The Lattice and Thermal Radiation Conductivity of Thermal Barrier Coatings

Dongming Zhu and Charles M. Spuckler
NASA Glenn Research Center

The lattice and radiation conductivity of thermal barrier coatings was evaluated using a laser heat flux approach. A diffusion model has been established to correlate the apparent thermal conductivity of the coating to the lattice and radiation conductivity. The radiation conductivity component can be expressed as a function of temperature and the scattering and absorption properties of the coating material. High temperature scattering and absorption of the coating systems can also be derived based on the testing results using the modeling approach. The model prediction is found to have good agreement with experimental observations.
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Dongming Zhu\textsuperscript{1} \* and Charles M. Spuckler\textsuperscript{2} \*

Durability and Protective Coatings Branch\textsuperscript{1}
Mechanics and Life Prediction Branch\textsuperscript{2}
Structures and Materials Division\textsuperscript{*}

NASA John H. Glenn Research Center
Cleveland, OH 44135, USA

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Motivation

Thermal and environmental barrier coatings help increase gas turbine operating temperatures, reduce cooling requirements, improve engine fuel efficiency and reliability.
Revolutionary Ceramic Coatings Greatly Impact Gas Turbine Engine Technology

— Ceramic thermal and environmental barrier coating system development goals
  - Meet engine temperature and performance requirements
  - Ensure long-term durability
  - Improve technology readiness
  - Develop design tools and lifing methodologies

— Crucial for envisioned supersonic vehicles: reduced engine emission, improved efficiency and long-term supersonic cruise durability
Revolutionary Ceramic Coatings Impact Gas Turbine Engine Technology - Continued

- Step increase in temperature capability
  - 2800°F combustor TBC
  - 2700°F Turbine TBC
  - 2700°F (1482°C) SiC/SiC CMC coatings
  - 2800°F SiC/SiC CMC and Si₃N₄ coatings

Temperature Capability

- Increase in \( \Delta T \) across T/EBC
- 2000°F (1093°C) Turbine TBC
- 2400°F (1316°C) Ceramic Matrix Composite
- 3000°F+ (1650°C+) Single Crystal Superalloy

Year

Gen I
- Gen II – Current commercial
- Gen III
- Gen. IV
Objectives

- Evaluate thermal conductivity and thermal radiation resistance of ceramic coatings at high temperatures (2700-3200°F), under realistically thermal gradient conditions

- Facilitate the development advanced thermal and environmental barrier coatings

- Improve understanding of the coating thermal radiation performance

(a) Internal radiation
(b) Combined internal & external radiation
(c) External radiation
NASA Steady-State Laser Heat-Flux Approach for Ceramic Coating Thermal Conductivity Measurements

- A uniform laser (wavelength 10.6 µm) power distribution achieved using integrating lens combined with lens/specimen rotation
- The ceramic surface and substrate temperatures measured by 8 micron and two-color pyrometers and/or by an embedded miniature thermocouple
- Thermal conductivity measured at 5 second intervals in real time and thermal cycling incorporated
Ceramic Coating Thermal Conductivity Measurement
Approach by the Laser High-Heat-Flux Testing

\[ k_{\text{ceramic}}(t) = \frac{q_{\text{thru}} \cdot l_{\text{ceramic}}}{\Delta T_{\text{ceramic}}(t)} \]

where

\[ q_{\text{thru}} = q_{\text{delivered}} - q_{\text{reflected}} - q_{\text{radiated}} \]

\[ \Delta T_{\text{ceramic}}(t) = T_{\text{ceramic-surface}} - T_{\text{metal-back}} - \int_{0}^{l_{\text{bond}}} \frac{q_{\text{thru}} \cdot dl}{k_{\text{bond}}(T)} - \int_{0}^{l_{\text{substrate}}} \frac{q_{\text{thru}} \cdot dl}{k_{\text{substrate}}(T)} \]

8 µm pyrometer for \( T_{\text{ceramic-surface}} \)

Optional miniature thermocouple for additional heat-flux calibration

Two-color and 8 µm pyrometers for \( T_{\text{substrate-back}} \)

\( q_{\text{delivered}} \)

\( q_{\text{reflected}} \)

\( q_{\text{radiated}} \)

\( q_{\text{thru}} \)

ΔTₜₙ = ΔTₘₜₑₙₑ𝑑 - ΔTₙₜₜᵣₚₑₙ - ΔTₜₒₜₜₜₙ
Thermal Conductivity of Fully Dense Oxides

- The radiation conductivity component evaluated
- Significant conductivity increase due to increased radiation at high temperatures especially under thermal gradients

La$_2$Zr$_2$O$_7$

Hot-pressed specimens

Increasing porosity

ZrO$_2$ -8wt%Y$_2$O$_3$ plasma-sprayed porous coating

Free-standing coating

Sintering induced conductivity rise

Lattice conduction
Thermal Conductivity of Fully Dense Oxides
(continued)

![Graph showing thermal conductivity versus surface temperature for various oxides.]

- \( \text{La}_2\text{Zr}_2\text{O}_7 \)
- \( (\text{La},\text{Gd})_2\text{Zr}_2\text{O}_7 \)
- \( (\text{La},\text{Yb})_2\text{Zr}_2\text{O}_7 \)
- \( (\text{La},\text{Gd},\text{Yb})_2\text{Zr}_2\text{O}_7 \)
ZrO$_2$-8wt%Y$_2$O$_3$/BSAS/mullite+20wt%BSAS/Si coating on SiC/SiC CMC substrate

Conductivity determined by a steady-state laser heat-flux technique

Coating surface radiation can contribute 5-15% total heat transfer at 1650°C
Radiative Diffusion Models

- The diffusion conduction equations

\[
q_{\text{total}} = k_{\text{cond}} \frac{dT}{dx} + \frac{16\sigma \cdot n^2 \cdot T_{\text{ave}}^3}{3(a + \sigma_s)} \frac{dT}{dx} = \left( k_{\text{cond}} + \frac{16\sigma \cdot n^2 \cdot T_{\text{ave}}^3}{3(a + \sigma_s)} \right) \frac{dT}{dx}
\]

\[
k_{\text{effective}} = k_{\text{cond}} + \frac{16\sigma \cdot n^2 \cdot T_{\text{ave}}^3}{3(a + \sigma_s)} = k_{\text{cond}} + k_{\text{rad}}
\]

\[ q_{\text{total}} = \text{Total heat flux}\]
\[ k_{\text{cond}} = \text{Intrinsic lattice conductive thermal conductivity}\]
\[ k_{\text{rad}} = \text{radiation thermal conductivity}\]
\[ k_{\text{effective}} = \text{effective thermal conductivity}\]
\[ \sigma = \text{Stefan-Boltzmann constant } 5.6704 \times 10^{-8} \text{ W/(m}^2\text{-K}^4)\]
\[ n = \text{Refractive index, 2.2}\]
\[ a = \text{Absorption coefficient, cm}^{-1}\]
\[ \sigma_s = \text{Scattering coefficient, cm}^{-1}\]
\[ \overline{T} = \text{Average temperature of the material, K}\]

\[
\begin{array}{c|c|c}
\text{opaque} & \text{Radiative diffusion approximation} & \text{transparent} \\
\text{0} & \nu_{e1} & \nu_{e2} \\
\hline
\end{array}
\]

\[ q_{r1} \]
\[ T_{g1} \]
\[ T_{s1} \]
\[ q_{r2} \]
\[ T_{g2} \]

Regions of optical thickness
Evaluation of Lattice and Radiation Thermal Conductivity of 3000F Coating Systems

- Freestanding coatings and gray layer radiative diffusion assumption models

\[ q_{\text{total}} = \frac{dT}{dx} + \frac{16\sigma \cdot n^2 \cdot T_{\text{ave}}^3}{3(a + \sigma)} \frac{dT}{dx} = \left( k_{\text{cond}} + \frac{16\sigma \cdot n^2 \cdot T_{\text{ave}}^3}{3(a + \sigma_s)} \right) \frac{dT}{dx} \]

\[ k_{\text{effective}} = k_{\text{cond}} + \frac{16\sigma \cdot n^2 \cdot T_{\text{ave}}^3}{3(a + \sigma_s)} = k_{\text{cond}} + k_{\text{rad}} \]
Scattering Component of Plasma-Sprayed Coating Systems

Blackbody radiation penetration $I/I_0$ vs. Coating thickness, microns

- Baselines
- Advanced coatings

Scattering:
- Baseline coatings
- Advanced coatings

Absorption:

Graph showing the penetration of blackbody radiation through coatings of different thicknesses.
Radiation Component of Ceramic Materials

![Graph showing radiation component data for different temperatures.]
Preliminary results showed doped HfO₂ coatings had better radiation resistance.
Concluding Remarks

- Laser heat-flux approach established for radiation thermal conductivity measurements and advanced coating development

- Lattice and radiation conductivity determined for dense materials and coatings

- Scattering and absorption determined for coatings under realistic thermal gradients at high temperatures

- Advanced coatings promising in reducing radiation conductivity