EFFECT OF AN OPAQUE REFLECTING LAYER ON THE THERMAL BEHAVIOR OF A THERMAL BARRIER COATING

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ABSTRACT

A parametric study using a two-flux approximation of the radiative transfer equation was performed to examine the effects of an opaque reflective layer on the thermal behavior of a typical semitransparent thermal barrier coating on an opaque substrate. Some ceramic materials are semitransparent in the wavelength ranges where thermal radiation is important. Even with an opaque layer on each side of the semitransparent thermal barrier coating, scattering and absorption can have an effect on the heat transfer. In this work, a thermal barrier coating that is semitransparent up to a wavelength of 5 micrometers is considered. Above 5 micrometers wavelength, the thermal barrier coating is opaque. The absorption and scattering coefficient of the thermal barrier was varied. The thermal behavior of the thermal barrier coating with an opaque reflective layer is compared to a thermal barrier coating without the reflective layer. For a thicker thermal barrier coating with lower convective loading, which would be typical of a combustor liner, a reflective layer can significantly decrease the temperature in the thermal barrier coating and substrate if the scattering is weak or moderate and for strong scattering if the absorption is large. The layer without the reflective coating can be about as effective as the layer with the reflective coating if the absorption is small and the scattering strong. For low absorption, some temperatures in the thermal barrier coating system can be slightly higher with the reflective layer. For a thin thermal barrier coating with high convective loading, which would be typical of a blade or vane that sees the hot sections of the combustor, the reflective layer is not as effective. The reflective layer reduces the surface temperature of the reflective layer for all conditions considered. For weak and moderate scattering, the temperature of the TBC-substrate interface is reduced but for strong scattering, the temperature of the substrate is increased slightly.

INTRODUCTION

Thermal barrier coatings (TBCs) are being developed for use in gas turbine engines. 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, for thermal radiation purposes zirconia can be semitransparent up 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 between two semitransparent materials 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 the material depends on the square of the refractive index. The internal thermal radiation passing through the semitransparent interface is decreased by internal surface reflections, which

includes total internal reflection, so the energy emitted by the semitransparent layer can not exceed that of a blackbody. If there is an opaque layer on the semitransparent material the radiation emitted into the material depends on the refractive index squared and the emissivity of the opaque layer. The refractive index can have a considerable effect on the temperature profile in a semitransparent layer.

The scattering and absorption coefficients determine the amount of thermal radiation absorbed, emitted, and scattered by a semitransparent material. 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 the absorption because it increases the path length of radiation through the material. Here scattering will act as additional absorption in determining the temperature profiles in a material ref. 4.

Putting a highly reflecting layer on the TBC is being considered as a method to improve their performance by reducing the radiative heat flux through the TBC. In reference 5 a gray semitransparent highly reflectance multilayered TBC system was designed and modeled. The results indicate the coating has potential for reducing the metal temperature. Here an opaque reflecting layer is considered. The absorption coefficient, scattering coefficient, and index of refraction still determine the radiative heat transfer through the semitransparent layer even though it is between opaque layers. Because scattering depends on the material structure and the absorption is affected by impurities and temperature, the absorption and scattering coefficients are increased and decreased from the base line values of a = 0.1346 cm^{-1} for the absorption coefficient and σ_s = 94.38 cm^{-1} for the scattering coefficient. These coefficients are a wavelength integrated average of those in ref. 2 for zirconia in wavelengths where it is semitransparent. The thermal behavior of a TBC with a highly reflecting opaque layer is compared to a normal TBC as a function of scattering and absorption.

MODEL

The models used, figure 1, are semi-infinite semitransparent layers on a substrate. One semitransparent layer does not have a reflective coating and the other has an opaque reflective coating. The semitransparent layer is semitransparent for thermal radiation up to 5 μm. For radiation above 5 μm the semitransparent layer is opaque. There is diffuse radiative and convective heat transfer on each side of the layers. The external radiative heating is q_{r1}^o and q_{r2}^o. The hot side gas and surrounding temperatures, T_{s1} and T_{g1}, cold side temperatures T_{s2} and T_{g2}, heat transfer coefficients, thickness of reflective coating d_{rf}, TBC thickness $d_{TBC,}$ and substrate thickness d_{sub} are given in Table 1. TBCs of the type that would be on a combustor liner and on a blade or vane are considered. For both the combustor and the blade and the emissivity of the back side of the metal substrate, ε_m, is 0.6. The thermal conductivity of TBC and the substrate are 0.8 w/mK and 33 w/mK. These conditions including those in Table 1 except for the reflective layer thickness were used by Siegel (ref. 6) to determine internal radiation effects in a zirconia based TBC. The thermal conductivity of the reflective coating, which is based on a dense zirconia-alumina multilayer coating, is 2.8 w/mK. The refractive index, n, of the semitransparent layer is 2.1. The refractive index of the gas is assumed to be one. The
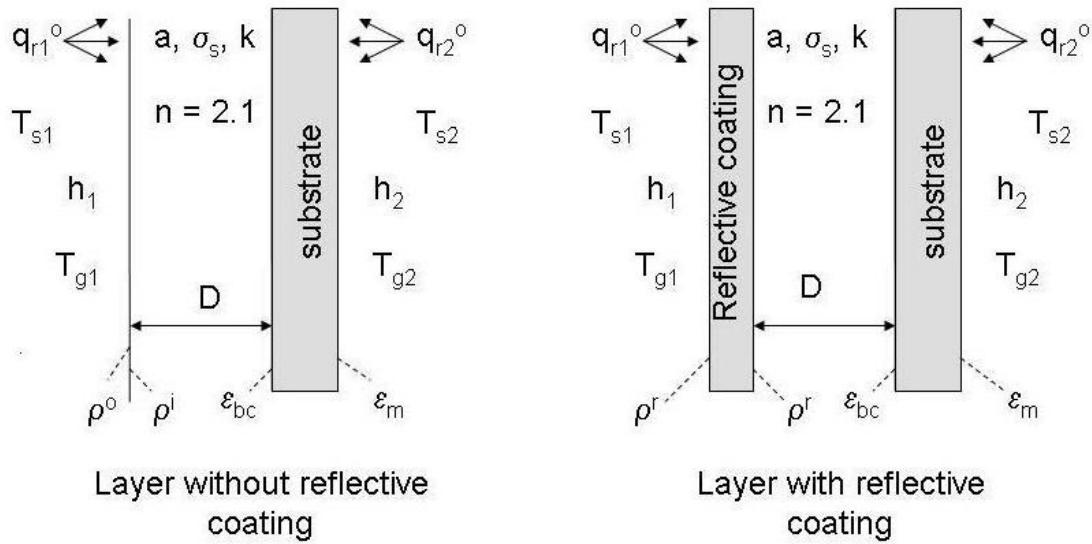
Figure 1 Heat transfer model

emissivity of the bond coat ε_{bc} is 0.3. The reflectance on both sides of the opaque highly reflective coating ρ^r is assumed to be 0.9. The external surface reflection for the layer without a reflective coating, ρ^o, was calculated using Fresnel's equation for a non-absorbing layer. This assumption should be good for the absorption coefficients used here (ref. 7 and ref. 3 page 88). The internal surface reflection, ρ^i, for the uncoated TBC was determined from a relationship

Table 1

	T_{s1} K	T_{g1} K	T_{s2} K	T_{g2} K	h_1 w/(m²·K)	h_2 w/(m²·K)	d_{rc} mm	d_{TBC} mm	d_{sub} mm
Combustor	2000	2000	800	800	250	110	0	1.0	0.794
Combustor	2000	2000	800	800	250	110	0.111	0.889	0.794
Blade	2000	2000	1000	1000	3014	3768	0	0.25	0.762
Blade	2000	2000	1000	1000	3014	3768	0.111	0.139	0.762

using the refractive index and external surface reflection in ref. 8. A two flux approximation to the radiative transfer equation was used to calculate the heat flux and the temperature profiles. The boundary conditions for the two flux equations in ref. 9 were modified to account for the opaque substrate and reflective coating.

EFFECT OF ABSORPTION AND SCATTERING ON COMBUSTOR LINER TBC WITH AND WITHOUT AN OPAQUE HIGHLY REFLECTIVE COATING

Temperature profiles

The temperature profiles in the TBC and substrate for a system with and without a highly reflective coating on a combustor liner as a function of absorption are shown in figure 2 for the base line scattering coefficient of 94.38 cm⁻¹. The temperature in the TBC and substrate decrease significantly when a 0.111 mm. opaque layer with a reflectivity of 0.9 is used. Depending on the absorption the decrease in the gas-TBC interface temperature is between about 127 K for 0.0013 cm⁻¹ absorption coefficient and 277 K for 67.26 cm⁻¹ absorption coefficient.

The TBC-substrate interface temperature decrease is approximately 173 K for 0.0013 cm^{-1} absorption coefficient and 213 K for 13.46 cm^{-1} absorption coefficient. The temperature
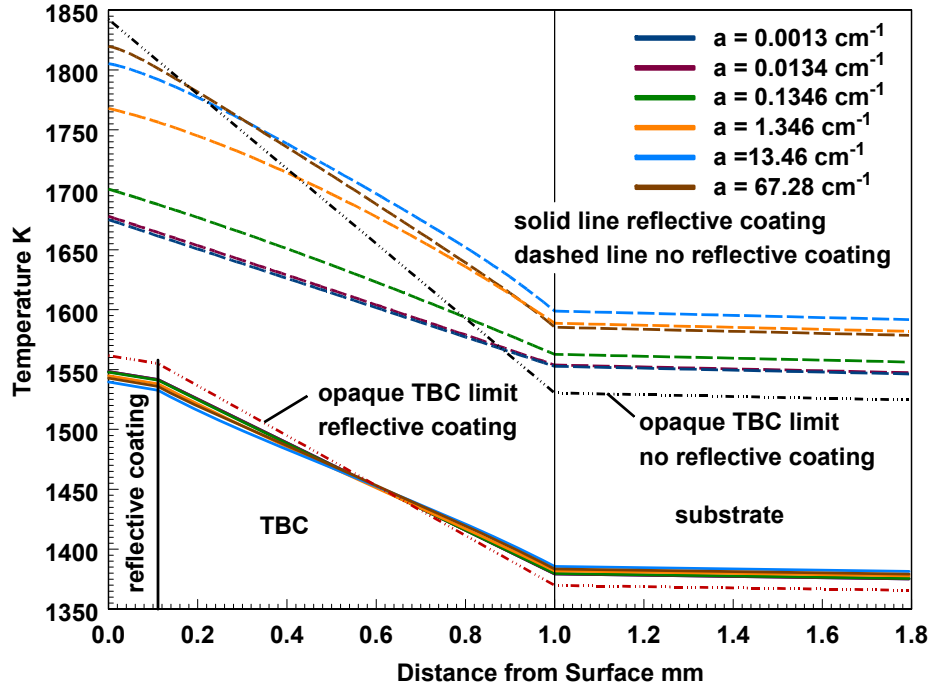

Figure 2. Temperature profiles in reflective coating, TBC, and combustor liner as a function of absorption for $\sigma_s = 94.38$ cm^{-1}.

difference due to a change in absorption also decreases significantly with a reflective coating compared to no reflective coating. Without a reflective coating the temperature change at the gas-TBC interface due to varying the absorption is about 145 K compared to 9 K with a coating. At the TBC-substrate interface, this temperature change is about 46 K without the reflective coating and about 6 K with the coating. Also, for this scattering coefficient, when there is no reflective coating the curvature of the temperature profiles indicate thermal radiation is playing a role. When an opaque reflective coating is present the thermal radiation role is decreased.

Interface temperatures and heat flux

The effect of a highly reflective coating compared to no coating on the gas-TBC interface temperature as a function of absorption and scattering is presented in figure 3. The reflective coating reduces the gas-TBC interface temperatures significantly for higher absorption and all scattering considered. For lower absorption the effects of the reflective coating are reduced as the scattering is increased. For very low absorption and very strong scattering (high scattering coefficients) the gas-TBC interface temperatures are about the same for layers with and without a reflective coating. When a reflective coating is applied to a semitransparent layer the effects of absorption and scattering on the gas-TBC interface temperatures are reduced significantly compared to the uncoated TBC. Only for weaker scattering (smaller scattering coefficients) does absorption have an effect on the gas-TBC interface temperature when an opaque reflective
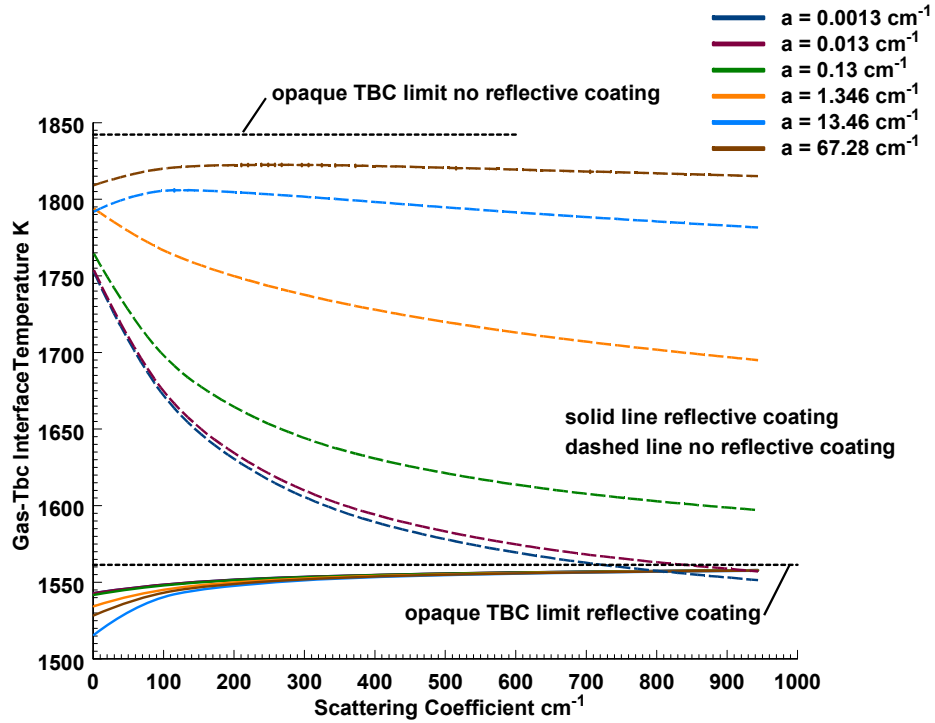
Figure 3. Gas-TBC interface temperature as a function of scattering and absorption for a TBC on a combustor liner

coating is present. The opaque limit shown in the figure is the temperature the TBC-gas interface would have if the TBC was opaque. For both the TBC without the reflective coating and the layer with the reflective coating the gas-TBC interface temperatures are less than the opaque limit, but for the TBC with a reflective coating the temperatures are approaching the opaque limit for strong scattering (higher scattering coefficients).

The temperatures of the TBC-substrate interface for two the layers are shown in figure 4. There is a large decrease in the TBC substrate interface temperature for weak scattering when a reflective coating is used. This temperature difference can be as high as 289 K. For very strong scattering and very low absorption this temperature difference decreases to around 10 K. The temperature difference decreases as scattering increases for all except the highest absorption and low scattering where the temperature difference decreases as absorption increases. When there is a reflective coating the effect of absorption and scattering is decreased substantially compared to a TBC without a reflective coating. For the layer with a reflective coating the effect of absorption decreases with scattering and only with weaker scattering is there an effect. For a TBC without a reflective coating the effect of absorption in general increases as the scattering increases. For a layer with an opaque reflective coating the TBC-substrate temperatures are higher for semitransparent TBC than an opaque TBC. For the TBC without the opaque reflective layer the TBC-substrate temperatures are lower than the opaque limit for some scattering and absorption coefficients. This was shown before in ref 10. The TBC-substrate interface temperature for a semitransparent TBC being higher than the opaque limit indicates an opaque TBC would perform better for these scattering and absorption conditions. The temperature profiles for the back of the substrate are similar to the TBC-Substrate temperatures and not presented here.
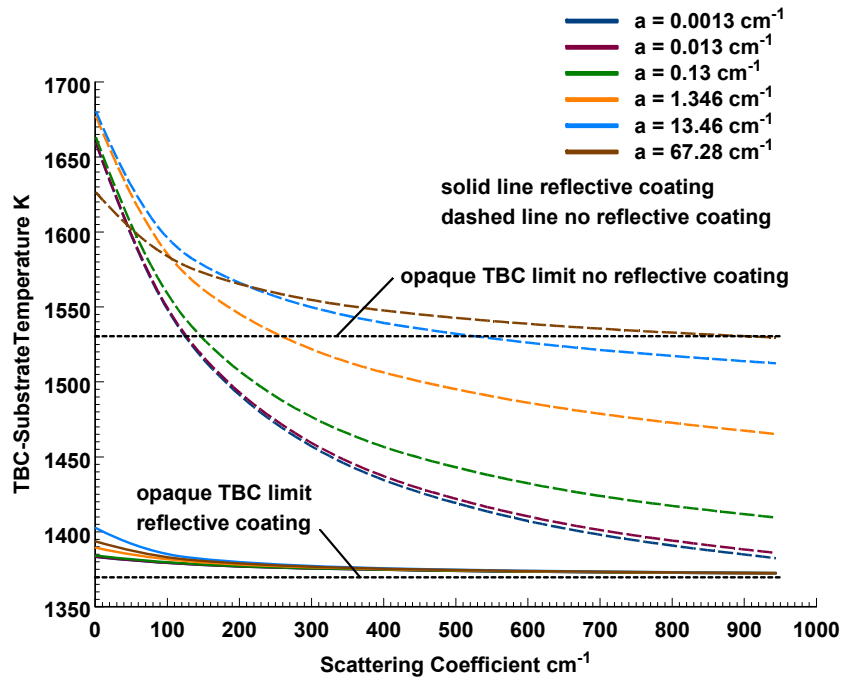
Figure 4 TBC-substrate interface temperatures as a function of scattering and absorption for a TBC on a combustor liner

The heat flux for layers with and without a highly reflective opaque layer as a function of absorption and scattering is shown in figure 5. The profiles and results are similar to the TBC -
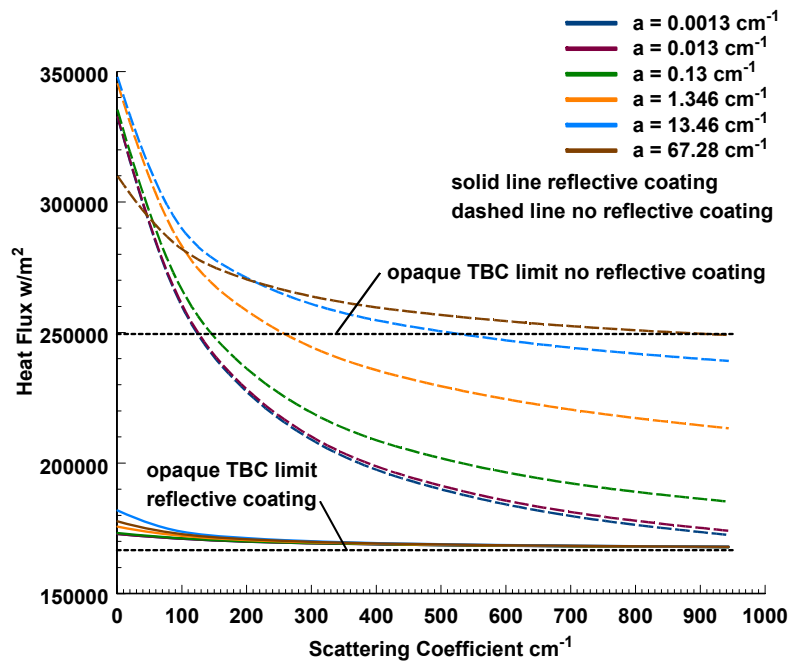

Figure 5 Heat flux as a function of scattering and absorption for TBC on a combustor liner

substrate temperatures. There is a significant decrease in the heat flux through the layer when a

highly reflective coating is used especially for smaller scattering coefficients. The difference in heat flux decreases as the scattering coefficient is increased and decreases as the absorption coefficient is decreased except for the highest absorption coefficient and lower scattering coefficients. The effects of scattering and absorption are small and decrease as the scattering coefficient is increased when there is a reflective coating on the TBC. When there is no reflective coating on the TBC the effects of scattering and absorption can be large. With a reflective coating, the heat flux for a semitransparent TBC is larger than an opaque TBC with a reflective coating. This means it would be better to have an opaque TBC as far as the heat flux is concerned. With no reflective coating the heat flux for the semitransparent TBC is higher mainly for lower scattering coefficients. For the conditions where the heat flux is higher than the opaque limit, an opaque TBC would perform better.

EFFECT OF ABSORPTION AND SCATTERING ON BLADE OR VANE TBC WITH AND WITHOUT AN OPAQUE HIGHLY REFLECTIVE COATING

Temperature profiles
    The temperature profiles for a TBC and substrate system for a vane or blade with and without a reflective coating are shown in figure 6. The thickness of the TBC is decreased from
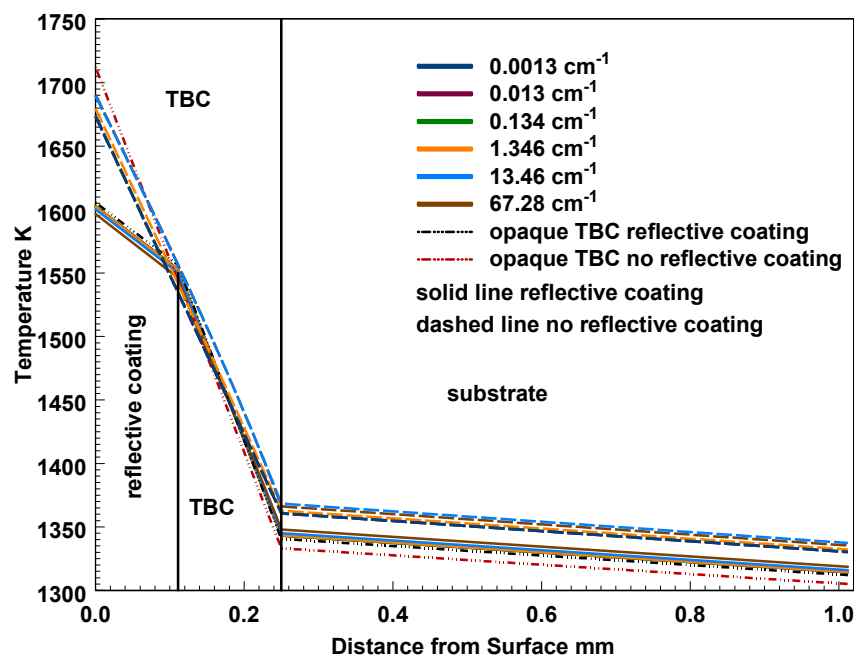

Figure 6 Temperature profiles in reflective coating, TBC, and blade or vane as a function of absorption for σ_s = 94.38 cm^{-1}.

that of a combustor and the convective loads are increased.   Here the reflective coating is nearly half of the TBC thickness. The vane and blades are at the front of the turbine so they have a high radiation load for the combustor and soot. When a reflective coating is on the TBC, the surface temperature of the TBC for the base line scattering coefficient of 94.38 cm^{-1} is reduced between

70 and 94 K depending on the absorption. The temperature at the back of the reflective coating is about the same as that of a TBC with out a reflective coating at the same distance 0.111 mm. The TBC-substrate interface temperature decreases between 17 and 24 K depending on the absorption coefficient. The decrease in temperature at the back surface is between 15 and 22 K which is similar to the TBC-substrate interface temperature drop.

Interface temperatures and heat flux

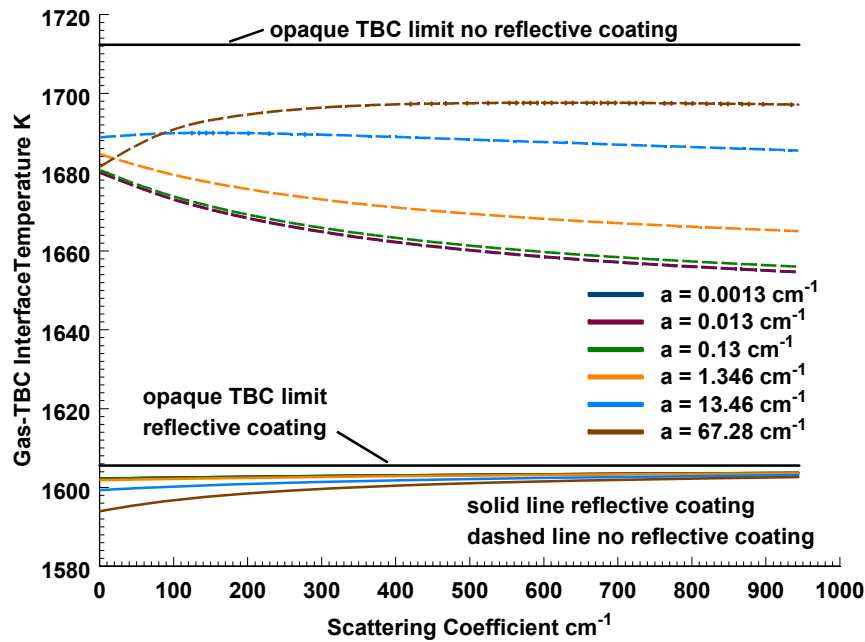The effect of scattering and absorption on the gas-TBC and gas-reflective coating

Figure 7. Gas-TBC interface temperature as a function of scattering and absorption for vane or blade

interface temperatures is shown in Figure 7. When there is no reflective coating, the temperature decreases with scattering except for the two highest absorptions coefficients used where the temperatures at first increases with scattering then decreases. The temperature increases with absorption except for the highest absorption used with weak scattering. The effects of absorption are small for absorption coefficients between 0.0013 cm^{-1} and 0.13 cm^{-1}. When there is a reflective coating the effect of absorption on the temperature is small and decreases as the scattering increases. For weak scattering the temperature variation due to absorption is about 12 K. For strong scattering there is essentially no temperature difference. For the TBC without a reflective coating and the TBC with the reflective coating the gas-surface interface temperature is lower than those that would occur if the TBC was opaque. The reduction in the gas TBC interface temperature with a reflective coating can be as high as about 97 K and as low as about 51 K depending on the scattering and absorption.

The temperature of the TBC-substrate interface as a function of scattering and absorption for a layer with and without a reflective coating are shown in Figure 8. The TBC-substrate interface temperature decreases with increased scattering and increases with increased absorption

for a TBC with and without a reflective layer. The only exception is for a layer without a reflective coating where the temperature decreases for the highest absorption used when the scattering is moderate to weak. For weak scattering the TBC-substrate interface temperature is at most 40 K lower with a reflective coating. For strong scattering this reverses and the interface temperature is nearly 19 K lower without the reflective coating. For the TBC with the reflective layer the TBC-substrate interface temperature is slightly higher than the temperature that would occur if the TBC was opaque. For strong scattering and low absorption the temperature for the layer without a reflective coating is lower than the opaque limit. This indicates that for some conditions considered an opaque TBC without a reflective coating would perform better than a
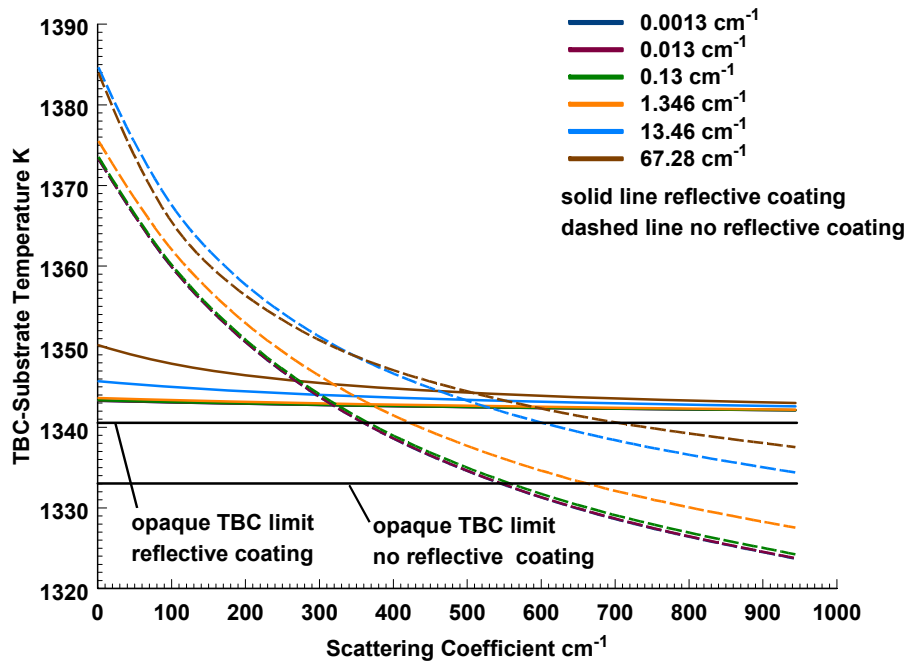

Figure 8 TBC-substrate interface temperatures as a function of scattering and absorption for a TBC on vane or blade

semitransparent TBC with or without a reflective coating if the thermal conductivity remained the same. It is also interesting to note that the temperature for an opaque TBC with a reflective coating is slightly higher that an opaque layer without a reflective coating. This is caused by the higher thermal conductivity coating taking up nearly half of the TBC thickness. Using a simple opaque analysis may give some insight on what thickness of a reflective coating can be tolerated. For the back of the substrate the results are similar to those for the TBC-substrate interface and are not presented.

The heat flux as a function of scattering and absorption is given in figure 9. The profiles and the results are similar to those for the TBC-substrate interface temperatures. For a TBC without a reflective coating the heat flux decreases as the scattering increases. The heat flux also increases as the absorption increases except the largest absorption coefficient when the heat flux decreases when the absorption is increased for weak to moderate scattering. When there is a

reflective layer on the TBC the heat flux decreases as the scattering increases and in general increases as the absorption is increased. When there is a reflective coating, the effects of scattering on the heat flux are decreased significantly compared to a TBC without a reflective coating. Also the effects of absorption are reduced for strong scattering when a reflective coating is used. Here as with the TBC-substrate interface temperatures, the heat flux for a TBC with a reflective coating is decreased for weak to moderate scattering. For moderate to strong scattering depending on the absorption, the TBC without a reflective coating has a lower heat
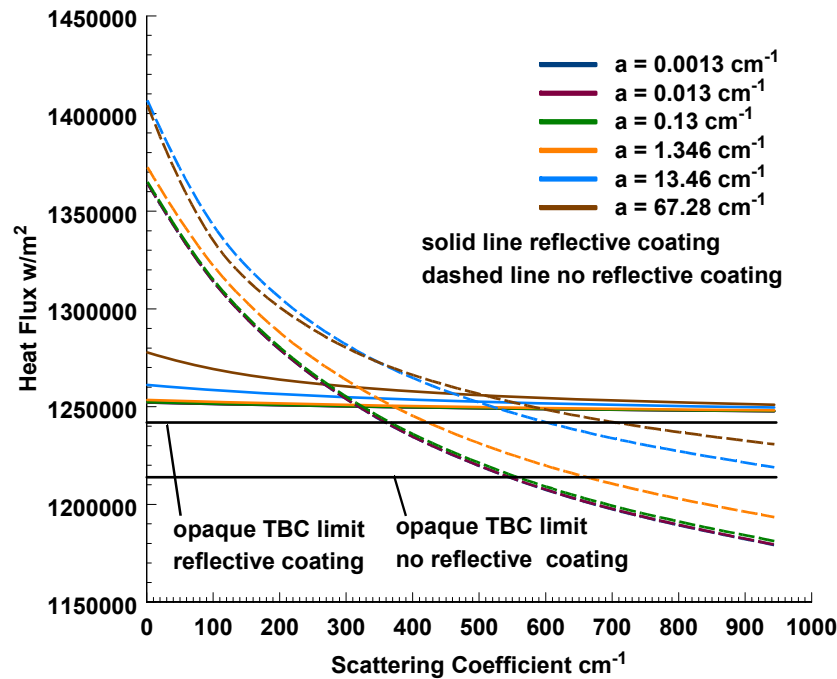

Figure 9. Heat flux as a function of scattering and absorption for TBC on a vane or blade

flux. For a TBC without a reflective coating with strong scattering and low to moderate absorption, the heat flux is lower than that of an opaque TBC. Here like the TBC- substrate temperatures, the heat flux for an opaque TBC with a reflective coating is higher than the heat flux for an uncoated opaque TBC. Also an opaque TBC will perform better than a semitransparent TBC over some of the conditions considered if the thermal conductivity remains the same. It seems like the scattering and absorption condition at which the change in performance occurs is the same for TBC-substrate temperatures and the heat fluxes.

SUMMARY AND CONCLUSIONS

A parametric study using a two-flux approximation to the radiative transfer equation was performed to examine the effects of an opaque reflective layer on the thermal behavior of a typical semitransparent thermal barrier coating on an opaque substrate as a function of scattering and absorption of the TBC. A one dimensional model was used. A TBC 1 mm thick on a 0.794 mm thick substrate with lower convection coefficients was used for the combustor TBC model. A 0.25 mm thick TBC on a 0.762 mm substrate with high convection coefficients was used to model the vane or blade TBC. The highly reflective coating was 0.111mm thick and this

reduced the thickness of the underlying TBC to keep the total coating thickness unchanged. The substrate emissivity was 0.3 on the TBC side and 0.6 on the back side. The highly reflective coating has a reflectivity of 0.9 on both sides. The TBC was semitransparent up to 5 μm. Above 5 μm the TBC was opaque. There is radiative and convective heat transfer on each side of the layers. The absorption and scattering coefficients were varied.

For a combustor with a 1.0 mm thick TBC and convection coefficients 250 w/m^{2}K on the hot side and 110 w/m^{2}K on the cold side, the use of a 0.9 reflectivity coating 0.111 mm thick as part of the TBC can be effective in reducing the temperatures and heat flux in a TBC. The reflective coating is very effective at weak or low scattering at all absorption coefficients considered. For these conditions the gas-layer interface temperature decrease can be as high as about 280 K. For moderate to low absorption, the effectiveness of the uncoated semitransparent TBC increases with scattering so that adding a highly reflective coating does not add a significant benefit. For low absorption and strong scattering the gas-layer interface temperature can be higher with a reflective coating than without the reflective coating. At the TBC-substrate interface, the temperature decrease with a highly reflectivity coating can be as high as about 290 K for weak scattering depending on the absorption. The effectiveness of the reflective coating is reduced as the scattering is increased. For the lowest absorption and the highest scattering considered the temperature is 10 K lower when a reflective layer is used. The reduction in heat flux when a highly reflective coating is used is similar to the temperature reductions at the TBC-substrate interface. The largest decreases in heat flux occur for weak scattering. The reduction in heat flux with strong scattering can be quite significant if the absorption is large. It was also noted that when a reflective coating is put on a TBC the effects of the semitransparency, that is varying the scattering and absorption, are reduced drastically.

For a vane or blade with a 0.25 mm thick TBC, convection coefficients 3014 w/m^{2}K on the hot side and 3768 w/m^{2}K on the cold side, and a 0.9 reflectivity coating 0.111mm thick as part of the TBC, the reflective coating has mixed results on the temperatures and heat flux. The gas-TBC interface temperature is reduced by at least 50 K for all scattering and absorption considered. The largest difference in temperature in general occurs for high absorption. The TBC-substrate temperature deceases at least about 40 K for weak scattering. As the scattering increases the positive effects of the reflective coating decrease and become negative when the TBC-substrate temperature for the TBC with the reflective coating becomes greater than the TBC-substrate interface temperature for the uncoated TBC. The same phenomena occur for the heat flux. The decrease in effectiveness is probably due to the higher thermal conductivity reflective coating taking up almost half of the TBC thickness.

The TBC-substrate temperature and the heat flux for the combustor liner TBC without a reflective coating and the TBC–substrate temperatures and heat flux for a blade or vane TBC with and without a reflective layer were higher than that predicted for an opaque TBC material for some scattering and absorption conditions. For these conditions an opaque TBC with the same thermal conductivity would perform better than a semitransparent TBC.

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