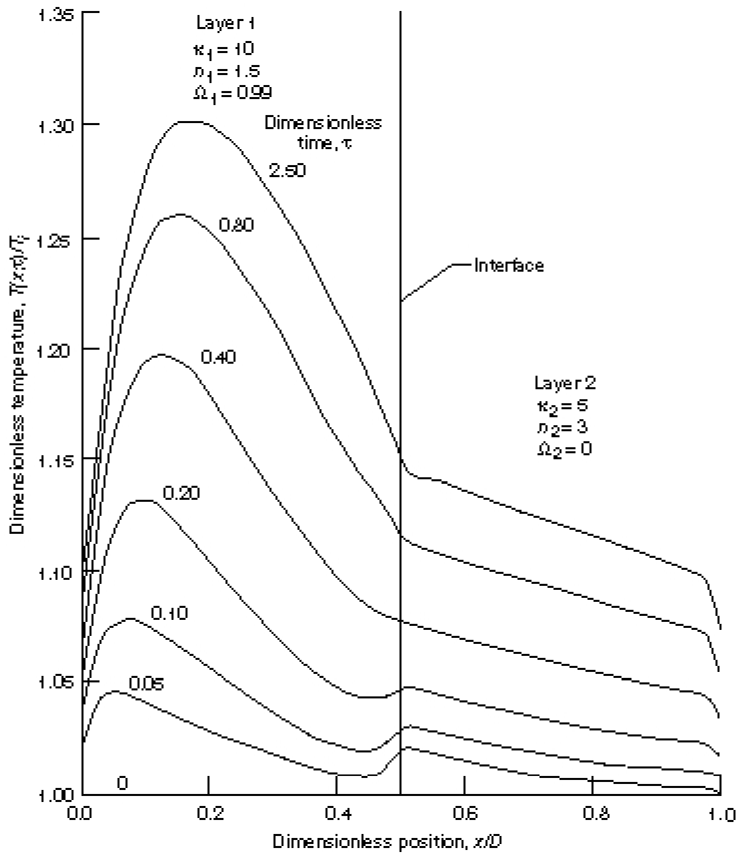
Thermal Radiation Effects Analyzed in Translucent Composite and Thermal Barrier Coating

Ceramic parts and coatings are needed to withstand high temperatures in advanced aircraft engines. In hot environments, such as in the combustion chambers of these engines, infrared and visible radiation can penetrate into some ceramics and heat them internally. The internal temperatures depend on radiative effects combined with heat conduction, and on convection and radiation at the material boundaries. Since engine temperatures are high, radiant emission can be large from within translucent parts and coatings, and this must be included in the analysis. Transient and steady-state behavior are both important. During a transient, radiant penetration provides more rapid internal heating than conduction alone, and the temperature distributions are usually considerably different than for steady-state conditions; this can produce transient thermal stresses.

Analytical and numerical methods are being used at the NASA Lewis Research Center to predict transient temperatures and heat flows in translucent materials. A transient analysis was done for a composite of two translucent layers. The layer refractive indices were larger than 1, producing internal reflections at the boundaries and at the internal interface. In addition, steady-state results were computed for a two-layer composite with one layer opaque. The results were used to assess the importance of internal radiation in a zirconia thermal barrier coating on a cooled metal wall.

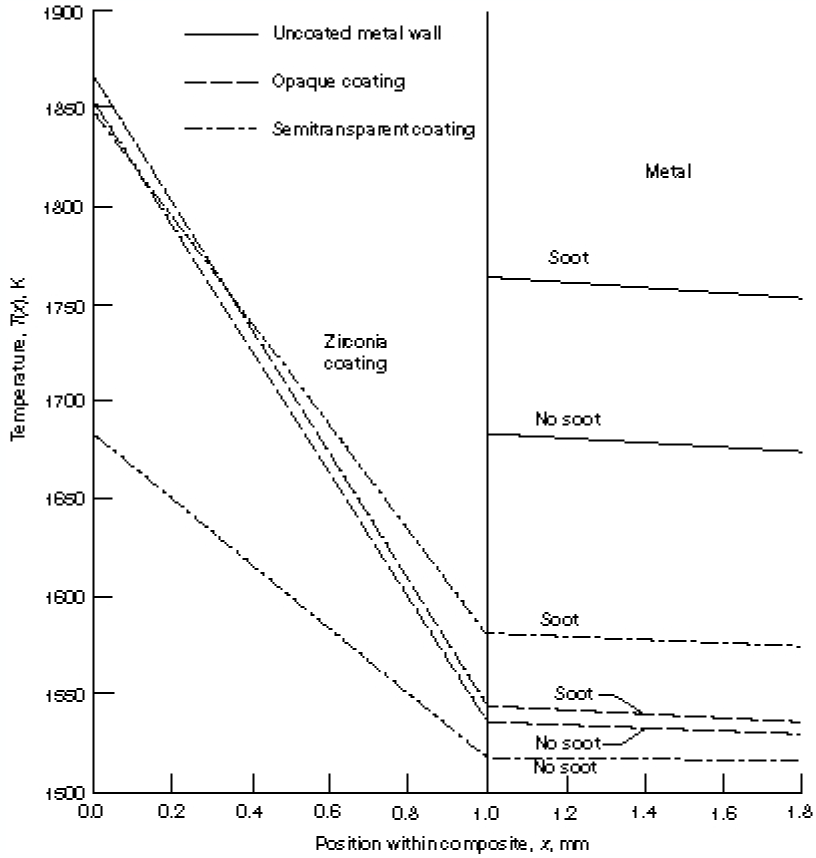
Since the radiative transfer equations are rather complex, especially when internal scattering is included, approximate methods are being investigated that might be convenient for computer design programs. An approximate two-flux method was used and verified by comparisons with solutions that used exact radiative transfer relations. The two-flux equations include scattering without increasing solution difficulty.



*Transient temperatures in a translucent***,** *two-layer composite following the sudden application of radiation to the boundary at x = 0. Scattering in the first layer shields the second layer from incident radiation, resulting in low temperatures in the second layer. (Optical thickness of layer,* k; *refractive index, n; scattering albedo,* W*; thickness of composite, D; and initial temperature,* T_i*.)*

Illustrative transient temperatures are shown in the figure above for a translucent two-layer composite. This demonstrates that scattering in the first layer shields the second layer from incident radiation that is suddenly applied to the boundary at *x* = 0. Simultaneously, both boundaries are strongly cooled by convection. Scattering decreases radiation penetration to the second layer, and the transient temperatures in the second layer remain low. The maximum temperature is in the first layer.

Related behavior is examined in the following figure for a 1-mm-thick zirconia coating on a high-alloy steel combustion liner; zirconia has high scattering. The results are for typical steady-state engine conditions. The solid lines represent an uncoated metal wall, with the lower solid line for metal oxidized on both sides. The upper solid line is for metal covered with soot on the combustion side. The temperatures are above the metal melting point, so a thermal barrier coating would have to be used to protect the metal. For comparison, metal with a zirconia coating assumed opaque so it has no internal radiation (dashed lines) is shown. With the coating, the metal temperature is substantially reduced, and soot on the coating increases metal temperatures only slightly. If the coating can be kept clean, there is an additional benefit when the coating is translucent (dot-dash lines). The high scattering of the clean zirconia coating reflects away much of the incident radiation, and temperatures in the zirconia are decreased (lower dot-dash line), with the temperature of the hot side of the metal reduced about 20 K. If the zirconia is covered with soot, however, the metal temperatures increase. Incident radiation is absorbed by the soot, and the translucence of the zirconia acts like increased thermal conductivity that reduces the insulating ability of the coating (upper dot-dash line).



Combustor liner temperature distributions for oxidized metal without a coating, with an opaque thermal barrier coating, and with a semitransparent thermal barrier coating. All cases shown both with and without soot on the exposed surface.

Bibliography

Siegel, R.: Green's Function and Two-Flux Analysis for Transient Radiative Transfer in a Composite Layer. ASME HTD-Vol. 325, National Heat Transfer Conference, Houston, Vol. 3, 1996, pp. 35-43.

Siegel, R.: Two-Flux Green's Function Analysis for Transient Spectral Radiation in a Composite, AIAA J. Thermophysics Heat Trans., vol. 10, no. 4, 1996, pp. 681-688.

Siegel, R.: Internal Radiation Effects in Zirconia Thermal Barrier Coatings, AIAA J. Thermophysics Heat Trans., vol. 10, no. 4, 1996, pp. 707-709.

Lewis contact: Dr. Robert Siegel, (216) 433-5831, robert.siegel@grc.nasa.gov

Author: Dr. Robert Siegel
Headquarters program office: OA