Thermal Management of High Power Electronics using COMSOL Multiphysics® Simulation Software

ACI Technologies, Inc.

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ACI Technologies, Inc. - The Navy Electronics Manufacturing Center of Excellence

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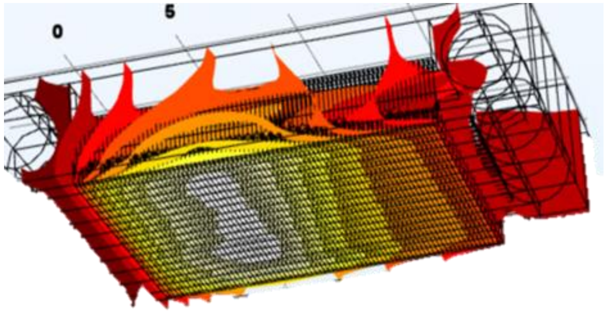
Thermal Management of High Power Electronics using COMSOL Multiphysics® Simulation Software

- Overview

Issue

- **Thermal management is typically considered after the electronics are designed.**
    - **Use available space.**
    - **Limited optimization of performance, size, weight, and cost.**
    - **Uses unique design configurations based on legacy programs and past performance requirements.**
- **Improved performance is required to enable future capabilities.**



Need

- **Maximized heat transfer.**
- **Optimized flow path.**
- **Low thermal resistance.**
- **Selective cooling for “hot spots”.**
- **Adaptive design to allow application in current and future platforms.**
- **Standardized approach for thermal management.**

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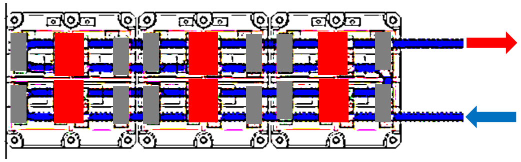
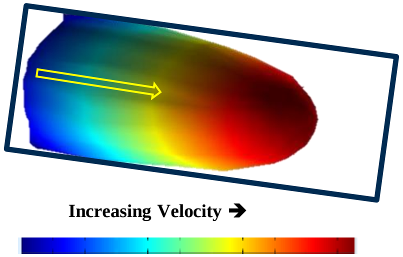
- Typical thermal designs

Tube / channel.



- Low cost.
- Simple design - coolant flows under each hot spot.
- Less effective thermal transfer through slow surface layer.
- Increased pressure drop with long path length.
- Sequential cooling path reduces effectiveness.



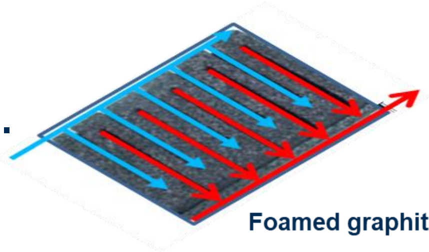
Injection molded copper pin fin.

Copper pin fin

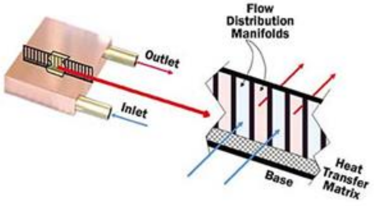
- Pins disrupt laminar flow and increase thermal transfer.
- Reasonable costs by injection molding powdered copper.
- Panelized pin arrays provide flexible design.

Foamed graphite and perpendicular flow microchannels.

- High performance.
- Very high surface area.
- Requires precision machining.
- Difficult to braze.
- Very expensive



Foamed graphite



Perpendicular flow microchannel plate *

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* Valenzuela, J., and Tom Jasinski. “High Heat Flux Cooling with a Normal Flow Cold Plate (NCP)”, *Thermal Management of Electronics Summit 2004*. Natick, MA, August 2004.

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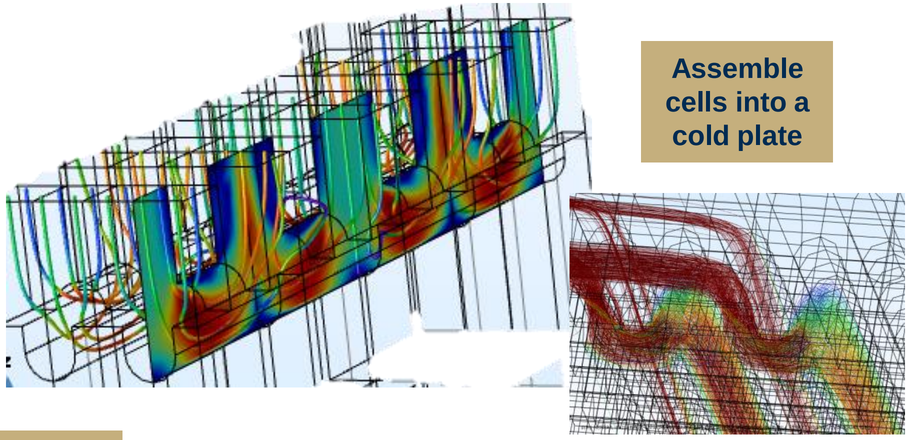
- COMSOL manifold microchannel design

Boundary Conditions

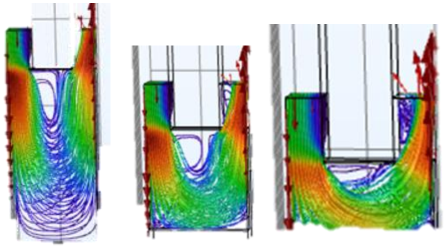
- Average velocity of 8 m/s.
- Initial temperature of 22 °C.
- Convective heat flow through the outlet .
- Heat flux applied at surface 1 W/mm^2.
- Determine optimal microchannel height and manifold height.

Modules

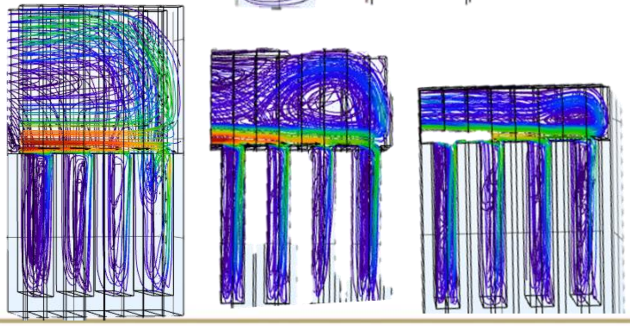
- Heat Transfer
- CFD



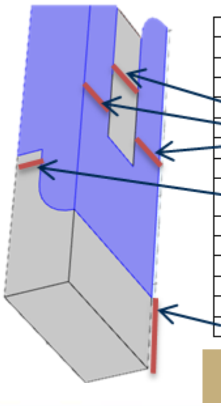
Assemble cells into a cold plate



Determine microchannel height



Determine manifold height



Initial temp	22[degC]
Inlet velocity	8.33[m/s]
Heat flux on top surface	1.1[W/mm^2]
Microchannel wall height	762 μ
Manifold wall thickness	508 μ
Inlet width	508 μ
Outlet Width	508 μ
Microchannel wall thickness	254 μ
Microchannel width	381 μ
Tube ID	.125[in]
Tube wall thickness	.030[in]
Inlet/Out tube length	1.5[in]
Microchannel base	.030[in]

Quarter cell properties

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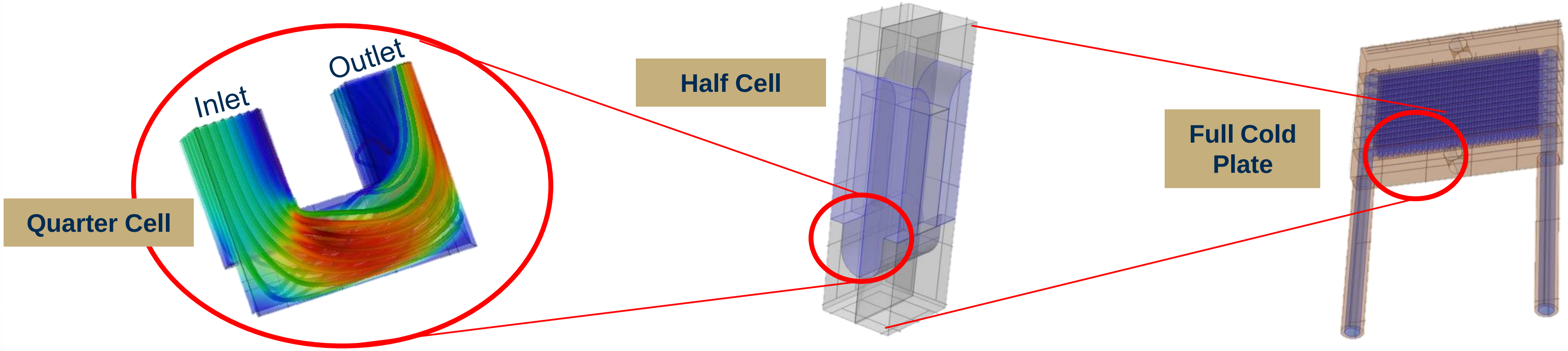
- COMSOL manifold microchannel design

- **Copper, aluminum, and titanium cold plates for single-phase flow were devised, manufactured, and tested.**
  - **Manufactured using direct metal laser sintering.**
  - **Incorporated complex internal passages to maximize heat transfer coefficient.**
  - **Massive parallel flow minimizes pressure drop and reduces path length in microchannels.**
  - **Followed DMLS process guidelines for wall thickness, feature detail, and surface finish.**
  - **Arches were required for any overhanging structure to eliminate temporary supports.**



Provides massive parallel flow to minimize pressure drop and reduce path length in microchannels.

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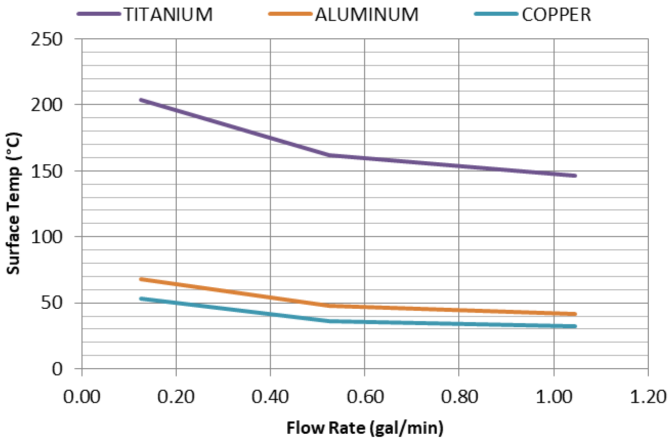
- COMSOL heat transfer coefficient analysis (h)

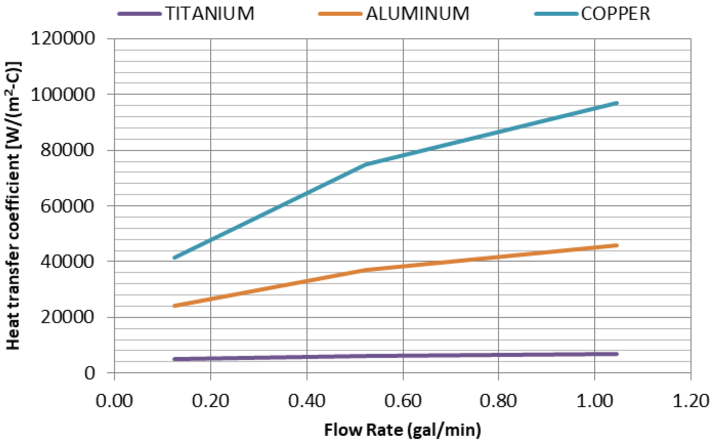
C18150 (CuCr1Zr) – **copper** chromium zirconium alloy - thermal conductivity of ~**323 W/mK**.
AlSi10Mg-0403 - **aluminum** silicon magnesium alloy - thermal conductivity of ~**160 W/mK**.
Ti6Al4V-0406 - **titanium** aluminum vanadium alloy - thermal conductivity of ~**7 W/mK**.

$$h^* = \frac{Q}{A\Delta T_m} = \frac{Q}{A\,[T_w - .5(T_{in}+T_{out})]}$$

Where:

h = Heat transfer coefficient [W/(m^2•°C)]
Q = Heat flow (watts)
A = Effective area of heat transfer (m^2)
ΔT_m = Mean temperature difference between heating surface (T_w) and the coolant $0.5(T_{in}+T_{out})$] (°C)
T_{in} = Inlet coolant temperature (°C)
T_{out} = Outlet coolant temperature (°C)





* Kermani, Elnaz, et al. "Experimental Investigation of Heat Transfer Performance of a Manifold Microchannel Heat Sink for Cooling of Concentrated Solar Cells." 2009 59th Electronic Components and Technology Conference, 2009, pp. 453–459.

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- Experimental testing for thermal resistance (θ)

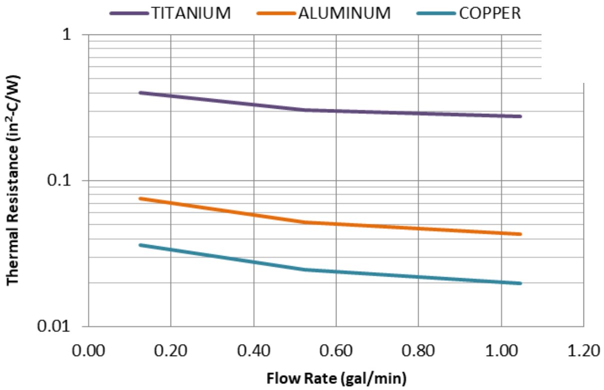
Performance of each cold plate was determined using a normalized thermal resistance (θ) calculation that allows direct comparisons of the technology independent of geometry.

- **The aluminum and titanium cold plates performed similar to the analysis predictions.**
- **The copper cold plate has a slightly higher thermal resistance than predicted (indicating lower performance).**
  - **The more thermally conductive copper cold plate performed lower than expected. The current process for printing copper has a lower resolution than the other two metals. The internal structure is probably not the exact dimensions that were modeled. Cross-section analysis will be used to determine the cause.**

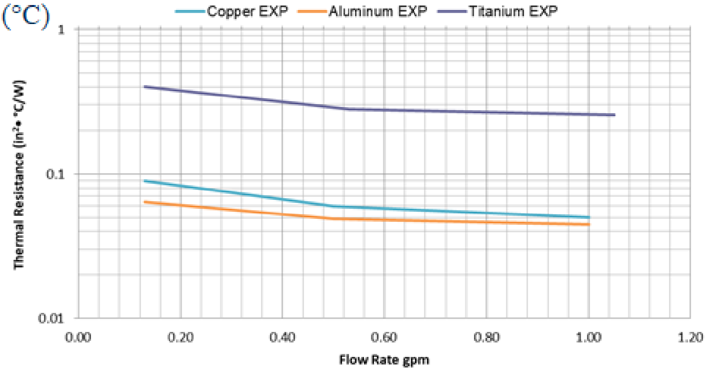
$$\theta = \frac{A\cdot(T_w - T_{out})}{Q} \quad [(m^2\cdot°C)/W]$$

Where: θ = Thermal resistance $(m^2\cdot°C)/W)$
Q = Heat flow (watts)
A = Effective area of heat transfer (m^2)
T_w = Temperature of heating surface (°C)
T_{out} = Outlet coolant temperature (°C)

COMSOL Multiphysics® Simulation



Experimental Test Data



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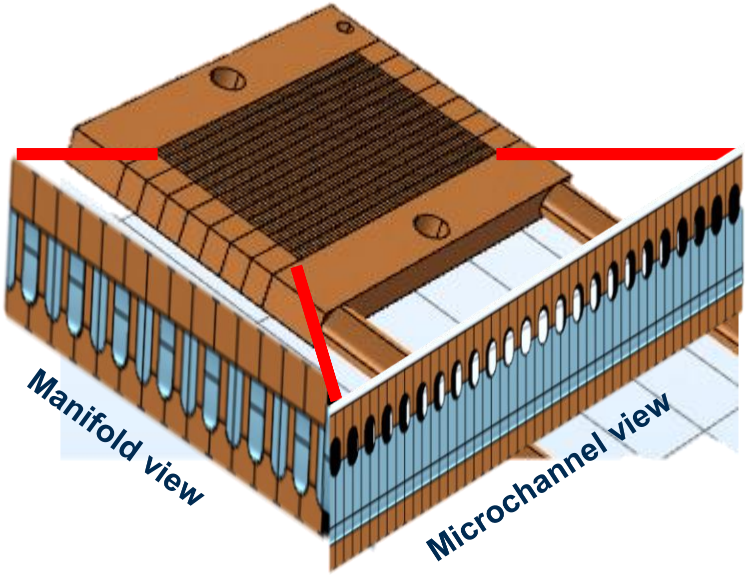
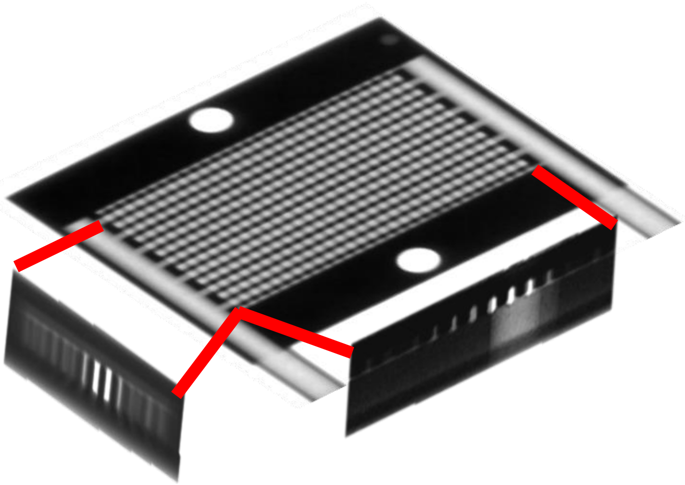
- COMSOL manifold microchannel design

- By evenly distributing the coolant and then directing flow into microchannels perpendicular to the heated surface, large heat transfer coefficients are obtained with a corresponding low cold plate thermal resistance <0.04 [in^2 • °C/W].



COMSOL drawing of cold plate

3D printed cold plate



X-ray analysis of 3D printed cold plate

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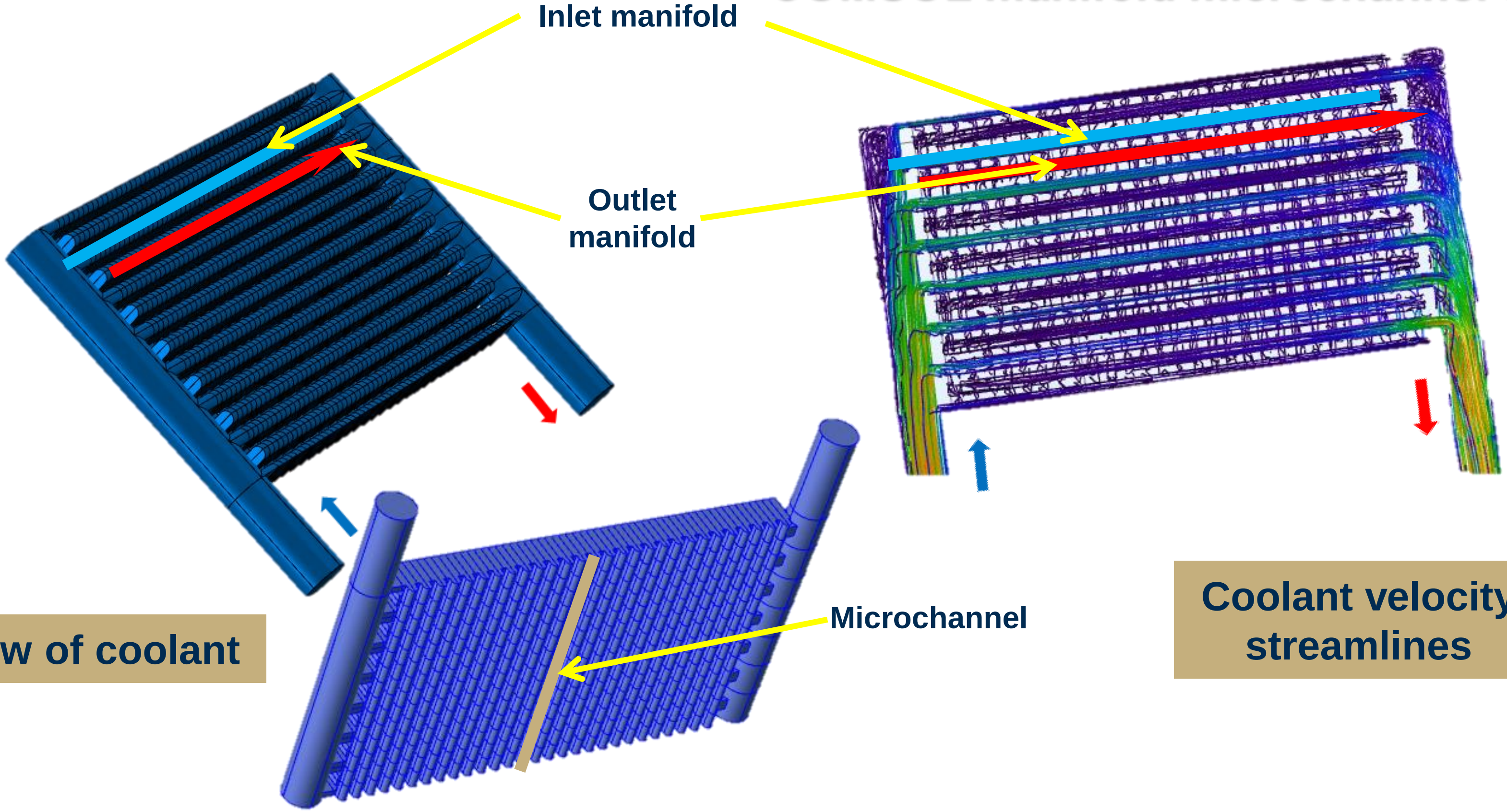
- COMSOL manifold microchannel design



Inlet manifold

Outlet manifold

Microchannel

3D view of coolant

Coolant velocity streamlines

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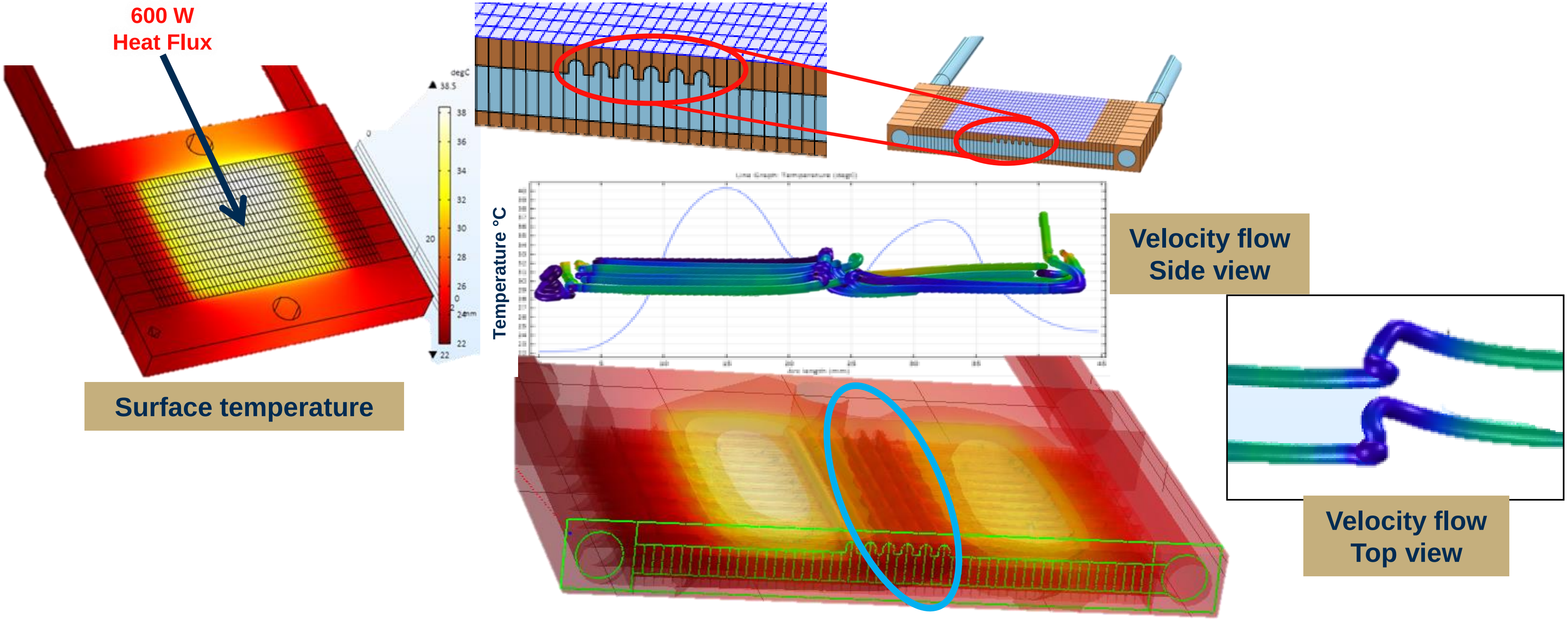
- Selective cooling by strategically placing microchannels



600 W Heat Flux

Surface temperature

Velocity flow Side view

Velocity flow Top view

Selective cooling - The impingement flow within the microchannels provides an additional 11°C temperature reduction when compared to areas with only parallel flow manifolds.

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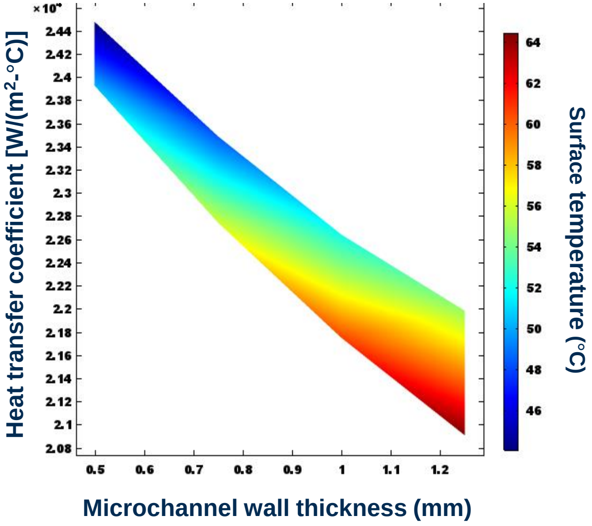
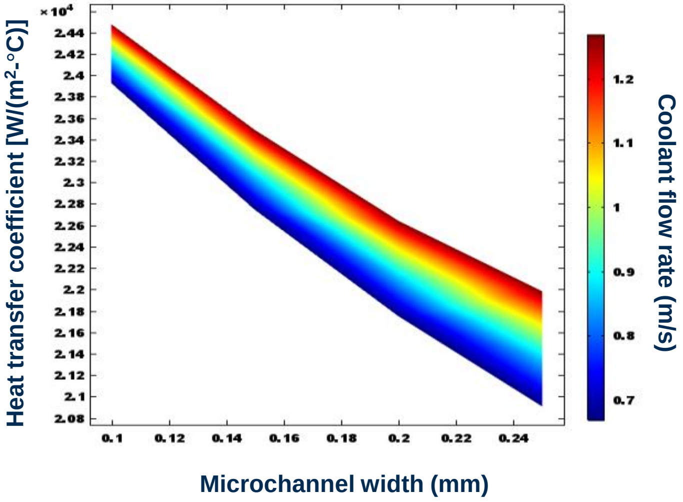
- COMSOL Multiphysics® simulation

- **Surface temperature, heat transfer coefficient, coolant flow, microchannel wall thickness, and microchannel width were all analyzed to understand their interactions to improve cooling.**

The heat transfer coefficient increases and surface temperature decreases.

- **Thinner microchannel width.**
- **Increased coolant flow rate.**
- **Thicker microchannel walls.**





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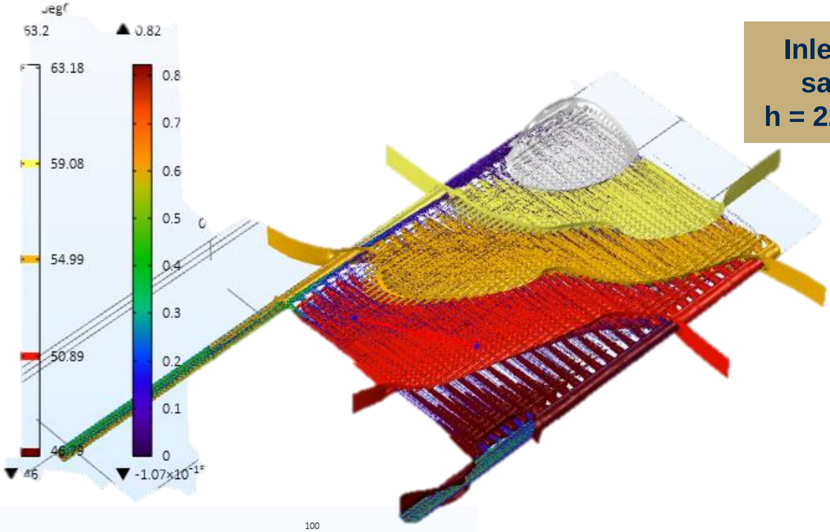
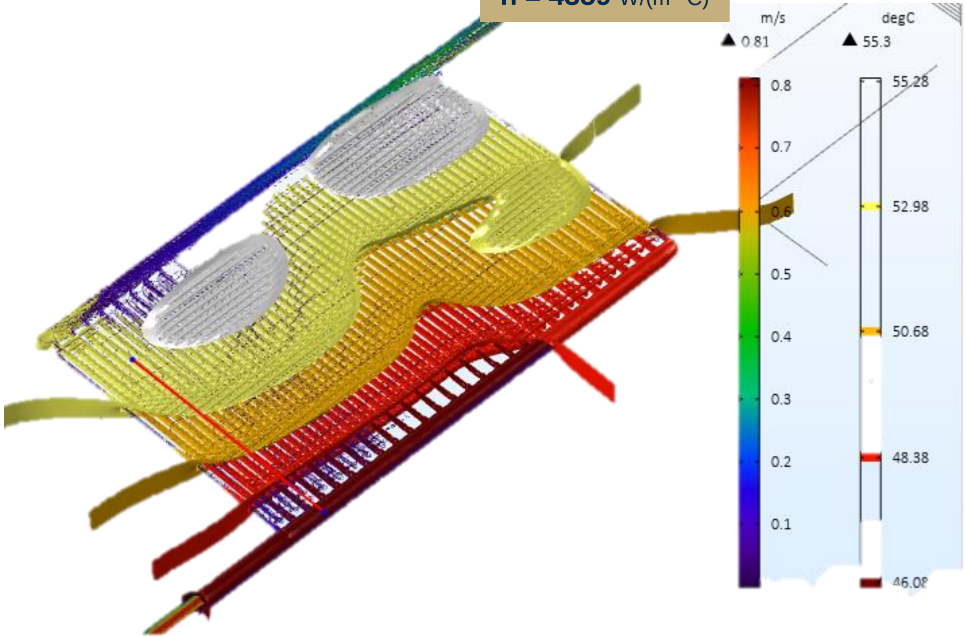
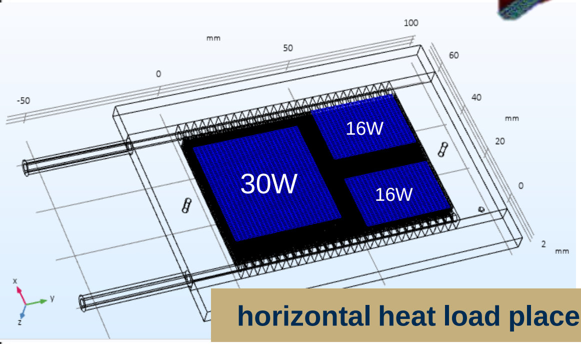
- Opposite outlet direction



Inlet & outlet same side
h = 2266 W/(m²°C)

Inlet & outlet opposite side
h = 4359 W/(m²°C)





horizontal heat load placement

Changing outlet direction has a significant effect on heat transfer performance and surface temp.

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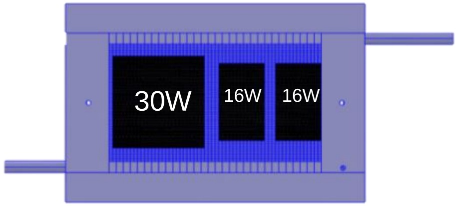
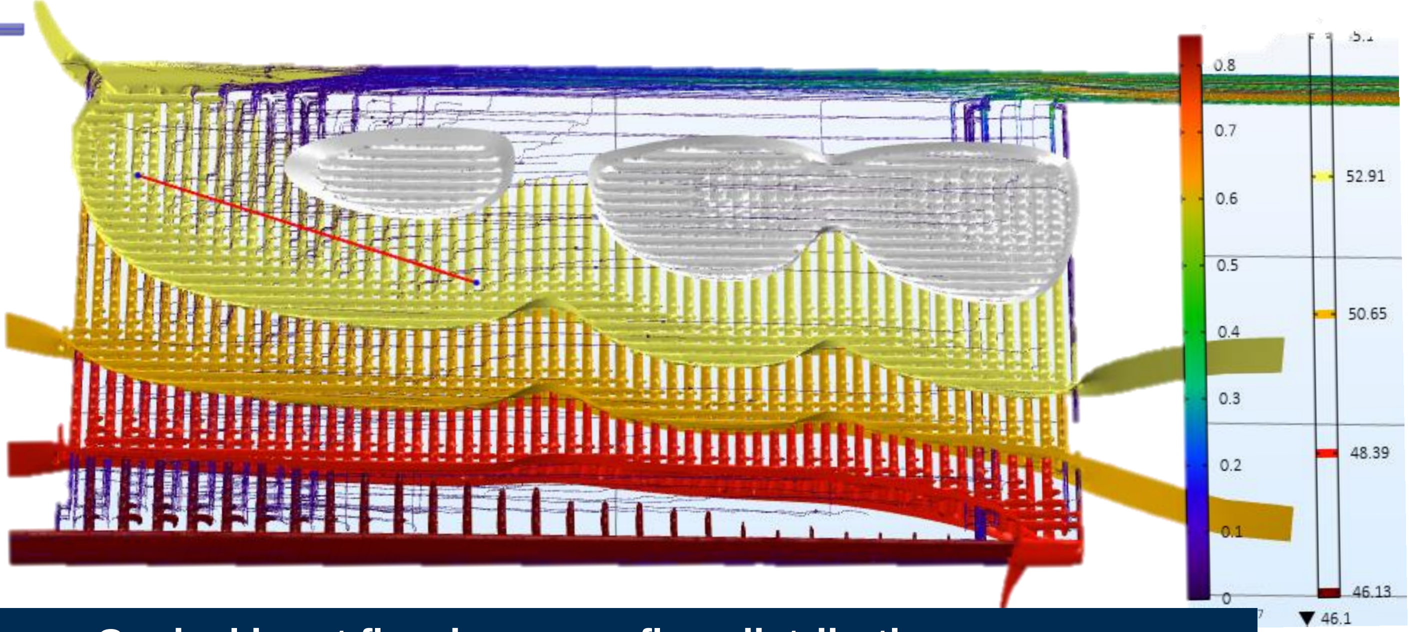
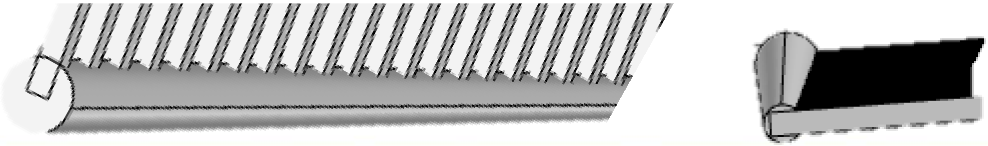
- Conical inlet



Vertical heat load placement



Conical input flow improves flow distribution.
Orientation of the heat load with the flow improves surface temperatures.



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- Summary of design changes

Initial temp (degC)	Integral ndflux Normal conductive heat flux (W)	FPGA heat flux (W)	MCM heat flux (W)	Aveop3 Average TOP T (degC)	Max TOP temp (degC)	Aveop Average Outlet T (degC)	AVERAGE Thermal resistance of coldplate (K*in^2/W)	Heat transfer coefficient (Kermani) TUBES top heat flux only (W/(m^2*K))	MAX Pressure (psi)	
45	63	30	33	56.2	65.2	54.2	0.211	2266	0.20	**Same side inlet / outlet**, Cylindrical Inlet, horizontal heat loads
45	63	30	33	53.1	56.4	54.2	0.118	4359	0.23	**Opposite side inlet / outlet**, Cylindrical Inlet, horizontal heat loads
45	63	30	33	52.8	56.4	54.2	0.164	4275	0.23	**Vertical heat loads**, Opposite side inlet / outlet, Cylindrical Inlet
45	63	30	33	52.8	56.3	54.2	0.166	4296	0.22	**Conical Inlet**, Vertical heat loads, Opposite side inlet / outlet
45	63	30	33	52.9	58.9	54.2	0.158	4070	0.23	**Larger output**, Conical Inlet, Vertical heat loads, Opposite side inlet / outlet

Changing outlet direction has the biggest effect on performance while orientation of the heat loads and shape of the input feeder improve overall surface temperature distribution.

Thermal Management of High Power Electronics using COMSOL Multiphysics® Simulation Software

- Conclusions

This effort demonstrates a flexible approach to thermal management using a manifold microchannel cold plate.

- Designed with COMSOL Multiphysics® simulation software.
- Additively manufactured using direct metal laser sintering.
- Provides base cooling to the entire circuit board.
- Provides selective cooling to specific high power components.
- Provides optimized heat dissipation through simulation.
  - Mitigates thermal issues.
  - Minimizes weight.
  - Minimizes coolant flow rate.
  - Minimizes pressure drop.

Allows changes in thermal demands to be re-evaluated and a successful solution redesigned and reprinted quickly.

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