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MATERIALS SCIENCE & ENGINEERING A

Analysis of thermal radiation effects on temperatures in turbine engine thermal barrier coatings

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Abstract

Thermal barrier coatings on combustor liners and on turbine vanes and rotating blades are important for reducing metal temperatures in current and advanced turbine engines. Some coating materials such as zirconia are partially transparent to thermal radiation, and radiation within a coating will increase as temperatures are raised for higher efficiency engines. Hence, it is necessary to determine if radiation effects in a coating are a design consideration. For this purpose, the engine thermal environment is first summarized with regard to factors affecting radiative heat transfer. Radiative and thermal properties of zirconia are then considered, and methods of radiative analysis are briefly discussed. Typical temperature distributions and heat fluxes are given from the analysis of zirconia thermal barrier coatings on vanes and rotating blades, and on a combustor liner where the coating surface is expected to be covered with soot. The effects of various thermal conditions and heat transfer parameters are examined to indicate when radiation effects might be significant within a coating in a turbine engine. The largest effects were found in the combustor where coatings are subjected to large incident radiation. For coatings on turbine blades away from the combustor, and hence without large incident radiation, effects of radiation were found to be very small.

Keywords: Thermal barrier coatings; Thermal radiation effects; Zirconia

1. Introduction

Thermal barrier coatings are important, and in some instances a necessity, for protecting metal parts in high temperature applications such as combustor liners, and turbine vanes and rotating blades for current and advanced turbine engines. Ceramic components being developed for these applications may also require an environmental or thermal protective coating. Some coating materials, such as zirconia which is in widespread use, are partially transparent to thermal radiation [1–4]. A translucent coating permits energy to be transported internally by radiation, thereby increasing the energy transfer above that by conduction alone. This degrades the insulating ability of the coating. Because of the strong dependence of radiant emission on temperature, internal radiative transfer effects are increased as temperatures are raised. Hence the possible significance of internal radiative transfer must be evaluated as temperatures are increased in advanced engines.

The radiative transfer partially depends on the amount of external radiative energy incident on a thermal barrier coating, and this depends on the coating location in the engine. In a combustor there is radiation from the flame, soot, and hot gases to the combustor liner, first stage turbine vanes, and partially to the first stage blades. Within a hot coating there is local internal radiant emission, absorption, and scattering, that act in combination with heat conduction. Further back in the engine away from the combustor, a turbine blade is surrounded by similar cooled blades so external radiative exchange is negligible; however, radiation inside the hot coating needs to be quantified relative to heat conduction.

Internal radiative behavior depends on the properties of the coating material. Zirconia is somewhat translucent for a considerable portion of the radiant energy spectrum at turbine engine temperatures. Heat transfer analyses for translucent zirconia coatings on a cooled metal wall in an turbine engine environment have been made in [5] and [6], and a detailed study was made in

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This paper will briefly summarize the radiative heat transfer conditions in an engine environment needed for computing temperature distributions in translucent thermal barrier coatings, and will briefly review the thermal properties of zirconia. Typical results for temperature distributions and heat flows within zirconia coatings are given for a combustor liner, a turbine vane and a rotating blade. Results including internal radiation in a coating are compared with heat conduction calculations omitting internal radiation. For this limiting condition radiant absorption and emission occur only at the external surface. The results provide insight on when internal radiation may be of concern in zirconia coatings for turbine engine applications.

2. Heat transfer environment in an engine

Radiative behavior is a strong function of temperature level. In a combustor the gas temperature can be in the approximate range of 1700–2000 K. Radiant fluxes from the gas and soot are given in [7] as up to 230000 W m^{-2}; this corresponds to a blackbody temperature of 1419 K. Higher radiative fluxes are expected in advanced engines. With radiative and convective heating, mostly convective for turbine vanes and rotating blades, the surface temperature at the hot side of the thermal barrier coating can be in the range of 1400–1800 K. Since the metal walls are cooled, the temperature decreases through the coating so the metal wall temperature on the hot side might be in the vicinity of 1300 K. Hence the temperature range throughout the coating is approximately 1300–1800 K. The temperature at the hot side of the coating must not be too high to avoid sintering the zirconia and increasing its thermal conductivity during continued operational exposure.

The local distribution of the internal radiation with wavelength, and hence the applicable radiative properties that depend on wavelength, are related to these temperatures. The radiation absorption properties of zirconia show that it is somewhat transparent for radiation in the wavelength range up to at least 5 μm (the 'cutoff wavelength'), and its transparency decreases rapidly for larger wavelengths. For zirconia crystals a translucent range from about 0.35–7 μm was obtained in [8]. The radiative behavior of zirconia depends on the amount of radiative energy within its translucent region. For energy with a blackbody spectrum, Fig. 1 shows the fraction of blackbody energy in the wavelength range up to cutoff wavelengths of $\lambda_c = 5$ and 6 μm. For the typical range of temperatures in a thermal barrier coating, a considerable fraction of the radiant energy is in the partially transparent spectral region. In [7] it was found that 95% of the radiation in a combus- largest radiation from the soot was in the range from $\lambda = 0.5$–4 μm. This indicates that at its hot side, a zirconia coating will be translucent for close to 90% of blackbody radiation emitted at the hot-side temperature. At the cooler side this decreases to perhaps 70% depending on the temperatures involved. Hence, internal radiation effects diminish somewhat as energy is transferred through the coating. Fig. 1 demonstrates in a qualitative way that radiative effects may be present in zirconia in an engine environment.

There are two sources for radiative transport within a coating. One is the transmission through the exposed coating surface of external radiation from hot combustion gases and soot. This penetrates into the coating and provides an internal heat source. The other is internal emission from within the hot coating itself, and the transport of radiation between volume elements of the hot coating by successive processes of emission, absorption and reemission, and by scattering. On the external surface of a coating in a combustor there is likely to be a soot deposit. Since soot is highly internally absorbing, a thin layer can eliminate direct transmission of external radiation into the zirconia coating. Incident radiation is absorbed by the soot, and there is reradiation into the coating and back into the combustor. In the coating, energy transfer continues by combined radiation and conduction.

For the exposed portions of a first stage vane, the conditions may be somewhat the same as for a combustor liner, as the vane would become somewhat coated with soot. Further into the blade rows away from the combustor, each cooled blade is surrounded by other

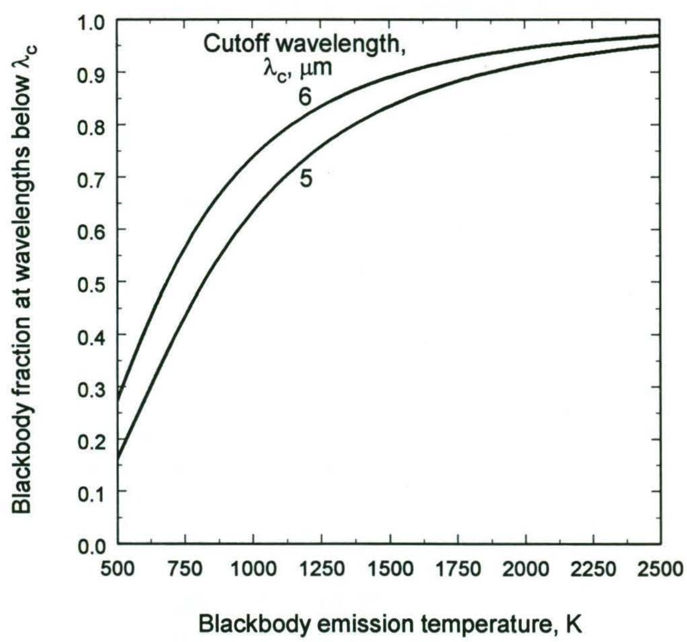

Fig. 1. Fraction of blackbody radiation in the wavelength range from

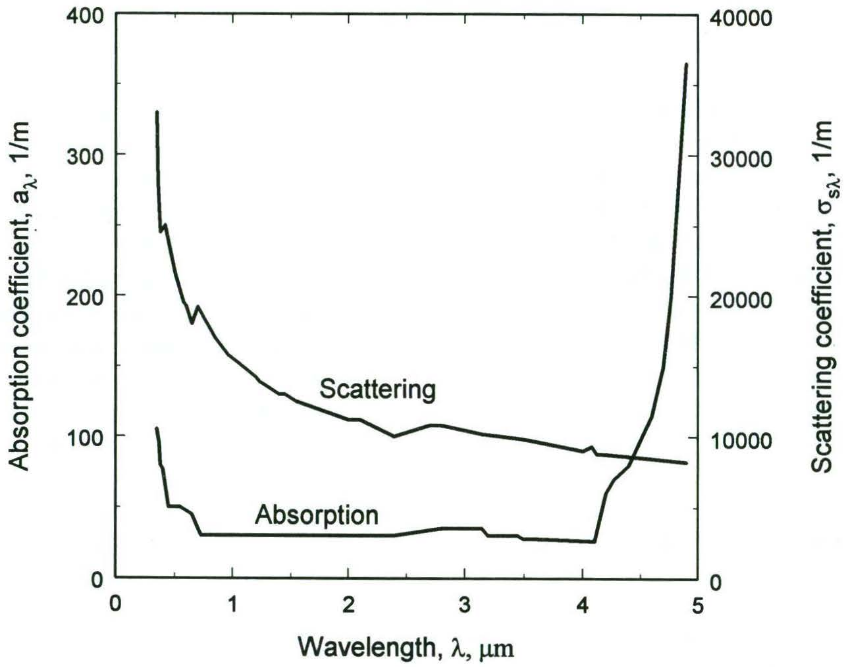

Fig. 2. Example of spectral absorption and scattering coefficients for zirconia.

similar cooled blades. There is very little radiative exchange between the blades, and radiative effects are produced only internally since the coating is hot and its volume is emitting. In the blade rows, this will be shown to have a small effect on temperature distributions for the engine conditions considered here; heat conduction is dominating for these conditions.

3. Heat transfer properties for a zirconia thermal barrier coating

For thermal barrier coatings in an engine, heat conduction is generally more dominant than radiation; hence, the thermal conductivity of zirconia is very important for estimating temperature distributions and heat flows. Unfortunately it is difficult to select a precise value because conductivity can vary with porosity, temperature, and with the time that the coating is in high temperature operation because of sintering its porous structure. The thermal conductivity for plasma sprayed zirconia is given in [9–14], and values range from 0.2 to 3.5 W m^{-1} K^{-1} (values as low as 0.2 W m^{-1} K^{-1} are unusual in practice); this range will yield large differences in predicted heat transfer performance. For consideration in turbine engines it is common to use values of $k_c = 0.8$–1 W m^{-1} K^{-1} for plasma spray coatings; in [1] $k_c = 0.8$ W m^{-1} K^{-1} was selected for diesel engine cylinder coating studies. In the present study most of the calculations are for $k_c = 0.8$ W m^{-1} K^{-1}, and the effect of conductivity is demonstrated by comparing with some results for $k_c = 2$ W m^{-1} K^{-1}

To predict thermal performance, radiative absorption and scattering properties of zirconia are required. Absorption and scattering coefficients define how rapidly radiation traveling along a path decays in an exponential manner. Both coefficients depend on the radiation wavelength. Some results from [1] are in Fig. 2. As evident from the left and right ordinates, at wavelengths between approximately 0 and 5 μm, scattering is much larger than absorption. Absorption is the means of direct interaction of radiation with the energy equation, and the local radiant emission from a volume element also depends on the absorption coefficient. The results in Fig. 2 are for one type of zirconia, and there is no assurance that these properties are characteristic of zirconia deposited in different ways or that has been sintered by being at high temperatures for extended periods of time. The results show that absorption is relatively low for small wavelengths up to about 5 μm, and becomes large for greater wavelengths.

Another important radiative property is the coating refractive index; this is because internal radiant emission depends on the refractive index squared. A larger refractive index also increases external and internal reflections from boundaries that are not covered with soot. Increased internal reflections lead to trapping of radiation within the material by multiple internal reflections. The refractive index of zirconia has been reported to have a range of values. In [1] values were from $n = 1.2$ to $n = 2.5$, and $n = 1.58$ was selected for calculations of zirconia coatings in a diesel engine cylinder. The values in [15–17] are within the range of $n = 2.0$–2.3, and in [8] $n = 2.11$–2.17 for zirconia crystals. For the calculations in [2], $n=1.6$ was used. To show the effect of n, results are given here for $n=1.58$ and $n=2.1$, which are typical of values in the references.

The refractive index is a factor in the optical relations that can be used to estimate the reflectivity at an interface with another material. The nature of the reflection at the surface of a clean coating, such as being diffuse or partly directional, is difficult to define accurately. There is also uncertainty in the amount of reflection at the zirconia–metal interface where there is a thin bond coat. This contributes to internal reflections that are included in the radiative boundary conditions. Note that the emissivity from the metal wall into the zirconia differs from that for the same metal into air because the zirconia refractive index is larger than one. Tabulated emissivities such as in textbooks [18] are for emission into air or vacuum that have a refractive index of one.

4. Heat transfer equations and simplifying assumptions

A brief outline of heat transfer relations is given here with the nomenclature in Appendix A. The relations consist of the energy equation that has conduction and radiation terms, and boundary relations with convection, conduction, and radiation. The two-flux method that has been found very useful to provide the radiative flux term in the energy equation, is briefly described in Appendix B, and additional relations are in [1], [5], [6], [19], and [20]. The relations are given in terms of frequency, which is convenient for analysis because frequency does not change when radiation travels into a material with a different refractive index.

A translucent thermal barrier coating is considered on a metal wall, Fig. 3. The zirconia and metal layers have thicknesses δ_c and δ_m. The gas temperatures on the two sides of the wall are T_{g1} and T_{g2}, and there is external convection on each side with heat transfer coefficients h_1 and h_2. Depending on the location in the engine, the external surface of the coating can be clean or have a thin opaque layer of soot. For an advanced engine the combustion chamber pressure is high enough that the combined gas and soot radiation is approximated as providing a black environment at a temperature T_{s1}. When the coating is soot covered, the outer surface of the soot has a total heat flux through it that consists of the external convection combined with the net radiation equal to absorption from the surroundings minus reemission:

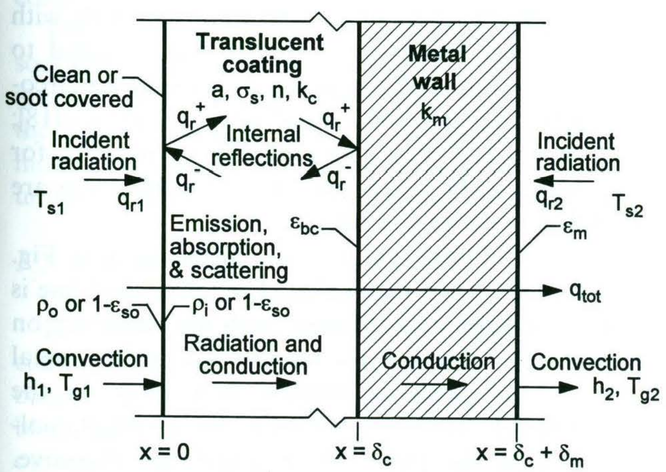

Fig. 3. Geometry and nomenclature for a thermal barrier coating on a metal wall with and without soot on the exposed surface of the coating, and with external radiation and convection at both outer

$$q_{tot} = h_1(T_{g1} - T_{so}) + \epsilon_{so}\sigma(T_{s1}^4 - T_{so}^4) \quad (1a)$$

where the soot emissivity, ϵ_{so}, can be assumed independent of frequency.

The soot is very thin so the very small temperature variation through its thickness is neglected. At the interface of the soot and the translucent coating, the radiative flux within the coating in the positive x direction consists of emission by the soot into the coating, and the small reflection by the soot of radiation incident at the coating–soot interface from the negative x direction. Then, for a frequency interval $d\nu$:

$$q_{\nu r}^{+}(0)\,d\nu = \epsilon_{so} n^2 e_{\nu b}(0)\,d\nu + (1-\epsilon_{so}) q_{\nu r}^{-}(0)\,d\nu \quad (1b)$$

If the coating surface is clean, as expected for vanes and rotating blades after the first few rows away from the combustor, the radiation in the positive x direction at the surface ($x=0$) inside the coating is composed of incident external radiation, $q_{\nu r1}\,d\nu$, transmitted through the surface, and the reflection of radiation from the negative x direction inside the thermal barrier coating:

$$q_{\nu r}^{+}(0)\,d\nu = (1-\rho_o) q_{\nu r1}\,d\nu + \rho_i q_{\nu r}^{-}(0)\,d\nu \quad (1c)$$

Within the translucent coating the energy equation states that the total heat flux consists of the sum of conduction and radiation, and is constant (not a function of x):

$$q_{tot} = -k_c \frac{dT_c(x)}{dx} + \int_{\nu=0}^{\infty} q_{\nu r}(x)\,d\nu = \text{constant} \quad (2)$$

The integral for radiative flux is evaluated only in the translucent spectral regions. The radiative flux $q_{\nu r}(x)$ is obtained from the approximate two-flux method in Appendix B. The $q_{\nu r}(x)$ in the coating depends on the local blackbody emission that depends on the local temperature. Since the temperature distribution is unknown, an iterative procedure is usually required to simultaneously obtain the spectral radiative flux $q_{\nu r}(x)$ and the temperature distribution $T_c(x)$ in the coating.

At the interface $x=\delta_c$ between the translucent coating and the metal, the temperature distribution is con-

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