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Application of Solution Mapping to Reduce Computational Time in Actively Cooled Power Electronics

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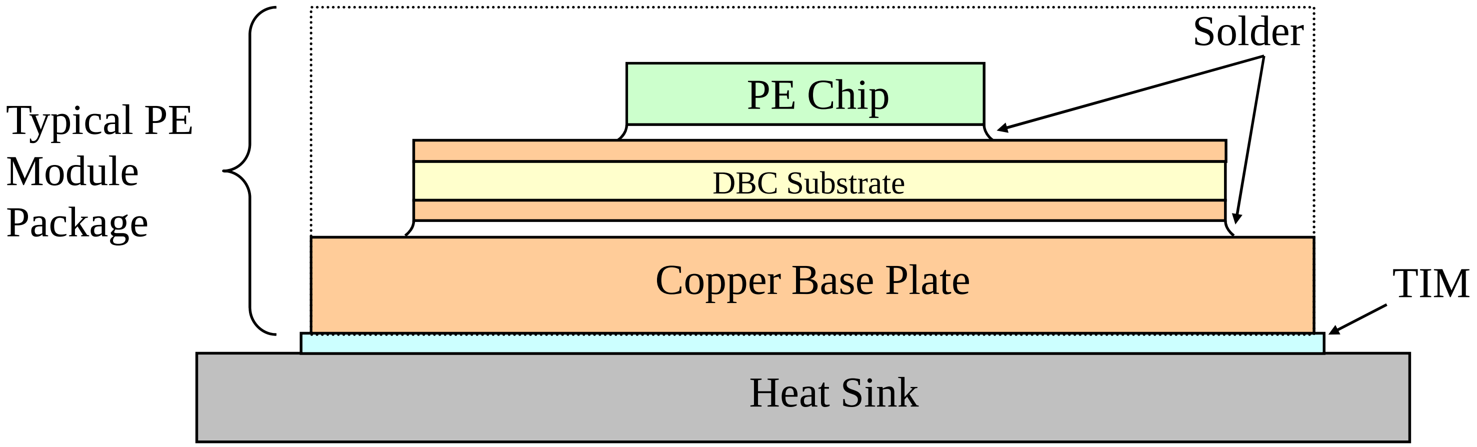
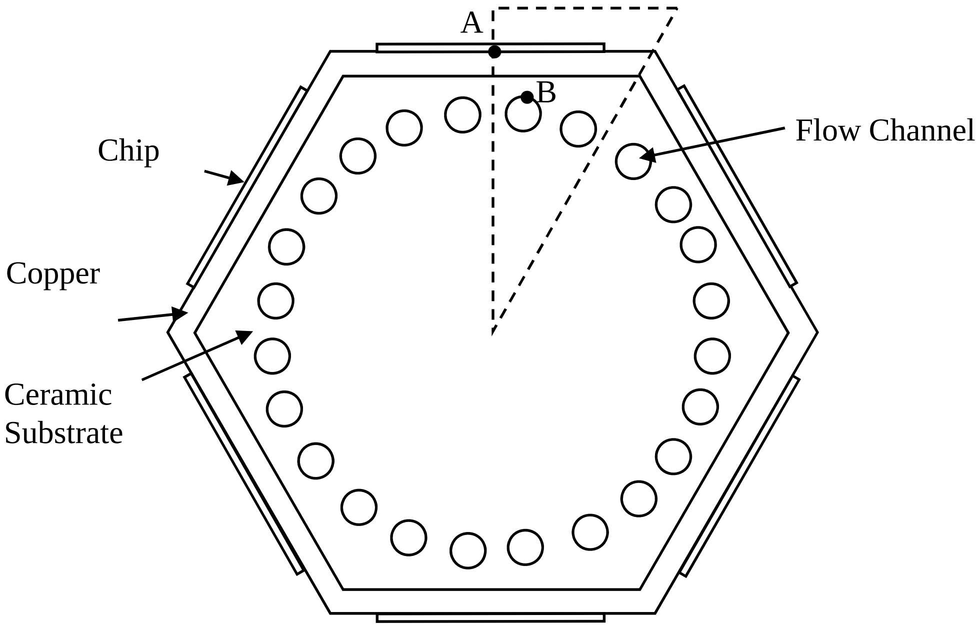
Problem Description

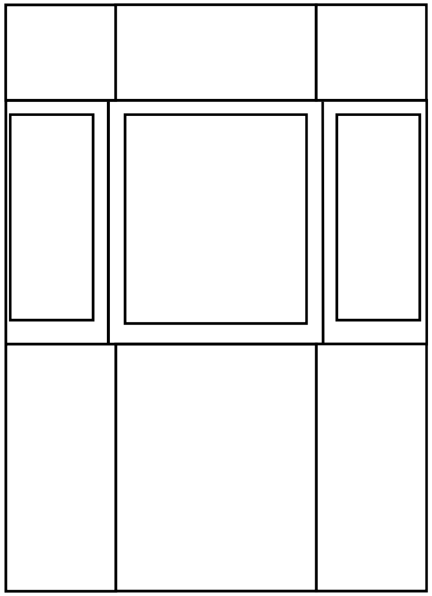
- Typical packaging has many layers
- Thermal resistance is large
- Commercial applications can require a coolant temperature over 100° C
- Thermal resistance must be reduced



Proposed Solution



Front View



Top View

Provision Patent 61/037,129

Proposed Solution (ii)

- Embeds heat sink into ceramic
- Eliminates TIM, copper base plate, one solder layer, and aluminum heat sink
- Thermal performance of coolant channel design is modeled to compare to design limitations.

Model Setup

- Fluid Dynamics $\rho\vec{u}\cdot\nabla\vec{u}=\nabla\cdot\left[-p\mathrm{I}+\eta\left(\nabla\vec{u}+\left(\nabla\vec{u}\right)^{T}\right)\right]$
  - → Incompressible Navier-Stokes
  - → Continuity $\nabla\cdot\vec{u}=0$
- Heat Transfer
  - → Conduction and Convection $\rho C_p\vec{u}\cdot\vec{\nabla}T=Q'''+k\nabla^{2}T$
- Constant Properties
- Steady State to predict worst-case-scenario
- Maximum Temperatures
  - → Fluid – 130° C
  - → Interface – 150° C

Solution Strategy

- Solve 2-D axisymmetric flow field
- Map solution to 3-D cylinders (Extrusion Coupling Variables)
- Apply thermal boundary conditions
- Solve for temperature distribution

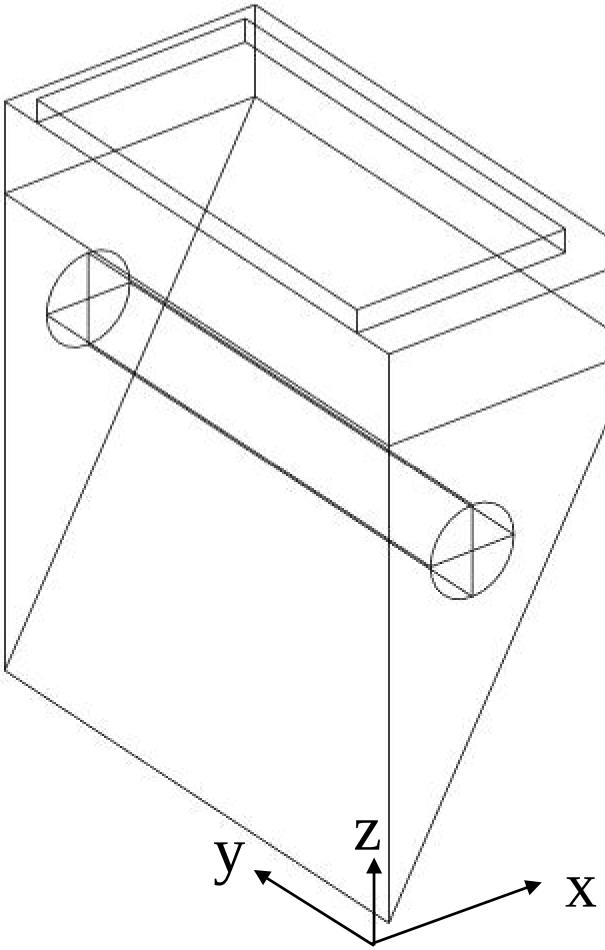
Boundary Conditions

- Inlet Velocity, $Re_{D,in}$
- Outlet, Pressure, no viscous stress, $p_0=0$
- Walls, no slip
- Chip Heat Load, 1.78e9 W/m^3
- Inlet Temperature, 105° C
- All other boundaries thermally insulated

Solution Mapping

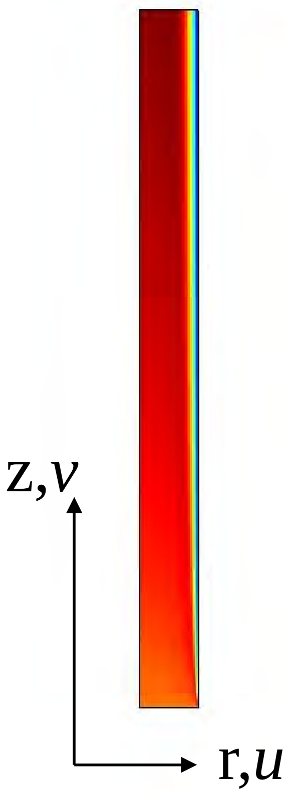
- Useful for simple flow field in more complex structure
- Solve 2-D axisymmetric flow field
- Map solution to 3-D cylinder using Extrusion Coupling Variables
- Translate axis as necessary
- Separate variables into directional components
- Incorporate into convection heat transfer
- Solve temperature distribution

Solution Mapping (i)

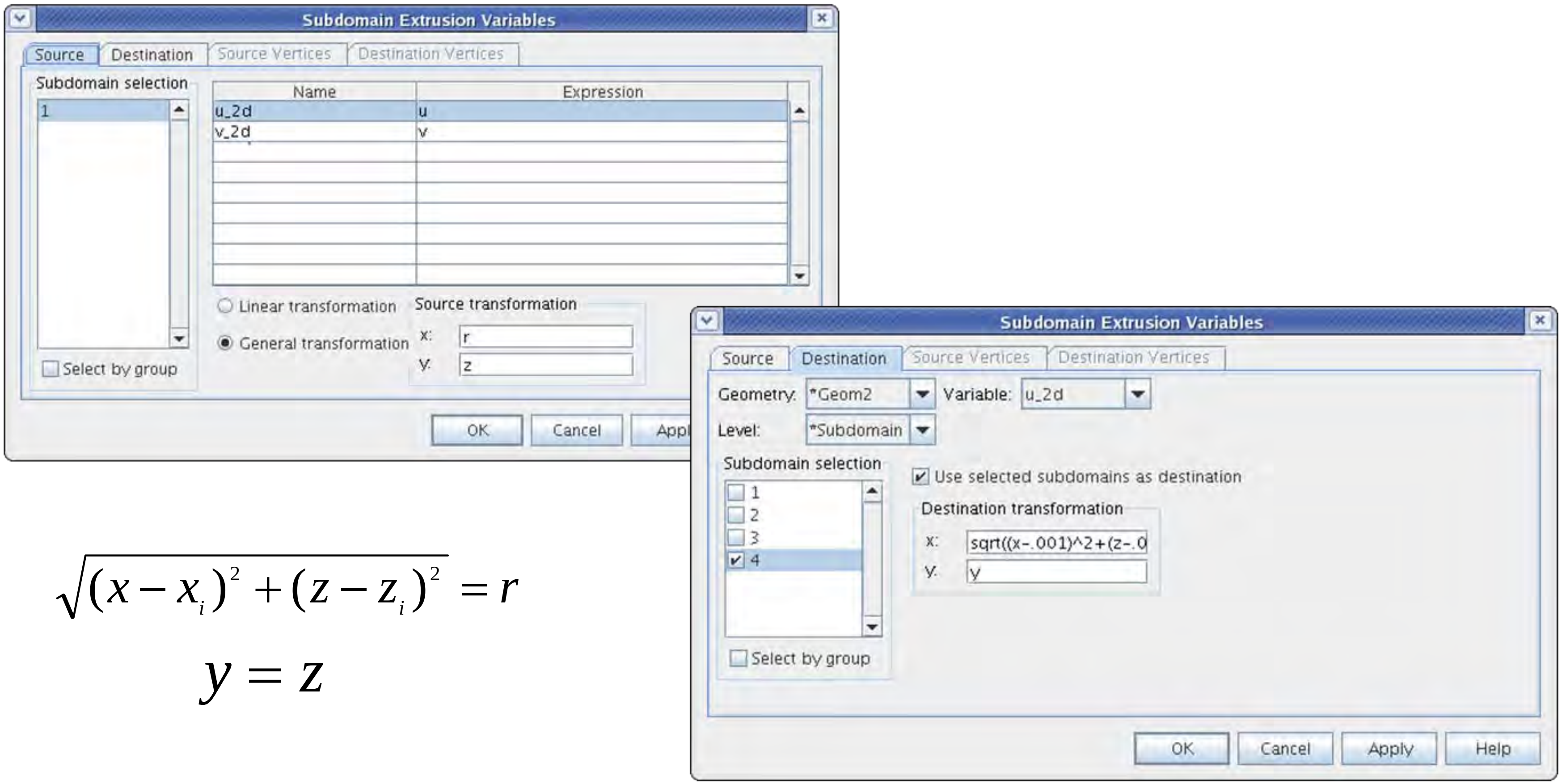


Solution Mapping (iii)

- 2-D axisymmetric solution
- Solved parametrically to desired input velocity or Reynolds number



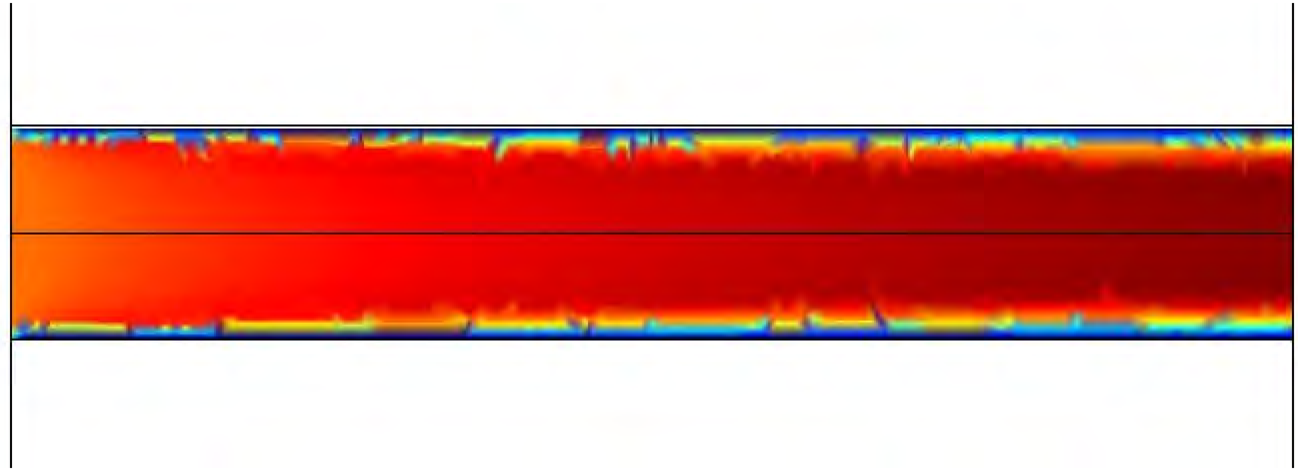
Solution Mapping (iv)



$$\sqrt{(x-x_i)^2+(z-z_i)^2}=r$$

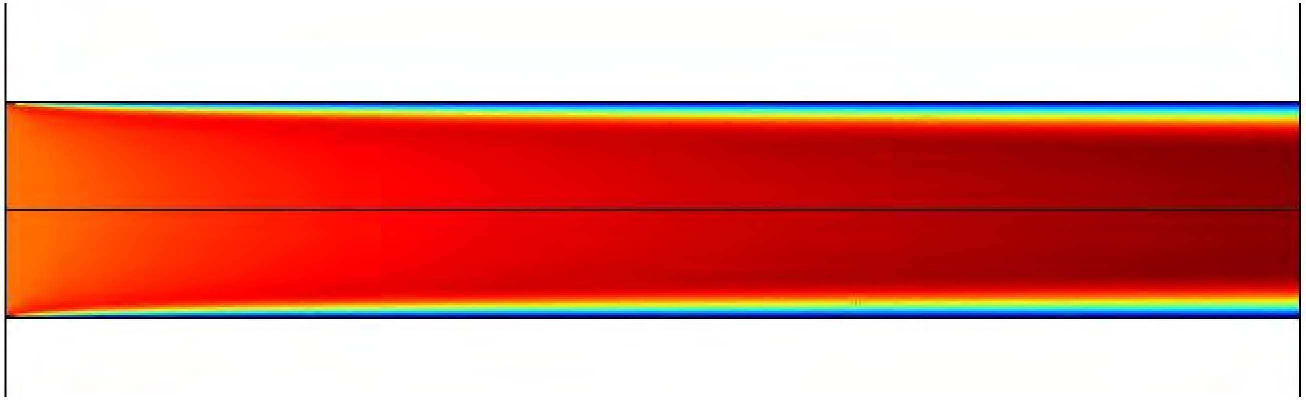
$$y=z$$

Solution Mapping (v)



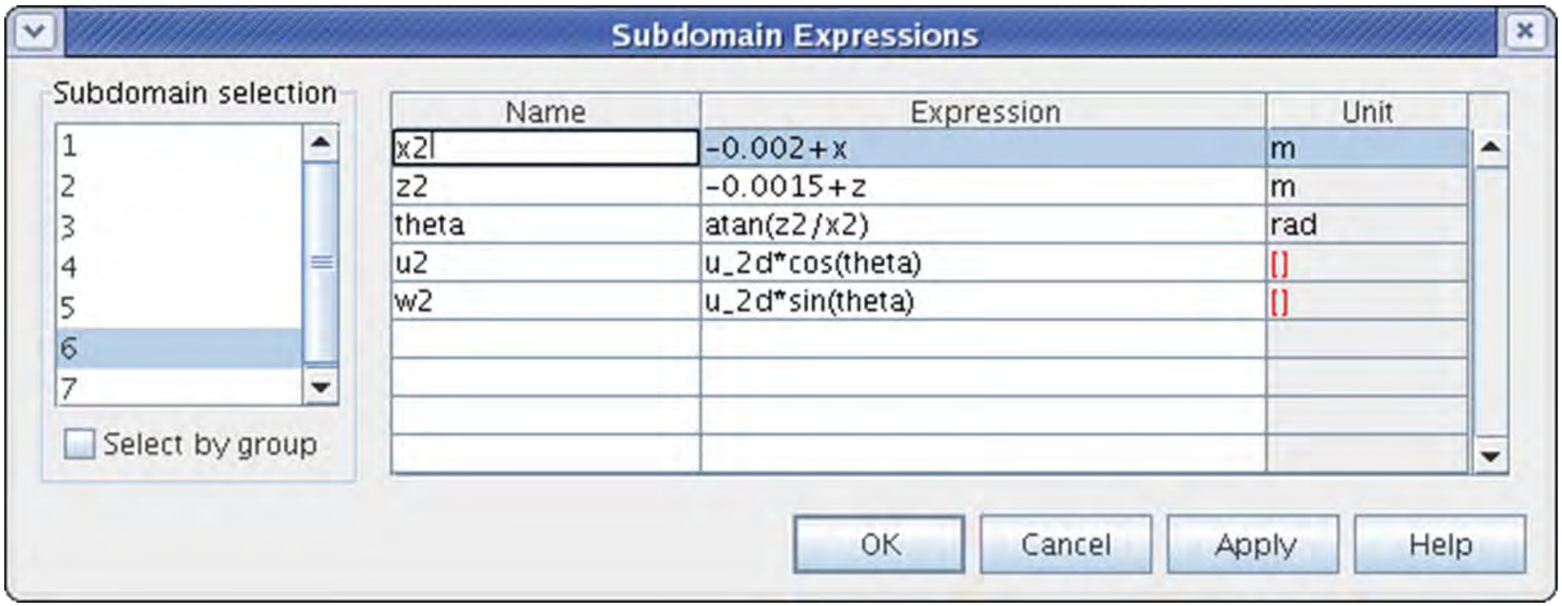
- Initial model update uses initialized (coarse) mesh
- Mesh refinement is necessary to transfer velocity data to convection regime

Solution Mapping (vi)

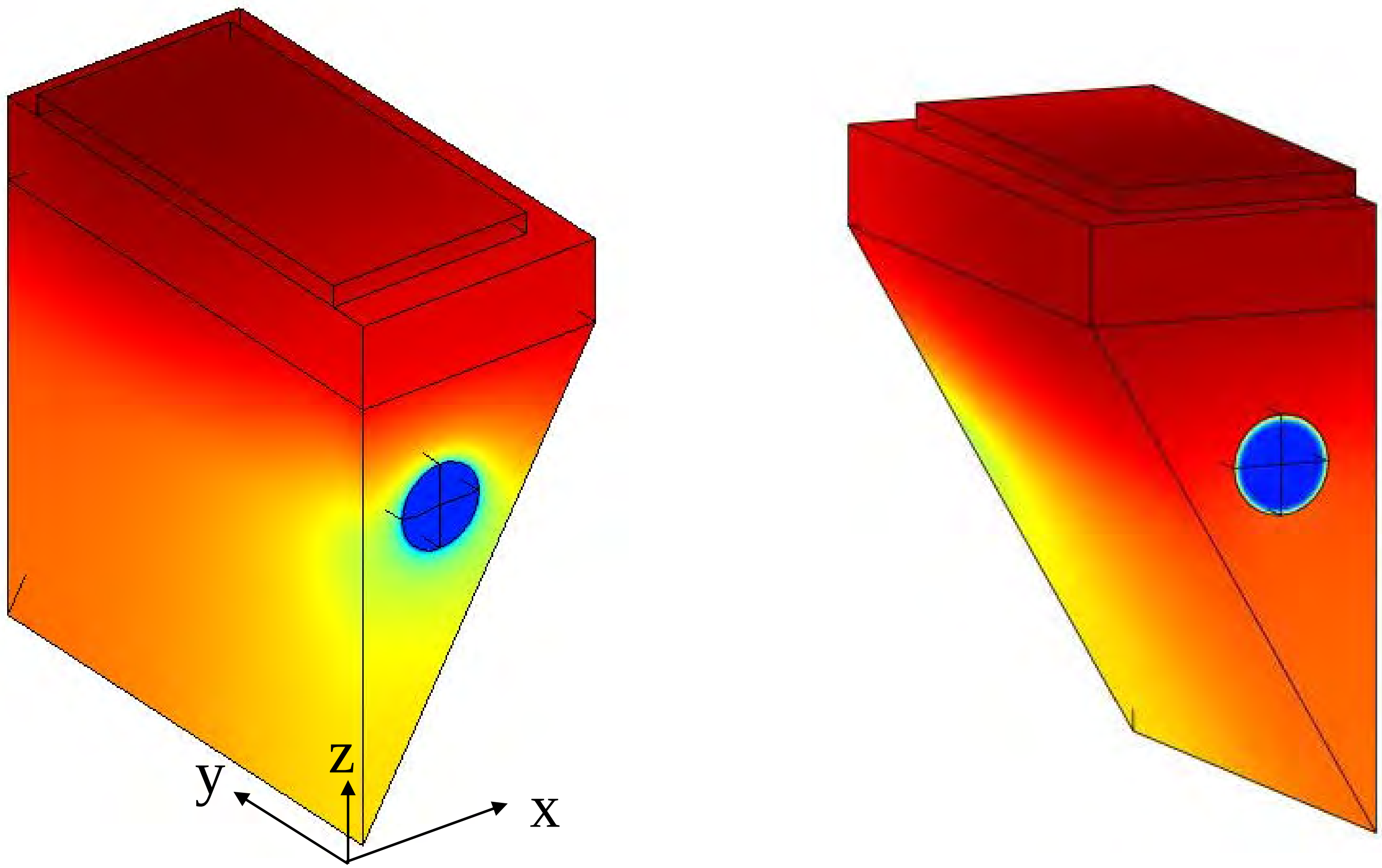


- Fine mesh better resembles the accuracy of the 2-D solution

Solution Mapping (vii)

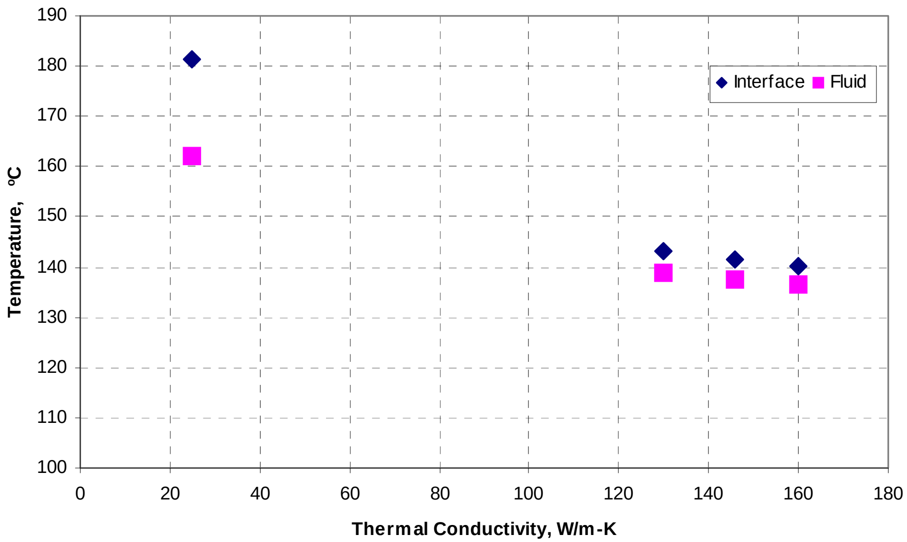


Solution Mapping (viii)



Results

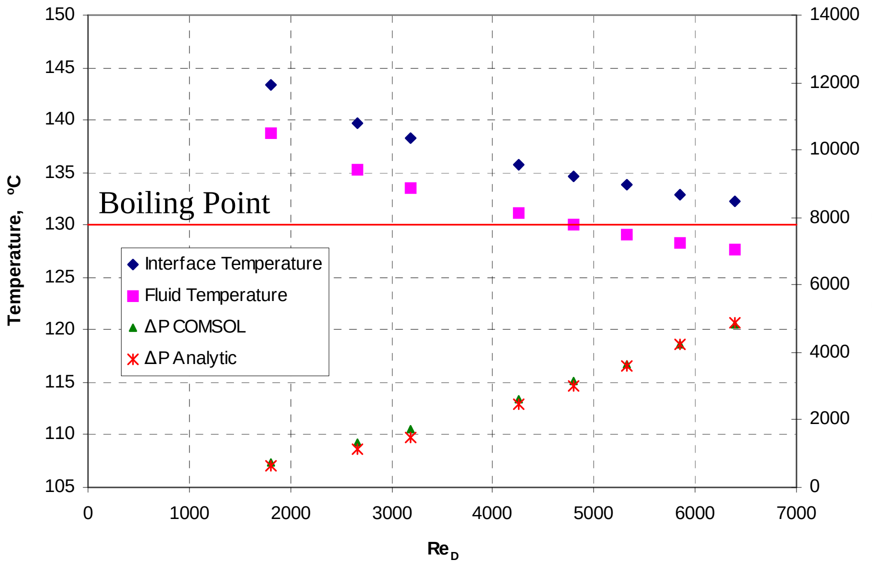
- High thermal conductivity ceramics produce lower maximum interface and fluid temperatures
- Chip temperatures are within design limits
- Working Fluid is above its boiling point



Maximum Interface and Fluid Temperatures of the Four Ceramic Materials at $Re_{D,in}$

Results (ii)

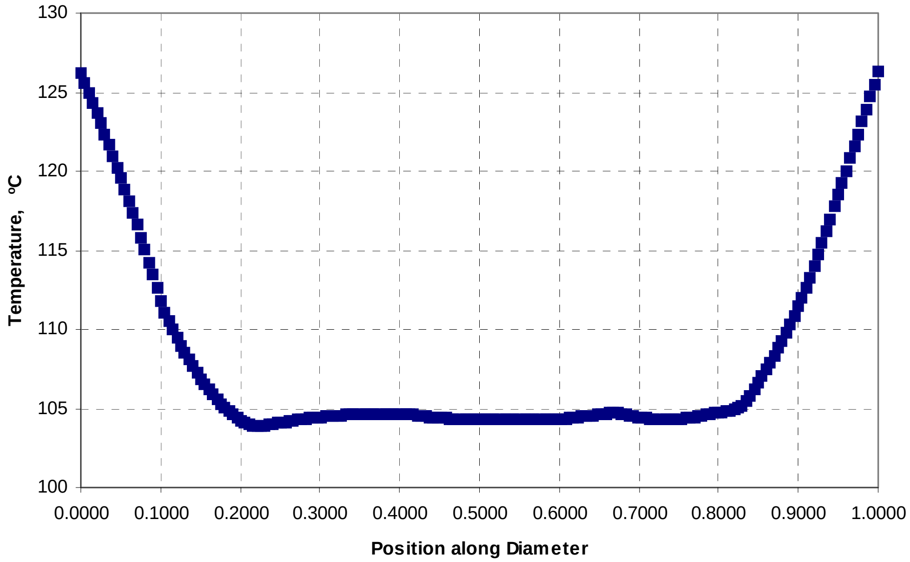
- Increasing inlet Re_D, decreases maximum temperatures
- Pressure drop is small
- Model pressure drop coincides well with analytic calculations



Variations of Maximum Interface and Fluid Temperatures and the Pressure for Ceramic 4

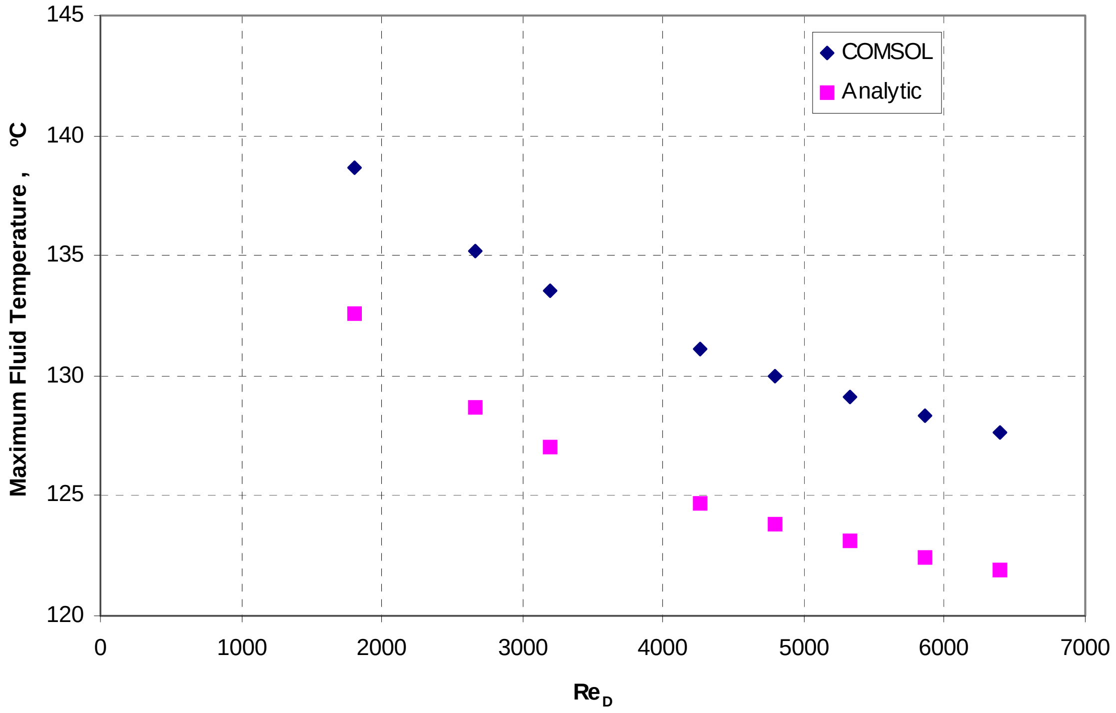
Results (iii)

- Large core of “cold” fluid at channel exit (41.3%)
- Diameter at mass manufacturing limit
- To improve cooling
  - → Surface enhancement
  - → Thermal conductivity enhancement



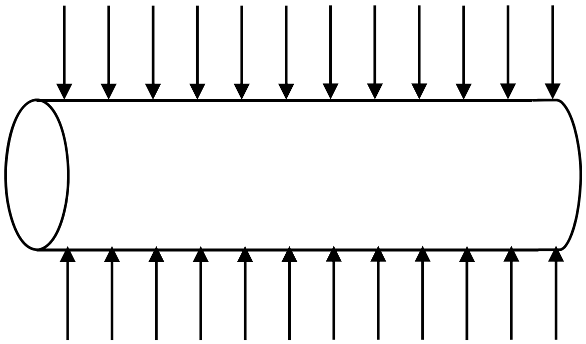
Fluid Temperature Along Diameter at Outlet of Hottest Channel in Ceramic 4

Solution Accuracy



Comparison of Maximum Fluid Temperature between COMSOL Solutions and Analytical Solution for a Constant Flux Tube

q"= constant



Solution Accuracy (ii)

- Analytic solution within 5% of simulation for all Reynolds numbers
- Model results are conservative
  - → Larger maximum temperatures
- Analytic solution provides good basis for initial sizing and feasibility

Conclusions

- New package substrate can enable the use of high temperature coolants
- High thermal conductivity ceramics are necessary to minimize thermal resistance for this coolant path design
- An increase in the nominal flow rate is required to meet the design limitations
- Solution mapping significantly decreases the amount of time required to solve 3-D convective flows
- Work continues to improve flow channel design and thermal conductivity of working fluid

Questions?