Multiphysics Simulation and Optimization for Thermal Management of Electronics Systems

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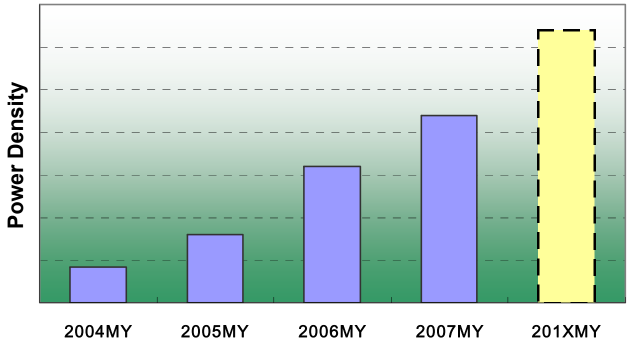
Wednesday, February 8, 2012, 2-5 p.m.
Orlando, FL

Overview

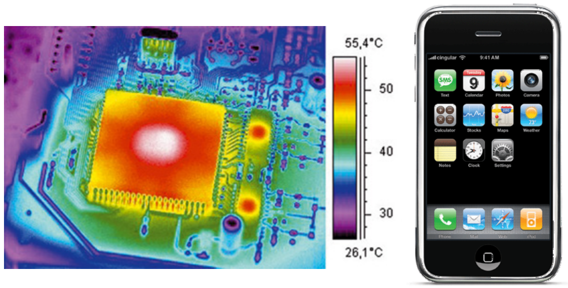
- Motivation & Background
- Topology Optimization Approach
- Application to Structure & Material Design
  - Branching Microchannel Cold Plate
  - Magnetic Fluid Cooling Device
  - Anisotropic Composite
- Conclusions

Motivation & Background

- Significant thermal challenges for future electronics systems



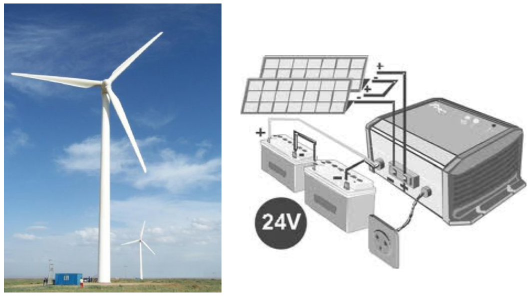
Trend in Electronics Power Density



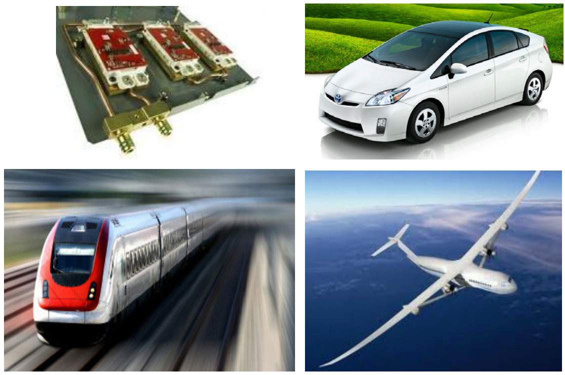
Consumer Electronics

<u>High Density, Reliable Electronics</u>

Efficient Cooling is a Key Enabling Technology



Sustainable Energy Applications



Transportation

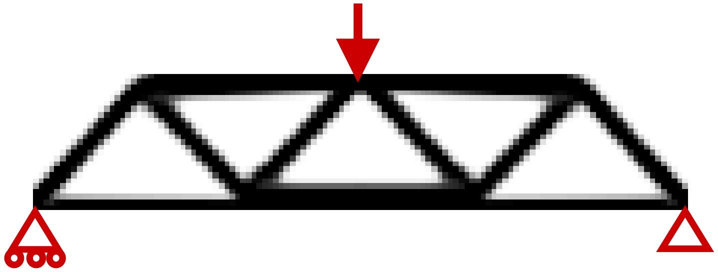
Lasers & Photonics Systems

***Note: Various images obtained from the web**

Topology Optimization Approach

- Method to Find an Optimal Geometry (Size, Shape, Number of holes)

E.g. Optimal Geometry for Stiffness

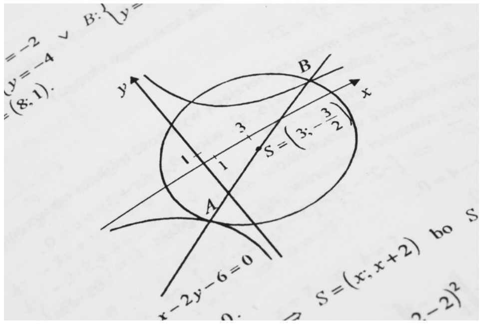


- A Mathematical Approach using Finite Element Analysis (FEA)

Engineer's Intuition (experience) or Iteration

Vs.

Mathematical Method



Topology Optimization Approach

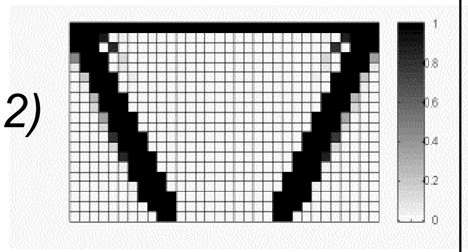
- Geometry description and topology optimization procedure

Mathematical representation of geometry

Density ρ of each finite element

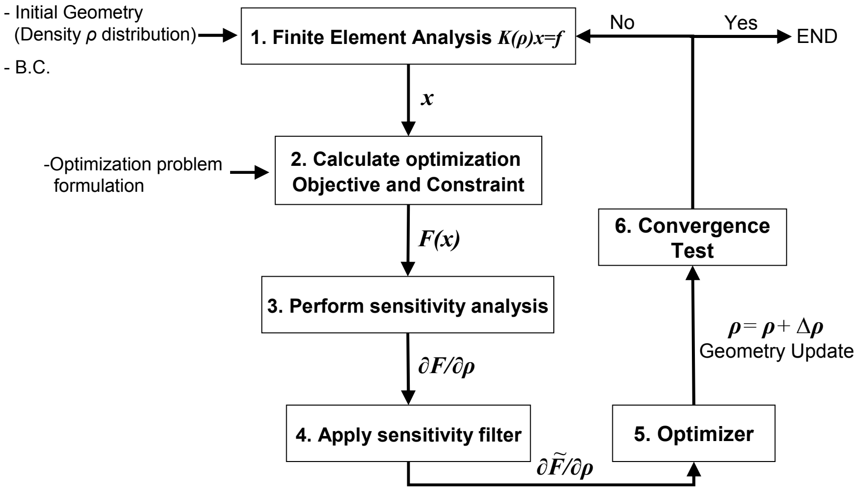
0: Void (Air/Material 1)
1: Solid (Steel/Material 2)

+



Material properties: function of density ρ

Ex) ρ: 0 → E=0 (void) ,   k=0.6 (water)
ρ: 1 → E=200 (steel), k=240 (aluminum)



- Initial Geometry (Density ρ distribution)
- B.C.

1. Finite Element Analysis $K(\rho)x=f$

x

-Optimization problem formulation

2. Calculate optimization Objective and Constraint

$F(x)$

3. Perform sensitivity analysis

$\partial F/\partial\rho$

4. Apply sensitivity filter

$\partial\tilde{F}/\partial\rho$

5. Optimizer

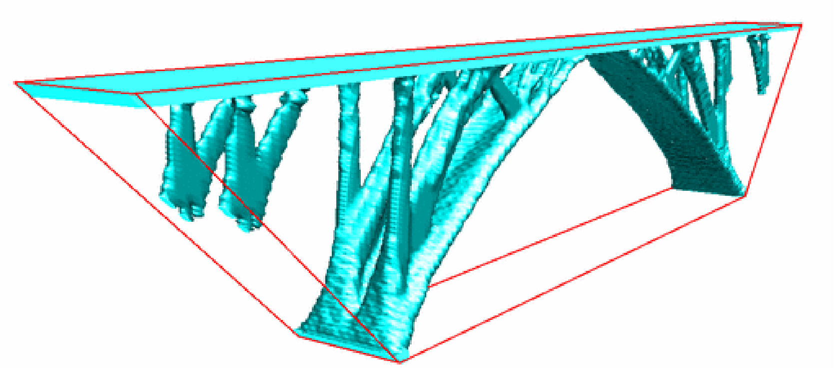
$\rho=\rho+\Delta\rho$
Geometry Update

6. Convergence Test

No

Yes

END



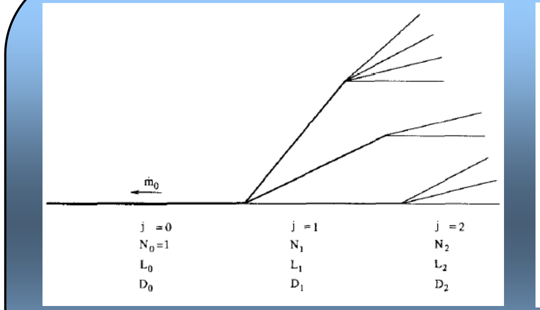
Geometry → Density ρ Distribution of Each Finite Element

Application to Structure & Material Design:

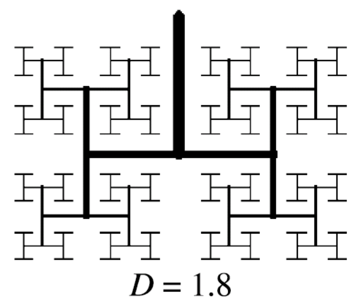
Example 1 - Branching Microchannel Cold Plate

Branching Microchannel Cold Plate

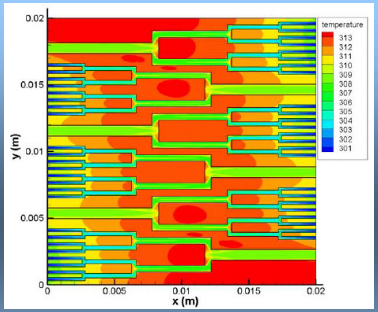
- State-of-the-art in hierarchical, branching, or fractal structures



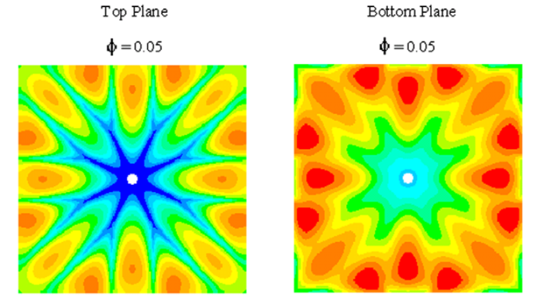
Ref.: A. Bejan, 1997



Ref.: Y. Chen & P. Cheng, 2002

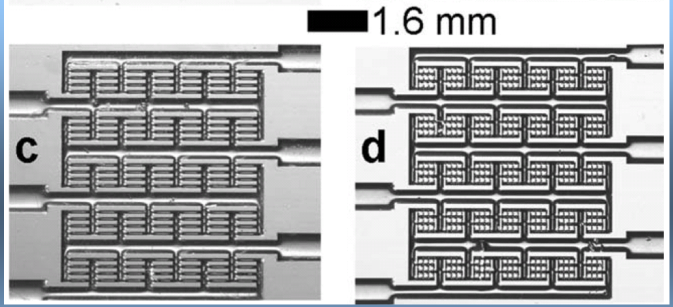


Ref.: X.-Q. Wang et al., 2009

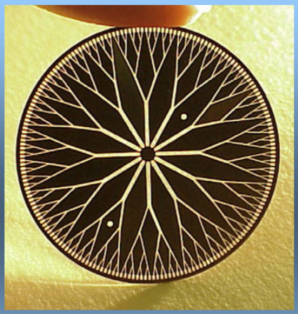


Ref.: L.A.O Rocha et al., 2009

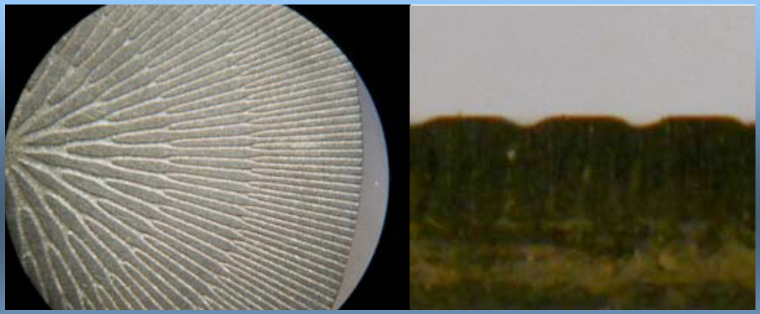
Sustained interest in branching networks for enhanced heat transfer & reduced pumping power



Ref.: J.P. Calame et al., 2009



Ref.: D. Pence, 2010



Ref.: A. Tulchinsky et al., 2011

Development of microscale fabrication techniques for fractal-like heat exchangers

Branching Microchannel Cold Plate

- Governing equations for multi-objective optimization of thermal-fluid systems
  - Minimize average temperature and fluid power dissipated in domain

    Ref.: M.P. Bendsoe & O. Sigmund, 2003; T. Borrvall & J. Petersson, 2003
  - Heat transfer
    - Interpolate thermal conductivity, k

$$\rho C(\mathbf{u}\cdot\nabla T)=\nabla\cdot(k(\gamma)\nabla T)+Q$$

  - Fluid mechanics
    - Interpolate inverse permeability, α

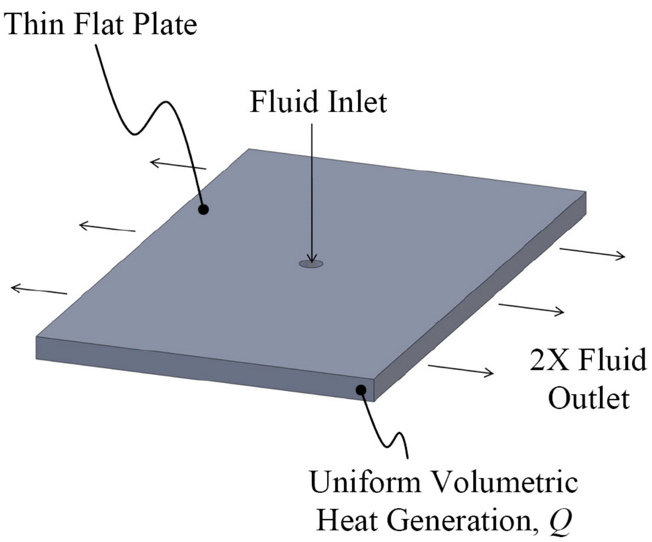
$$\nabla\cdot\mathbf{u}=0$$

$$\rho(\mathbf{u}\cdot\nabla\mathbf{u})=-\nabla P+\eta\nabla^2\mathbf{u}-\alpha(\gamma)\mathbf{u}$$

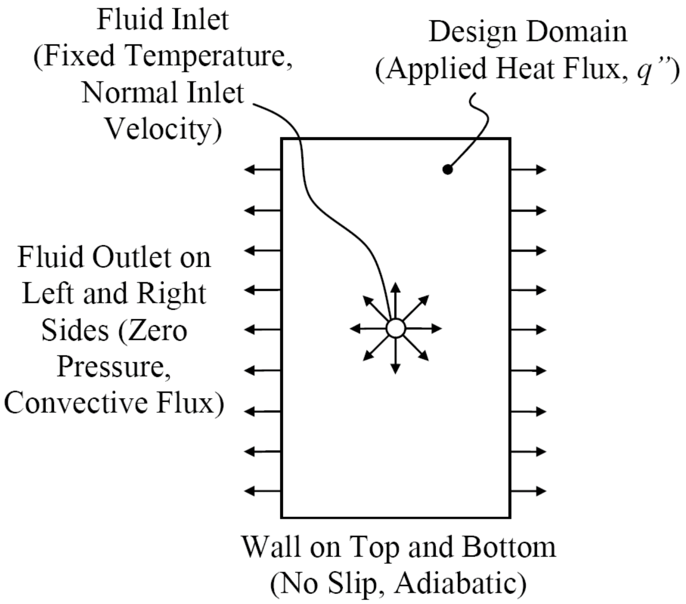
Branching Microchannel Cold Plate

- Problem description
  - Optimization of a heated plate with a center inlet

Ref.: E.M. Dede et al., 2009, 2010, & 2011



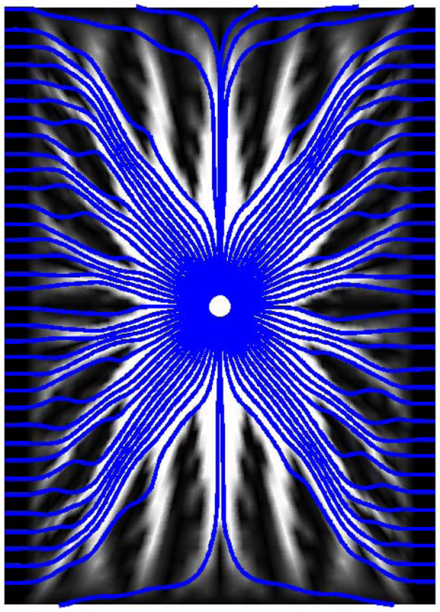
3-D schematic of the thin rectangular heated plate problem



2-D optimization domain, boundary conditions, and loads

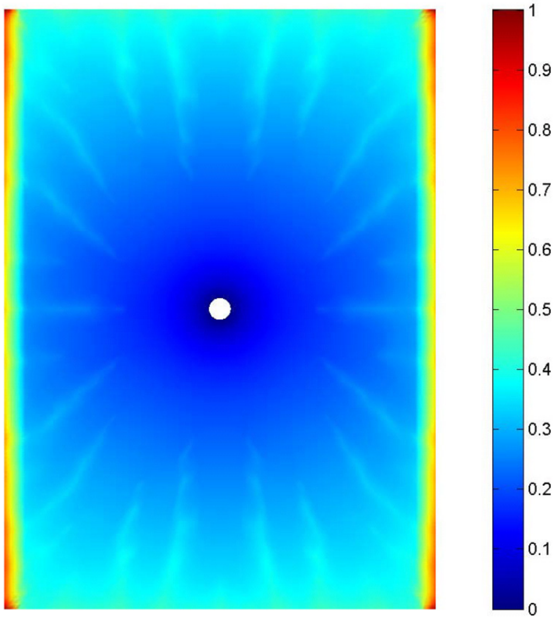
Branching Microchannel Cold Plate

- Optimization of heated plate with center inlet
  - Results emphasizing minimization of average temperature

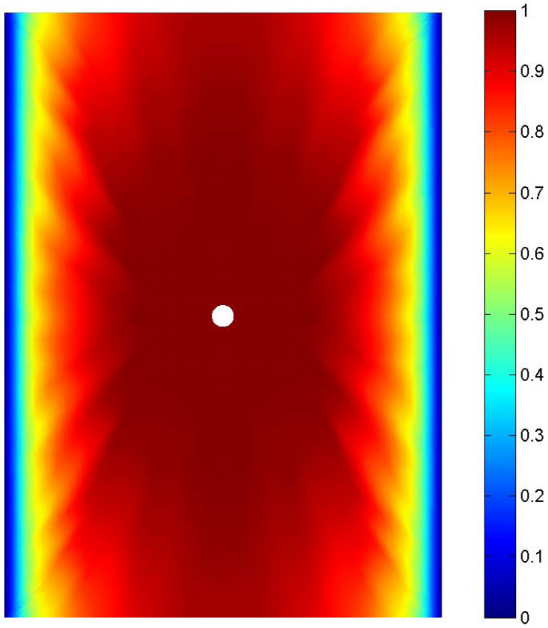


(45% fluid volume fraction)

Optimal topology with fluid streamlines



Normalized temperature contours

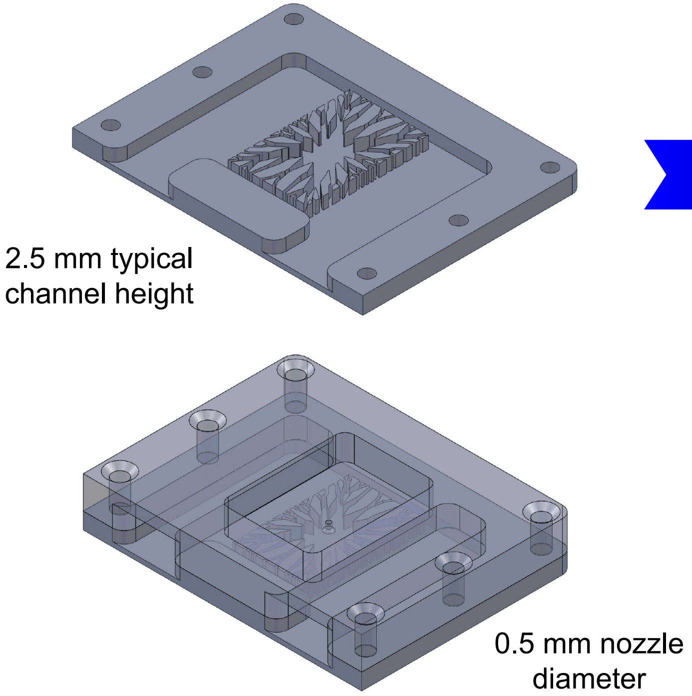


Normalized pressure contours

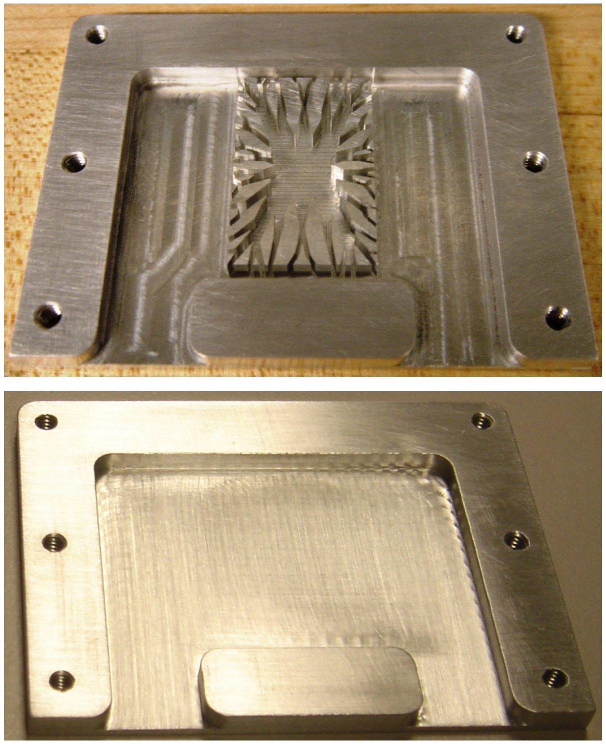
Branching Microchannel Cold Plate

- Synthesis of 3-D hierarchical channel structure
  - Optimized microchannel and flat (benchmark) target plates studied
  - Addition of jet plate creates ‘manifold-like’ heat sink structure

  Ref: G.M. Harpole & J.E. Eninger, 1991; Y.I. Kim et al., 1998



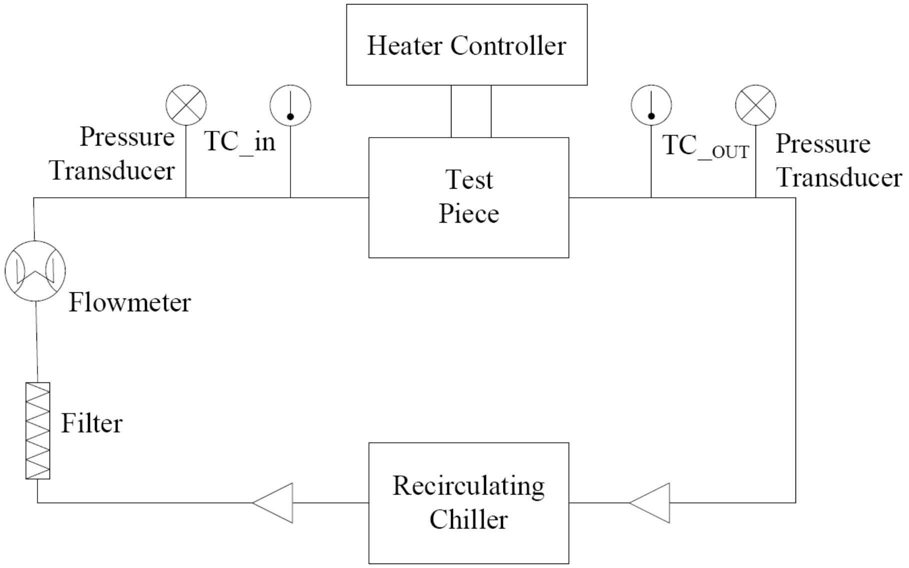
Hierarchical microchannel cold plate without (top) and with (bottom) jet plate



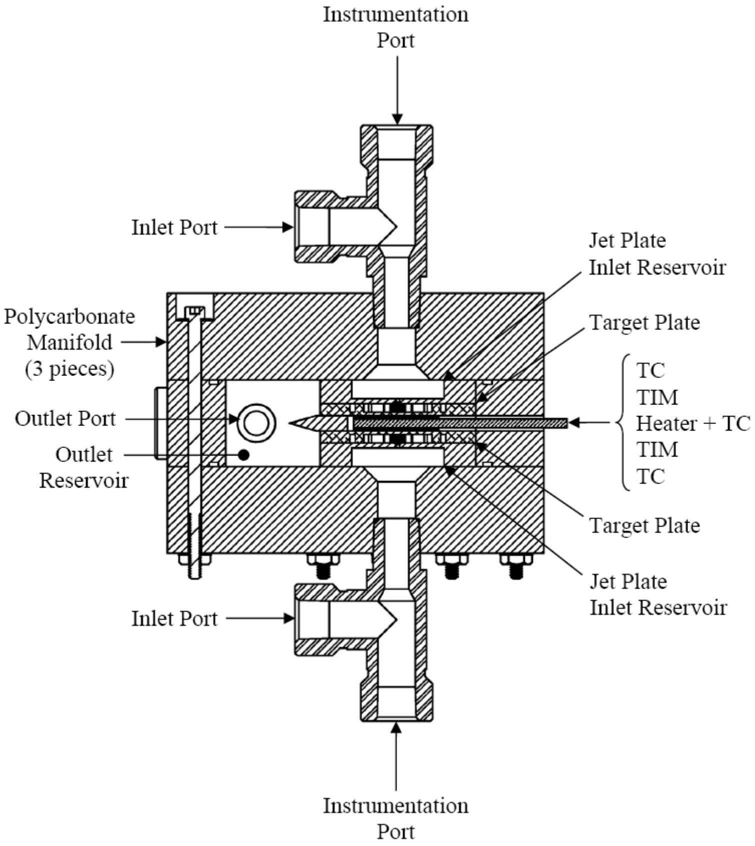
Prototype Al cold plates with (top) and without (bottom) the channel topology

Branching Microchannel Cold Plate

- Experimental test setup
  - Single-phase thermal-fluid test bench

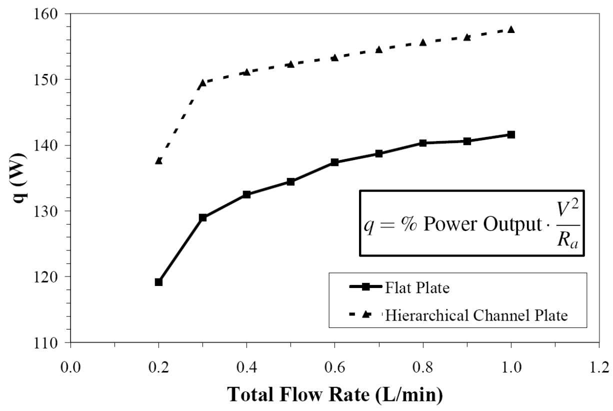


Schematic for Experimental Flow Loop

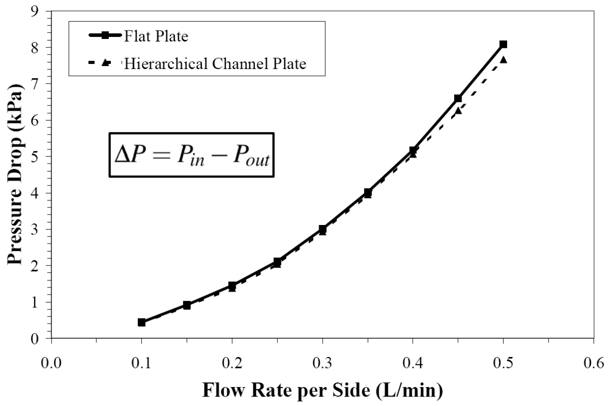


Side Cross-Section View of Test Piece

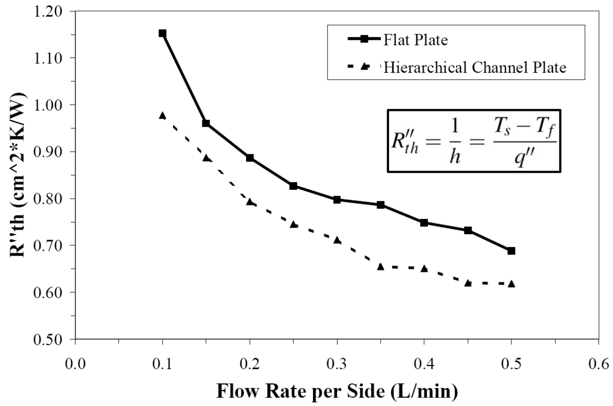
Branching Microchannel Cold Plate



Test Piece Total Power Dissipation



Cold Plate Pressure Drop



Cold Plate Unit Thermal Resistance

ΔP = 7.53 kPa

ΔP = 7.37 kPa

Pressure Drop Numerical Study at 0.5 L/min – Fluid Streamlines (Top View)

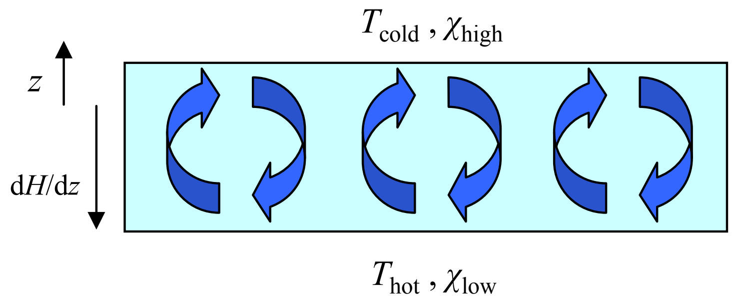
Optimized cold plate design provides enhanced heat transfer without pumping power penalty

Application to Structure & Material Design:

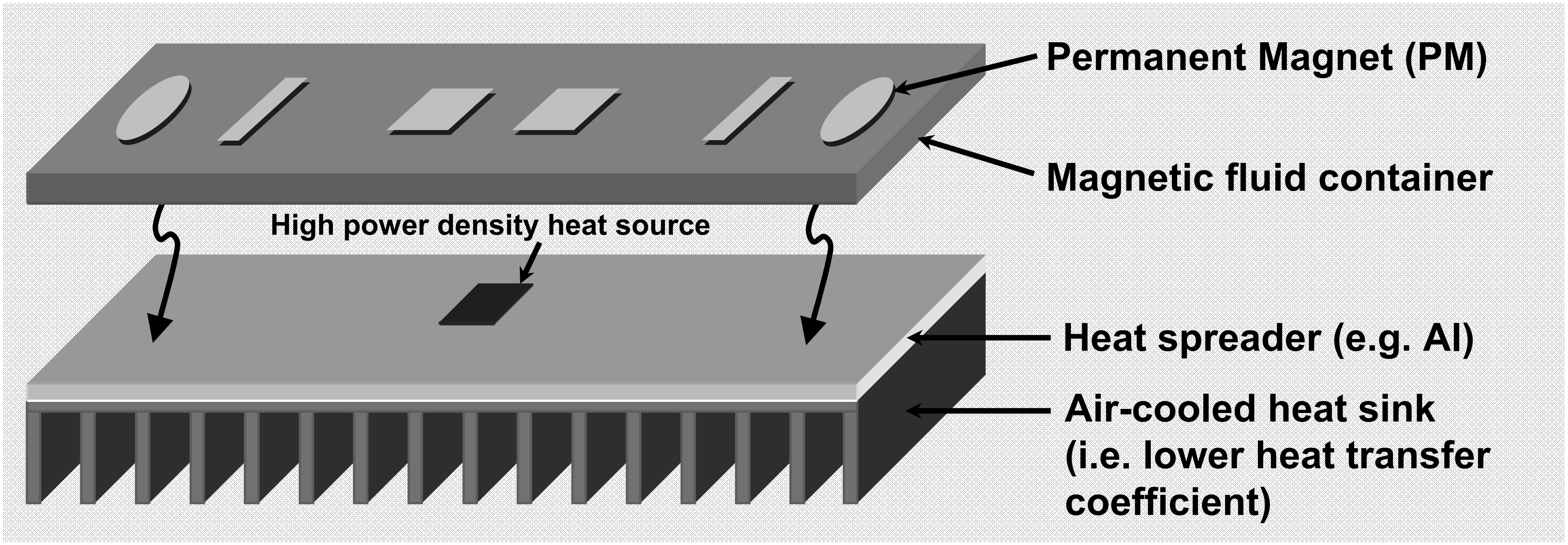
Example 2 – Magnetic Fluid Cooling Device

Magnetic Fluid Cooling Device

- **Motivation:** improve **heat spreading**
  - Uses: 1) concentrated heat source; 2) air-cooling
- **Objective:** Develop **magnetic fluid** enhanced heat spreader
  - Reduce size / mass relative to metal heat spreader
- **Concept:** Exploit thermo-magnetic siphoning inside container via thermal and magnetic fields



Thermo-magnetic instability, Ref.: R.E. Rosensweig, 1985 (cold fluid is more strongly magnetized and drawn to region of higher magnetic field strength thus displacing hotter fluid)



Permanent Magnet (PM)

Magnetic fluid container

High power density heat source

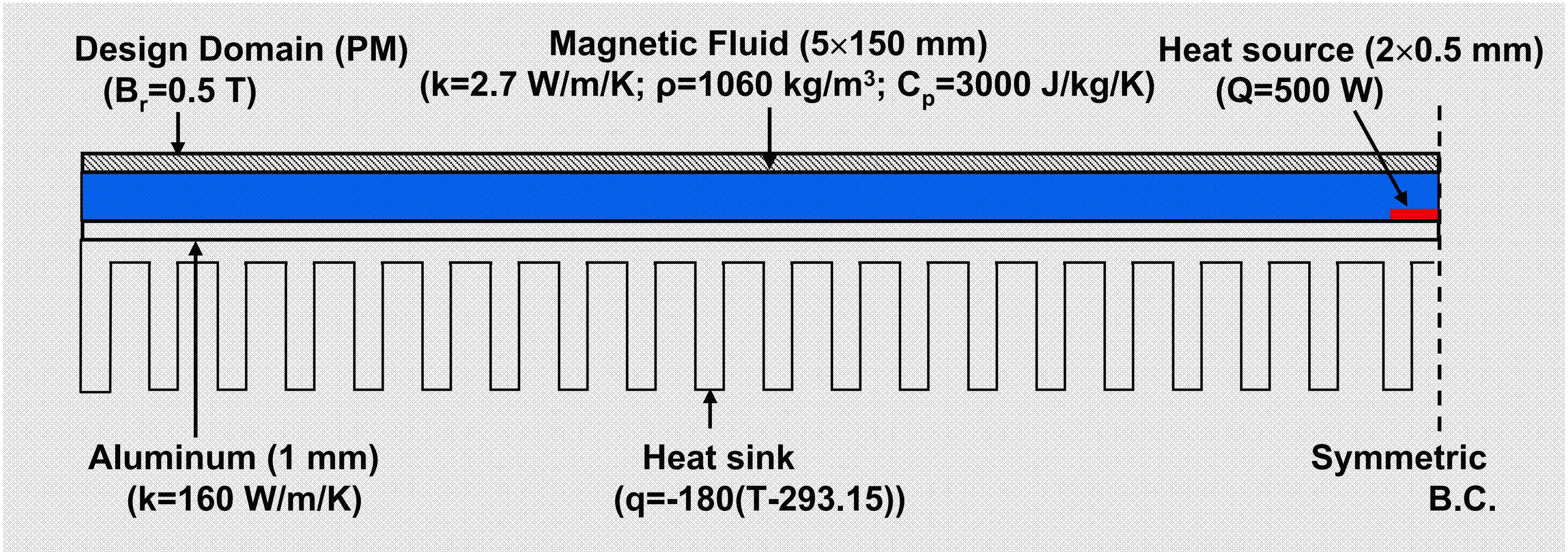
Heat spreader (e.g. Al)

Air-cooled heat sink (i.e. lower heat transfer coefficient)

Magnetic Fluid Cooling Device

- Design optimization problem

Find	**Magnet location** and **Magnetization direction**
Minimize	**Temperature at heat source**
	(Maximize heat spreading enhancement)
Subject to	**Magnetic-thermal-fluid equation**



Design Domain (PM)
(B_r=0.5 T)

Magnetic Fluid (5×150 mm)
(k=2.7 W/m/K; ρ=1060 kg/m³; C_p=3000 J/kg/K)

Heat source (2×0.5 mm)
(Q=500 W)

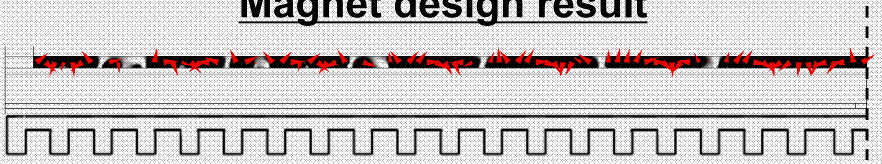
Aluminum (1 mm)
(k=160 W/m/K)

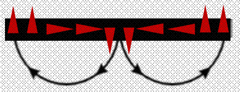
Heat sink
(q=-180(T-293.15))

Symmetric B.C.

Magnetic Fluid Cooling Device

Magnet design result

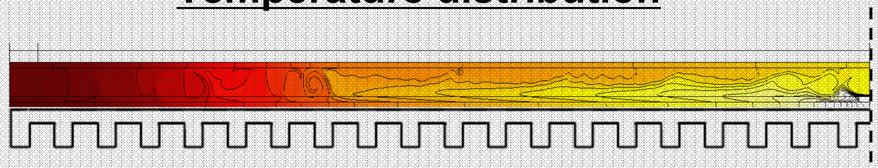




Design result →

Halbach array (One-side strong flux)

Temperature distribution



Heater temperature=361.4 ºK (88.3 ºC)

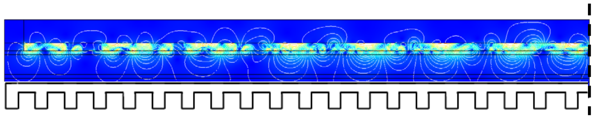
Magnetic analysis

$$\nabla\times\left(\frac{1}{\mu}\nabla\times\mathbf{A}\right)=\nabla\times\left(\frac{1}{\mu}\mathbf{B}_{\mathbf{r}}\right)$$

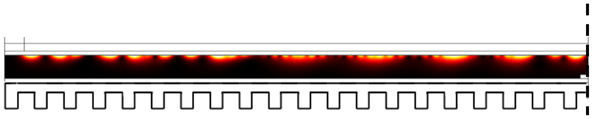
$$\nabla(-k\nabla T)=Q-\rho C_{p}\mathbf{u}\nabla\mathbf{T}$$

Thermal analysis

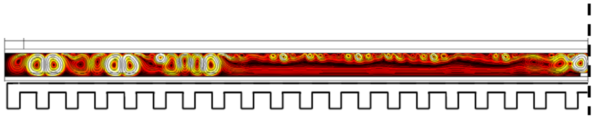
Magnetic field distribution



Fluid body force distribution



Fluid streamline



Magnetic body force calculation

$$f=\frac{1}{2}\mu_{0}\chi\nabla\left(H^{2}\right)$$

Fluid analysis

$$\rho(\mathbf{u}\cdot\nabla)\mathbf{u}=\nabla\cdot\left(-p\mathbf{I}+\eta\left(\nabla\mathbf{u}+\nabla\mathbf{u}^{T}\right)\right)+f$$

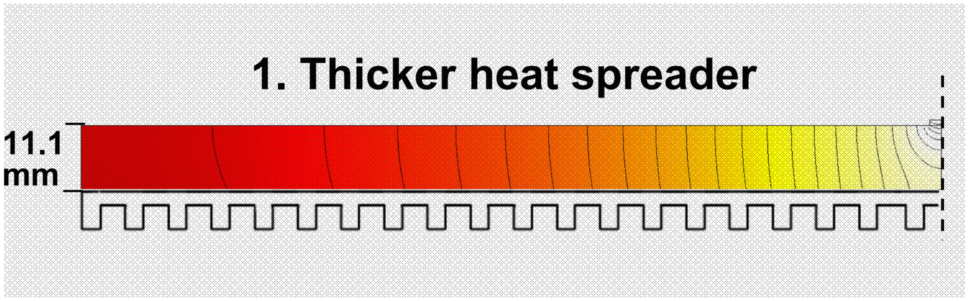
$$\nabla\cdot\mathbf{u}=0$$

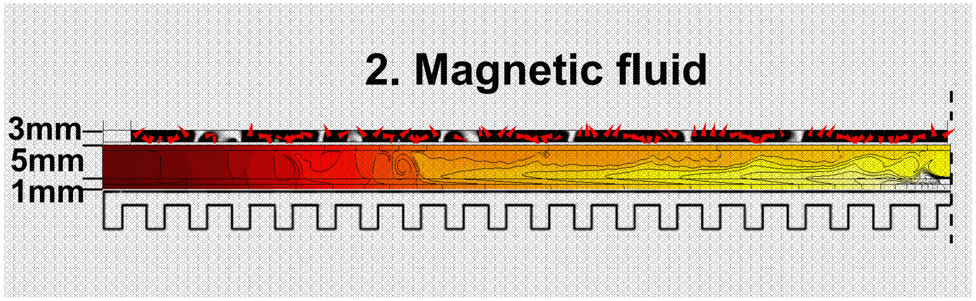
Fluid motion control thru magnetic body force → related to fluid magnetic susceptibility and magnitude of applied vector field

Magnetic Fluid Cooling Device

- Comparison with a thicker aluminum heat spreader

Both designs target the same heater temperature (i.e. 88.3 ºC)


1. Thicker heat spreader


2. Magnetic fluid

	Size	**Weight**
1. Thicker spreader	11.1 mm thickness	45 g/cm
2. Magnetic fluid	9 mm thickness (↓ 19% reduction)	22.1 g/cm (↓ 51% reduction)

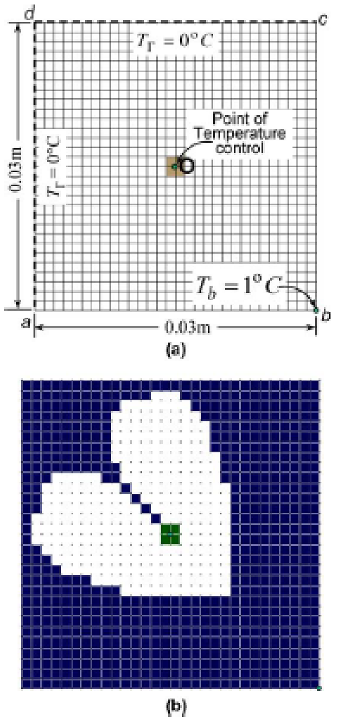
Achieved design of magnetic fluid cooling device that is smaller and lighter than equivalent performance metal heat spreader

Application to Structure & Material Design:

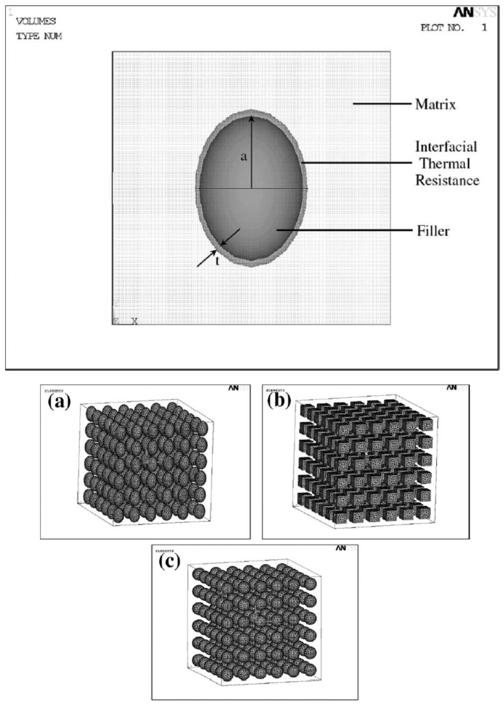
Example 3 – Anisotropic Composite

Anisotropic Composite

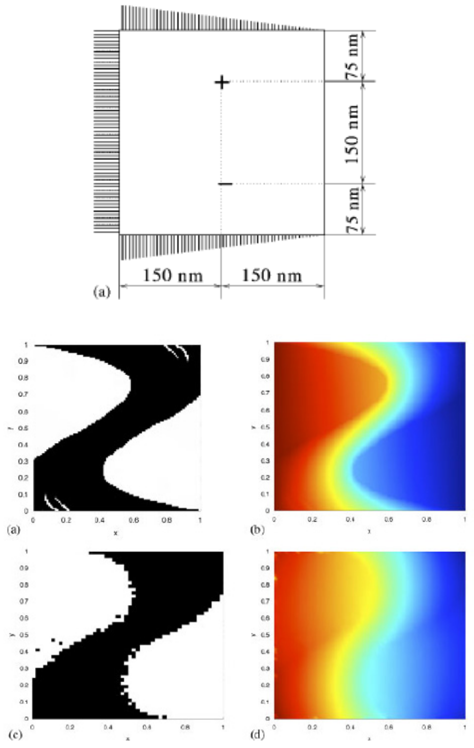
- Motivation
  - Heat conduction modeling and control is active field
    - Various scales involved for novel thermal design



Ref.: Q. Li, et al., 2004



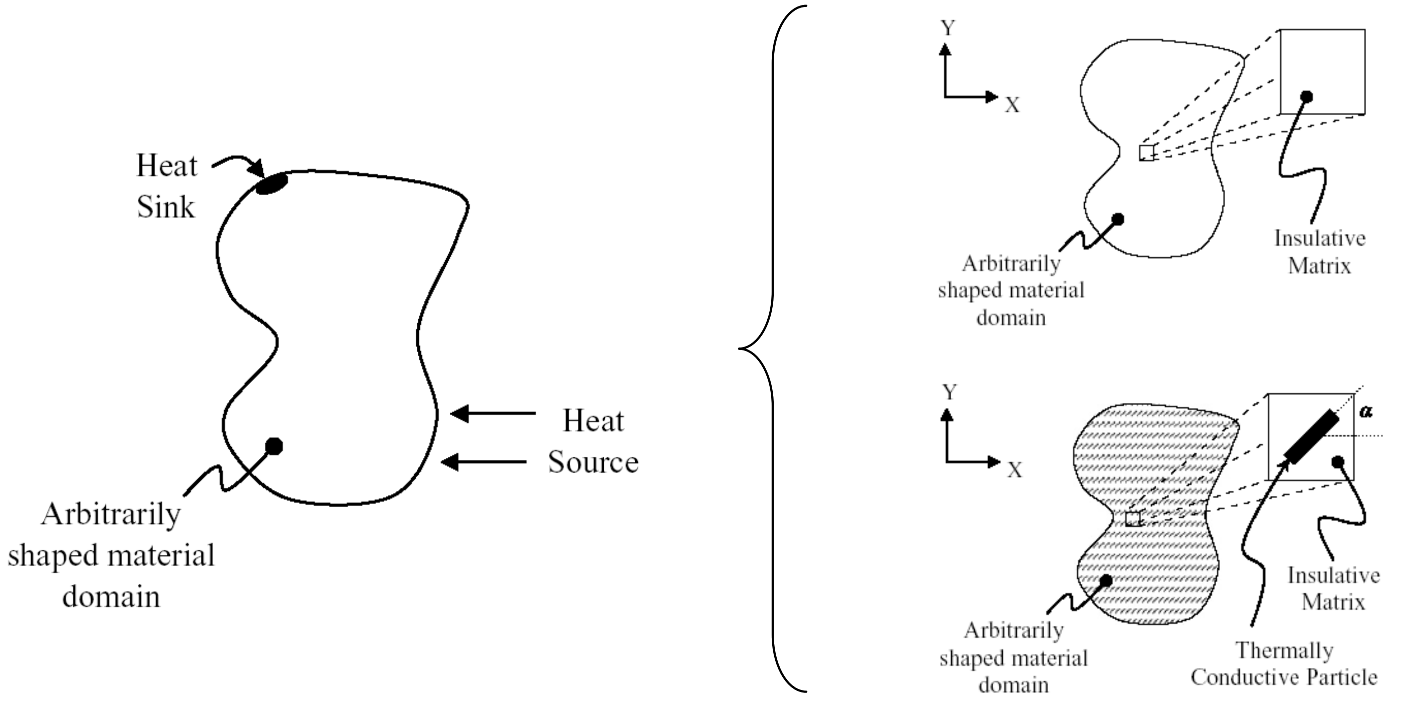
Ref.: J. Zeng, et al., 2009



Ref.: A. Evgrafov, et al., 2009

Anisotropic Composite

- Problem description
  - Arbitrarily shaped design domain
  - Optimize heat flow path from heat source to sink
    - Orient conductive filler particles to minimize R_{th}



Anisotropic Composite

- Technical approach
  - Design anisotropic thermal conductivity
    - Interpolation scheme: α varies 0 to 90 deg
      - Determine 'absolute' value of particle angle
      - Heat flux vector determines final quadrant

$$\mathbf{K} = \begin{bmatrix} K_{11} & 0 \\ 0 & K_{22} \end{bmatrix}$$

, where

Design variable

$$K_{11} = k_{11} \cdot \cos^2(\alpha) + k_{22} \cdot \sin^2(\alpha)$$

$$K_{22} = k_{11} \cdot \sin^2(\alpha) + k_{22} \cdot \cos^2(\alpha)$$

Coordinate transformation

$$\boxed{k_{11} = \nu \cdot k_f + (1-\nu) \cdot k_m}$$

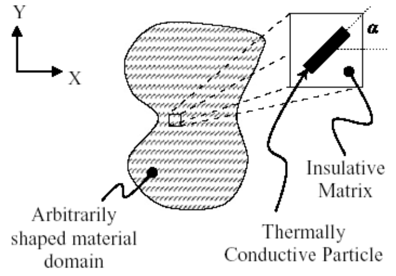
$$\boxed{k_{22} = \left(\frac{\nu}{k_f} + \frac{(1-\nu)}{k_m} \right)^{-1}}$$

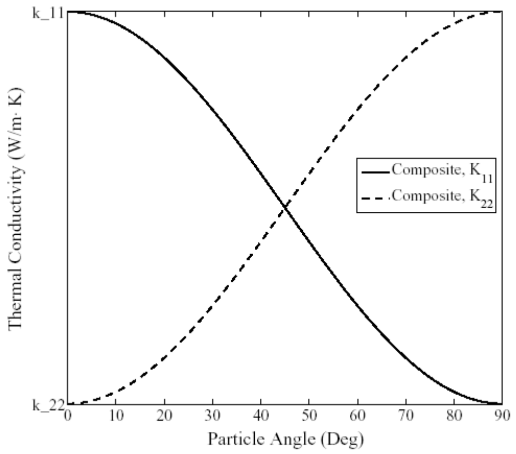
Fiber volume fraction

Matrix conductivity

Fiber conductivity

Basic slab model for unit cell

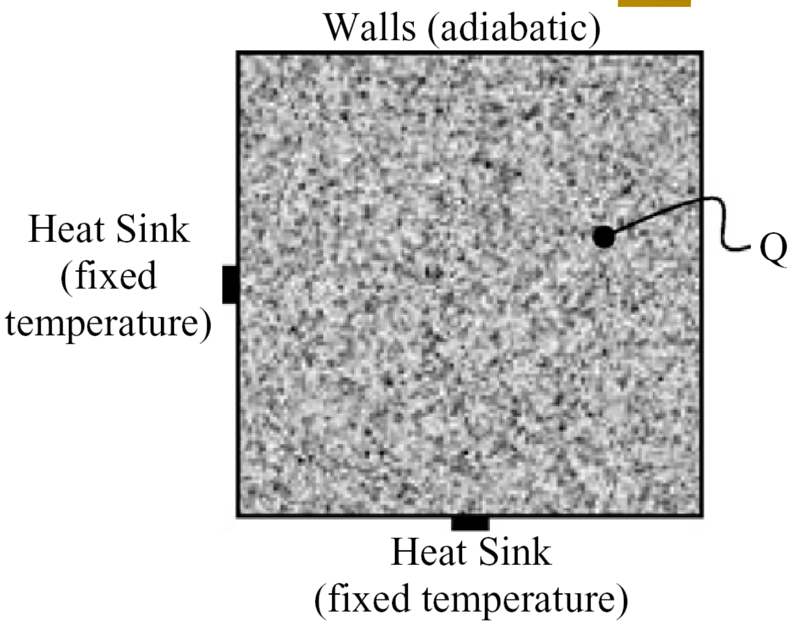




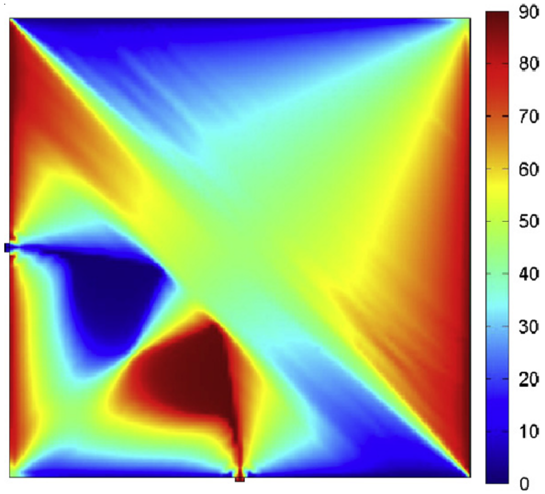
Ref.: E.M. Dede, 2010

Anisotropic Composite

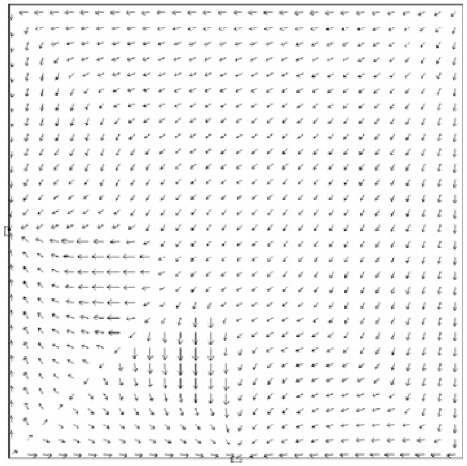
- Optimization results



2-D Design Domain



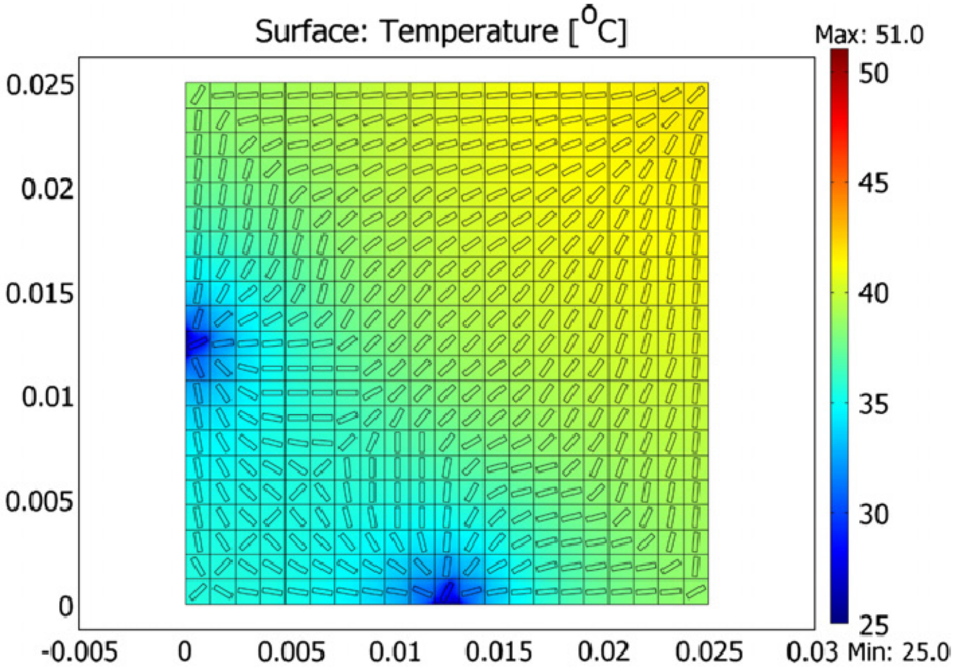
Absolute Value of Particle Angle



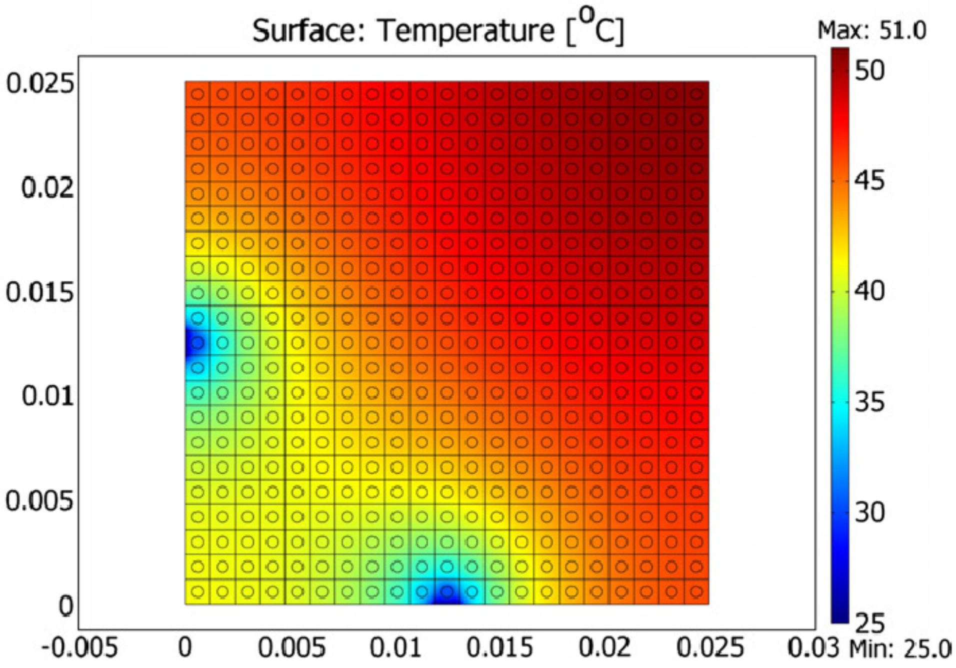
Normalized Heat Flux Vectors

Anisotropic Composite

- Composite material synthesis
  - Optimized vs. benchmark material (25 mm x 25 mm) with same filler volume fraction → copper ‘fiber’ in nylon matrix



Optimized Material



Benchmark Material

Achieved 9 °C reduction in maximum temperature with 34% reduction in thermal resistance, ($R=\Delta T/Q$)

Conclusions

- Topology optimization technique may be extended from single to multi-physics problems
  - Thermal-fluid, magnetic-thermal-fluid, and composite material design applications demonstrated
- Novel approach to initial concept development
  - Method typically provides ‘informed starting point’ for design exploration
- Optimization method may be applied to variety of applications and additional physical systems
  - E.g. electro-mechanical design, thermal-stress, etc.

References

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