Extending Our Understanding of Compliant Thermal Barrier Performance

Jeffrey J. DeMange  
*The University of Toledo*

Joshua R. Finkbeiner, Patrick H. Dunlap  
*NASA Glenn Research Center*

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Content of Discussion

• Introduction
  ➢ Compliant Thermal Barriers (CTB) - What are they? Where are they used?
  ➢ Treatment of CTB’s – How are they implemented?
  ➢ Construction, requirements, and characteristics of thermal barriers

• Current Efforts to Improve Understanding
  ➢ Thermal
    o What we know
    o Modeling efforts
      o Case Study: Effect of core density on flow/leakage
  ➢ Mechanical
    o What we know
    o Modeling efforts
      o Case Study: Effect of core density on loads

• Still more to do
• Summary
INTRODUCTION
An Integral Part of the TPS

- Often referred to as “thermal seals” or “seals”
- One “class” of thermal barriers
- High-temp. ceramic-based fibrous materials
- Installed in TPS interface gaps
- Roles
  - Thermal – limit inboard temperatures
  - Structural – accommodate deflections
- Multitude of configurations…but share common elements
Compliant Thermal Barrier Construction

- **Outer sheath**
  - 1+ layers of aluminosilicate woven fabric (e.g., Nextel™)
  - Coatings: RTV, emissivity, etc.

- **Core**
  - Aluminosilicate blanket (e.g., Saffil)
  - Metallic spring tube

- **Other**
  - Stitching to control shape/size and keep insulation in tact
  - End treatments/closeouts
Compliant Thermal Barrier Requirements & Characteristics

• General Requirements
  - Survive in harsh environments (thermally, chemically, tribologically)
  - Mitigate heat transfer
    - Good thermal insulators
    - Minimize convective flow (in combination with inboard environmental barriers)
    - Mitigate radiation heat transfer
  - Exhibit flexibility/conformability
  - Remain resilient
  - Meet load requirements

• Characteristics
  - Made of high temperature ceramic fiber-based materials
  - Utilize high-performance insulation
  - Permeable
  - Compliant
  - Exhibit set/compaction (even at ambient temperatures)
  - Non-linear hysteretic loading behavior
General Perception vs. Reality

More Art than Science???

• Typically considered as “gap fillers” to fill a space – design it to fit
• Often an “after-thought” in design of TPS
• Minimal effort to optimize design → need guidance
  ➢ Thermally: How much insulation is needed? Is there an optimal orientation?
  ➢ Mechanically: Are there load requirements for the interface? What level of durability does the barrier need? What kind of gap change does it need to accommodate?
• Strong reliance on heritage use

The Case for More Science

• Case studies
  ➢ Door closure forces – Space Shuttle
  ➢ Panel installation – MPCV
  ➢ Potential tile debonding – MPCV
THE SCIENCE: CURRENT EFFORTS TO IMPROVE UNDERSTANDING OF THERMAL BEHAVIOR
Thermal Behavior: What We Know

• Heat transfer occurs via several mechanisms
  - Conduction (solid and gas)
  - Convection (natural? and forced)
  - Radiation

• Insulation density/pore size affect degree and modes of heat transfer

• Different modes are active/dominant under different conditions
  - Temperature (e.g., radiation dominant at high temperatures)
  - Pressure (e.g., gas conduction greater at higher pressures)

▷ Heat transfer in porous soft good TPS is a complex interplay of mechanisms affected by many variables!

(Daryabeigi et al., 2010)
Energy Equation for Porous Media

- Generalized heat transfer equation

\[
\left( \rho c_p \right) \frac{1}{g} \left[ \frac{(\rho c)_s}{(\rho c_p)} \frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right] = \nabla \cdot (k_e \nabla T) + q'' + \frac{\mu}{K} \vec{u}^2
\]

- Convection
- Conduction + Radiation
- Heat Generation
- Viscous dissipation

Darcy Velocity: \( \vec{u} = \frac{m}{\rho_g} = \phi u_p \)

- Heat transfer coefficients (Daryabeigi et al., 2010)

\[
k_e = k_s + k_g + k_r
\]

Conduction \ Radiation

\[
k_s(T) = F_S f_v b \kappa_s^* (T) \quad k_g(T, P) = \frac{k_{g_0}(T)}{\Phi + 2\Psi \beta \Pr K n}
\]

\[
k_r = \frac{16\sigma n^2 T^3}{3\rho e}
\]
Case Study: Effect of Core Density on Flow

![Diagram showing the relation between porosity and permeability](DeMange_unpublished)

![Graph showing flow perpendicular to 2D fibrous media with different in-plane fiber orientations](Shuo_et_al_2011)

\[-\nabla P = \frac{\mu}{K} \bar{u} + \rho C |\bar{u}| \bar{u}\]

(Stanek & Szekely, 1974)

\[
\frac{(P_1^2 - P_0^2)A}{2\dot{m} \mu RT} = \frac{1}{K} + C \frac{\dot{m}}{A \mu}
\]
THE SCIENCE: CURRENT EFFORTS TO IMPROVE UNDERSTANDING OF MECHANICAL BEHAVIOR
Mechanical Behavior: What We Know

- Similar behavior to low-density porous foam materials
  - Linear elasticity (cell wall bending) → fiber bending
  - Plateau (cell wall buckling) → fiber breakage?
  - Densification (cell collapse) → pore collapse
- Strong effect of core density on mechanical performance (opposite to effect on insulating properties)
  \[ \sigma \propto \left( \frac{\rho^*}{\rho_s} \right)^n \]
- Exhibit hysteresis during loading, unloading
- Display compaction/set (even at RT) that decreases with number of cycles
Modeling Efforts

• Van Wyk modeled compressibility of fibrous wool (1946)
  ➢ Fiber as straight rod supported horizontally between 2 other rods
  ➢ Many other studies based off Van Wyk’s model
    o Komori, et al. (1977, 1992) – Orientation of fibers, fiber crimp
    o Beil, et al. (2002) – Friction of fibers
    o Barbier, et al. (2009) – Hysteresis and friction

\[ p = \frac{kEm^3}{\rho^3} \left( \frac{1}{v_i^3} - \frac{1}{v_o^3} \right) = kE \left( SVF_i^3 - SVF_o^3 \right) \]

  \( p = \) contact load
  \( k = \) empirically determined constant (structure of fiber mass)
  \( E = \) Young’s modulus of fibers
  \( m = \) mass of fibers
  \( \rho = \) density of fiber
  \( v_i = \) instantaneous bulk volume
  \( v_o = \) initial bulk volume
  \( SVF_i = \) instantaneous solid vol. fraction (volume fibers/bulk volume)
  \( SVF_o = \) initial solid vol. fraction (volume fibers/bulk volume)

• Pineda (2014) modeled Saffil insulation using energy method

\[ U_{4P} = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 + C_{40}(I_1 - 3)^4 \frac{K}{2}(\ln J)^2 \]

\[ T = \frac{2}{J} \left[ \left( \frac{\partial U}{\partial I_1} + I_1 \frac{\partial U}{\partial I_2} \right) B' \right] \left[ \frac{\partial U}{\partial I_1} B'^2 + \frac{\partial U}{\partial J} 1 \right] \]
Case Study: Effect of As-Fabricated Core Density on Loads

- Load behavior is highly nonlinear
- Nonlinear increase in peak load vs. as-fabricated density
Case Study: Initial Modeling Efforts

- Van Wyk provides a reasonable first approximation of behavior of CTB’s
- Pineda model matches Saffil performance well
- Models need expansion and refinement to incorporate effects from various sources
Still so much to do...

- Heat transfer modeling
  - Need more data
    - Insulation – Effect of orientation (e.g., Saffil mat is transversely isotropic), other types (e.g., OFI, MLI, aerogels), how to reliably measure density
    - Effect of size/configuration – Hard to measure thermal properties on small samples
    - Variation between samples
    - Validation of models – How do we validate with combined conduction, convection, and radiation?

- Mechanical modeling
  - Need more data
    - Insulation – Basic mechanical material properties, effect of orientation (e.g., Saffil mat is transversely isotropic), other types (e.g., OFI, MLI, aerogels), how to reliably measure density
    - Effect of size/configuration (e.g., inclusion of spring tube, stitching, coatings)
    - Variation in samples
    - Effect of environment (temperature, pressure, space)
  - What’s the best model?

Goal: Develop a thermal barrier thermo-mechanical design/sizing tool
Summary

• Thermal barriers are integral to successful TPS performance
  ➢ Considered more art, but need more science
  ➢ Vehicle designers need guidance in designing, implementing, and maintaining thermal barriers

• Behavior of thermal barriers
  ➢ Thermal performance
    o Heat transfer in porous soft goods is complex
    o Good baseline understanding of heat transfer in porous TPS
    o Challenges remain in characterization (e.g., lack of data, difficulty in testing small samples)
  ➢ Mechanical performance
    o Less studied and understood
    o Very few models exist
    o Multitude of configurations and implementations creates modeling challenges

• Still much to do
Points of Contact

Jeff DeMange  jeffrey.j.demange@nasa.gov
Pat Dunlap  patrick.h.dunlap@nasa.gov
Josh Finkbeiner  joshua.r.finkbeiner@nasa.gov
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References


Appendix
Comparison to Van Wyk Model

- Variability in compression performance of samples evident
- Suggest $k$ varies from sample to sample (Van Wyk, 1946)
- Initial nonlinearity may be due to fiber slippage (Dunlop, 1974)
Variation of $k$ for Samples

- $k$ is function of initial density of core fibers (Dunlop, 1974)
- $k$ is complex function of fiber configuration (e.g., layer orientation)
Effect of Insulation Density on Effective Thermal Conductivity

(Daryabeigi et al., 2010)