Metal Foams as Compact High Performance Heat Exchangers

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<th>2. REPORT TYPE</th>
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<td>See Also ADM001348, Thermal Materials Workshop 2001, held in Cambridge, UK on May 30-June 1, 2001. Additional papers can be downloaded from: <a href="http://www-mech.eng.cam.ac.uk/onr/">http://www-mech.eng.cam.ac.uk/onr/</a></td>
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<td>a. REPORT</td>
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Standard Form 298 (Rev. 8-98)  
Prescribed by ANSI Std Z39.18
Contents

• Thermal management of IGBT’s
• Metal foam heat exchanger configuration
• Experiments & Results
• Numerical Simulations
• Structure improvement
• Conclusions
Enhanced Heat Dissipation

- Thermal management of IGBT modules
  - Heat dissipation +100 W/cm²
  - Low, uniform operating temperatures increase chip life

- Current configuration
  - Simple flat plate
  - High coolant velocity
  - Significant temperature gradients on the chip

- Possible improvements
  - Implement a highly conductive solid
  - Increase heat convection area
  - Better flow mixing structures
Aluminum Foam Properties

- High surface area to volume ratio
  - ~3000 m²/m³ uncompressed (natural form)
  - ~10,000 m²/m³ compressed
- Highly conductive solid (~218 W/m•K)
- Tortuous flow path
- Easily machined to final size

Aluminum foam in as-manufactured, unaltered state (92% porous)

Aluminum foam (73% porous) compressed by a factor of four

10 cm

6.5 cm
Typical Heat Exchanger Configurations

- Simplest design
- High flow velocity
- Mixing depends on upstream channel configuration

- Relatively simple
- Minimal increase in surface area
- Improved mixing through turbulence enhancers
Metal Foam Heat Exchanger Configurations

- Similar to turbulence enhancement array
- Lower flow resistance
- Less foam required
- Lower clogging likelihood

- Distributes heat throughout the coolant stream
- Provides a better basis for comparison of metal foam performance data
Compressed Foam Experimentation

- Utilize compressed foam—specific surface area $\sim 10,000 \text{ m}^2/\text{m}^3$
- Porosities between 48 – 89%
- Coolant (water) flow velocities up to 2 m/s
- Convection coefficient (measured at plate) $+150 \text{ kW/m}^2\cdot\text{K}$
Experimental Apparatus

- Pressure drop measurement
- Coolant temperature at various locations
- USB data acquisition device
  - Temperatures
  - Pressure
- 1200 W delivered by cartridge heaters
- Power input
  - Oscilloscope measurement
  - Temperature change in coolant
Pressure Drop and Heat Convection Coefficients

- Forchheimer-extended Darcy equation

\[ \frac{\Delta p}{L} = \frac{\mu}{K} v + \frac{c_F}{\sqrt{K}} \rho v^2 \]

- Convection coefficient measured at plate

\[ h'' = \frac{mc(T_{w, outlet} - T_{w, inlet})}{(T_{plate} - T_{w, inlet}) \cdot A_{foam-plate}} \]

- Symbols:
  - \( c_F \): Forchheimer coefficient
  - \( K \): permeability
  - \( L \): foam length
  - \( v \): flow velocity
  - \( \Delta p \): pressure difference
  - \( \mu \): dynamic viscosity
  - \( \rho \): fluid density
  - \( A \): area
  - \( c \): specific heat
  - \( h'' \): convection coefficient
  - \( m \): mass flux
  - \( T \): temperature
Flow Characterization Experimental Results

- Porosity decrease = pressure drop decrease
- Significant pressure drop compared to flat plate

- Monotonic increase of K with porosity
- Increase in sensitivity of K with increase in porosity
Heat Transfer Experimental Results

- Higher solid fraction provides a higher heat convection coefficient
- Results are independent of heater attachment

- Control of temperature gradient
- Poor performance by plate
- Note: Limited range for full power for the bare plate
Power-Thermal Resistance Comparison

- Basis for real-world performance comparison
- Favorable power—thermal resistance curve
- Poor performance by bare plate
- Locate optimum configuration
Scaled Performance Comparison

- Scaled to predict behavior with 50% ethylene glycol-water solution
- Assumptions/Considerations
  - Identical K and $c_F$
  - Similar operating temperature
  - Increase in flow rate compensates lower heat capacitance

Heat Exchanger with Turbulence

0.2 mm Narrow Gap (clear)

Behr Heat Exchanger
Numerical Approaches

• Experimentally measure flow characteristics
  – Requires a wide variety of foam samples
  – Large time expenditure
  – Limited applicability
    • Foam configuration
    • Coolant type & flow rate range

• Pore-based analysis
  – Idealized three-dimensional solid matrix structure
  – Determine periodic flow behavior
  – Calculate interstitial convection coefficient
Foam Structure Idealization

- 14-sided tetrakaidecahedron
- Tetrahedral angle (~109°)
- Adjustments of shape

Close-up of a single open cell
Model of the tetrakaidecahedron

5 mm
Periodic Cell Boundary Conditions

- Periodic Length $L$
  - Velocity
    \[ \vec{V}(x, y, z) = \vec{V}(x + L, y, z) = \vec{V}(x + 2L, y, z) = \ldots \]
  - Pressure
    \[ p_x(x, y, z) = -Bx + P(x, y, z) \]
    where
    \[ B = \frac{p_x(x, y, z) - p_x(x + L, y, z)}{L} \]
    then
    \[ p_y, z(x, y, z) = p_y, z(x + L, y, z) = p_y, z(x + 2L, y, z) = \ldots \]
Visualization of the Flow Field

- Colored pressure gradient
- Red particle traces
- Non-turbulent flow
  - \( \text{Re}_K < 100 \) where
  - \( \text{Re}_K = \rho VK^{1/2} \mu^{-1} \)
- Vortex development in wake
  - Describe lack of “transitional range” in porous media
  - Insight into dispersion effects
Periodic Configuration

- Tetrakaidecahedron base unit
- Not numerically optimized to minimize surface energy
- Possible tunneling effects
- Inconsistent porosity
- Improvement needed
Improvement in Periodic Cell Representation
Wetted Form

- Wetted Weaire-Phelan form
- Numerically optimized surface energy
- 0.3% lower surface energy
- Composition
  - 8 equal volume cells
    - 2 dodecahedra
    - 6 fourteen sided figures
      - 2 hexagonal faces
      - 12 pentagonal faces
Conclusions

• Aluminum foam heat exchanger experiment:
  – Significantly higher heat convection coefficient
  – More uniform chip operating temperature
  – Favorable power input to thermal resistance curve

• Approach of pore-based numerical analysis
  – Analyze “transitional” region in porous media
  – Possibly directly calculate dispersion effects
  – Reduce extensive experimentation