Experimental and Analytical Investigation of Compact Liquid Cooled Heat Sinks

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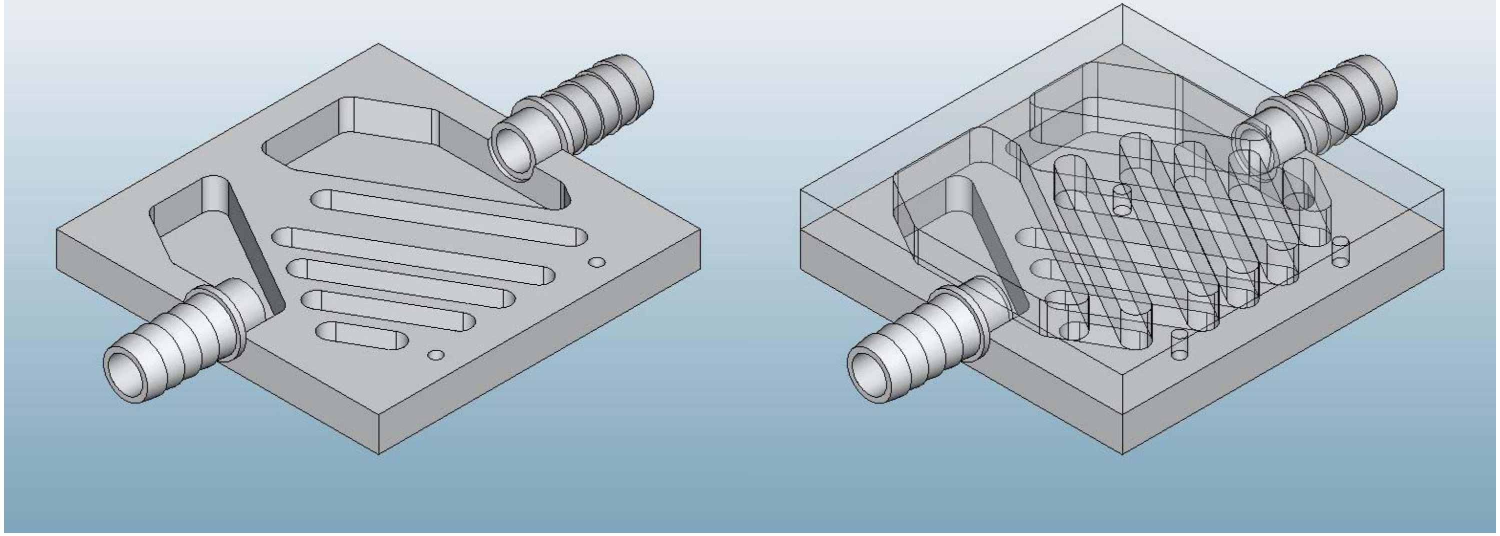
Outline

- Introduction, problem description, objectives
- Experimental measurements
- Model development and validation
- Summary and conclusions

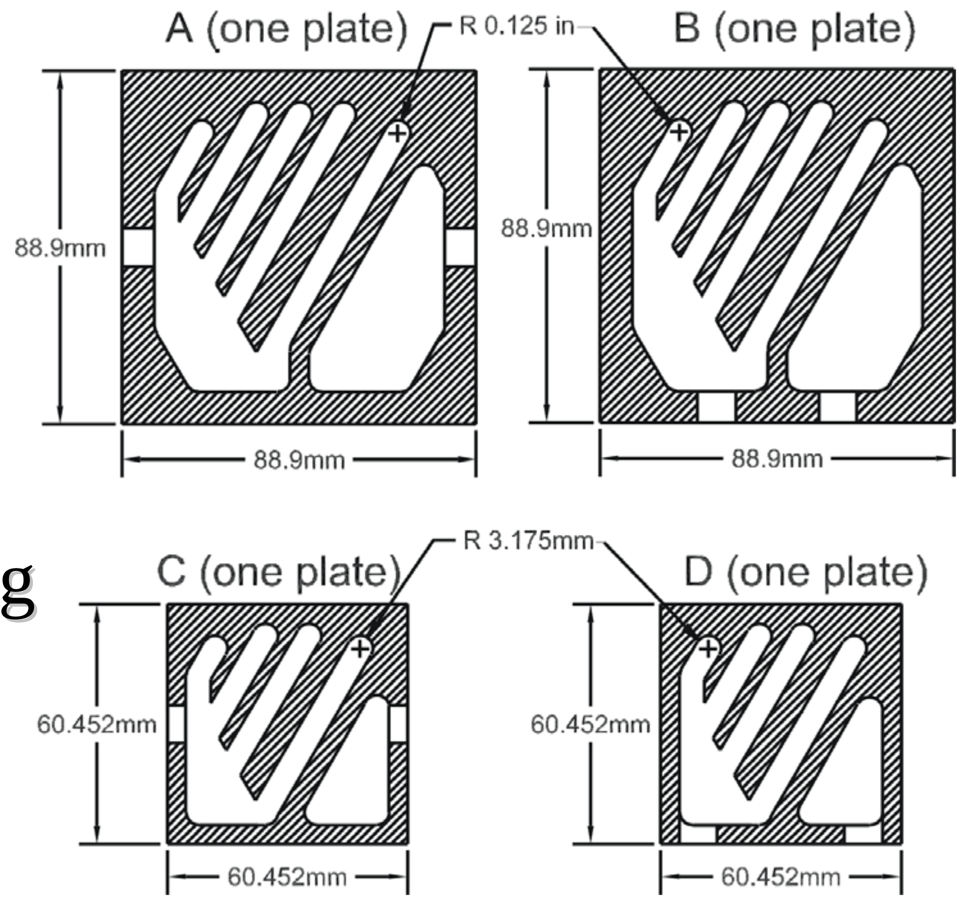
Introduction

- Collaborative project to improve *calistor* design methodology
- **Goal**: to provide design tools in form of analytical models as an alternative to current trial-and-error approach
- Model includes common design features of current *calistor*
  - Two identical halves joined together to form flow passages
  - Angled channels, equal cross sectional dimensions
  - Plenums with fixed inlet, outlet locations

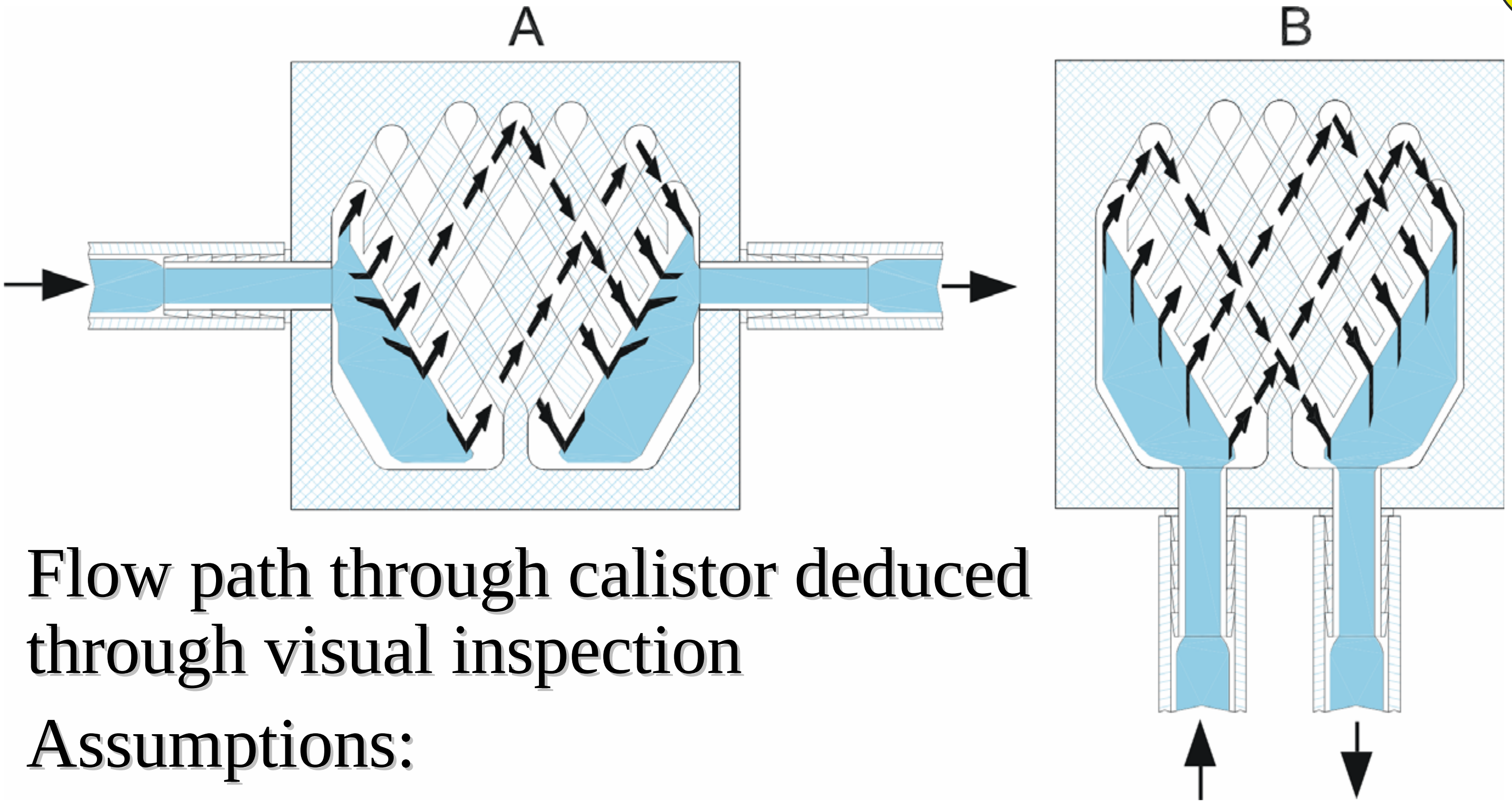


Objectives

- Develop analytical models for pressure drop and thermal resistance for current calistor design
- Function of:
  - Geometry
  - Flow rate
  - Fluid properties
- Validate the models using experimental data from four existing calistors

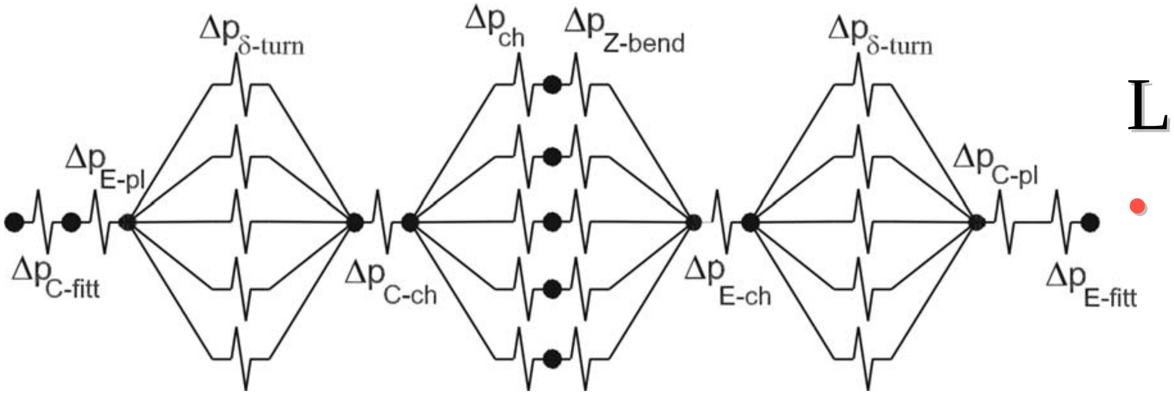


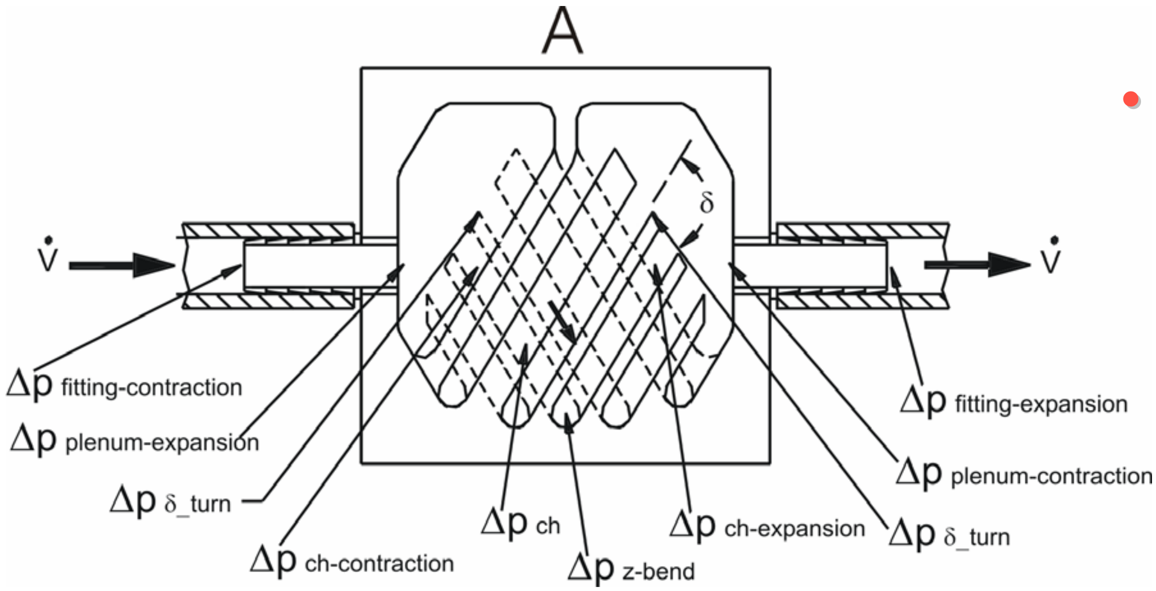
Pressure Drop Model



- Flow path through calistor deduced through visual inspection
- Assumptions:
  - Flow evenly distributed among all channels
  - Flow continues to end of channel before turning (Z-bend)
  - Uniform fluid temperature, constant properties

Hydraulic Resistance Network

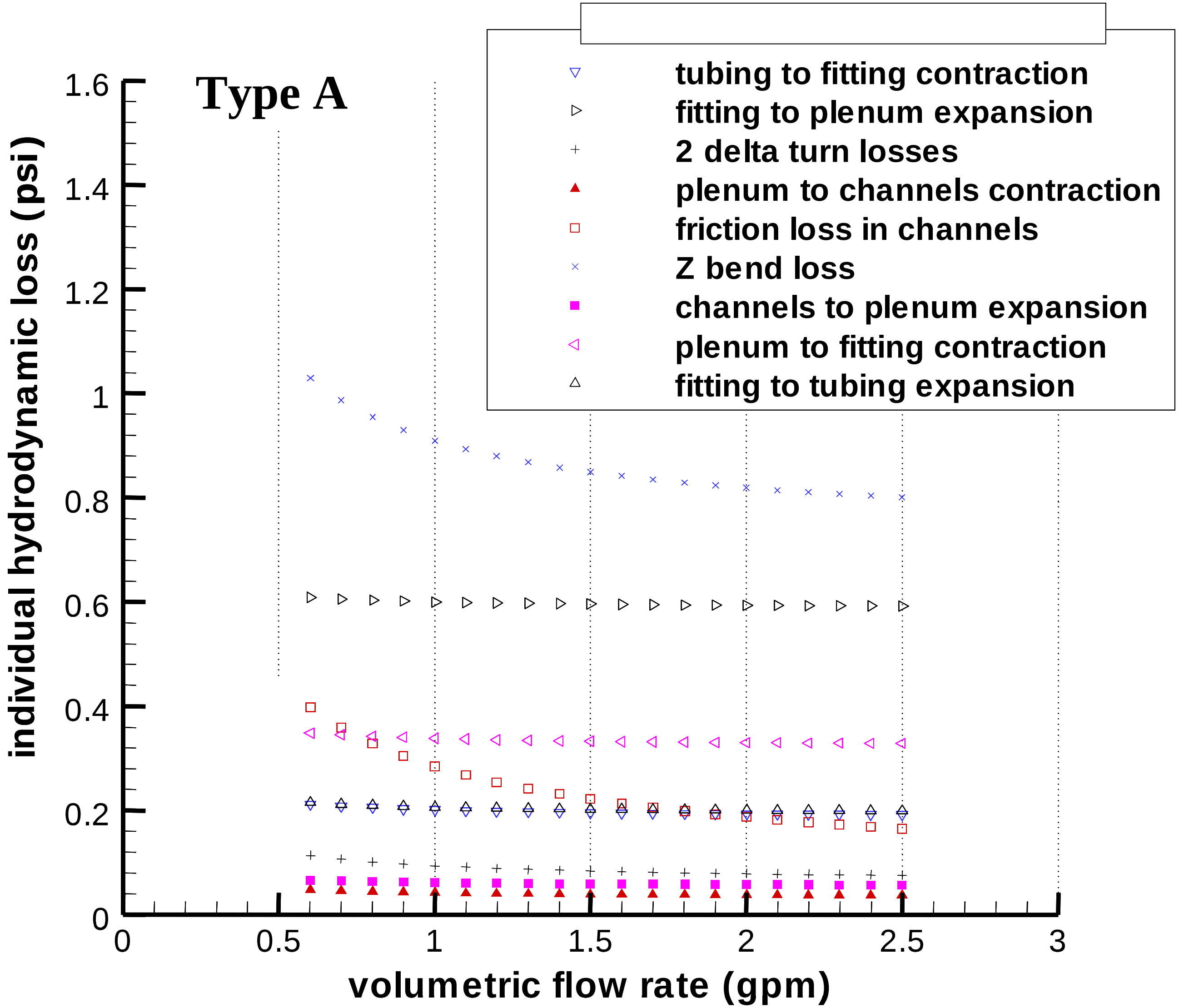




Loss coefficients:

- Handbook correlations (Idelchik, Blevins, White)
  - Contraction / expansion
  - Angled bend
- Analytical models (Muzychka)
  - Frictional losses in channel flow

Pressure Drop Model Components



Thermal Resistance Model

- Assume uniform wall temperature boundary conditions
- Energy balance

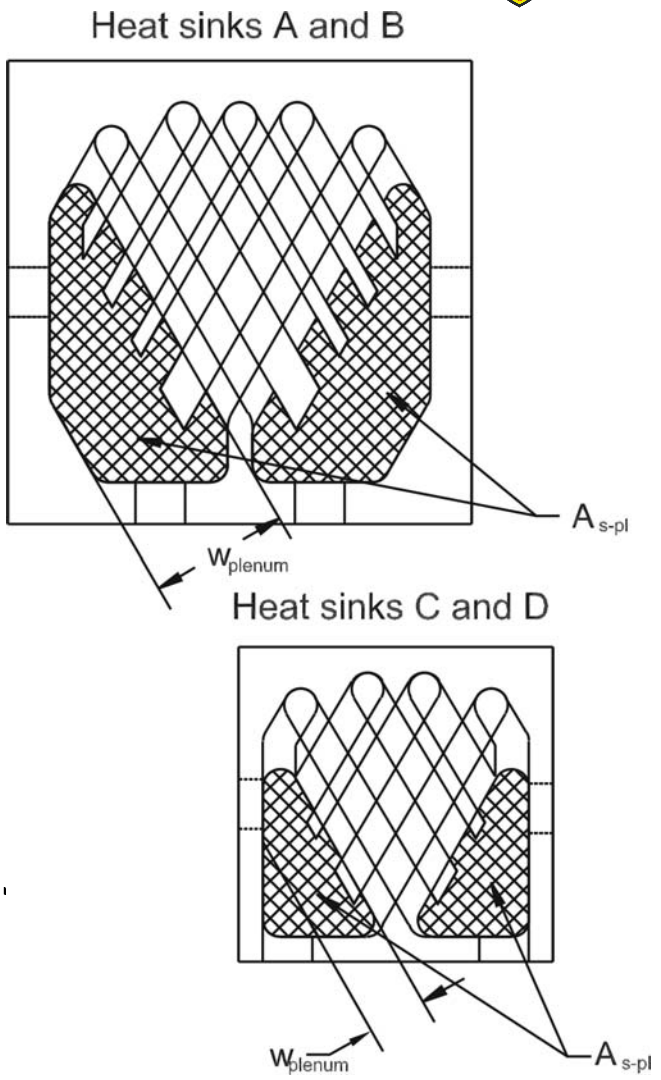
$$Q_{tot} = Q_{core} + 2Q_{plenum}$$

$$\bar{h}_{tot}\, A_{tot}\, \Delta T_{lm} = \bar{h}_{ch}\, A_{core}\, \Delta T_{lm} + 2\bar{h}_{plenum}\, A_{plenum}\, \Delta T_{lm}$$

$$\bar{h}_{tot} = \bar{h}_{ch} \frac{A_{core}}{A_{tot}} + 2\bar{h}_{plenum} \frac{A_{plenum}}{A_{tot}}$$

- Non-dimensionalize using Colburn

$$j\,\mathrm{Re} = \frac{\overline{Nu}}{\mathrm{Pr}^{1/3}} = \frac{1}{\mathrm{Pr}^{1/3}} \frac{\bar{h}_{tot}\sqrt{A_{tot}}}{k_f}$$



Duct Heat Transfer Model

- Model for average Nusselt number for a plain UWT duct (Muzychka, 2000)

$$Nu_{\sqrt{A}}(\ell^*) = \left[\left(\left\{ C_1 C_2 \left(\frac{f\,\mathrm{Re}_{\sqrt{A}}}{\ell^*_{\sqrt{A}}} \right)^{1/3} \right\}^5 + \left\{ C_3 \left(\frac{f\,\mathrm{Re}_{\sqrt{A}}}{8\sqrt{\pi}\,\varepsilon^{\gamma}} \right) \right\}^5 \right)^{m/5} + \left(\frac{C_4 f(\mathrm{Pr})}{\sqrt{\ell^*_{\sqrt{A}}}} \right)^m \right]^{1/m}$$

$$f(\mathrm{Pr}) = \frac{0.564}{\left[1 + (1.664\,\mathrm{Pr}^{1/6})^{9/2}\right]^{2/9}} \qquad z^*_{\sqrt{A}} = \frac{z/\sqrt{A}}{\mathrm{Re}_{\sqrt{A}}\,\mathrm{Pr}} \qquad \mathrm{Re}_{\sqrt{A}} = \frac{\rho\sqrt{A}V_{duct}}{\mu}$$

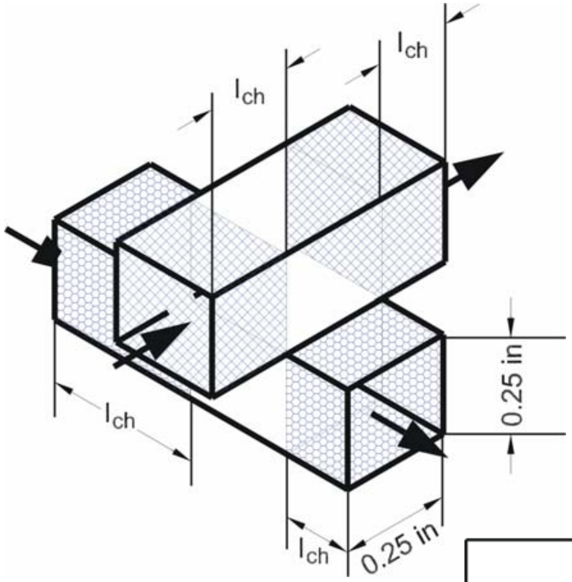
$$z = \begin{cases} L_{plenum}, & \text{effective channel length of plenum} \\ L_{ch}, & \text{core channel length} \end{cases}$$

Heat Transfer Coefficients

- Core modeled based on equivalent unit cell

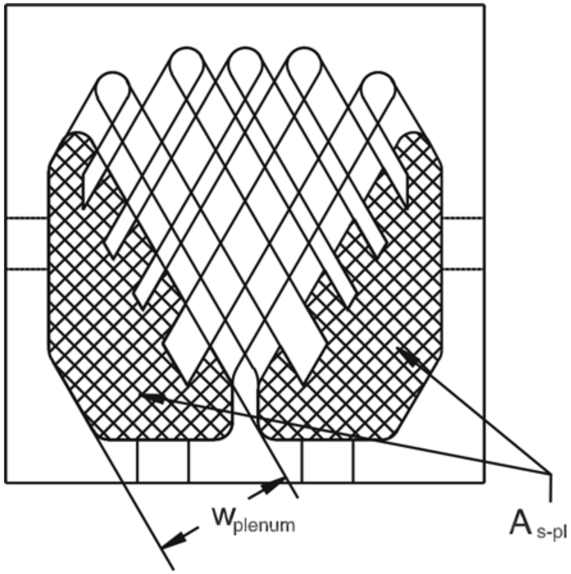
$$l_{ch} \cong 6\,mm$$

$$A_{ch} = (0.25in)^2$$



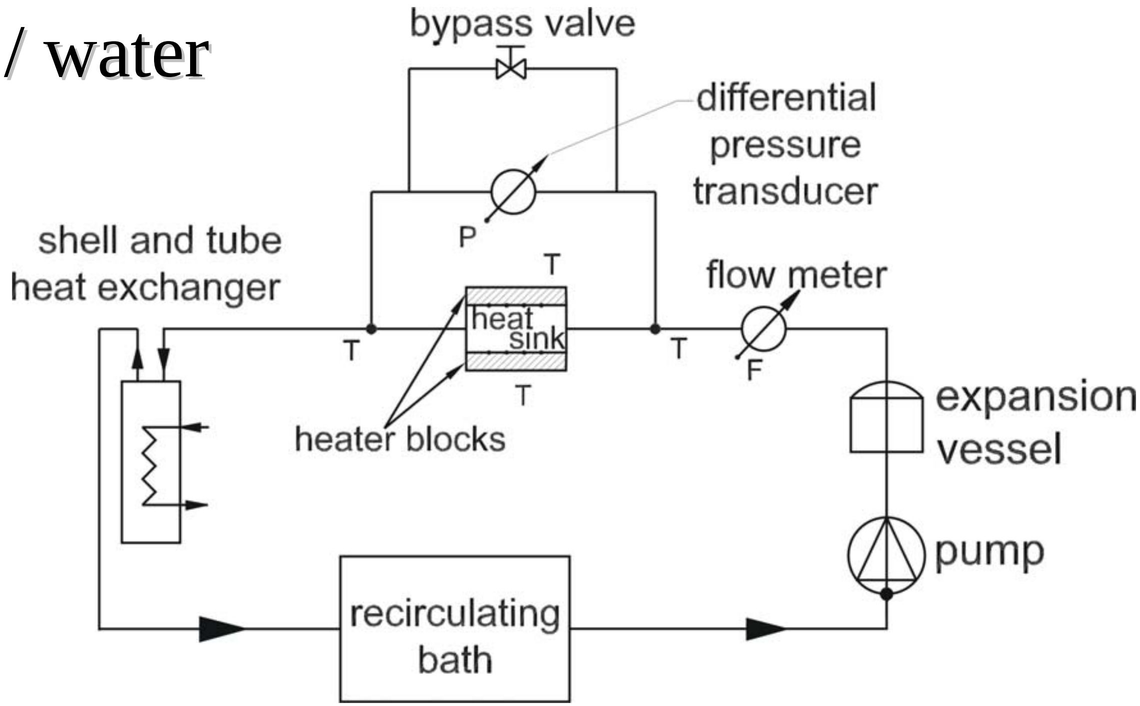
- Plenum modeled as straight rectangular ducts with effective length L_{plenum}

$$A_{s-pl} = 2(W_{plenum} + H_{plenum}) \times L_{plenum}$$



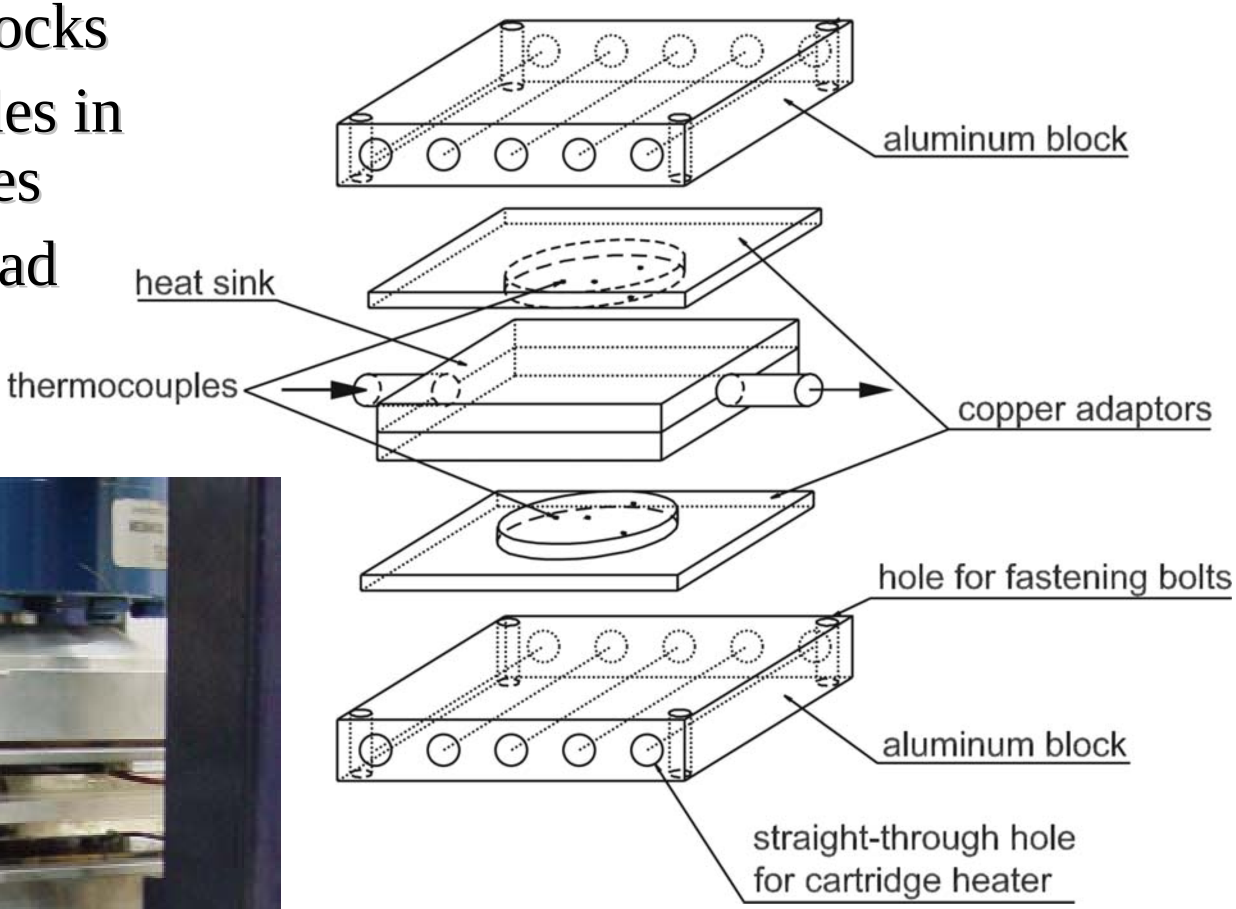
Experimental Measurements

- Measurements for thermal resistance, pressure drop performed separately for 4 different calistors
- T-type thermocouples measure surface temperatures, fluid temperature rise between inlet and outlet
- 1:1 Ethylene glycol / water mixture
- 0.5 to 2.5 *gpm*
- $Q_{in} = 1.5\ kW$



Experimental Apparatus

- Cartridge heaters in aluminum heater blocks
- T-type thermocouples in copper adaptor plates
- Hydraulic press / load cell for repeatable, uniform load



Data Analysis

- Total heat transfer rate

$$Q = \rho \dot{V} c_p \left(T_{out} - T_{in}\right)$$

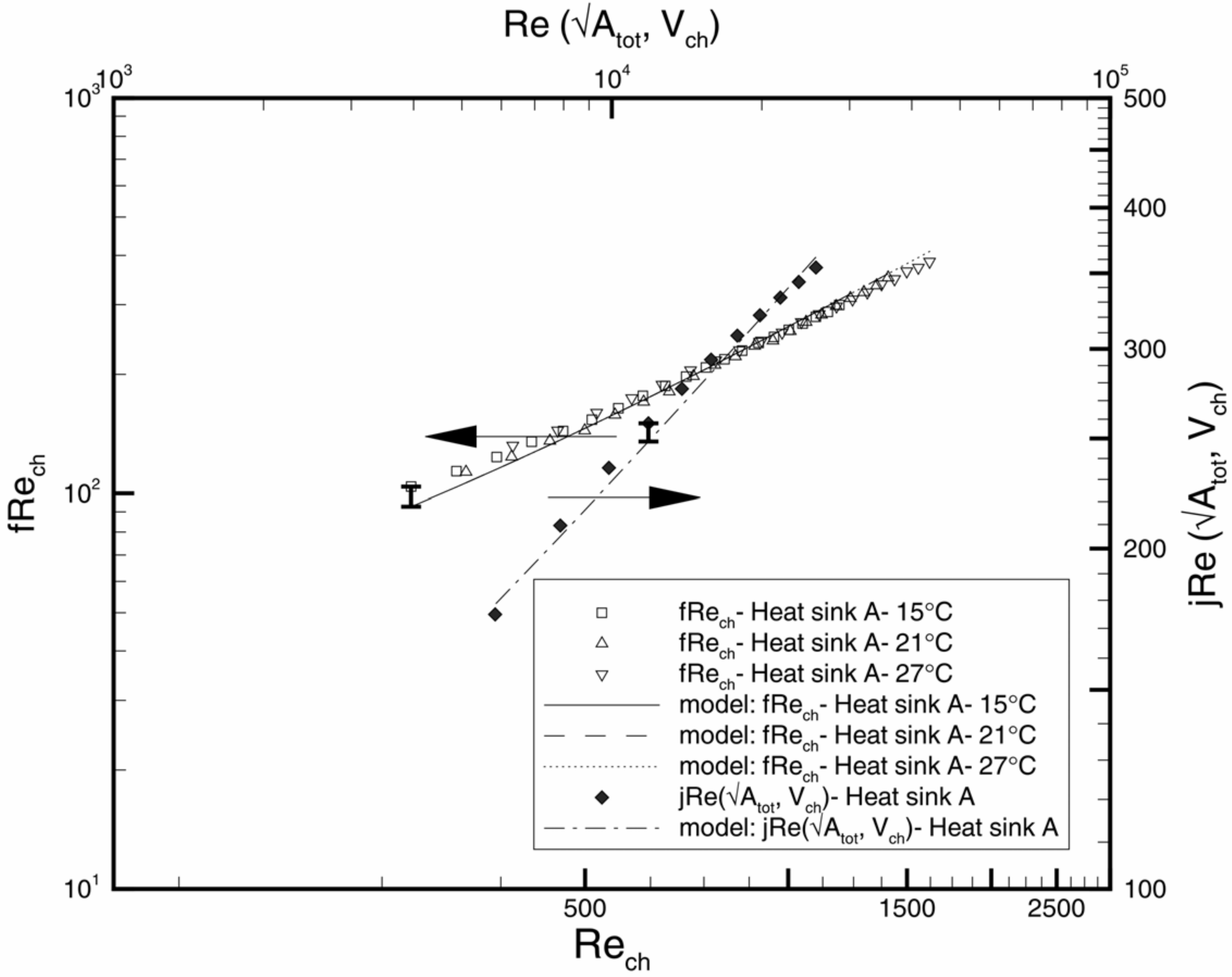
- Total heat transfer coefficient

$$h_{tot-\exp} = \frac{\rho \dot{V} c_p \left(T_{out} - T_{in}\right)}{A_{tot}\, \Delta T_{lm}} \qquad \Delta T_{lm} = \frac{T_{out} - T_{in}}{\ln\left(\dfrac{T_s - T_{in}}{T_s - T_{out}}\right)}$$

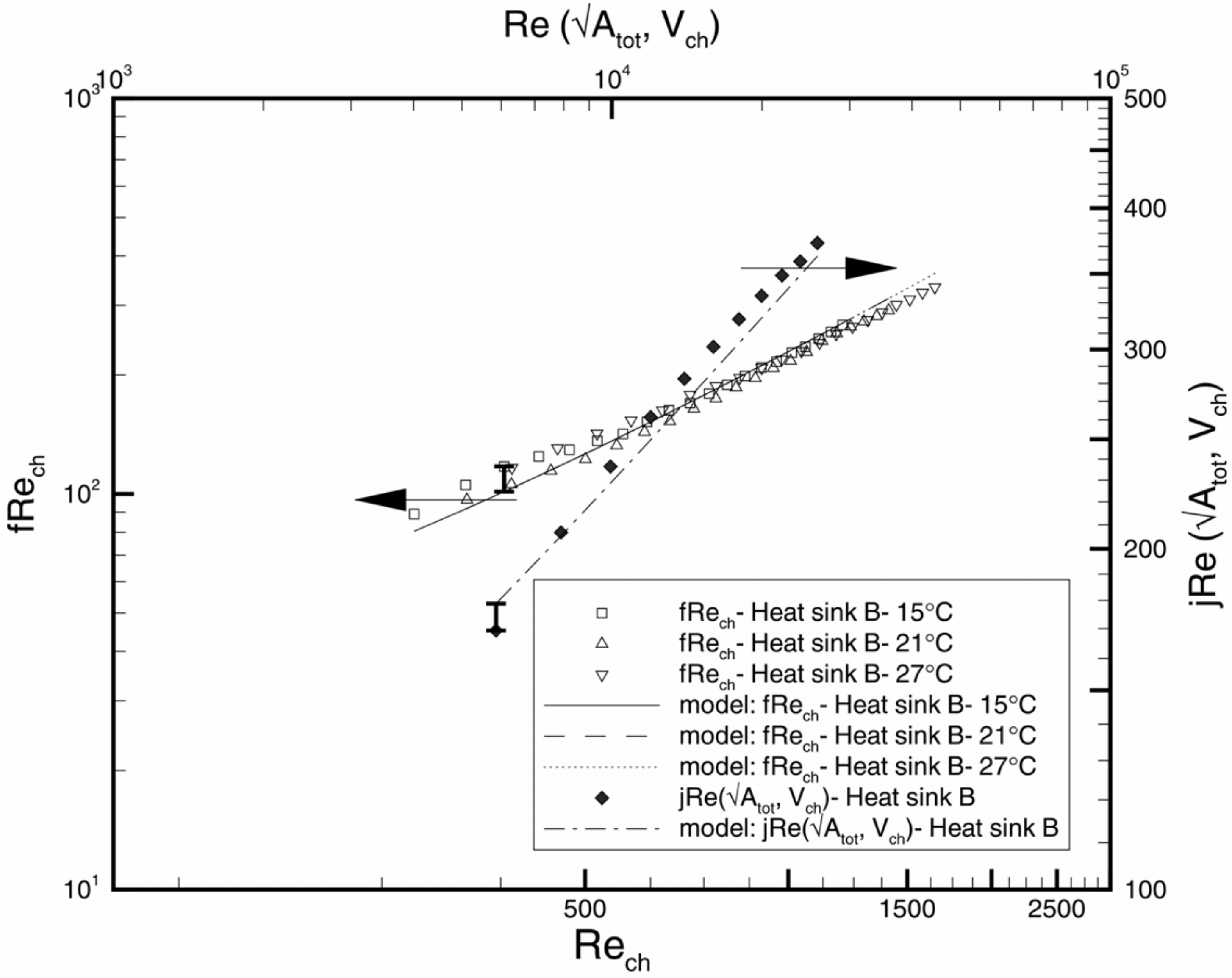
- Non-dimensional parameters

$$\mathrm{Re}_{ch} = \frac{\rho b V_{ch}}{\mu} \qquad f = \frac{\Delta p_{tot} A_{ch}}{\frac{1}{2} \rho V_{ch}^2} \qquad \mathrm{Re}_{\sqrt{A_{tot}}} = \frac{\rho \sqrt{A_{tot}}\, V_{ch}}{\mu} \qquad j\,\mathrm{Re} = \frac{h_{tot} \sqrt{A_{tot}}}{k_f} \frac{1}{\mathrm{Pr}^{1/3}}$$

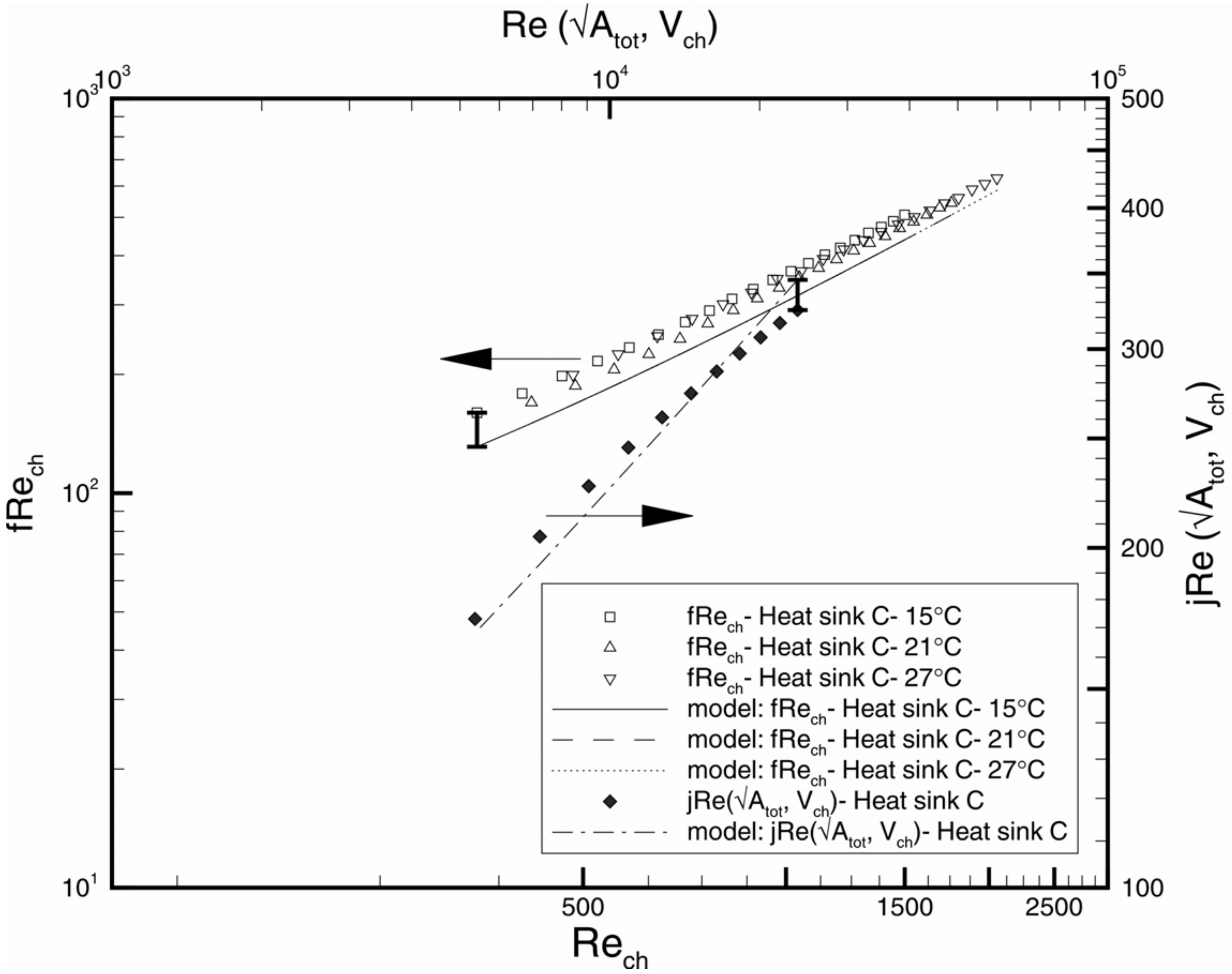
Model Validation – Heat Sink A



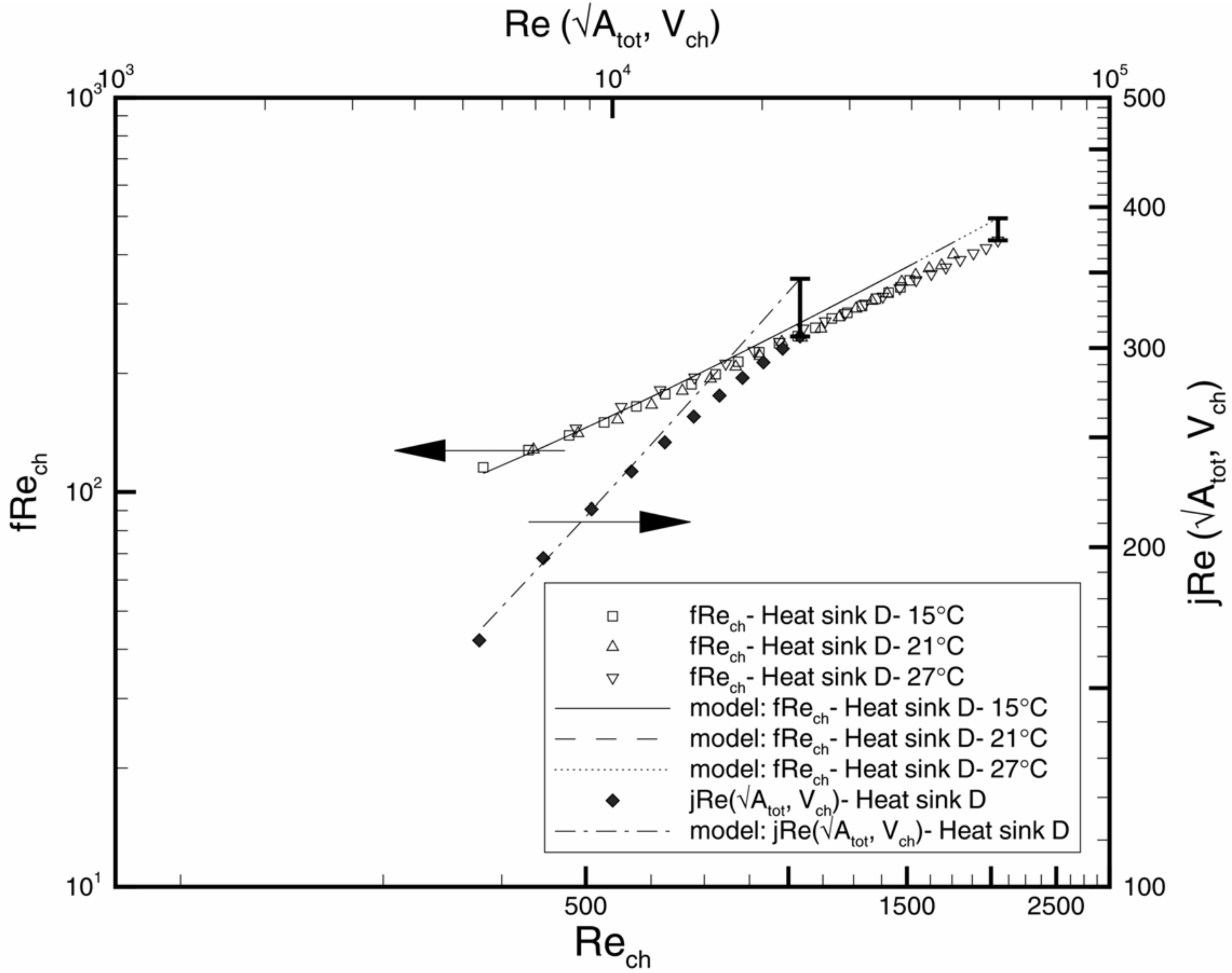
Model Validation – Heat Sink B



Model Validation – Heat Sink C



Model Validation – Heat Sink D



Summary and Conclusions

- Combined experimental and analytical study of pressure drop and thermal resistance in liquid-cooled heat sinks
- Pressure drop model from hydraulic resistance network
- Heat transfer model based on plain duct flow in equivalent channels
- Good agreement between model and data < 15% RMS
- Models provide starting point for design improvements
  - Parametric studies
  - Sensitivity analyses