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Curt H. Liebert and Raymond E. Gaugler
Lewis Research Center
Cleveland, Ohio

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by

Curt H. Liebert and Raymond E. Gaugler
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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SUMMARY

A study was conducted to determine if thermal contact resistance between layers is important in heat transfer through two-layer, plasma-sprayed thermal barrier coatings applied to turbine vanes at the NASA Lewis Research Center. Results obtained herein with a system of NiCrAlY bond and yttria-stabilized zirconia ceramic show that thermal contact resistance between layers is negligible. These results also verified other studies at Lewis which showed that thermal contact resistance is negligible for a different coating system of NiCr bond and calcia-stabilized zirconia ceramic. The zirconia-stabilized ceramic thermal conductivity data scatter presented in the literature is +20 to -10 percent about a curve fit of the data. The study herein shows that the designer can more accurately predict heat transfer and metal wall temperatures when the thermal conductivity values are used at the +20 percent level.

INTRODUCTION

Ceramic thermal barrier coating (TBC) systems are of growing importance as a class of materials for aerospace applications primarily because of their high thermal resistance or low thermal conductivity k property. These coatings have been studied extensively at the Lewis Research Center because of their potential for reducing the cooling-air requirements in turbine blades. The TBC is applied to turbine vanes and blades at Lewis by plasma spraying, and it consists of a NiCrAlY bond coat covered by a ceramic layer of yttria-stabilized zirconia. Data [ref. 1] have been obtained for the thermal conductivity of the individual layers of the materials of the TBC used at Lewis. However, thermal conductivity data alone may not be sufficient for heat transfer calculations on coated turbine components because the overall heat resistance may also be sensitive to the thermal contact resistance (TCR) at the ceramic-bond and bond - metal wall interfaces. Reference 2 showed that for plasma-sprayed layers of ceramic and bond materials, TCR was significant. Studies of the Battelle Laboratories [ref. 3], however, indicated that TCR was not significant.

A study was conducted at the NASA Lewis Research Center to determine if TCR between layers is important in heat transfer through two-layer, plasma-sprayed thermal barrier coatings as applied to turbine vanes. Comparisons were made between calculated and experimental metal wall temperatures. The calculated metal wall temperatures were determined with a quasi-three-dimensional heat transfer model [ref. 4] in which published thermal conductivity data of metal and ceramic materials were used. The experimental metal temperatures were obtained at the leading-edge region from tests with two air-cooled turbine vanes in a hot cascade facility. Experimental data from the uncoated vanes were used as a basis for adjustment of a prediction model to give best agreement with uncoated metal temperatures. This model and the resulting data scatter between predicted and measured metal temperatures for uncoated vanes was compared with the data scatter with coated vanes. The comparisons permitted the evaluation of the significance of TCR. The gas temperatures and pressures for the tests were 1550 K and 85 N/cm^2 over a range of coolant-to-gas flow ratios of 0.029 to 0.065. The range of measured metal temperatures was 655 to 1205 K. The thickness of the bond coating was 0.013 centimeter, and the thickness of the ceramic coating was 0.037 to 0.052 centimeter.

This report presents the results of this experimental and analytical study. Plots of measured versus calculated data are presented showing the extent of data scatter. Conclusions are made about the importance of TCR. The significance of the data scatter and of the published ceramic thermal conductivity values is discussed.

APPARATUS AND PROCEDURE

Hot Cascade Facility

The cascade facility was designed for operation at gas temperatures and pressures to 1600 K and 100 N/cm^2. The facility [ref. 5] consisted of five sections: inlet, combustor, transition, test, and exit. The test section walls were coated with a ceramic to increase their surface temperature and thus minimize heat radiation loss from the vanes. For the tests herein, experimental vane metal temperatures were obtained at gas temperatures and pressures of 1550 K and 85 N/cm^2 with coolant flow ratios through the test vanes ranging from 0.029 to 0.065.

Uncoated and Coated Test Vanes

Experimental leading-edge metal wall temperatures were obtained with two air-cooled turbine vanes. The vanes were full-size J-75 vanes and were internally impingement cooled. The midspan of both vanes was instrumented with Chromel-Alumel thermocouples at the stagnation point and at distances of 0.39 and 0.49 centimeter from the stagnation point on the pressure and suction surfaces, respectively (fig. 1). The method of thermocouple assembly and installation is described in reference 5. Thermocouple calibration was done after the thermocouple assemblies were installed in the vane walls.

The procedure used to deposit the ceramic coating [ref. 6] onto the metal wall was to prepare the wall by grit-blasting with pure aluminum oxide material, plasma-spray on a bond coat of Ni-16Cr-6Al-.6Y, and then plasma-spray on a ceramic coating of 12-weight-percent yttria-stabilized zirconia. Further details on coating procedure are given in reference 7. Coating thickness was measured by comparing 10-times-size airfoil profiles drawn with a plotting machine of the uncoated vanes and of the vanes after coating. Ceramic coating thickness was 0.037 to 0.052 centimeter, bond coating thickness was 0.013 centimeter, and metal thickness was 0.152 centimeter.

The heat transfer effects of the coating were determined by first testing the uncoated vanes and then testing the same vanes after the TBC had been applied. In these tests the combustion gas temperatures and pressures were established and then the cooling-air flow rate was varied in a stepwise manner from test point to test point. Steady-state data were recorded at each cooling-air flow rate. Twenty-four data points were obtained with the uncoated vanes at coolant-to-gas flow ratios of 0.029, 0.037, 0.059, and 0.065; also 24 data points were obtained with the same vanes after coating at coolant-to-gas flow ratios of 0.036, 0.049, 0.058, and 0.065.

ANALYSIS

Heat Transfer

The calculated metal temperatures were determined with a quasi-three-dimensional heat transfer model [ref. 4] in which radiation was assumed to be negligible. Because of limitations in the heat transfer model, the metal bond coating thickness was added to the metal wall thickness, and the thermal conductivity k of the metal wall (MAR-M-302, ref. 8) was used for this composite of wall and bond materials. These simplifications can be shown to have a negligible effect on the results.

Parameters and Uncertainties

Gas-side parameters. - The gas temperature and pressures for these tests are known within ±2 percent. The external heat transfer coefficients are affected not only by gas temperature and pressure, but also by such factors as gas flow conditions, airfoil curvature, and free-stream turbulence. Unpublished experimental investigations of vane pressure distribution, gas turbulence, and boundary layer thickness carried out in the cascade indicated that the external heat transfer coefficients around the leading-edge region are known ±10 percent.

Coolant-side parameters. - The coolant flow temperatures, pressures, and flows were measured ±1 percent. The local coolant-side heat transfer coefficient accuracy is not well known because of difficulties in fabrication of the insert and associated unknown positions of the insert relative to the metal wall profile. This large uncertainty necessitates the use of a statistical control concept on uncoated vanes to establish a semi-empirical heat transfer model for evaluating the significance of TCR on coated vanes. This was done by adjusting the coolant-side heat transfer coefficient equations of reference 4 in order to obtain a modified equation, which, when used in the computer code in reference 4 (TACT1), gave the best correspondence of experimental versus calculated uncoated vane metal wall temperatures at coolant-to-gas flow ratios of 0.029 to 0.065.

Ceramic, bond, and metal wall material parameters. - The thermal conductivities of the metal wall and bond coating are known within ±10 percent. The experimental error of metal wall temperature measurement was ±1 percent. Values of k for yttria-stabilized zirconia are known within +20 percent to -10 percent of a curve fit of the data given in reference 1. This uncertainty is due to measurement inaccuracies and variations of ceramic material structure with time, such as sintering and densification changes as k was being measured. A curve fit of the data presented in reference 1 gives the following equations for k as a function of temperature for this ceramic:

$$k = 0.483 + 1 \times 10^{-4}T, \text{ W/mK, at temperatures of 370 to 970 K} \quad (1)$$
$$k = 0.275 + 3.14 \times 10^{-4}T, \text{ W/mK, at temperatures of 970 to 1320 K} \quad (2)$$

These equations were used to analytically determine if TCR is negligible. This was done by assuming that TCR was negligible and then varying k values of the ceramic material throughout the range of these data. The three levels of k considered were 1.2, 1.0, and 0.9 times the k-values calculated with equations (1) and (2).

Statistical Inference

To determine the significance of the data scatter, the analysis presented in references 9 and 10 was applied to the data points of measured versus calculated metal wall temperatures obtained with the uncoated vanes and with the coated vanes. The analysis was used at a 95 percent confidence level to determine if the results and conclusions obtained from the sample data would still be valid if larger amounts of data had been obtained.

RESULTS AND DISCUSSION

Uncoated Vanes

Correspondence of measured wall temperatures. - Figure 1 presents a comparision of uncoated metal wall temperatures at the stagnation point, the pressure surface, and the suction surface leading edge region for vanes designated A and B. Measurement agreement was within 10 percent and repeatability was within 2 percent. This agreement and repeatability show that the cascade is functioning in a reasonably consistent manner. It is not unusual to find this amount of experimental uncertainty in hot cascades and engines.

Correspondence of calculated and measured wall temperatures. - Data points of calculated versus measured uncoated vane metal wall temperatures at the leading-edge locations are plotted in figure 2. The data scatter is within 10 percent about a line of perfect agreement of calculated and measured temperatures. This scatter demonstrates that the TACT1 computer program and the adjustment made to the coolant-side heat transfer coefficient equations used in this program result in a predictive model that can be used to correlate control-vane heat transfer data over the range of coolant flow ratios considered herein. This spread of ±10 percent in predicted versus measured temperature and the predictive model was used as the basis (control) for determining the significance of the thermal contact resistance.

Coated Vanes

Data points of calculated versus measured coated vane metal wall temperatures at the same leading-edge locations as for the uncoated vanes are presented in figures 2 and 3. The results at the 1.2 k level are shown in figure 2. The data scatter is within the ±10 percent scatter about the line of perfect agreement and, because of the TBC, the data are lower than the measured wall temperatures of the uncoated vane. If thermal contact resistance (TCR) were added in the analysis, then values of k which are higher than the maximum of published values would have to be used, and this would be unreasonable.

Figure 3 presents calculated versus measured metal wall temperatures at the other k levels of 1.0 k and 0.9 k. This figure shows some data which are displaced below the ±10 percent control region obtained with the uncoated vanes and with the coated vanes at the 1.2 k level. If TCR were included in the calculation with 0.9 k and 1.0 k, then there would be even greater displacement and less correspondence of calculated and measured metal wall temperatures. These trends in figures 2 and 3 support the initial assumption that TCR was negligible. This conclusion agrees with calculations presented in reference 11, which also neglected TCR on a two-layer TBC using NiCr bond and 5-weight-percent calcia-stabilized zirconia ceramic. The results also show that the designer can more accurately predict heat transfer and metal temperature when k values of yttria-stabilized zirconia are used at published values which are 20 percent above the curve fit of the data. The statistical analysis used at the 95 percent confidence level showed that there is a 95 percent probability that these results would still be valid if larger amounts of data had been taken.

CONCLUDING REMARKS

Results of comparisons of calculated and measured metal wall temperatures of uncoated vanes and the same vanes coated with a thermal barrier coating system of NiCrAlY bond and yttria-stabilized zirconia ceramic showed that thermal contact resistance between layers is negligible. This result also verified other results obtained with a different coating system of NiCr bond and calcia-stabilized zirconia ceramic. The data showed that the designer can more accurately predict heat transfer and metal temperatures when equations presented herein are used at published values which are 20 percent above a curve fit of the data. Statistical analysis showed that there is a 95 percent probability that these observations would still be valid if a larger amount of data had been taken.

REFERENCES

1. L. T. Shiembob, "Development of a Plasma Sprayed Ceramic Gas Path Seal for High Pressure Turbine Applications," (PWA-5521, Pratt & Whitney Aircraft: NASA Contract NAS3-19759). NASA CR-135183, 1978.

2. H. G. Price, Jr., R. L. Schact and R. J. Quentmeyer, "Reliability and Effective Thermal Conductivity of Three Metallic-Ceramic Composite Insulating Coatings on Cooled Hydrogen-Oxygen Rockets," NASA TN D-7392, 1973.

3. K. E. Wilkes and J. F. Lagedrost, "Thermophysical Properties of Plasma Sprayed Coatings," (Battelle Columbus Labs.; NAS3-13329) NASA CR-121144, 1973.

4. R. E. Gaugler, "TACT1, A Computer Program for the Transient Thermal Analysis of a Cooled Turbine Blade or Vane Equipped with a Coolant Insert, 1. Users Manual," NASA TP-1271, 1978.

5. H. J. Gladden and C. H. Liebert, "Effects of a Ceramic Coating on Metal Temperatures of an Air Cooled Turbine Vane," NASA TP-1598, 19.

6. S. Stecura and C. H. Liebert, "Thermal Barrier Coating System," U.S. Patent 4,055,705, Oct. 1977.

7. C. H. Liebert, R. E. Jacobs, S. Stecura and C. R. Morse, "Durability of Zirconia Thermal-Barrier Ceramic Coatings on Air-Cooled Turbine Blades in Cyclic Jet Engine Operation," NASA TM X-3410, 1976.

8. "MAR-M-302. High Temperature, High Strength Nickel Base Alloys," (The International Nickel Co., Inc., New York, Rev. ed., 1964), Table III, p. 9.

9. N. L. Johnson and F. C. Leone, <u>Statistics and Experimental Design In Engineering and the Physical Sciences</u>, (Wiley, New York, 1964).

10. M. R. Spiegel, <u>Schaum's Outline of Theory and Problems of Statistics</u>, (McGraw-Hill, New York, 1961).

11. C. H. Liebert and F. S. Stepka, J. Aircr. 14, 487 (1977).

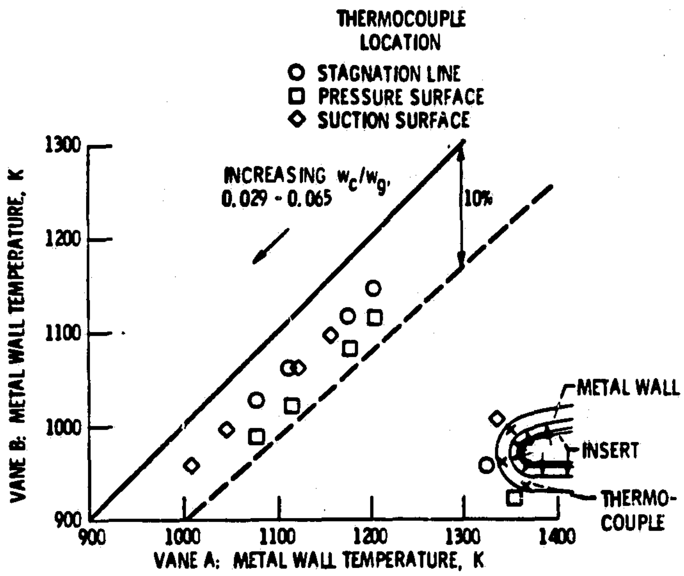

Figure 1. - Comparison of experimental metal wall temperatures at leading edge region of two uncoated control vanes.

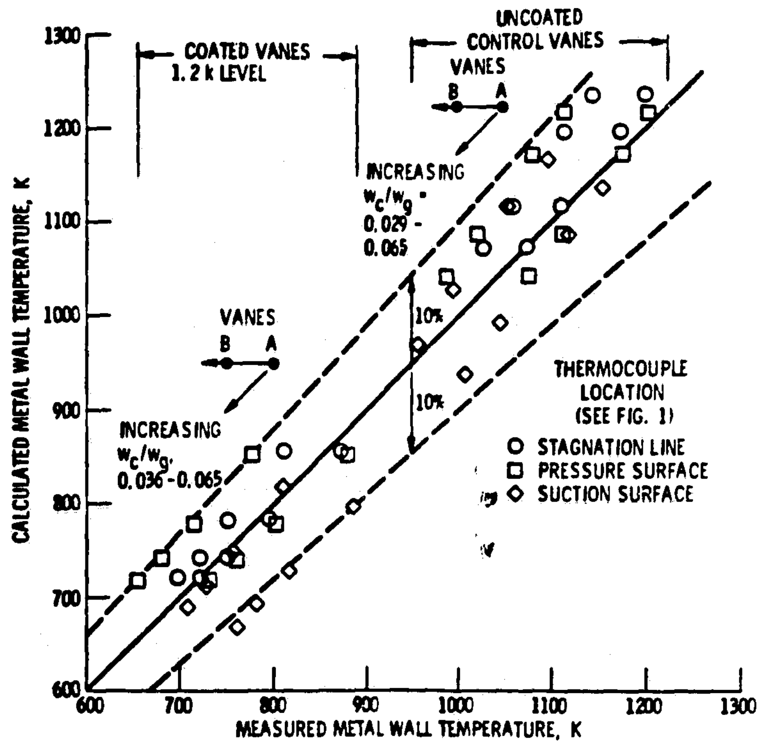

Figure 2. - Comparison of calculated and measured vane metal temperatures at leading edge for uncoated control vane and for coated vane. (Ceramic thermal conductivity 20% higher than curve published in ref. 1.)

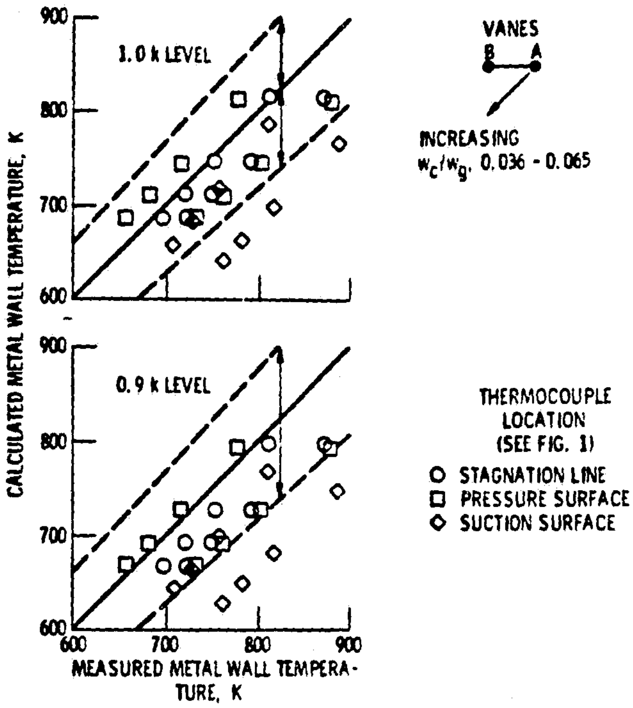

Figure 3. - Comparison of calculated and measured vane metal temperatures at leading edge for coated vane. (Ceramic thermal conductivity zero % and minus 10% lower than curve published in ref. 1.)