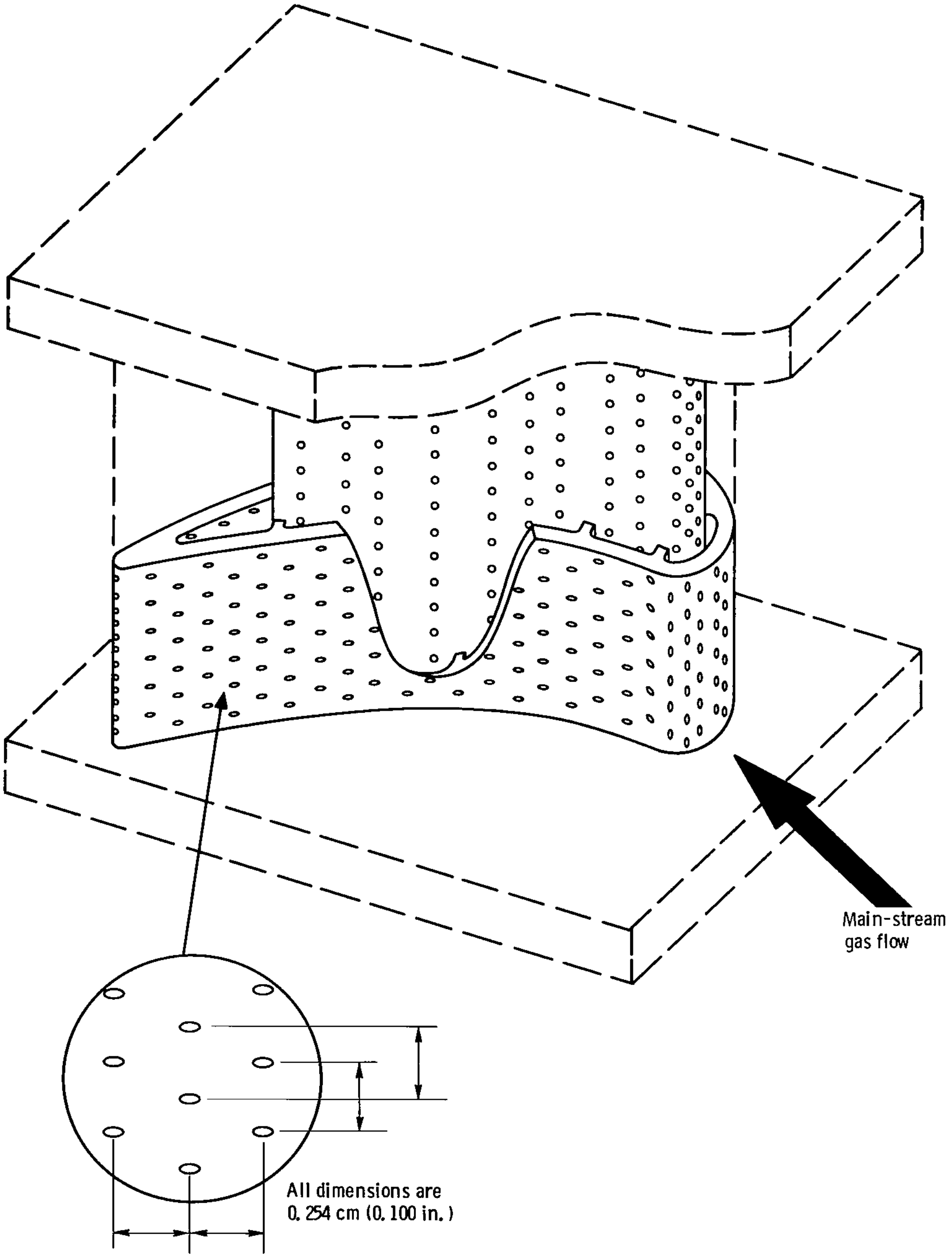
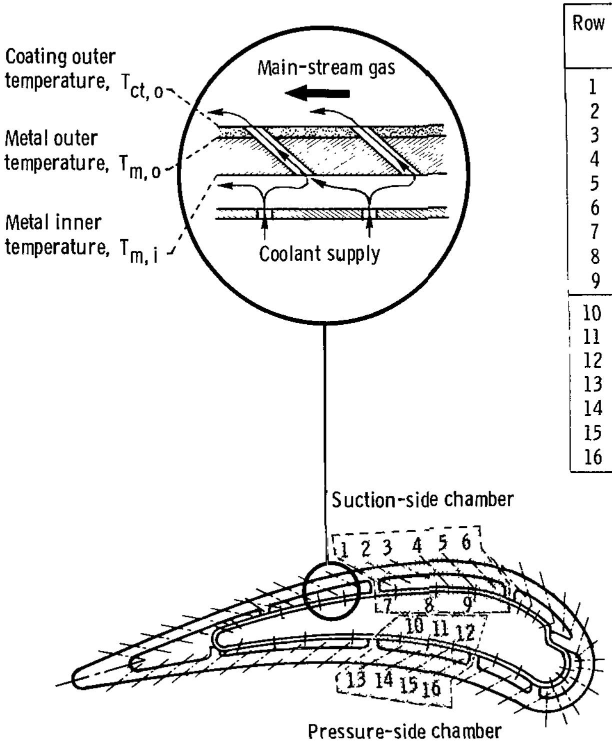
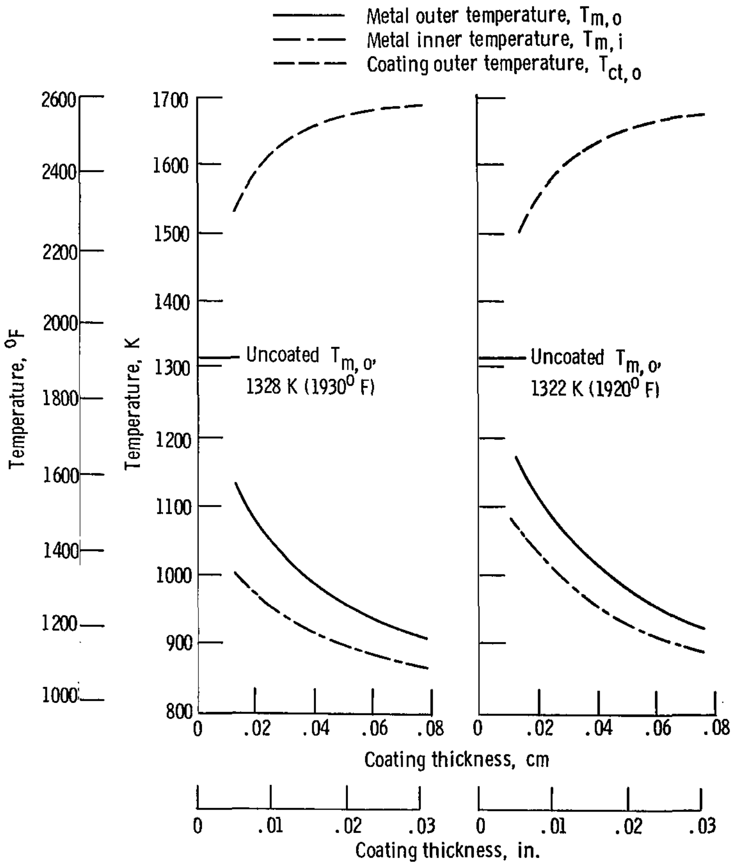


Figure 1. - Full-coverage-film-cooled vane and film-cooling hole spacing.



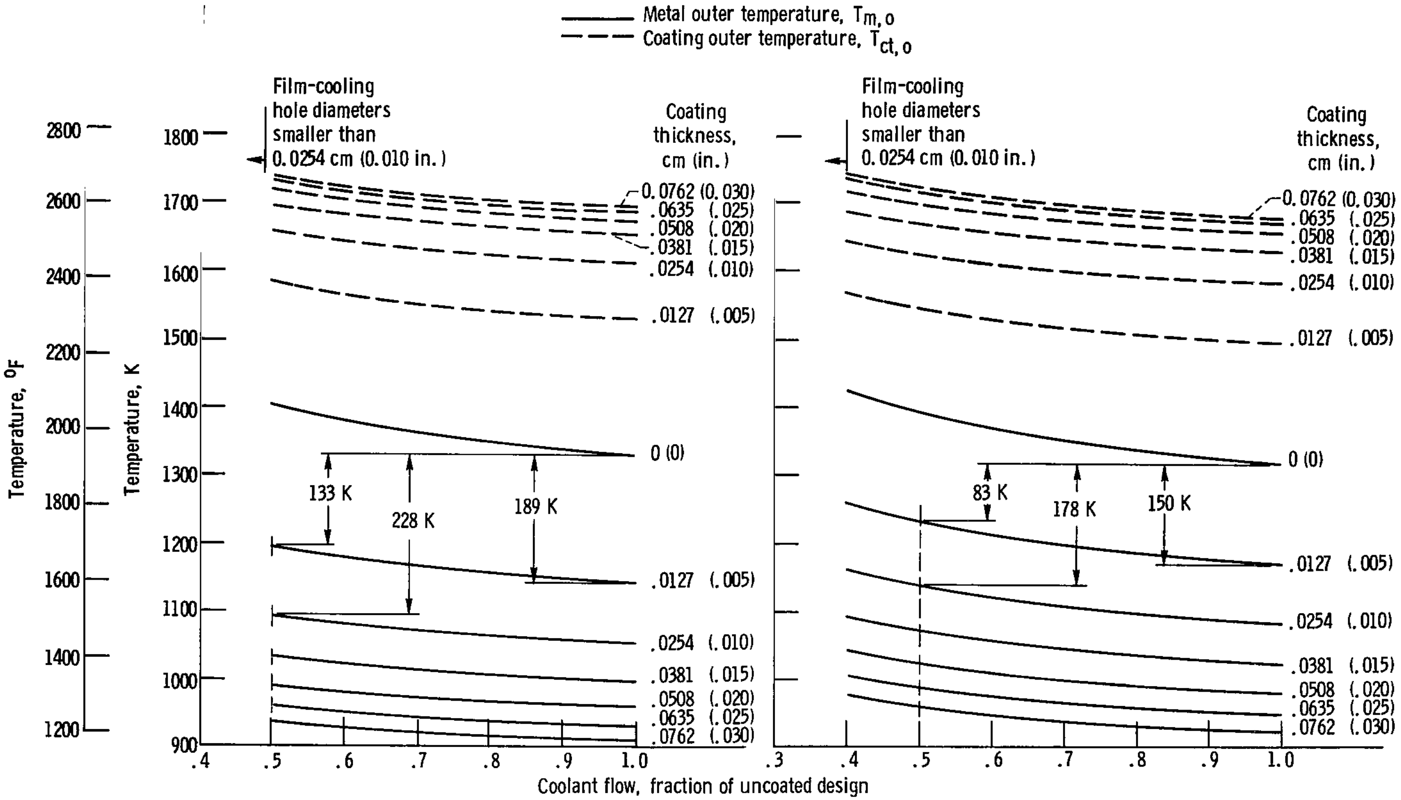
Row	Hole diameter	
	cm	in.
1	0.0356	0.014
2	.0356	.014
3	.0356	.014
4	.0381	.015
5	.0381	.015
6	.0381	.015
7	.033	.013
8	.033	.013
9	.033	.013
10	0.0508	0.020
11	.0508	.020
12	.0508	.020
13	.0381	.015
14	.0406	.016
15	.0406	.016
16	.0406	.016

Figure 2. - Cross section of full-coverage-film-cooled vane, showing chambers for which calculations were performed and definitions of temperatures.



(a) Suction side. (b) Pressure side.

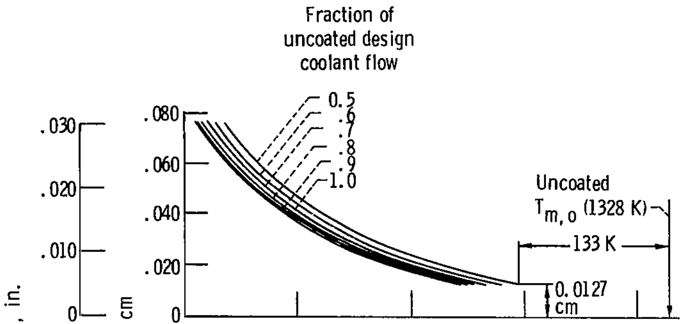
Figure 3. - Full-coverage-film-cooling coating and metal temperatures as function of coating thickness at design (uncoated) coolant flow.



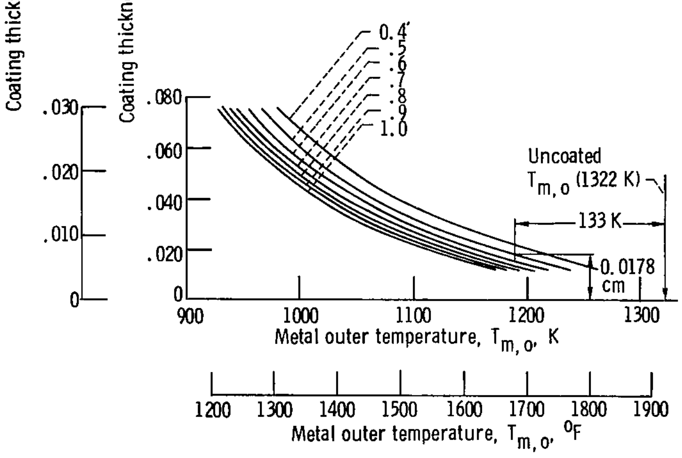
(a) Suction side.

(b) Pressure side.

Figure 4. - Full-coverage-film-cooling metal temperatures as function of coolant flow at various coating thicknesses.



(a) Suction side.



(b) Pressure side.

Figure 5. - Variation of coating thickness with chamber average metal outer temperature at various coolant flows.

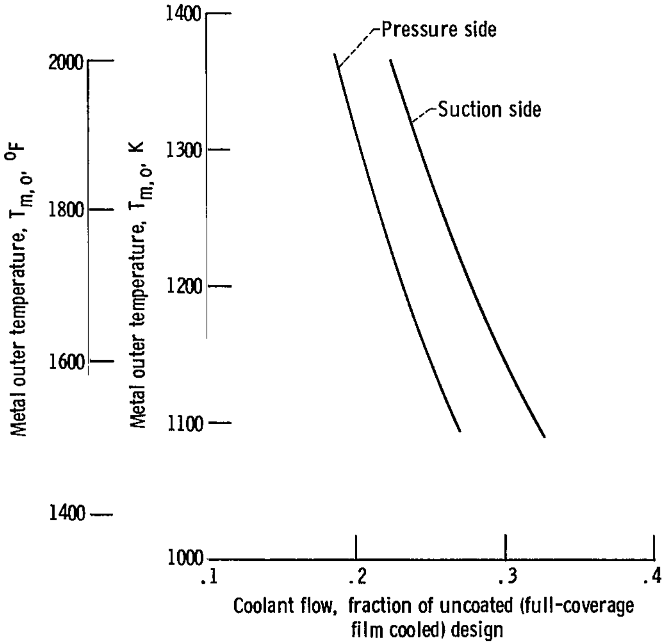


Figure 6. - Transpiration-cooling metal outer temperature as function of coolant flow.

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16. Abstract

The potential benefits of combining full-coverage film cooling with a thermal-barrier coating were investigated analytically for sections on the suction and pressure sides of a high-temperature, high-pressure turbine vane. Metal and ceramic coating temperatures were calculated as a function of coating thickness and coolant flow. With a thermal-barrier coating, the coolant flows required for the chosen sections were half those of an uncoated design, and the metal outer temperatures were simultaneously reduced by over 111 K (200° F). For comparison, transpiration cooling was also investigated. Full-coverage film cooling of a coated vane required more coolant flow than did transpiration cooling.

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