The Influence of Channel Aspect Ratio on the Performance of Optimized Thermal-Fluid Structures

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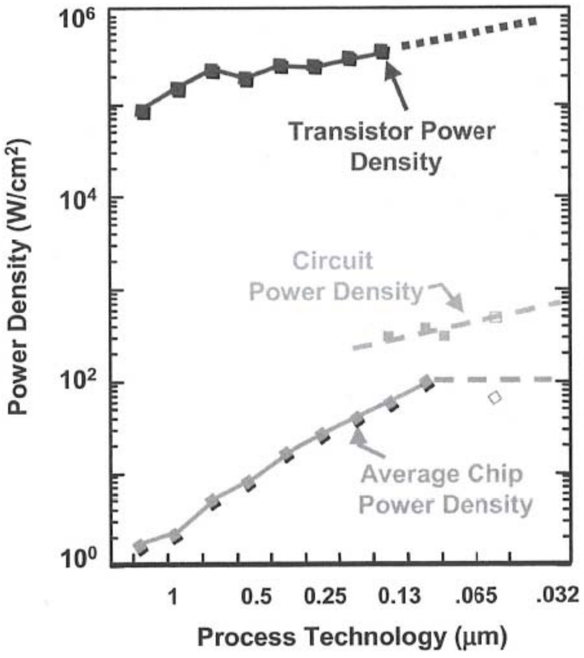
Overview

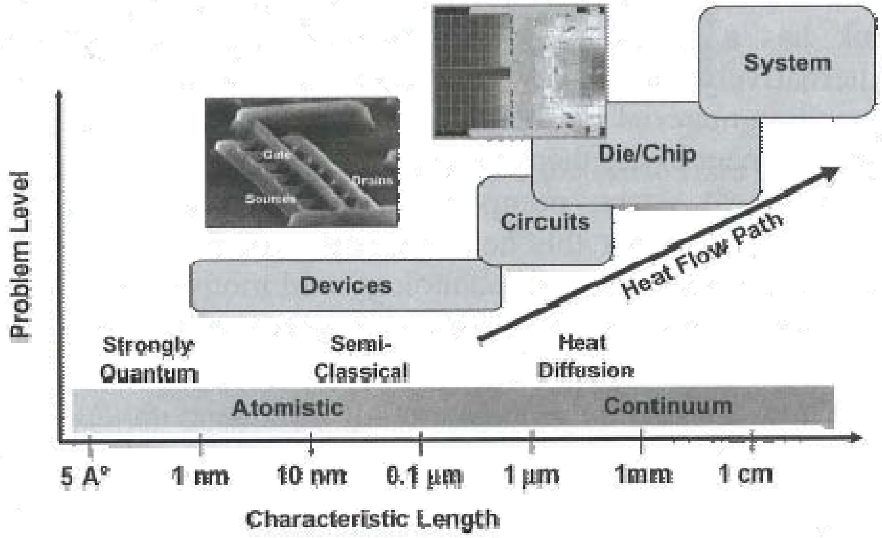
- Background
- Problem Description
- Topology Optimization Results
- Cooling Structure Synthesis
- Simulation Results & Comparisons
- Conclusions

Background

- Significant thermal challenges exist for future electronics systems
  - Ref. Yavatkar (2007)
- ☐ High heat transfer with low pumping power required



Trend in Power Density



Characteristic Length Scales

Background

- Governing equations for multi-objective optimization of thermal-fluid systems
  - Minimize average temperature and fluid power dissipated in domain
    - Ref. Dede (2009)
  - Heat transfer
    - Interpolate thermal conductivity, k

Eq. 1 $$\rho C(\mathbf{u}\cdot\nabla T) = \nabla\cdot(k(\gamma)\nabla T) + Q$$

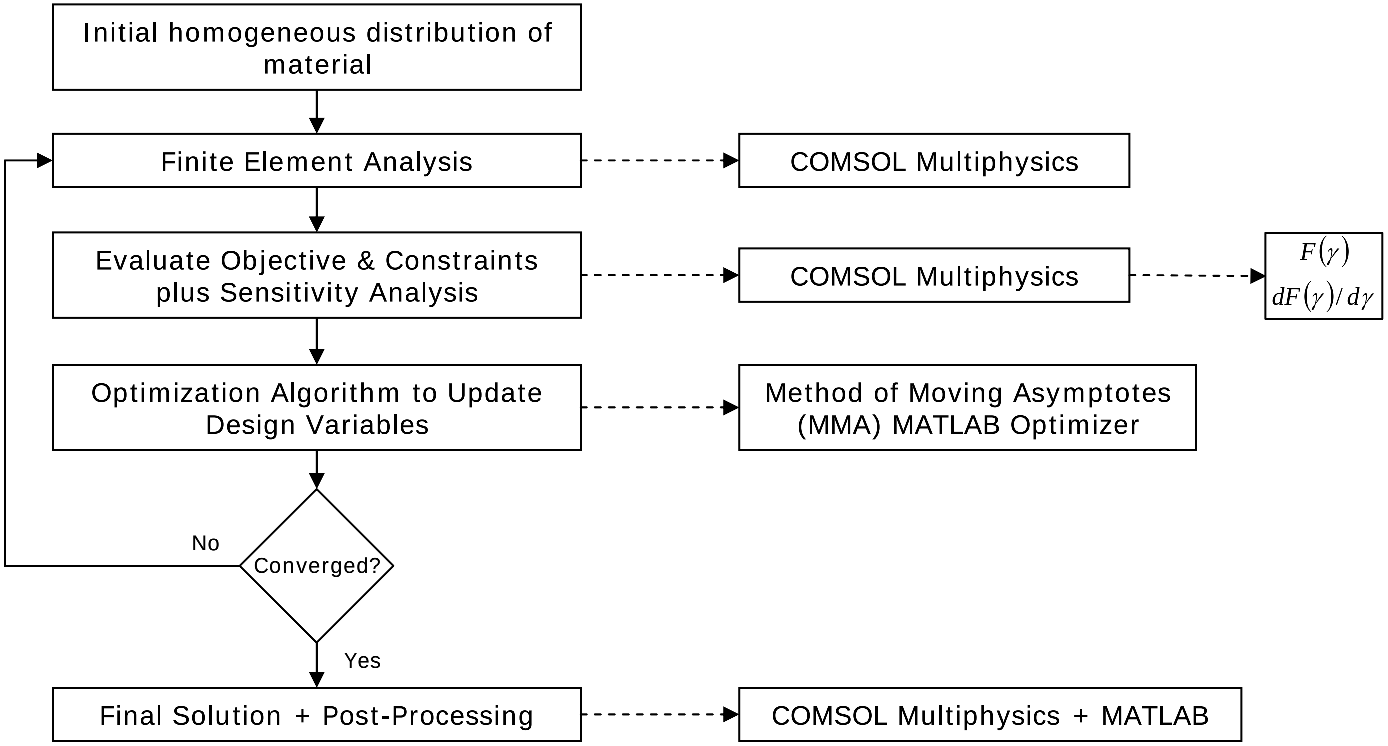
  - Fluid mechanics
    - Interpolate inverse permeability, α

Eq. 2 $$\nabla\cdot\mathbf{u} = 0$$

Eq. 3 $$\rho(\mathbf{u}\cdot\nabla\mathbf{u}) = -\nabla P + \eta\nabla^2\mathbf{u} - \alpha(\gamma)\mathbf{u}$$

Background

- Topology optimization implementation
  - COMSOL v.3.5a + MMA in MATLAB environment
    - Ref. Olesen et al. (2006)



Initial homogeneous distribution of material

Finite Element Analysis → COMSOL Multiphysics

Evaluate Objective & Constraints plus Sensitivity Analysis → COMSOL Multiphysics → $F(\gamma)$, $dF(\gamma)/d\gamma$

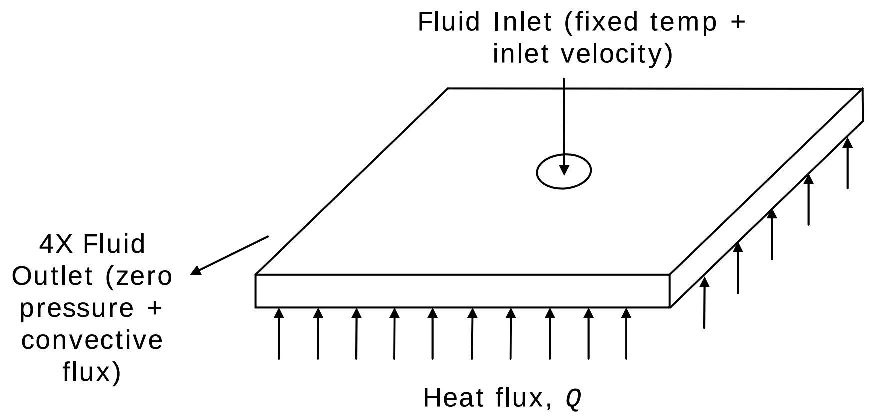
Optimization Algorithm to Update Design Variables → Method of Moving Asymptotes (MMA) MATLAB Optimizer

Converged? No → Finite Element Analysis; Yes → Final Solution + Post-Processing

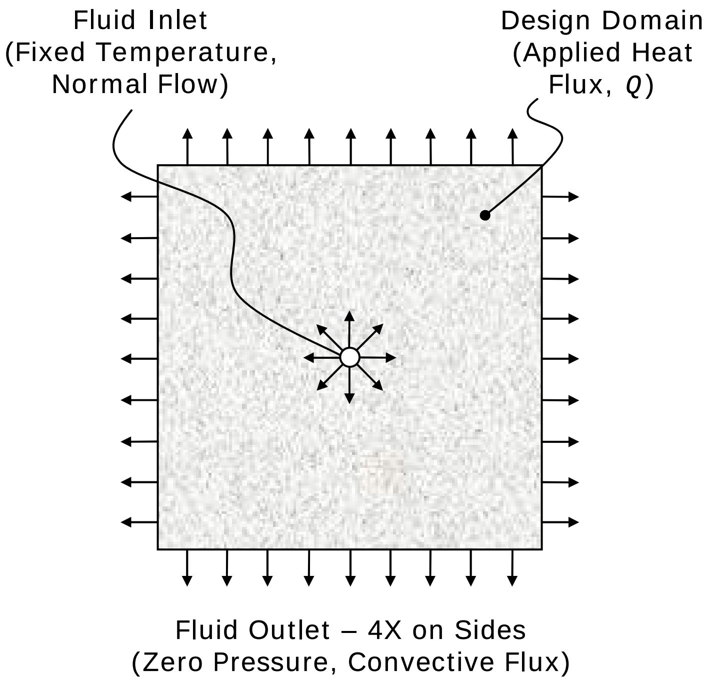
Final Solution + Post-Processing → COMSOL Multiphysics + MATLAB

Problem Description

- Optimization of a heated plate with a center inlet
  - Ref. Dede (2010)



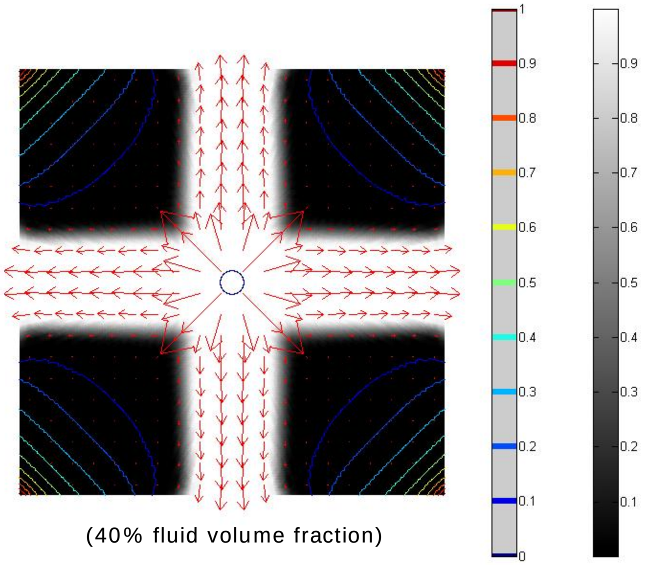
3-D schematic of the thin heated plate problem



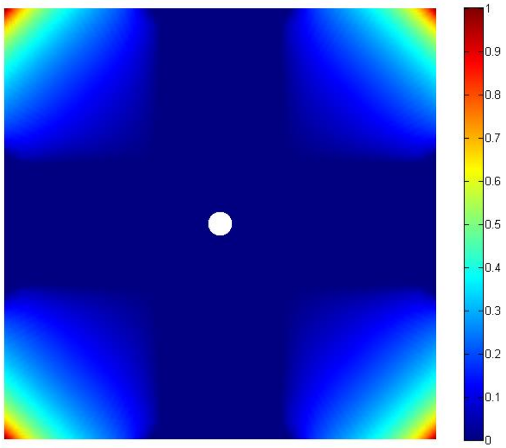
2-D optimization domain, boundary conditions, and loads

Topology Optimization Results

- Optimization of a heated plate with a center inlet
  - Results for $w_1 = 0$ and $w_2 = 1$ in objective function
    - I.e. prioritize minimization of fluid power dissipation in domain



(40% fluid volume fraction)

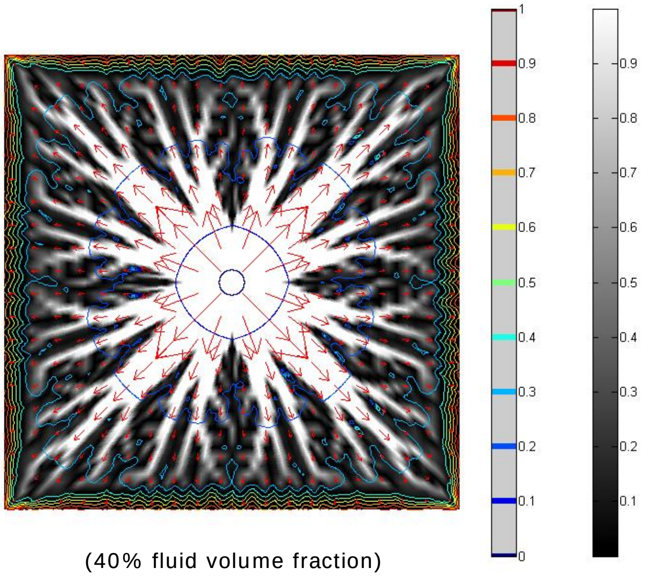


Optimal topology with normalized temperature contours and fluid velocity vectors

Normalized temperature contours of optimized domain

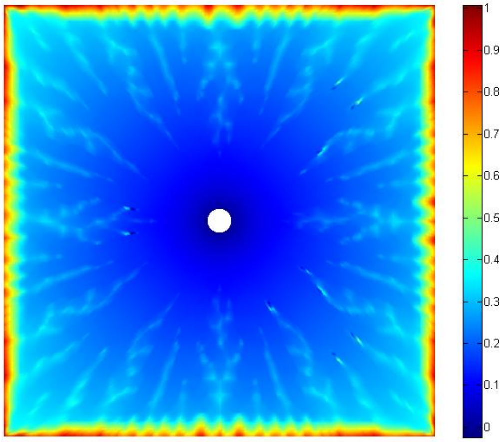
Topology Optimization Results

- Optimization of a heated plate with a center inlet
  - Results for $w_1 >> w_2$ in objective function (approx. 30:1 ratio)
    - I.e. prioritize minimization of average temperature of domain



(40% fluid volume fraction)

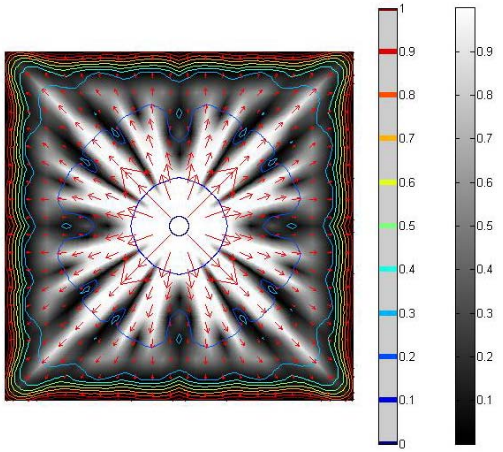
Optimal topology with normalized temperature contours and fluid velocity vectors



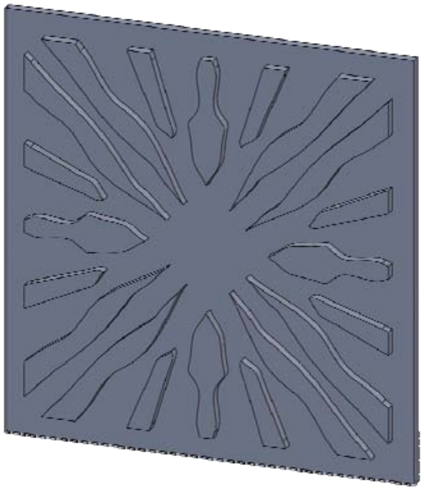
Normalized temperature contours of optimized domain

Cooling Structure Synthesis

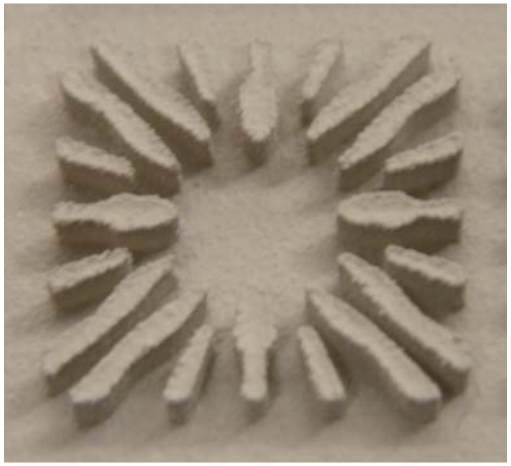
- Development of 3-D hierarchical channel structure
  - Concept based on coarse mesh optimization result
  - ~20 mm square plate impinged by nozzle jet
  - Initial channel height, h, of .5 mm



Coarse mesh optimization result



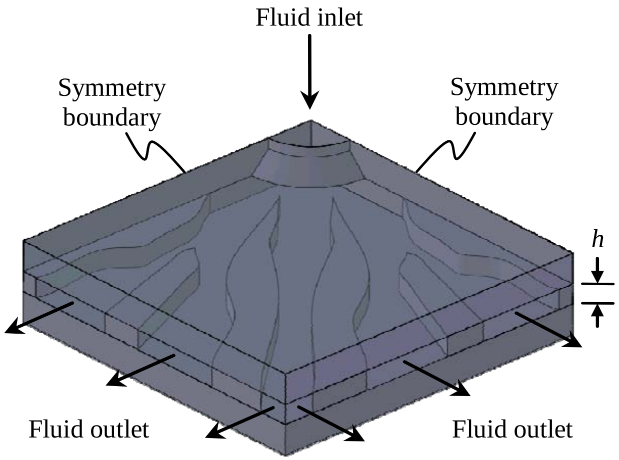
3-D CAD model of 1-level branching structure; similar to heat sinks described in Incropera (1999)



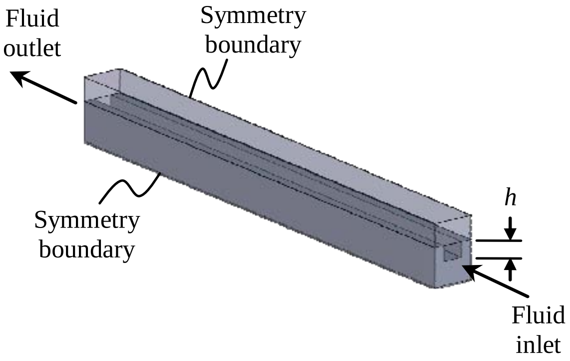
Example rapid prototype branching channel structure

Cooling Structure Synthesis

- Conjugate heat transfer model compared with the performance of a similarly sized microchannel
  - Parametric study in COMSOL v.4.0a to study *h* (0.5 to 2 mm)
  - Aluminum and water material properties assumed
  - Fluid flow rate ramped from zero to 0.15 L/min
  - Uniform applied heat flux of 100 W/cm^2
  - Fixed inlet temperature of 65 °C



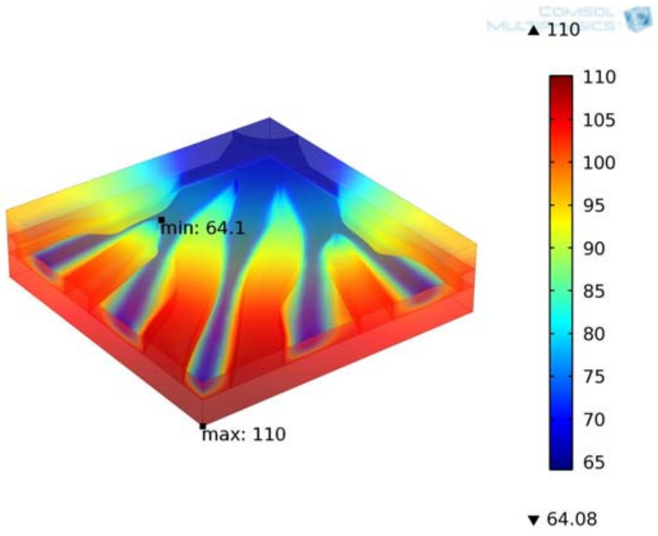
1/4-symmetry model of branching channel (BC) structure



Symmetry model of microchannel (MC) structure

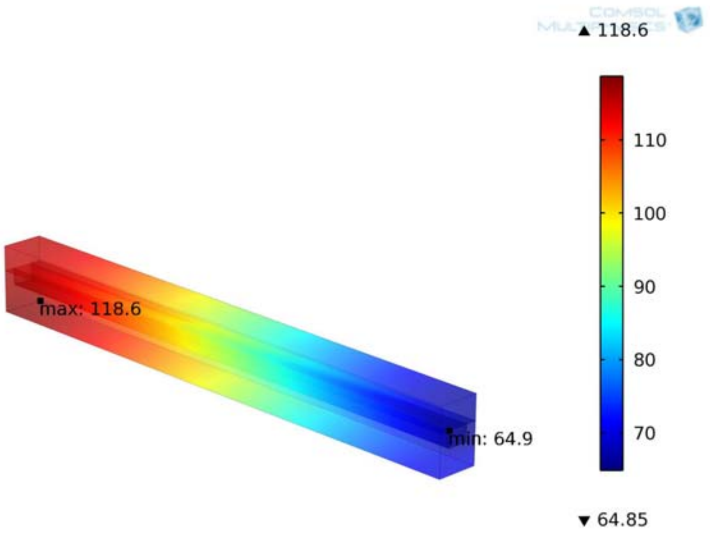
Simulation Results & Comparisons

- Sample temperature contour results
  - 0.5 mm channel height and 0.15 L/min flow rate
    - Branching structure exhibits lower T_{max} and ΔP with a lower temperature gradient across substrate surface



T_{max} = 110 °C
$T_{max} - T_{min}$ = 35 °C
ΔP = 243 Pa

Branching channel (BC) structure

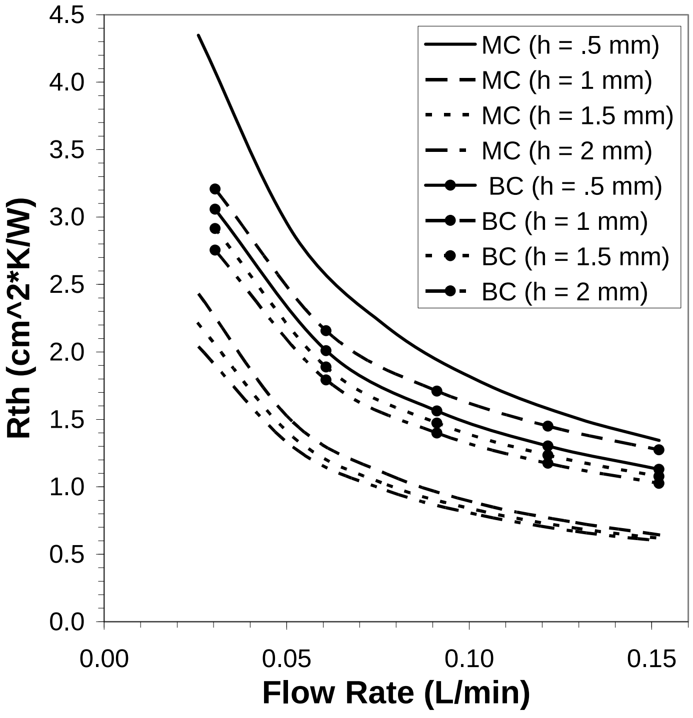


T_{max} = 119 °C
$T_{max} - T_{min}$ = 48 °C
ΔP = 2,090 Pa

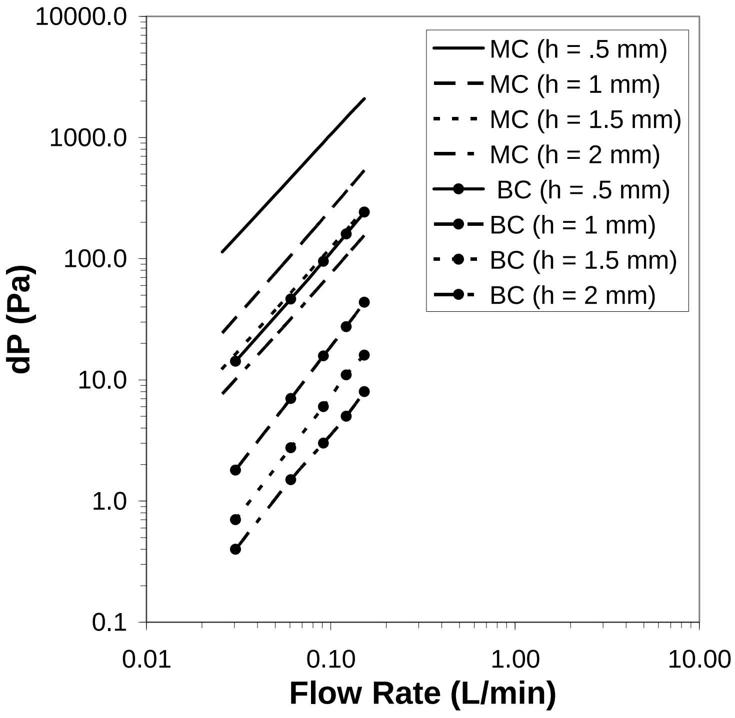
Microchannel (MC) structure

Simulation Results & Comparisons

- Thermal resistance and pressure drop curves
  - MC structure → lower R_{th} but significantly higher ΔP
  - BC structure → good for pumping power constrained applications



Thermal resistance vs. flow rate



Pressure drop vs. flow rate

Conclusions

- Multiphysics optimization of thermal-fluid structures was reviewed
  - Heat transfer and fluid flow effects logically produce different ‘optimal’ results

- The derived branching microchannel structure exhibits higher R_{th} but nearly negligible ΔP
  - Desirable for pumping power constrained applications

- The optimization method may be applied to a broad variety of vehicle applications
  - Other physical systems are also currently being explored
    - E.g. electromagnetic applications