EFFECT OF SCATTERING ON THE COMBINED REFLECTION AND THERMAL RADIATION EMISSION OF A TYPICAL SEMITRANSPARENT TBC MATERIAL

Charles M. Spuckler
NASA Glenn Research Center
21000 Brookpark Rd.
Cleveland, OH 44135

ABSTRACT

A parametric study was undertaken to examine the effects of scattering on the combined reflection and thermal radiation emission of a typical semitransparent thermal barrier coating material. Some ceramic materials are semitransparent in the wavelength ranges where thermal radiation is important. Therefore, absorption, emission, and scattering of thermal radiation by the layer will affect the heat transfer and temperatures profile. The total radiation leaving one side of the layer is the external radiation reflected back by the interface, radiation emitted internally by the layer and transmitted through the interface, radiation scattered by sites in side the layer and transmitted through the interface, and radiation transmitted through the layer from the surroundings on the opposite side. Total internal reflection of scattered and internally emitted radiation, affects the radiation leaving the layer and the temperature profile. A one dimensional model of a semitransparent layer heated on one side and cooled on the other by convection and radiation is used. The coating is assumed to be gray (absorption and scattering coefficients are not function of wavelength). The absorption coefficient, scattering coefficient, and convective heat transfer coefficient are varied. The total radiation leaving the layer in each direction is presented as a function of scattering for a range of absorption coefficients. Temperature profiles inside the layer are presented showing the effect of scattering and absorption.

INTRODUCTION

Thermal barrier coatings (TBCs) are being developed for use in gas turbine engines. The TBCs can be made more effective by decreasing the heat conducted and/or radiated through them. Some thermal barrier coatings are partially transparent to thermal radiation. For example, zirconia is semitransparent to around 5 μm (refs. 1 and 2). In semitransparent materials, both thermal radiation and heat conduction determine the temperatures and the heat transferred. Scattering, absorption, emission, and the refractive index determine the radiative heat transfer in a semitransparent material. The external and internal reflection of an interface depends on the refractive index of the materials on each side of the interface. If thermal radiation is going from a material with a higher refractive index to one with a lower refractive index, there is a total reflection of the radiation at angles greater than the critical angle. Also, the thermal radiation emitted internally by a material depends on the square of the refractive index. The thermal radiation passing through the interface is decreased by internal reflections, which includes total internal reflection, so the energy emitted by the layer can not exceed that of a blackbody. The refractive index can have a considerable effect on the temperature profile in a layer.

The scattering and absorption coefficients determine the amount of thermal radiation absorbed, emitted, and scattered. These coefficients have units of reciprocal length. The reciprocal of the coefficients can be considered as the mean distance traveled before absorption or scattering occurs (ref. 3 page 424). The smaller the coefficient the larger the distance thermal radiation will travel before being absorbed or scattered. When thermal radiation is absorbed or emitted by a material its temperature changes. Absorption and emission therefore have a direct effect on the temperature of a material. Scattered thermal radiation has no effect on the temperature of a material unless it is absorbed. Scattering in some cases can augment absorption in determining the temperature profiles in a material ref. 4.

Increasing the scattering of a TBC is being considered as a method to improve there performance. A parametric study was performed to determine the effect scattering and absorption has on the thermal radiation reflected and emitted by a gray (absorption and scattering not a function of wavelength) layer. An absorption coefficient of a = 0.1346 cm^{-1} and a scattering coefficient of σ_s = 94.38 cm^{-1} were used as a base line. These coefficients are in the range of those of zirconia in wavelengths where it is transparent ref. 2. Because scattering depends on the material structure and the absorption is affected by impurities and temperature, the absorption and scattering coefficient are increased and decreased from the base line. The thermal radiation reflected, emitted, and transmitted through the layer is presented along with some internal temperature profiles.

MODEL

The model used, Fig. 1, is a semi-infinite surface. There is diffuse radiative and convective

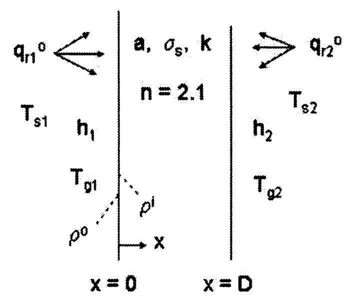

Figure 1 Heat transfer model

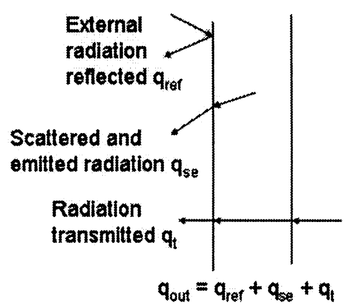

Figure 2 Radiation from layer

heat transfer on each side. The external radiative heating is q_{r1}^o and q_{r2}^o. The hot side gas and surrounding temperatures, T_{s1} and T_{g1}, are 2000K and the cold side temperatures T_{s2} and T_{g2} are 800K. The layer is 1 mm thick and has a thermal conductivity k = 0.8 w/mK. The base line heat transfer coefficients are h_1 = 250 w/m^2K on the hot side and h_2 = 110 w/m^2K on the cold side. These condition were used by Siegel (ref. 5) to determine internal radiation effects in a zirconia based TBC. The refractive index, n, of the layer is 2.1. The surface reflections, ρ, were calculated using Fresnel's equation (see appendix A) for a non-absorbing layer. This assumption is good for the absorption coefficient used here, (refs. 6 and 7). A two flux approximation was used to calculate the thermal radiation coming from the hot and cold sides and the temperature profiles in the layer. The two flux equations and a method of solving them are in ref. 8. The thermal radiation coming from the each side of the layer, q_{out}, is the sum of the incoming thermal radiation reflected back by the interface q_{ref}, the thermal radiation emitted and scattered internally and transmitted through the interface q_{se}, and the thermal radiation from the opposite side transmitted through the layer q_t Fig. 2.

EFFECT OF ABSORPTION AND SCATTERING

The effect of scattering and absorption on the radiation leaving each side of a plane layer is present in Fig. 3. The thermal radiation leaving the layer has been normalized by the thermal radiation incident on the layer from the hot surroundings, so $q_{nout} = q_{out}/\sigma T_{s1}^4$ The thermal radiation leaving the hot side of the layer increases with the scattering coefficient, while the thermal radiation on the cold side decreases with scattering coefficient. The effects of scattering

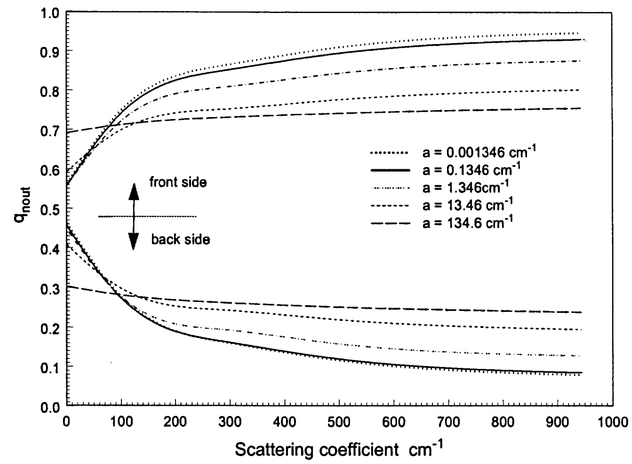

Figure 3. Effect of absorption on the reflected, emitted and transmitted thermal radiation as a function of scattering

on q_{nout} are greater for lower scattering coefficients. As the absorption of the layer increases, the effect of scattering decreases. At the highest absorption coefficient of, a = 134.6 cm^{-1}, the effect of scattering is small. As the absorption increases the thermal radiation leaving the hot side decreases and the thermal radiation leaving the cold side increases, except at lower scattering coefficients where some opposite effects take place. For low scattering, coefficients the radiation out from the hot side at first decreases with absorption and the increases. On the cold side the thermal radiation out increases with absorption for low scattering coefficients.

The effects of scattering on the temperature profiles in the semi-transparent layer are shown in figures 4 and 5. Included in the figures are the temperatures profiles for an opaque and transparent layer (see appendix A for the equations). Figure 4 is for the base line absorption

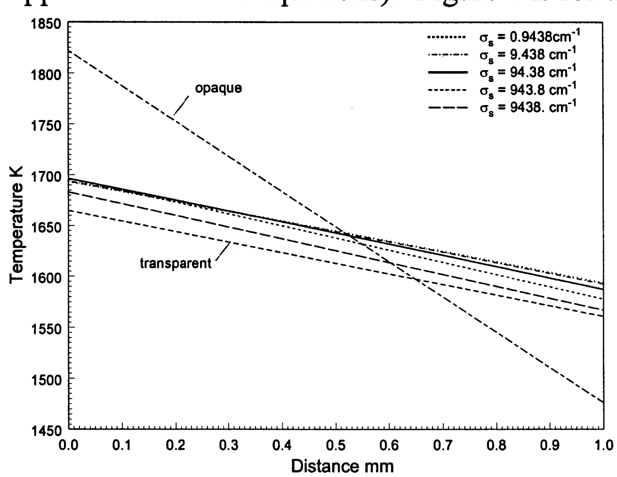

Figure 4. Effect of scattering on temperature profiles for an absorption coefficient of 0.1346 cm^{-1}

coefficient of a = 0.1356 cm^{-1}. The temperatures are nearly the same at the front surface for all but the highest scattering coefficient which is lower and closer to the transparent limit. As the absorption coefficient is reduced the temperatures profiles approach those of a transparent layer. Reducing the absorption coefficient by a factor of 10 to 0.01356 cm^{-1}, results in temperature profiles that are within about 5K of a transparent layer. When the absorption coefficient is reduced by a factor of 100 to 0.001356 cm^{-1} the profiles are about the same as those in a transparent layer.

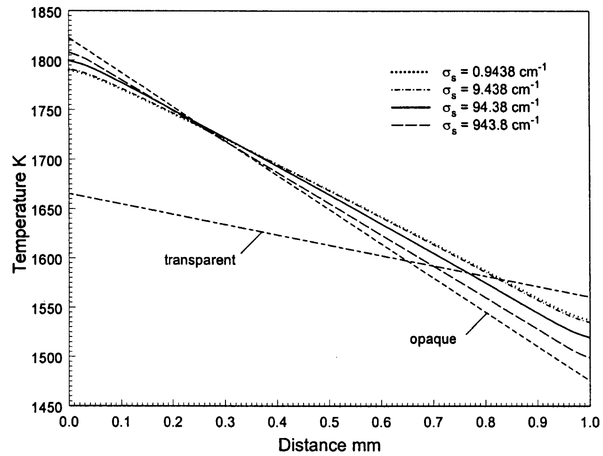

Figure 5. Effect of scattering on themperture profiles for an absorptioncoefficient of 134.6 cm^{-1}

In figure 5 the absorption coefficient of the layer is increased by a factor of 1000 to 134.6 cm^{-1}. The temperature profiles now are approaching the opaque limit. The temperatures near the front side of the layer are lower than those of an opaque layer, while the temperatures near the backside of the layer are higher than those of an opaque layer. As the scattering increases the temperature profiles come even closer to the opaque limit. There is a slight curvature in the temperature profiles near the external surfaces indicating radiation plays a role in the heat transfer process.

Effect of heat transfer coefficient

The effect increasing the heat transfer coefficients from the base line, $h_1 = 250$ w/m^2 and $h_2 = 110$ w/m^2, is shown in figures 6 and 7. The absorption coefficient in figure 6 is the base line 0.1346 cm^{-1}. Increasing the heat transfer coefficient has almost no effect on the thermal

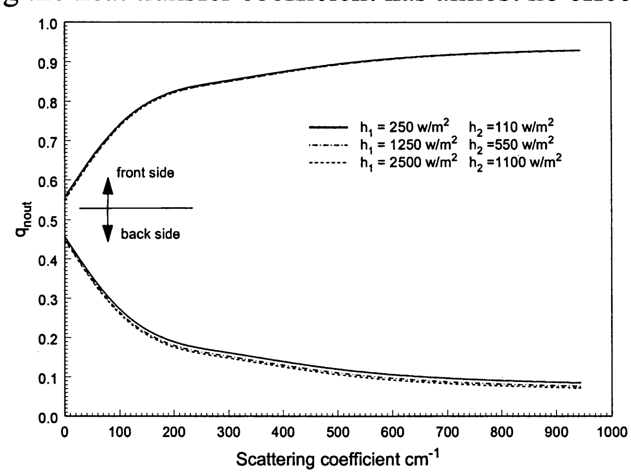

Figure 6. Effect of heat transfer coefficient as a function of scattering for an absorption coefficient of 0.1346 cm^{-1}

radiation leaving the front side of the layer. There is a small effect on the back side, where the thermal radiation leaving decreases slightly with increasing heat transfer coefficient. In figure 7 the absorption coefficient is increased by a factor of 1000 to 134.6 cm^{-1}. Now the thermal radiation leaving the front side increases with the heat transfer coefficient, while the thermal radiation leaving the backside decreases as the heat transfer coefficient increases. The change in q_{nout} with heat transfer coefficient is larger on the back side of the layer than the front side.

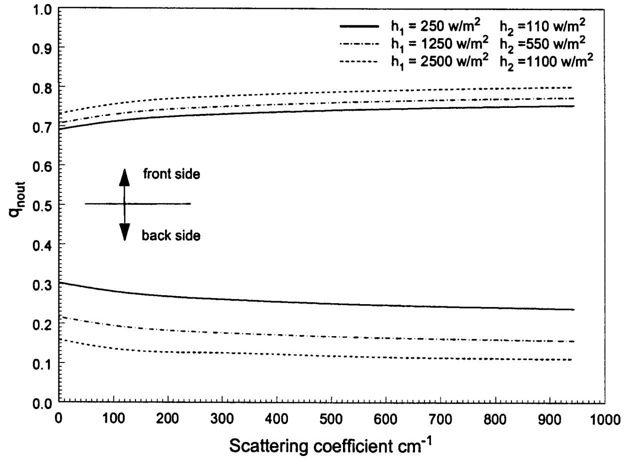

Figure 7. Effect of heat transfer coefficient as a function of scattering for an absorption coefficient of 134.6 cm^{-1}

CONCLUSIONS

Scattering can have a significant effect on the thermal radiation that leaves the surfaces of a semitransparent layer. A parametric study was performed to determine the effects scattering and absorption have on the thermal radiation leaving the surfaces of a semitransparent layer. A one dimensional model was used. There is radiative and convective heat transfer on each side of the layer. The absorption coefficient, scattering coefficient and heat transfer coefficients were varied. As the scattering coefficient increased the thermal radiation leaving the front (hot) side increased and the thermal radiation leaving the back (cold) side deceased. Scattering can be effective in reducing the radiative transfer through a layer for lower absorption coefficients. For high absorption, the absorption process dominates and scattering has little effect. For low absorption the temperature profile approach the transparent limit for all scattering considered. For high absorption, the temperature profiles approach the opaque limit. Increasing the scattering for high absorption brings the profiles even closer to the opaque limit. Increasing the heat transfer coefficient had little effect on the thermal radiation leaving the layer for low absorption. This study indicates that scattering can be effective in reducing the radiative heat transfer in a TBC if the absorption coefficient is not high. A study on the effects of scattering and absorption in a semitransparent layer on a substrate should be done to confirm this and determine the magnitude of these effects for a TBC.

REFERENCES

[1]Wahiduzzaman, S and Morel, T., Effect of Translucence of Engineering Ceramics on Heat Transfer in Diesel Engines, ORNL/Sub/88-22042/2, April 1992.

[2]Makino,T., Kunitomo, T., Sakai, I., and Kinoshita, H., Thermal Radiation Properties of Ceramic Materials, *Heat Transfer-Japanese Research*, **13**, [4] 33-50 (1984)

[3]Seigel. R. and Howell, J. R. *Thermal Radiation Heat Transfer*, 4th ed., Taylor & Frances, New York, 2002

[4]Spuckler, C. M. and Siegel, R., "Refractive Index and Scattering Effects on Radiative Behavior of a Semitransparent Layer," *Journal of Thermophysics and Heat Transfer*, **7**[2], 302-10 (1993)

[5]Siegel, R. "Internal Radiation Effects in Zirconia Thermal Barrier Coatings," *Journal of Thermophysics and Heat Transfer*, **10**[4],707-9 (1996?)

[6]Cox, R. L., "Fundamentals of Thermal Radiation in Ceramic Materials,"; pp. 83-101 in Symposium on Thermal Radiation of Solids, edited by S.Katzoff, NASA SP-55, 1965

[7]Hering, R. G. and Smith, T. F., "Surface Radiation Properties from Electromagnetic Theory," *International Journal of Heat and Mass Transfer,* **11**[10] 1567-71 (1968)

[8] Siegel, R. and Spuckler, C. M., "Approximate Solution Methods for Spectral Radiative Transfer in High Refractive Index Layers," *International of Heat and Mass Transfer,*" **37** [Suppl. 1] 403-13 (1994).

[9]Richmond, J. C., "Relation of Emittance to Other Optical Properties," *Journal of Research ot the National Bureau of Standards*, **67C**[3], 217-26 (1963)

APPENDIX A

Fresnel's equation for a non attenuating dielectric is (ref. 3 page 87)

$$\rho^{o}(\mathrm{n})=\frac{1}{2}+\frac{(3\mathrm{n}+1)(\mathrm{n}-1)}{6(\mathrm{n}+2)^{2}}+\frac{\mathrm{n}^{2}(\mathrm{n}^{2}-1)^{2}}{(\mathrm{n}^{2}+1)^{3}}\ln\left(\frac{\mathrm{n}-1}{\mathrm{n}+1}\right)-\frac{2\mathrm{n}^{3}(\mathrm{n}^{2}+2\mathrm{n}-1)}{(\mathrm{n}^{2}+1)(\mathrm{n}^{4}-1)}+\frac{8\mathrm{n}^{4}(\mathrm{n}^{4}+1)}{(\mathrm{n}^{2}+1)(\mathrm{n}^{4}-1)^{2}}\ln(\mathrm{n})$$

The reflection for radiation going from a higher to lower refractive index material is ref. 9

$$\rho^{i}(n)=1-\frac{1}{n^{2}}\left[1-\rho^{o}(n)\right]$$

The equations for the opaque layer are.

$$q_{tot}=h_{1}\left[T_{g1}-T(0)\right]+\sigma(1-\rho_{o})\left[T_{s1}^{4}-T^{4}(0)\right]$$

$$q_{tot}=\frac{k}{D}\left[T(0)-T(D)\right]$$

$$q_{tot}=h_{2}\left[T(D)-T_{g2}\right]+\sigma(1-\rho_{o})\left[T^{4}(D)-T_{s2}^{4}\right]$$

These equations have to be solved simultaneously.

For a transparent layer radiation has no effect on the temperature in the layer, because is not absorbed or emitted. The equations for a transparent layer are

$$q_{tot}=h_{1}\left[T_{g1}-T(0)\right]$$

$$q_{tot}=\frac{k}{D}\left[T(0)-T(D)\right]$$

$$q_{tot}=h_{2}\left[T(D)-T_{g2}\right]$$