Microchannel Cooling of IGBT and Passive Components

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Microchannel Cooling of IGBT and Passive Components

INTRODUCTION

GOAL: To Improve Components Used In Compact Power Systems That Operate With High Power, High Energy, And High Repetition Rate

State-Of-The-Art For Waste Heat Removal From Active Electronics

STTR N03-T022 Advanced Thermal Management (IGBT modules)
Cites Current Practical Power Dissipation of 100 W/cm^2
Future Requirement Is For 1,000 W/cm^2

Application of Microchannel Cooling to heat exchanger for IGBT

Thermal Resistance Model
Microchannel Heat Exchanger
Design Considerations

Application to Film Resistors, Film Capacitors, and Conductors

Microchannel Cooling of IGBT and Passive Components

LITERATURE SEARCH

- **Over 30 References: Theory, Experiment, Applications**
- **Research Stems From Tuckerman and Pease (1981)**
  - Laminar Flow In High Aspect Ratio Channels
- **Gillot, Schaeffer, and Bricard (2000)**
  - Application to IGBT 230-350 W/cm^2
- **Lorenzen, Bonhaus, Fahner et al (2001)**
  - Application to Diode Laser Bars With Diamond Heat Spreader
- **Vidmar and Barker (1998)**
  - Application to Particle Beam Transmission Windows
  - Fully Developed Turbulence, 3 kW/cm^2 Experiments

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THERMAL RESISTANCE MODEL

- **Series And Parallel Thermal Circuits Similar To Ohm's Law**
  - $\Delta T = PR$ ΔT = Temperature Difference [K]
    $(V = IR)$ P = Power Flowing Through Element [P]
    R = Thermal Resistance [K/W]
  - Series Circuit: $R_{series} = R_1 + R_2 + \bullet\bullet\bullet$
  - Parallel Circuit: $1/R_{parallel} = 1/R_1 + 1/R_2 + \bullet\bullet\bullet$
- **Thermal Resistance of Material Layers**
  - $R_{layer} = \Delta x/kA$ [K/W] Δx = Layer Thickness [m], A = Area [m^2]
    k = Thermal Conductivity [W/m-K]
- **Thermal Resistance At A Convective Interface**
  - $R_{conv} = 1/h_cA$ [K/W] h_c = Convective Coefficient [W/m^2-K]

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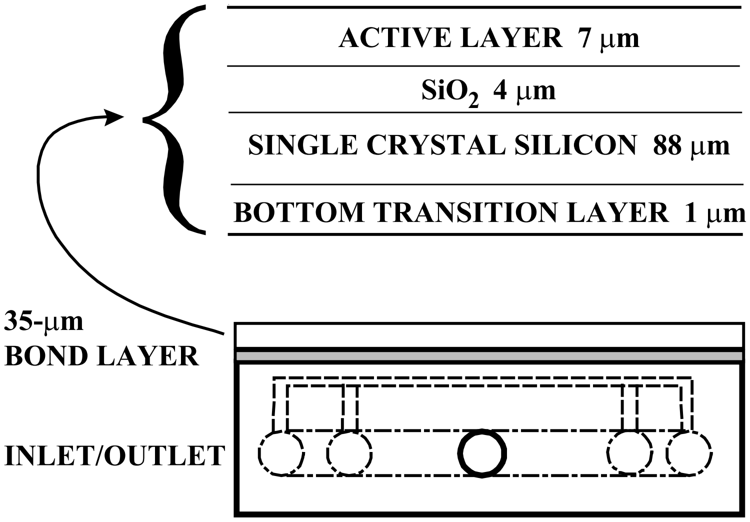
THERMAL RESISTANCE MODEL: IGBT



COMMERCIAL DIE OR CUSTOM DEVICE	THERMAL CONDUCTIVITY	THERMAL RESISTANCE
ACTIVE LAYER 7 μm	k_{active} = 150 W/m-K	R_{active} = 0.0004667 K/W
SiO_2 4 μm	k_{SiO_2} = 1.38 W/m-K	R_{SiO_2} = 0.0289900 K/W
SINGLE CRYSTAL SILICON 88 μm	k_{Si} = 150 W/m-K	R_{Si} = 0.0058670 K/W
BOTTOM TRANSITION LAYER 1 μm	k_{bottom} = 150 W/m-K	R_{bottom} = 0.0000667 K/W
		R_{device} = 0.0353904 K/W
35-μm BOND LAYER	k_{bond} = 57 W/m-K	**R_{bond} = 0.0061403 K/W**

SIDE VIEW

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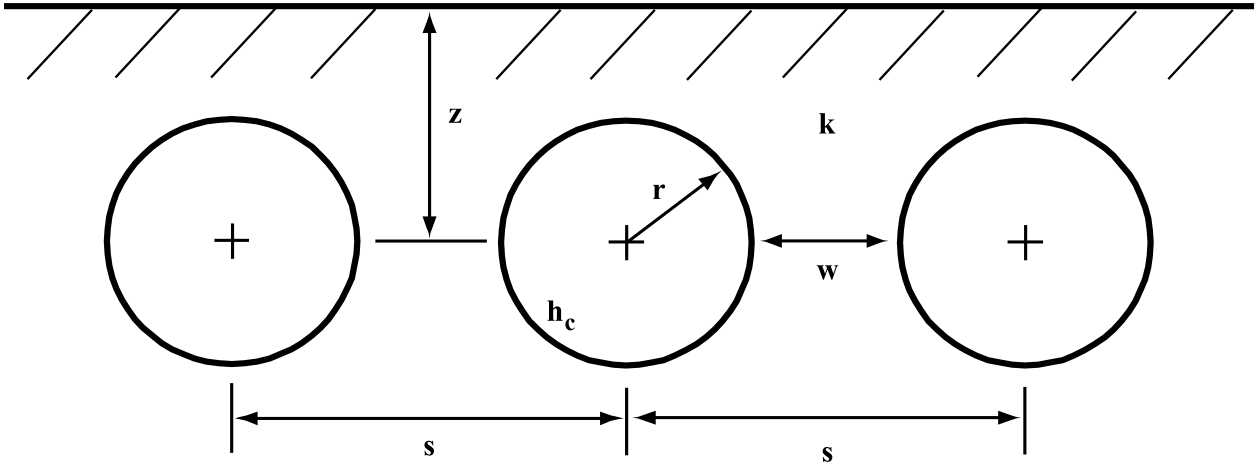
THERMAL RESISTANCE MODEL: PIPE ARRAY



$$R_{pipe} = \frac{1}{2\pi k L}\, ln\left[\frac{s}{\pi r}\sinh\left(\frac{2\pi z}{s}\right)\right] \text{ PER PIPE} \qquad R_{conv} = \frac{1}{2\pi r L h_c} \text{ PER PIPE}$$

L = PIPE LENGTH, k = THERMAL CONDUCTIVITY, h_c = CONVECTIVE HEAT-TRANSFER COEFFICIENT

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TOTAL THERMAL RESISTANCE AND OPTIMIZATION

$$R_{total} = R_{device} + R_{bond} + \frac{1}{N_{pipes}}\left(R_{pipe} + R_{conv}\right)$$

$$R_{total} = R_{device} + R_{bond} + \frac{s}{L}\left\{\frac{1}{2\pi k L}\, ln\left[\frac{s}{\pi r}\sinh\left(\frac{2\pi z}{s}\right)\right] + \frac{1}{2\pi r L h_c}\right\}$$

$$R_{total} = R_{device} + R_{bond} + \frac{r+w}{L^2}\left\{\frac{1}{k}\left[1+\frac{2r+w}{2\pi(r+w)}\, ln\left(\frac{2r+w}{2\pi r}\left\{1\text{-}\exp\left[-\frac{4\pi(r+w)}{2r+w}\right]\right\}\right)\right]+\frac{1}{2\pi r(r+w)h_c}\right\}$$

CONSTRAINTS: $S_{hoop} = \frac{pr}{w}$ **, Minimize Fluid Friction Loss, And Maximize** $h_c(r, p/L)$

- **Optimization Is Difficult Due To Constraints And Nonlinearity**
  - Fluid and Material Properties Versus Temperature Are Nonlinear
  - Thermal Expansion Compatibility May Force Adverse Thermal Properties

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MICROCHANNEL HEAT EXCHANGER: MECHANICAL

- **Design Issues**
  - **Minimize Wall Thickness Between Pipes**

    Increases The Number Of Pipes And Minimizes $R_{thermal}$
  - **Minimize Temperature Variations Across Heat Exchanger**

    Reduce End-To-End Differential Expansion Stress On IGBT Die
  - **Match Thermal Expansion Coefficient Of IGBT**

    Minimize Differential Expansion Stress on IGBT Die

- **Counterflow Design**
  - Minimize Wall Thickness
  - Minimize Temperature Variations Across Heat Exchanger

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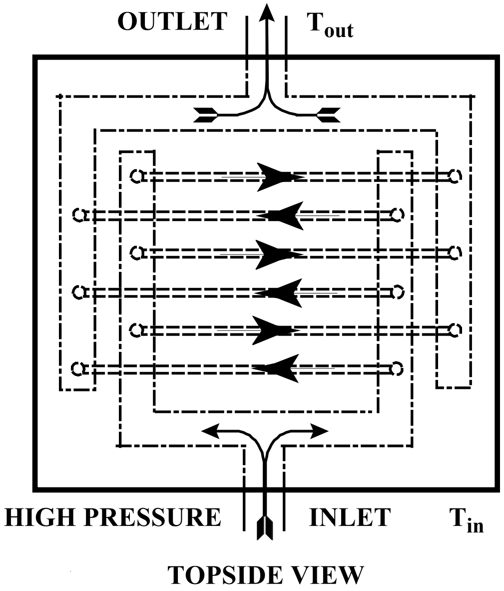
SYSTEM CONSIDERATIONS: COUNTERFLOW DESIGN



- **Hoop Stress Around Pipe**
  - Stress = p r/ w   p = Pressure [Pa]   r = Pipe Radius [m]
    w = Pipe Wall Thickness [m]

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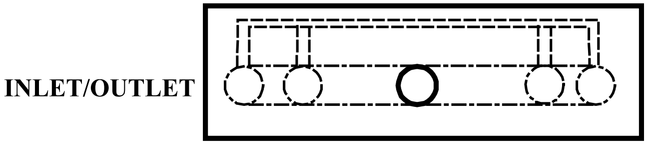
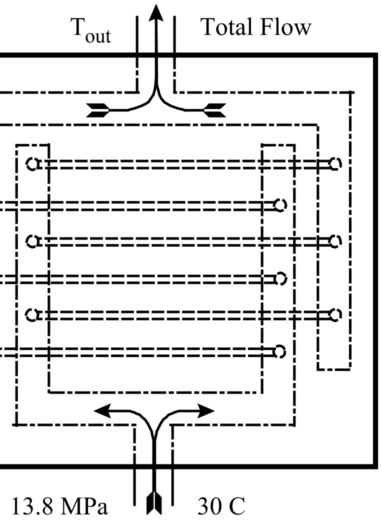
THERMAL RESISTANCE MODEL: HEAT EXCHANGER



SIDE VIEW



TOPSIDE VIEW

1-cm SQUARE WITH 4 IGBTs

$\frac{P}{A}$ **= 1,180 W/cm^2**

HEAT-SINK SPECIFICATIONS

$L = 10{,}000\ \mu m$ $r = 25\ \mu m$ $p = 13.8$ MPa $T_{inlet} = 30$ C

Cu alloy $z = 67\ \mu m$ $w = 42\ \mu m$ $s = 92\ \mu m$ $N_{pipes} = 108$
$k = 189$ W/m-K $h_c = 460$ kW/m^2-K $Y = 83$ MPa
$T_{out} = 65.1$ C Total Flow = 9.18 g_{H_2O}/s

Invar 42 $z = 37\ \mu m$ $w = 12\ \mu m$ $s = 62\ \mu m$ $N_{pipes} = 160$
$k = 10.7$ W/m-K $h_c = 326$ kW/m^2-K $Y = 295$ MPa
$T_{out} = 55.1$ C Total Flow = 13.5 g_{H_2O}/s

THERMAL RESISTANCES PER PIPE

Cu alloy $R_{pipe} = 0.340$ K/W $R_{conv} = 1.384$ K/W
Invar 42 $R_{pipe} = 4.194$ K/W $R_{conv} = 1.953$ K/W

PARALLEL THERMAL RESISTANCES

$$R_{sink} = (R_{pipe} + R_{conv})/N_{pipes}$$

HEAT SINK TOTAL THERMAL RESISTANCE

$R_{Cu\ alloy} = 0.01596$ K/W **$R_{Invar\ 42} = 0.03841$ K/W**

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CONCLUSIONS

- **Microchannel Heat Sink Counterflow Design For IGBT**
  - Power Dissipation of 1,180 W/cm^2 (11.8 MW/m^2)
  - Active Region Temperature With 30 C Inlet Fluid

    115 C for Commercial Bronze and 137 C for Invar 42
  - Active Region Temperature With -20 C Refrigerated Inlet Fluid

    75 C for Commercial Bronze and 95 C for Invar 42
- **Optimized Design Has Many Competing Factors**
  - Fluid and Material Properties Versus Temperature Are Nonlinear
  - Thermal Expansion Compatibility May Force Adverse Thermal Properties
- **Applications**
  - IGBT, Custom Die, Conductor, Beam Dump
  - Tungsten Film Power Resistor And Some Film Capacitors