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The Lattice and Thermal Radiation Conductivity of Thermal Barrier Coatings: Models and Experiments

Dongming Zhu and Charles M. Spuckler
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The Lattice and Thermal Radiation Conductivity of Thermal Barrier Coatings: Models and Experiments

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Abstract

The lattice and radiation conductivity of ZrO₂-Y₂O₃ thermal barrier coatings was evaluated using a laser heat flux approach. A diffusion model has been established to correlate the coating apparent thermal conductivity to the lattice and radiation conductivity. The radiation conductivity component can be expressed as a function of temperature, coating material scattering, and absorption properties. High temperature scattering and absorption of the coating systems can be also derived based on the testing results using the modeling approach. A comparison has been made for the gray and nongray coating models in the plasma-sprayed thermal barrier coatings. The model prediction is found to have a good agreement with experimental observations.
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

---

**Step increase in temperature capability**

- **Combustor TBC**: 2700 °F (1482 °C)
- **SiC/SiC CMC and Si$_3$N$_4$ coatings**: 3100 °F (1650 °C)
- **Ceramic Matrix Composite**: 2400 °F (1316 °C)
- **Single Crystal Superalloy**: 2000 °F (1093 °C)
- **Gen IV**
- **Gen III - Current commercial**

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Revolutionary Ceramic Coatings Impact Gas Turbine Engine Technology (Continued)
**Objectives**

- Evaluate thermal conductivity and thermal radiation resistance of ceramic coatings at high temperatures (2700 to 3200 °F), under realistically thermal gradient conditions
- Facilitate the development of advanced thermal and environmental barrier coatings
- Improve understanding of the coating thermal radiation performance

**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 µm and two-color pyrometers and/or by an embedded miniature thermocouple
- Thermal conductivity measured at 5 sec intervals in real time
Ceramic Coating Thermal Conductivity Measurement Approach by the Laser High-Heat-Flux Testing

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

Where

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

and

\[ \Delta T_{\text{ceramic}}(t) = T_{\text{ceramic-surface}} - T_{\text{metal}} - \Delta T_{\text{metal-substrate}} - \Delta T_{\text{metal-bond}} \]

Two-color and 8 μm pyrometers for \( T_{\text{ceramic-surface}} \)

Optional miniature thermocouple for additional heat-flux calibration

---

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

- Laser heat flux
- Laser heat flux
- Laser heat flux

Ceramic coating

(a) Internal radiation
(b) Combined internal & external radiation
(c) External radiation

La₂Zr₂O₇

Hot-pressed specimens

Increasing porosity

La₂Zr₂O₇ sol-gel hot-press
La₂Zr₂O₇ sol-gel hot-press
La₂Zr₂O₇ hot-press

ZrO₂-8wt%Y₂O₃ plasma-sprayed porous coating

Free-standing coating

La₂Zr₂O₇ hot-press

Increasing porosity

La₂Zr₂O₇ sol-gel hot-press
La₂Zr₂O₇ sol-gel hot-press
La₂Zr₂O₇ hot-press

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**Thermal Conductivity of Fully Dense Oxides (Continued)**

![Graph showing thermal conductivity vs. surface temperature](image)

**Evaluation of Lattice and Radiation Thermal Conductivity of TEBC Systems at High Temperatures**

- 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 to 15% total heat transfer at 1650 °C

![Graph showing normalized thermal conductivity vs. time](image)

![Graph showing normalized thermal conductivity vs. temperature](image)
 Radiative Diffusion Models

The diffusion conduction equations

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

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

\[ q_{r1} \]

\[ T_{g1} \]

\[ D \]

\[ T_{g2} \]

\[ q_{r2} \]

\[ T_{s1} \]

\[ q_{s} \]

\[ T_{s2} \]

\[ T_{g} \]

\[ T_{m} \]

\[ T_{ave} \]

\[ \sigma \]

\[ \sigma_s \]

\[ a \]

\[ n \]

\[ \text{Stefan-Boltzman constant} \]

\[ 5.6704 \times 10^{-8} \text{ W/(m}^2\text{-K}^4) \]

\[ 2.2 \]

\[ \text{Absorption coefficient, cm}^{-1} \]

\[ \text{Refractive index} \]

\[ \text{Scattering coefficient, cm}^{-1} \]

\[ \text{Average temperature of the material, K} \]

\[ \text{Total heat flux} \]

\[ k_{\text{cond}} \]

\[ k_{\text{rad}} \]

\[ k_{\text{effective}} \]

\[ \text{Intrinsic lattice conductive thermal conductivity} \]

\[ \text{Radiation thermal conductivity} \]

\[ \text{Effective thermal conductivity} \]

\[ \sigma = 5.6704 \times 10^{-8} \text{ W/(m}^2\text{-K}^4) \]

\[ a = \text{Absorption coefficient, cm}^{-1} \]

\[ n = \text{Refractive index} \]

\[ \sigma_s = \text{Scattering coefficient, cm}^{-1} \]

\[ T_{ave} \]

\[ q_{r1} < q_{r2} \]

\[ q_{s} \]

\[ T_{s1} \]

\[ T_{s2} \]

\[ T_{g1} \]

\[ T_{g2} \]

\[ D \]

Regions of optical thickness

[Image: Diagram of radiative diffusion models for nongray materials]
Evaluation of Lattice and Radiation Thermal Conductivity of 3000 °F Coating Systems

- Freestanding coatings and gray layer radiative diffusion assumption models

\[ \begin{align*}
q_{\text{ext}} &= k_{\text{cond}} \frac{dT}{dx} + \frac{16\sigma \cdot \pi^2 \cdot T_d^2}{\lambda(a + \sigma)} \frac{dT}{dx} \\
&= \left( k_{\text{cond}} + \frac{16\sigma \cdot \pi^2 \cdot T_d^2}{3(a + \sigma)} \right) \frac{dT}{dx} \\
q_{\text{scatt}} &= k_{\text{cond}} + \frac{16\sigma \cdot \pi^2 \cdot T_d^2}{3(a + \sigma)} = k_{\text{cal}} + k_{\text{cond}}
\end{align*} \]

Radiation component

Thermal radiation evaluation of advanced coating materials

Scattering Component of Plasma-Sprayed Coating Systems

Absorption scattering:
- Baseline coatings
- Advanced coatings

Blackbody radiation penetration \( I/I_0 \)

Coating thickness, microns
Evaluation of Radiation Flux Resistance of Oxide Coating Systems

Preliminary results showed doped HfO₂ coatings had better radiation resistance.

\[ q_{\text{radthru}} = h(T_{\text{back}} - T_{\text{air}}) \]
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
- The diffusion conduction models established for gray and nongray coating materials
- Scattering and absorption determined for coatings under realistic thermal gradients at high temperatures
- Advanced coatings promising in reducing radiation conductivity
**The Lattice and Thermal Radiation Conductivity of Thermal Barrier Coatings: Models and Experiments**

Zhu, Dongming; Spuckler, Charles, M.

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**15. SUBJECT TERMS**
Thermal conductivity; Coatings; Scattering; Absorption; Absorbents; Thermal radiation; Oxides

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