Compact Models for Conductive and Convective Heat Transfer in Microelectronic Applications for the New Millenium

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34th National Heat Transfer Conference
August 22, 2000

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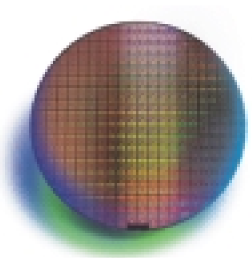
Outline

- Introduction
  - need for compact models
  - various types of compact models
- Examples of Compact Models
  - total resistance of multilayered substrates (vias)
  - natural convection in vented enclosures
  - natural convection plate fin heat sink
  - compact heat exchangers
- Concluding Remarks
- Future Directions

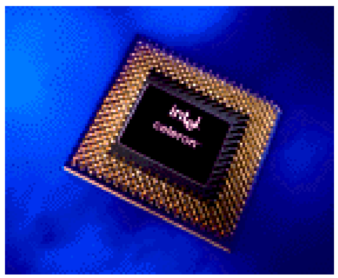
Microelectronic System Levels

Die



< 10 *mm*

Package



10 - 50 *mm*

Circuit Board

100 - 500 *mm*

Enclosure

> 500 *mm*

10 100

Scale of Dimensions (mm)

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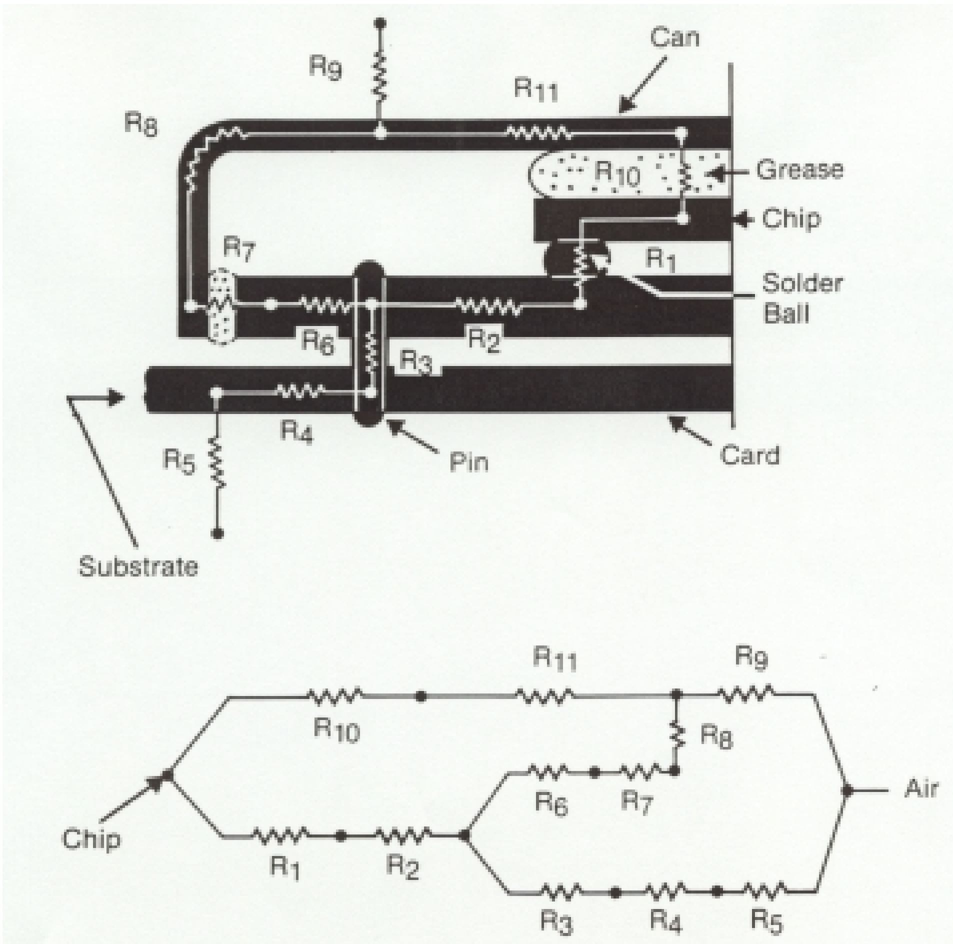
Compact Modeling Approaches

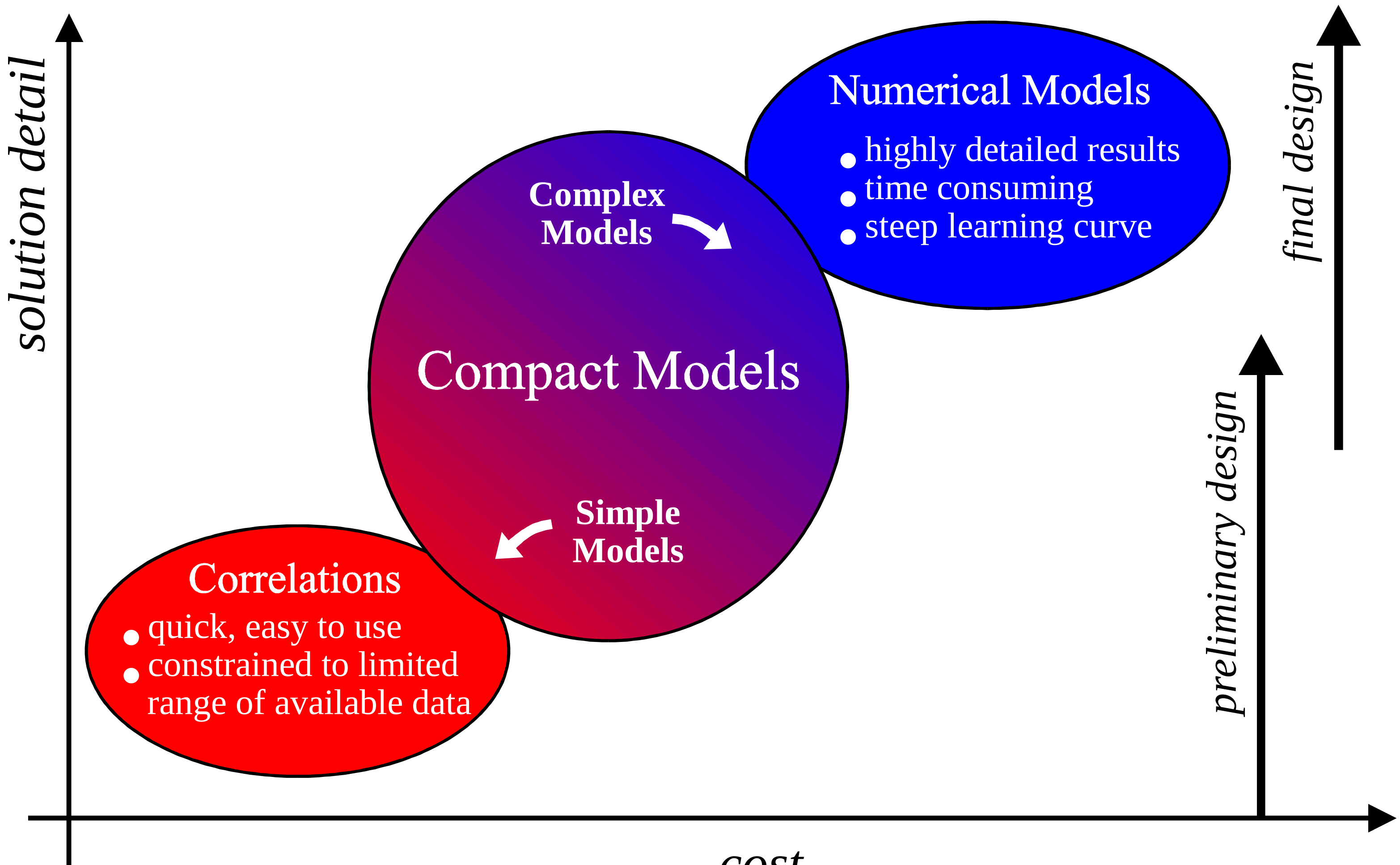
- Scale analysis
- Non-dimensionalization
- Thermal resistance modeling
- Combining asymptotic analytical solutions
- Development of bounds

Thermal Resistance Modeling Example



R. C. Chu and R. E. Simons, Thermal Management Concepts in Microelectronic Packaging, 1984, pp. 193 - 214.

Introduction



Why Not Always Use Detailed Models?

- Detailed models have value because....
  - predict local temperature distribution within packages
  - allow designers to easily make parametric changes in model
  - DELPHI has proposed that they be the starting point for the creation of compact models
- However, detailed models also...
  - reveal internal (often proprietory) construction details of packages
  - are computationally demanding due to large grid required

S. Shidore, Flomerics Inc.,
International Standards Committee Meeting, 1999.

Compact Models

- Compact models seek to capture the thermal behavior of the package accurately
  - at pre-determined critical points (junction, case etc.)
  - by using a reduced set of parameters to represent the package
- These parameters need not have a one-to-one correspondence with the package physical structure

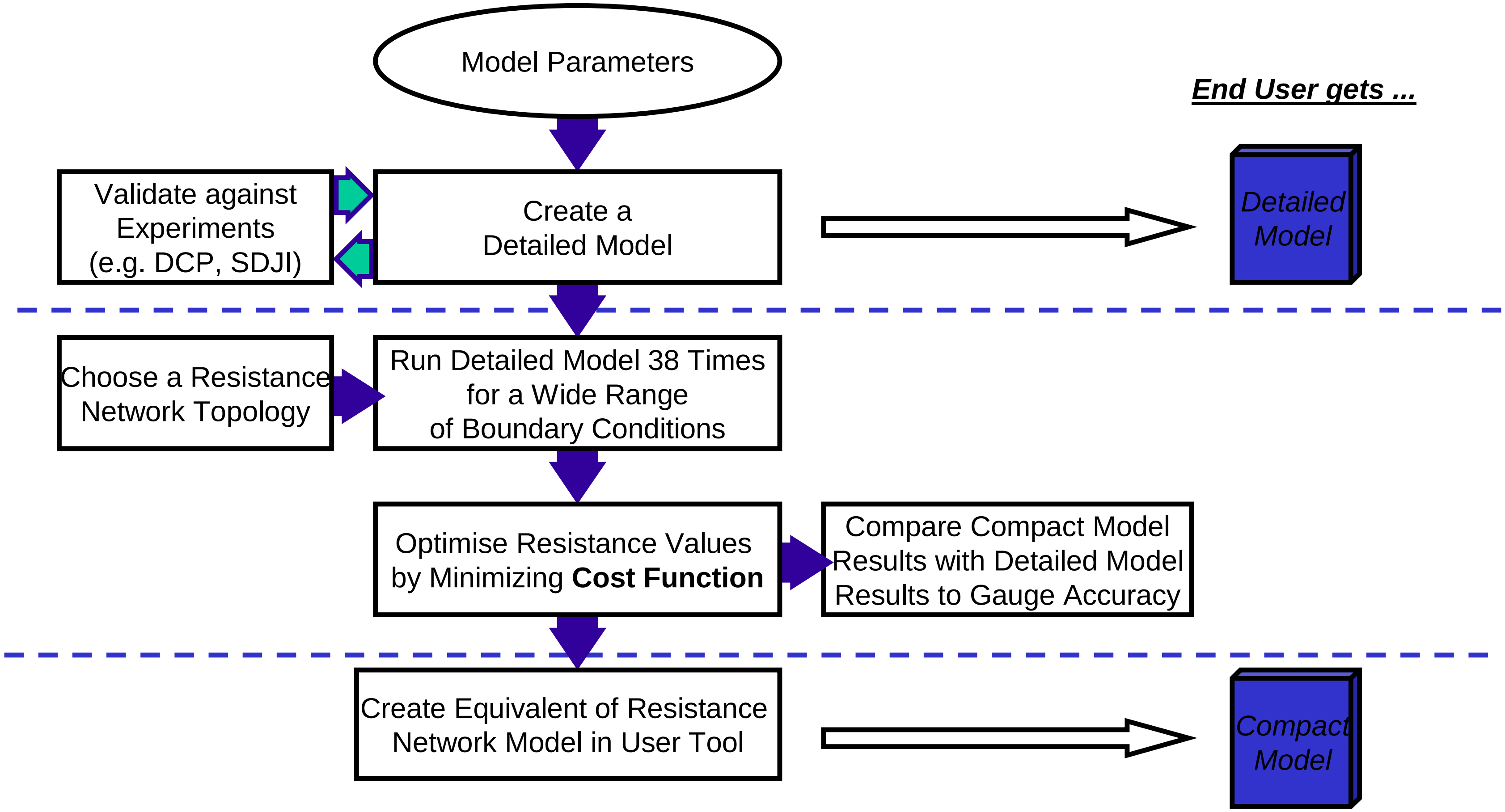
S. Shidore, Flomerics Inc.,
International Standards Committee Meeting, 1999.

What is (was) DELPHI?

- Project that proposed new methodologies for developing component computational models
- Ultimate Goal: to enable manufacturers to supply validated compact thermal models to end-users
- Results were:
  - detailed model understanding of several package types
  - 2 experimental systems (Double Cold Plate and Submerged Double Jet Impingement) for validation
  - compact model networks for several package types
  - a methodology to tie these together

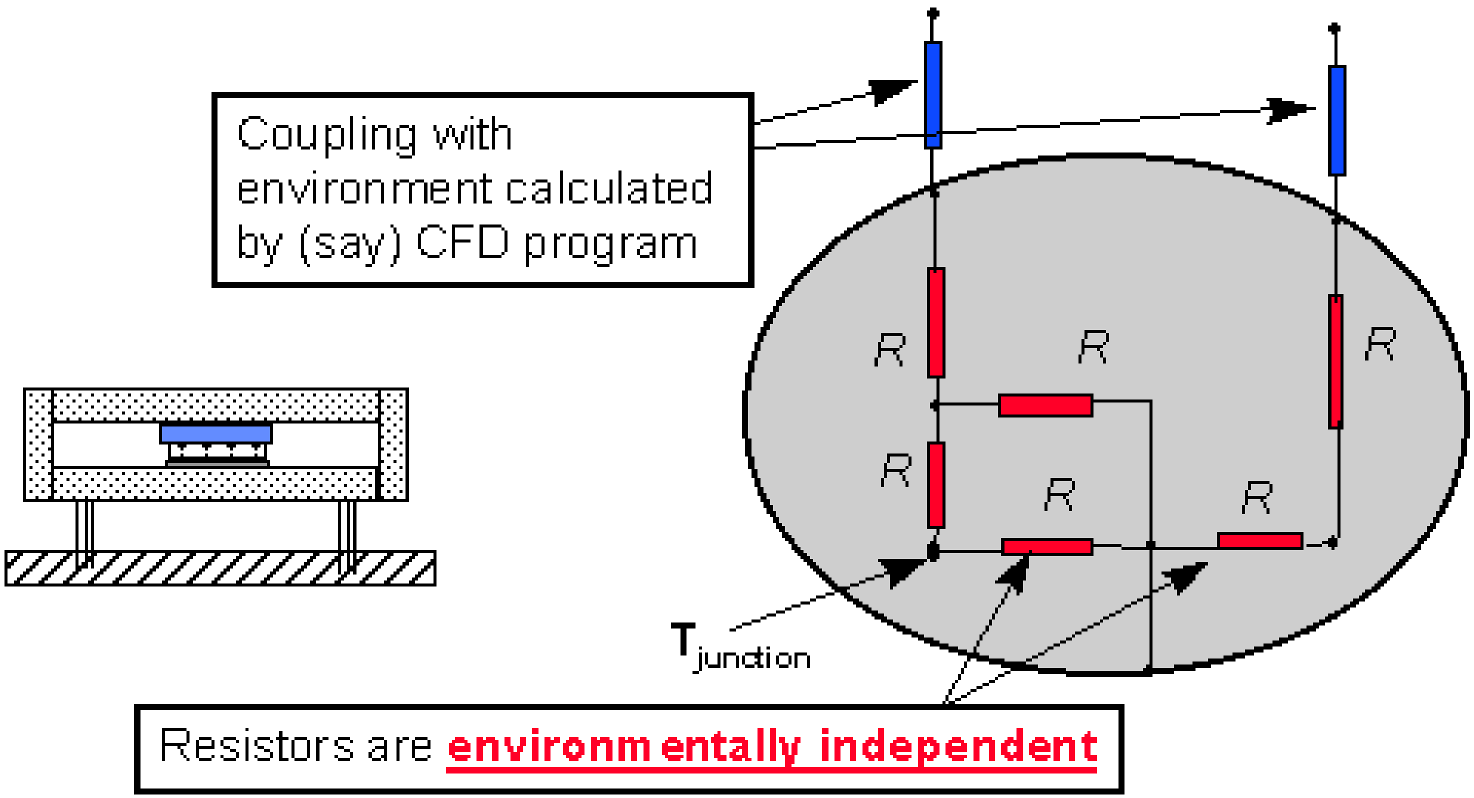
S. Shidore, Flomerics Inc.,
International Standards Committee Meeting, 1999.

The DELPHI Methodology



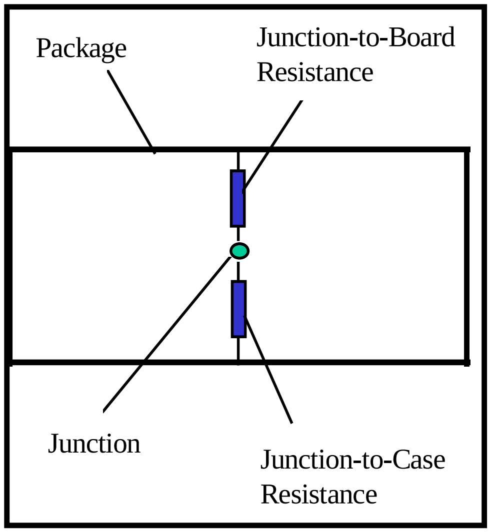
S. Shidore, Flomerics Inc.,
International Standards Committee Meeting, 1999.

Boundary Condition Independent Resistance Networks

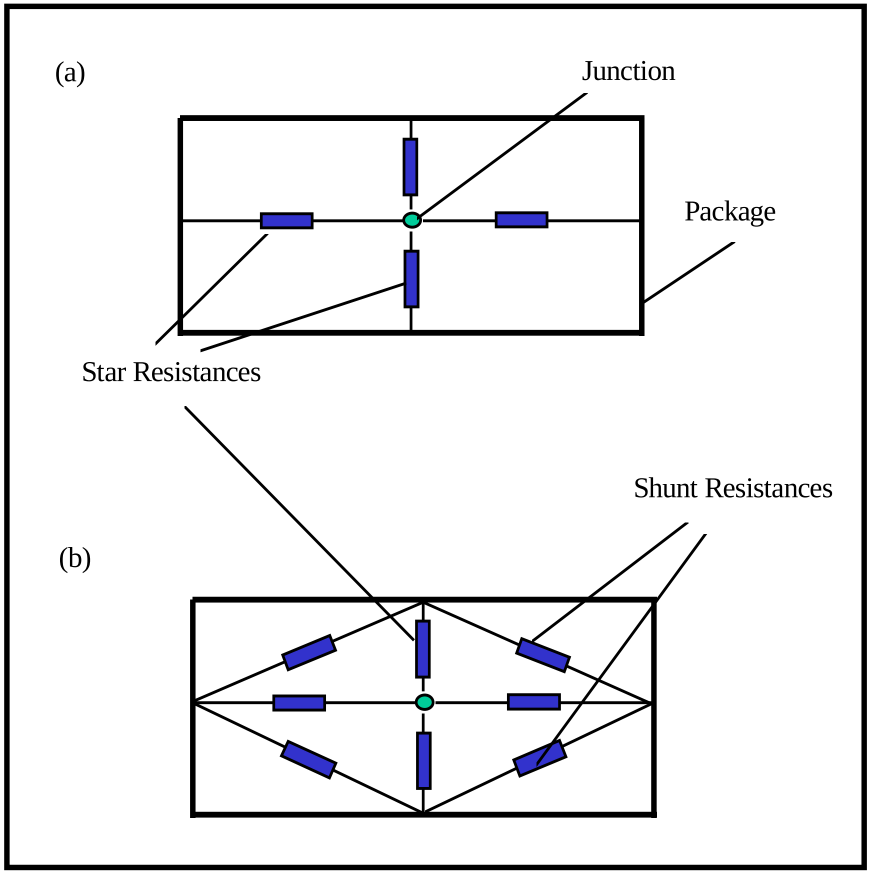


S. Shidore, Flomerics Inc.,
International Standards Committee Meeting, 1999.

Network Topologies



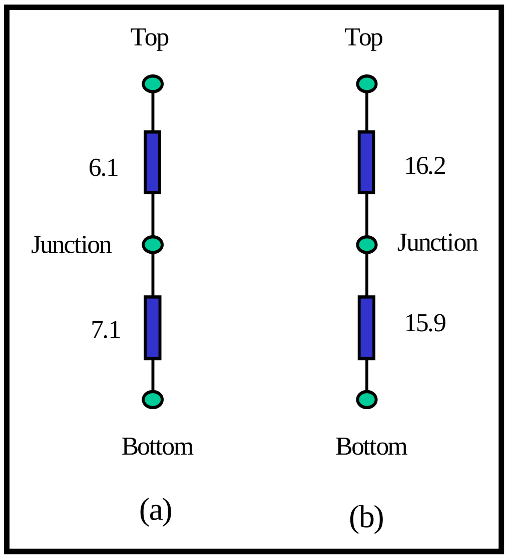
Two-Resistor



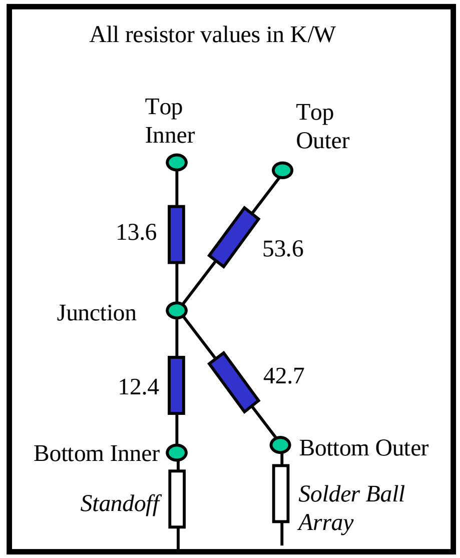
a) Star b) Shunt

S. Shidore, Flomerics Inc.,
International Standards Committee Meeting, 1999.

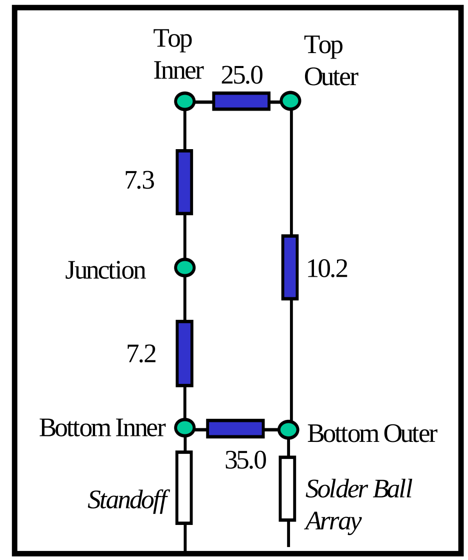
The Compact Models



Two Resistor Models
a) 2-Point Cold Plate Test
b) DELPHI Optimized

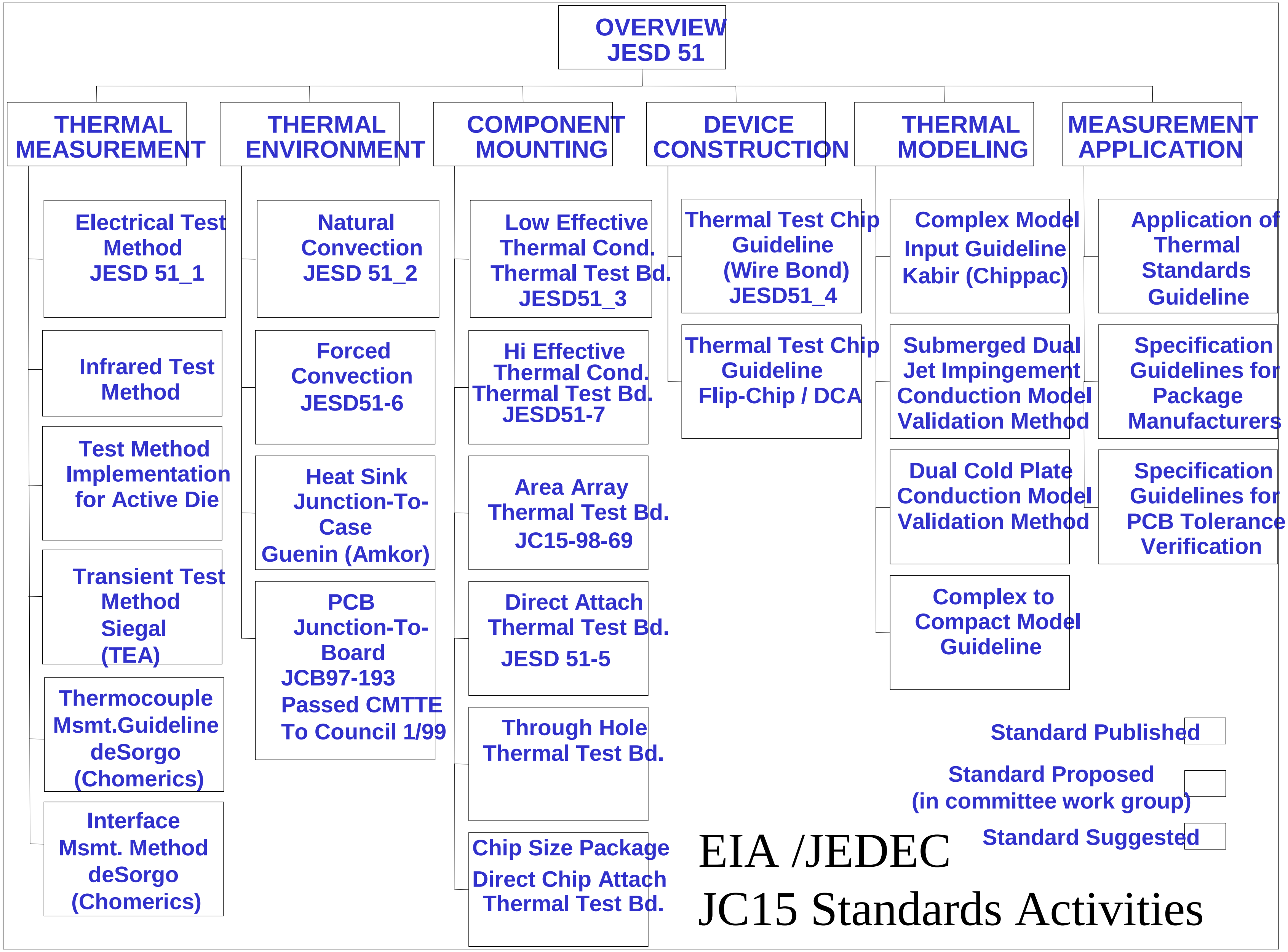


Star Model



Shunt Model

S. Shidore, Flomerics Inc.,
International Standards Committee Meeting, 1999.



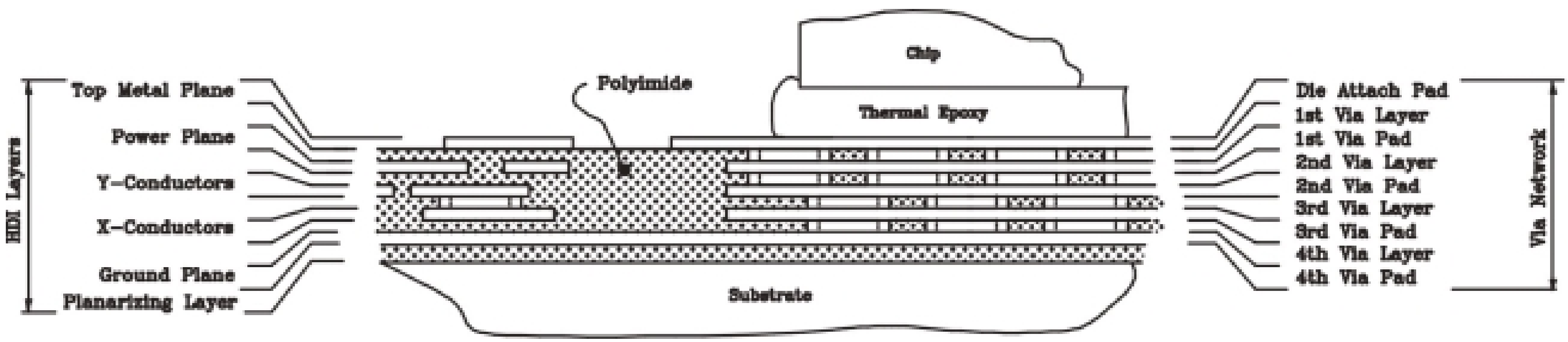
S. Shidore, Flomerics Inc.,
International Standards Committee Meeting, 1999.

Examples of Compact Models

- Total resistance of multilayered substrates (vias)
- Natural convection in vented enclosures
- Natural convection plate fin heat sink
- Compact heat exchangers

Thermal Vias

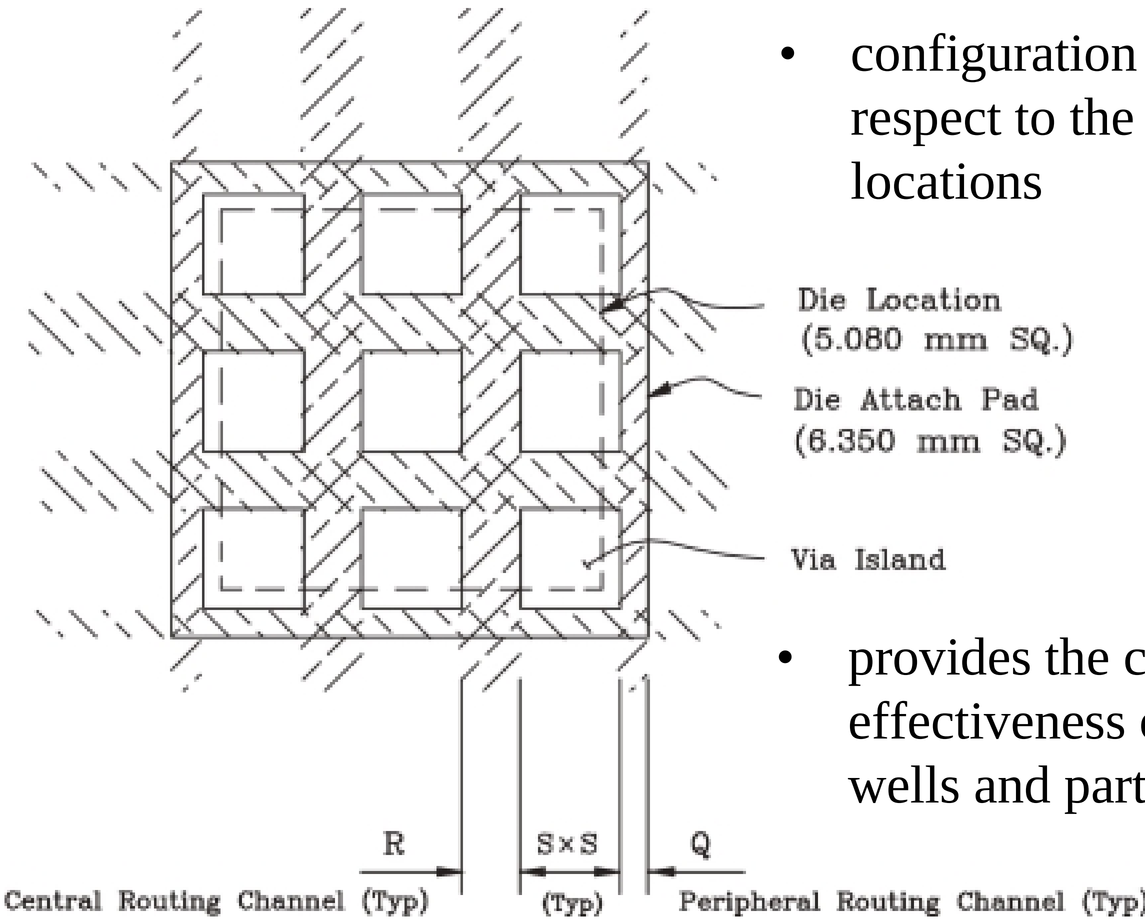
- Analytical model for via networks
- Typical configuration of a 5-layer High Density Interconnect
- 5 copper layers separated by 5 polyimide layers



Dimensions and Thermal Conductivities

Item	Dimensions (μm)	k (W/mK)
Die	5080 x 5080 x 25	150
Thermal Epoxy	5 (thickness)	3.8
Die Attach Pad	6350 x 6350 x 5	310
Planarizing Layer	5 (thickness)	0.19
HDI Dielectric, Polyimide Layers	5 (thickness)	0.19
HDI Conductive Layers, Via Pads	5 (thickness)	386
Vias	35 O.D. x 28 I.D. x 5	386
Ceramic Substrate	1016 (thickness)	30
Grease Layer	25 (thickness)	0.8

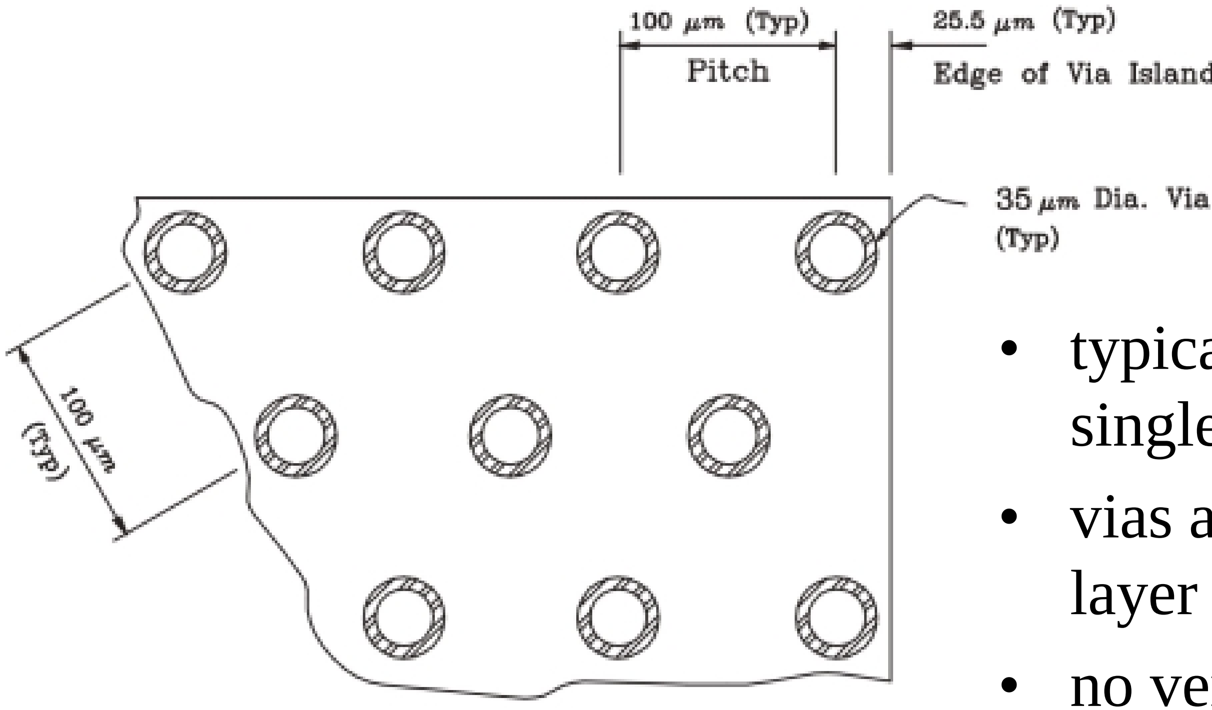
Thermal Vias



- configuration of the via island with respect to the die and the die attach pad locations

- provides the capability to compare the effectiveness of thermal vias, thermal wells and partial thermal wells

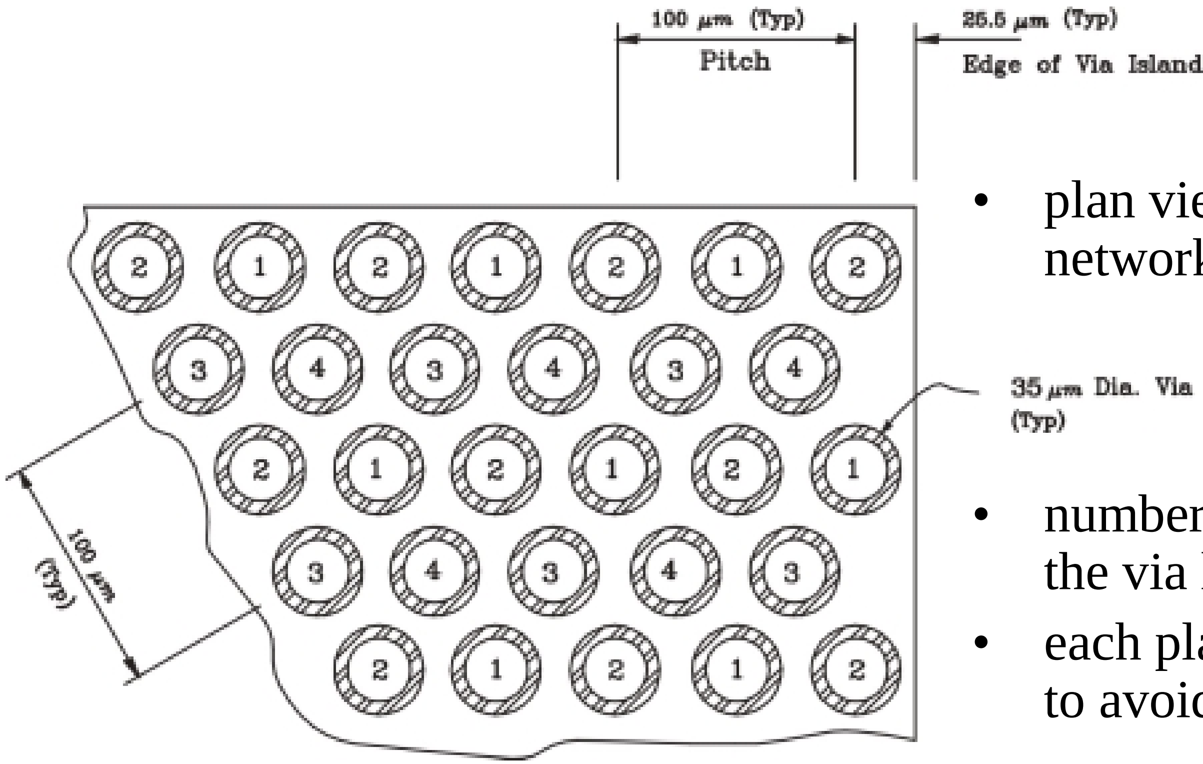
Thermal Vias



Typical section view of a via layer

- typical via layout within a single via layer
- vias are staggered from one layer to the next
- no vertical overlaps of vias occur through the layers

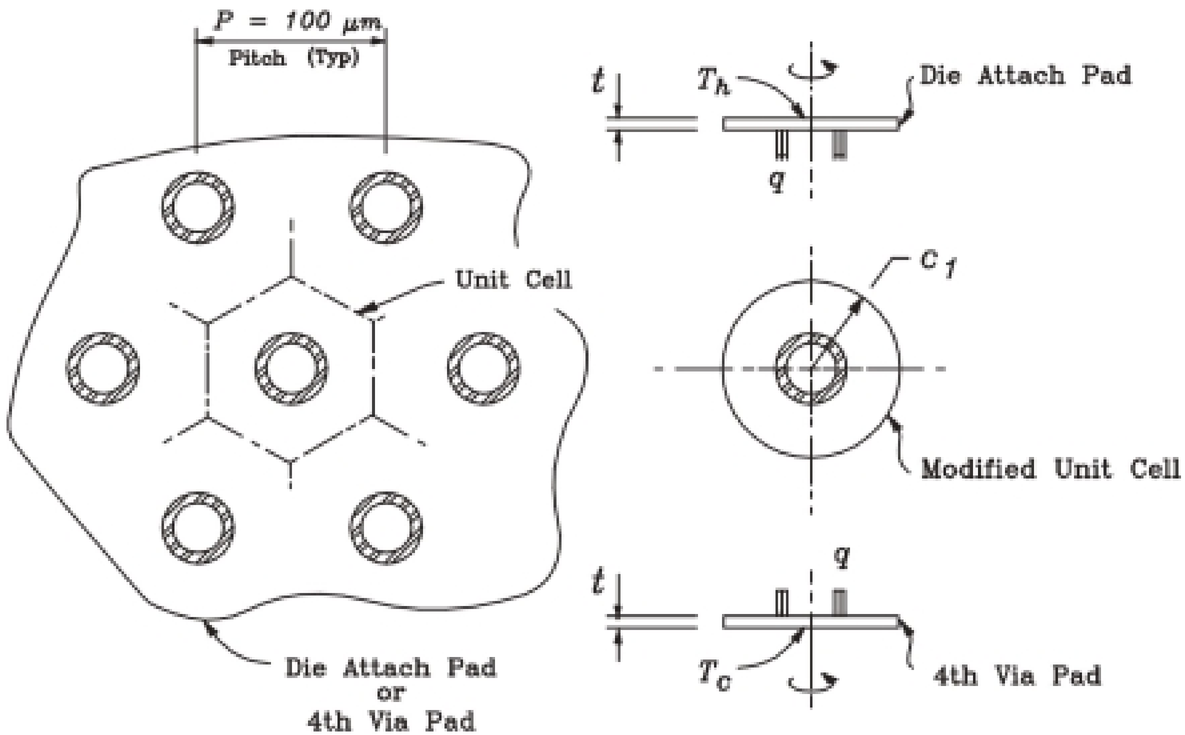
Thermal Vias



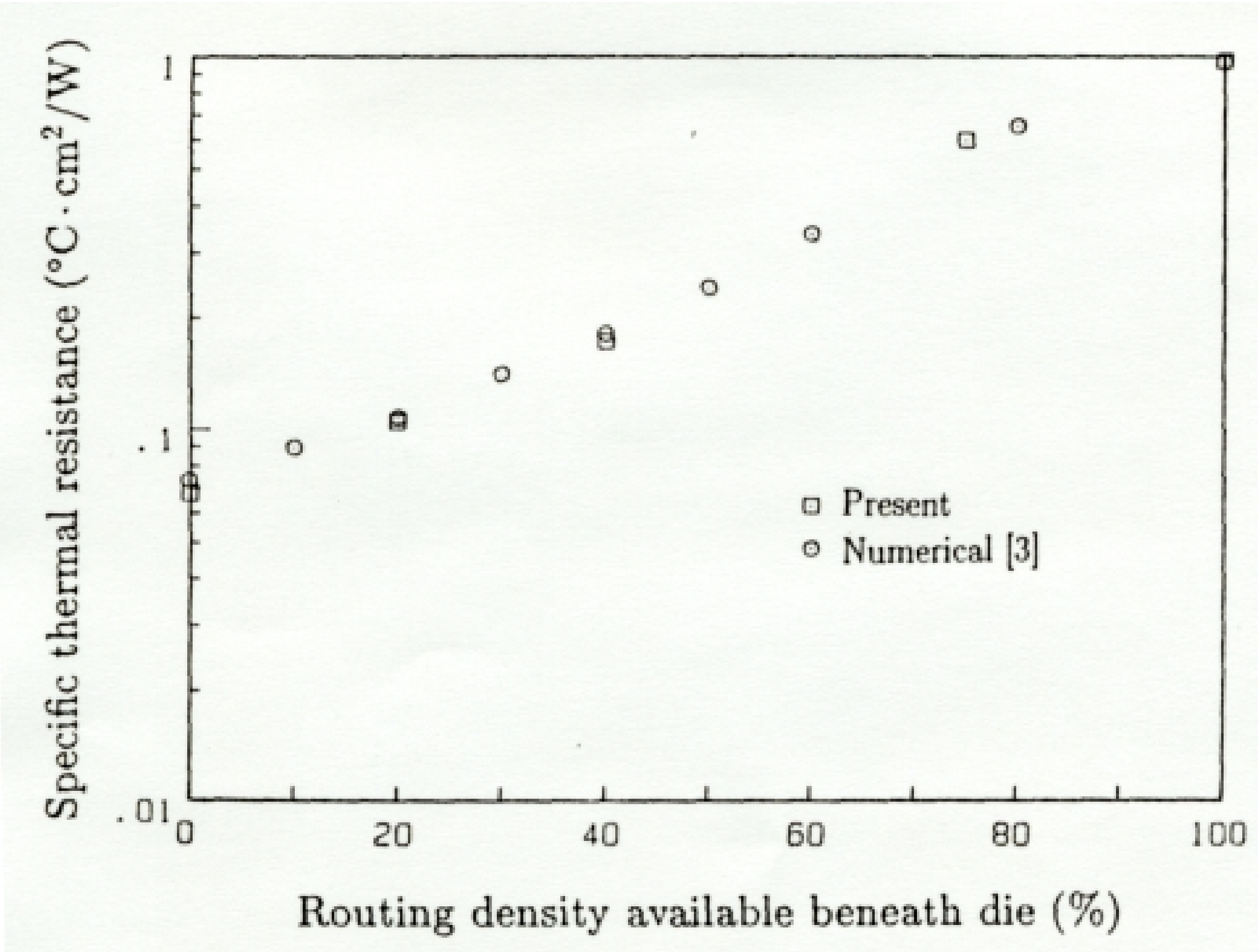
- plan view of a typical 4-layer via network
- numbers indicate the plane in which the via layer is located
- each plane has a 60 degree axis shift to avoid via overlap

Compact Model: Thermal Vias

- Isolate basic unit cell
- Model as a circular disk with an isoflux boundary



Model Validation



Natural Convection in Vented Enclosures

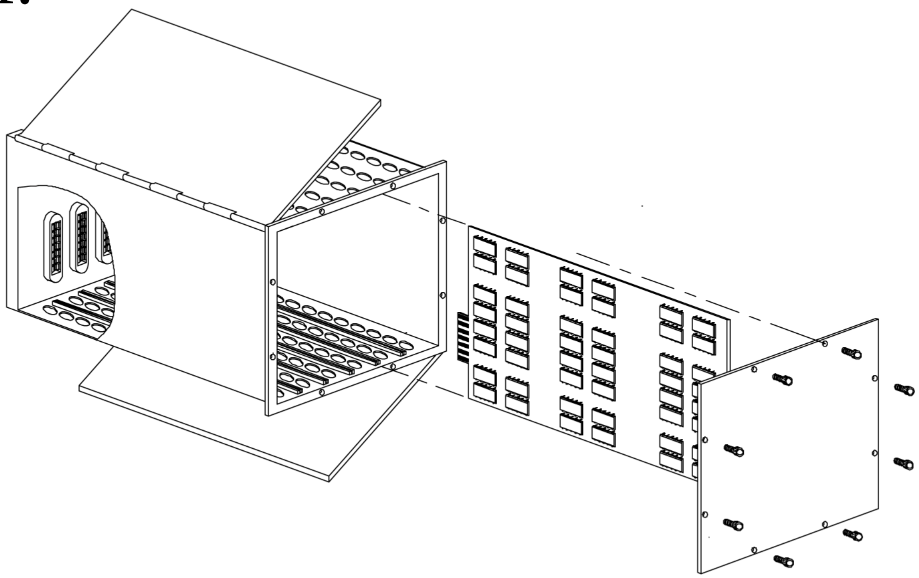
- Natural convection heat transfer for a parallel array of circuit boards in a vented enclosure
- Flow restrictions at inlet, outlet
- Solve for each channel:

$$\Delta \overline{T}_{fluid}$$

$$\overline{U}_{fluid}$$

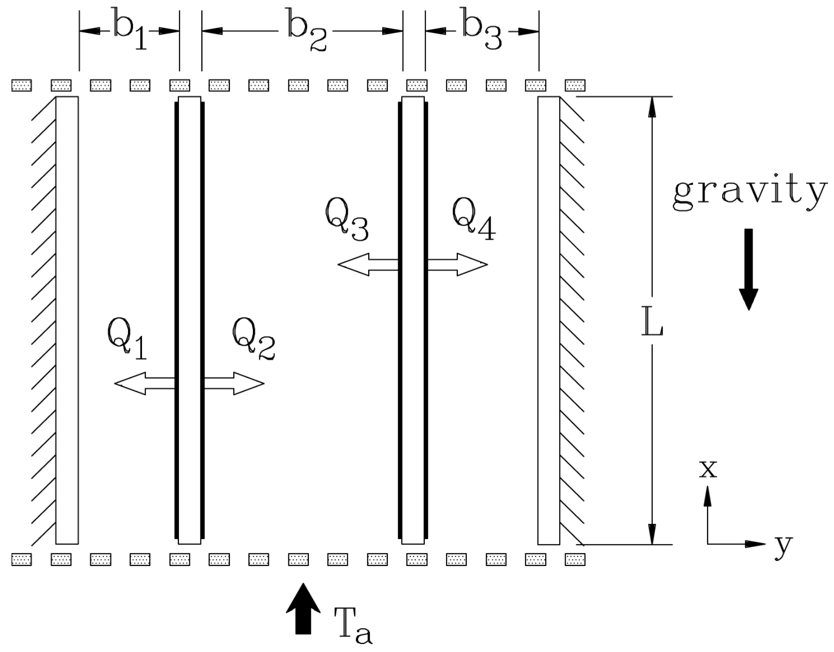
$$T_{max\,board}$$

$$Q_{1,2\,board}$$

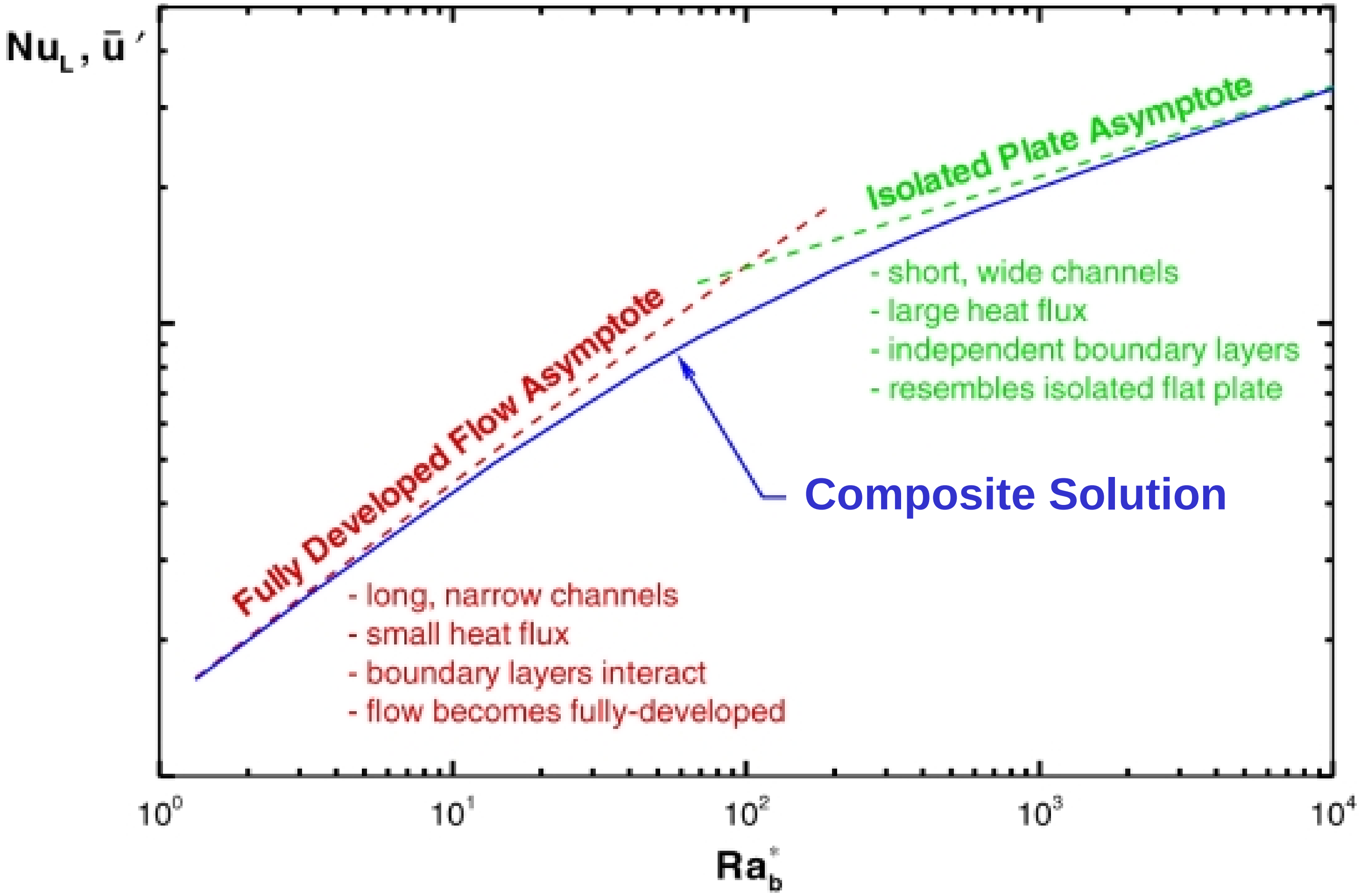


Modeling Approach

- Laminar natural convection between parallel plates
- Assumptions:
  - 2D channel flow
  - isoflux boundary conditions
  - adiabatic boundaries at outer walls
  - EMC screens at inlet, exit



Composite Solution Procedure

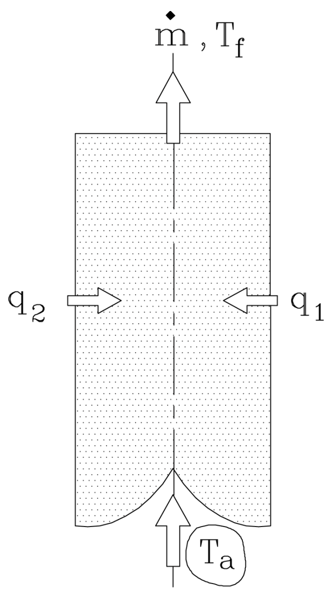


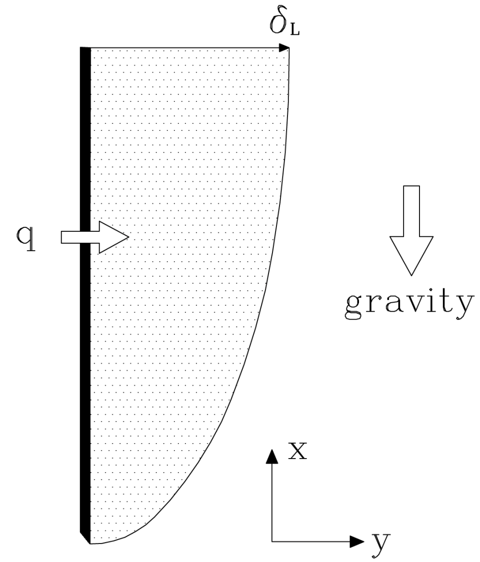
Nusselt Number

$$Nu_L = \frac{q\,L}{k\,\Delta T} = \left[\left(Nu_{fd}\right)^{-n} + \left(Nu_{ip}\right)^{-n}\right]^{-1/n}$$

Fully Developed Channel Flow

Isolated Plate, Laminar Boundary Layer Flow





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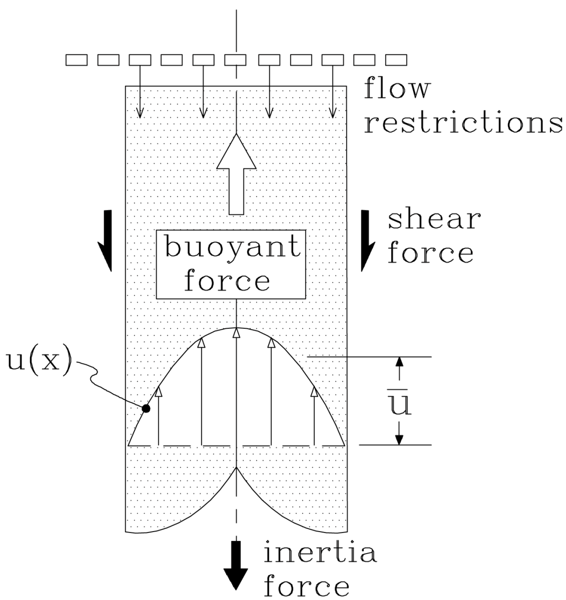
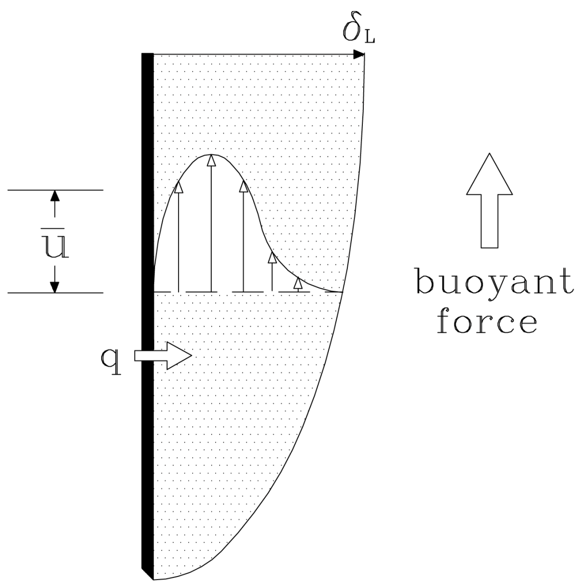
Mean Velocity

$$Re_b = \frac{\overline{U}\ b}{\upsilon} = \left[\left(Re_{fd}\right)^{-n} + \left(Re_{ip}\right)^{-n}\right]^{-1/n}$$

Fully Developed Channel Flow

Isolated Plate, Laminar Boundary Layer Flow





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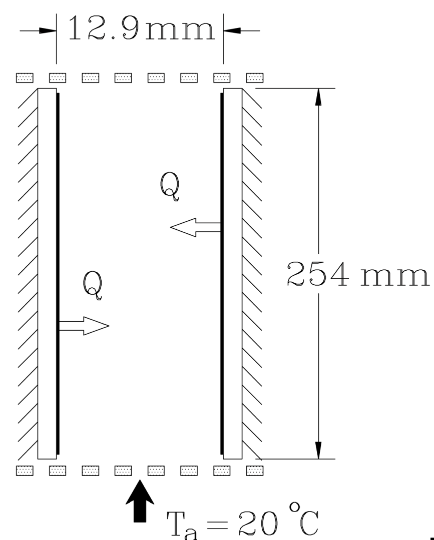
Model Validation

Q $(W / side)$	% open	K	Model ΔT_{board} $(°C)$	Model ΔT_{fluid} $(°C)$	Exp. Data ΔT_{board} $(°C)$	Exp. Data ΔT_{fluid} $(°C)$
5.25	100	0	22.5	15.7	22.2	14.7
5.25	62.8	4.3	25.0	20.1	26.4	18.5
4.0	49.2	8.2	22.2	19.2	23.5	18.0
4.0	38.4	14.8	24.4	22.0	26.9	21.1

- Symmetrically heated, single channel
- EMC screens at inlet, outlet



Air Cooled Electronic Heat Sinks

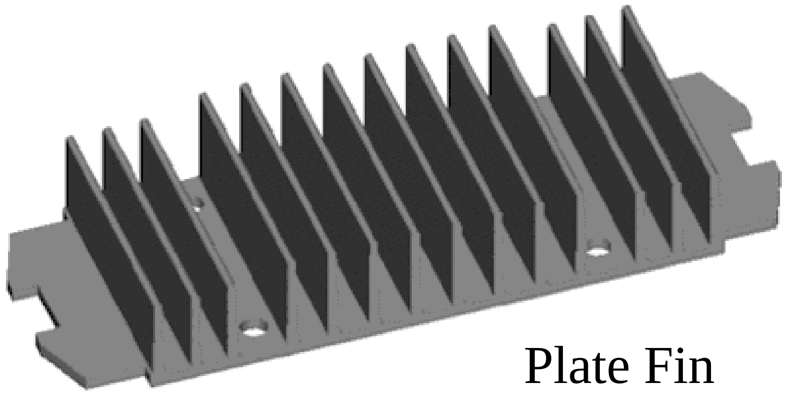
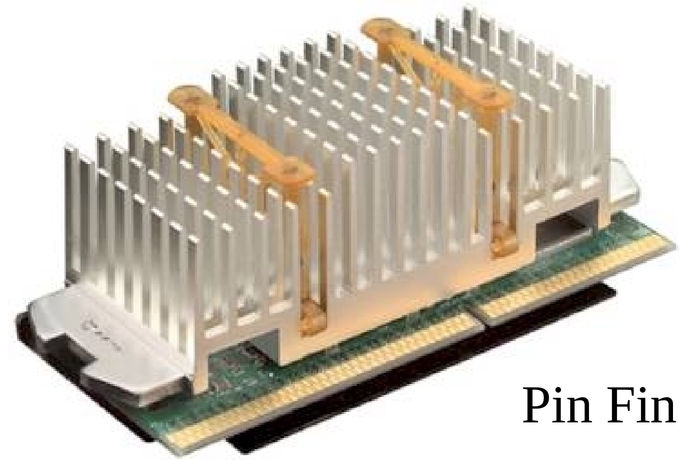
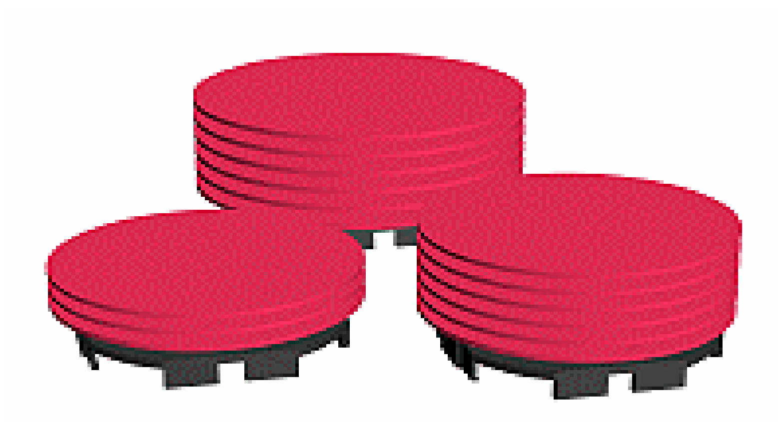


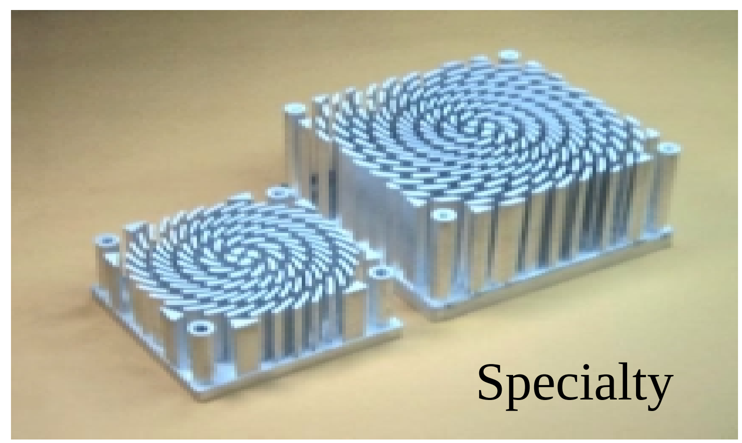
Plate Fin



Pin Fin

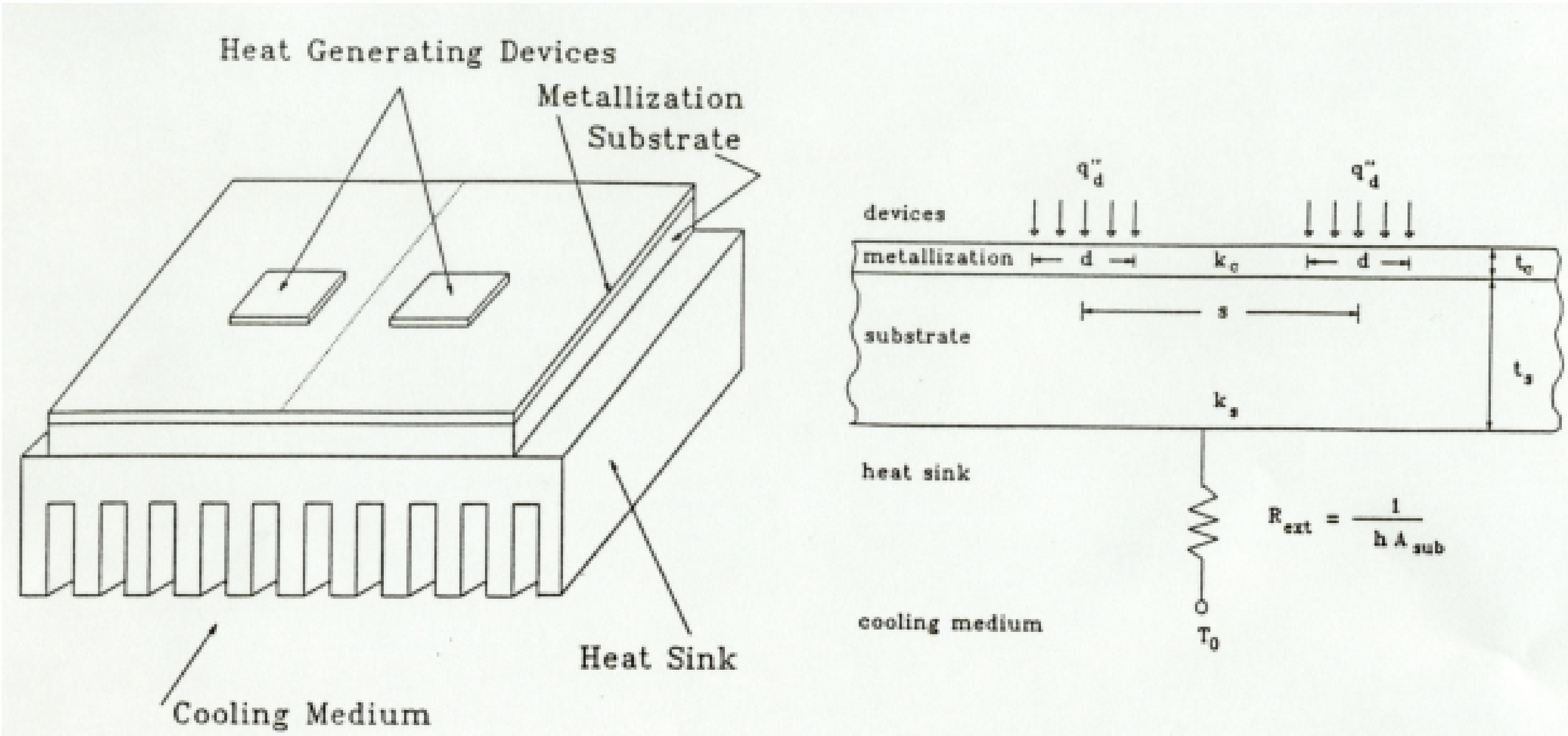


Radial Fin



Specialty

Microelectronics Heat Sink Application



M. M. Hussein et al., IEEE Semitherm Symposium, 1991, pp. 117 - 122.

Compact Model

$$Nu = \underbrace{Nu_0}_{} + \underbrace{\frac{1}{\left[\left(\frac{1}{Nu_2}\right)^2 + \left(\frac{1}{Nu_3 + Nu_4}\right)^2\right]^{-1/2}}}_{} + \underbrace{Nu_1}_{}$$

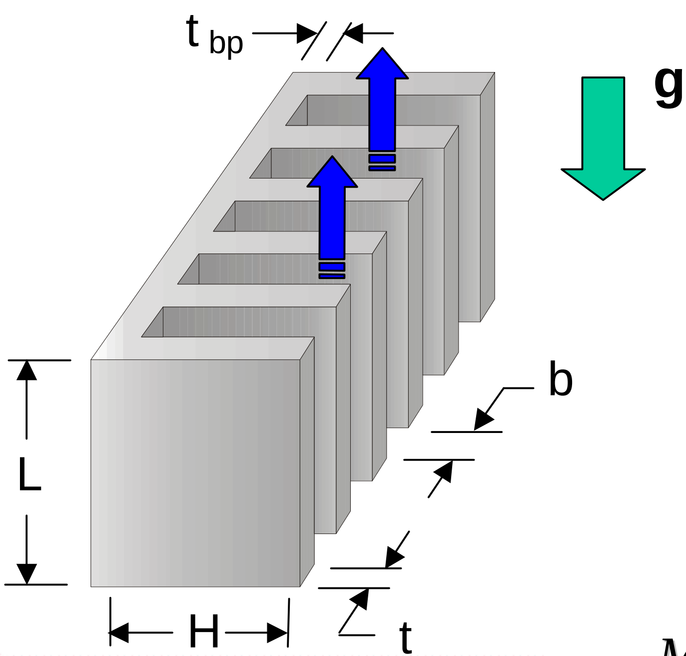
diffusion + channel flow + external boundary layer flow

Compact Modeling Procedure

Given: dimensions & temperature

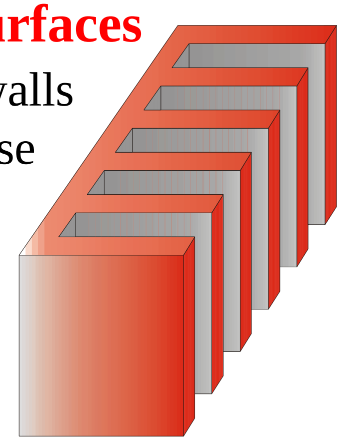
Find: Nu_b *vs.* Ra_b $\Rightarrow = \dfrac{g\beta\Delta T\, b^3}{\alpha\nu}\cdot\dfrac{b}{L}$

$$= \frac{h\,b}{k_f}$$



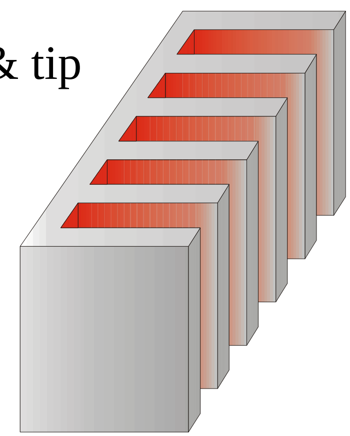
Interior Surfaces

- fins: side walls
- channel base



Exterior Surfaces

- fins: top, bottom, ends & tip
- base plate: top, bottom, ends and back



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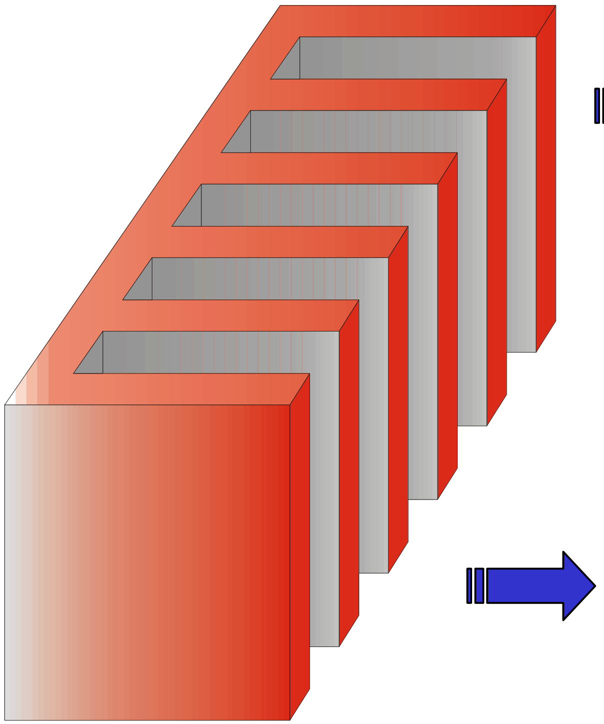
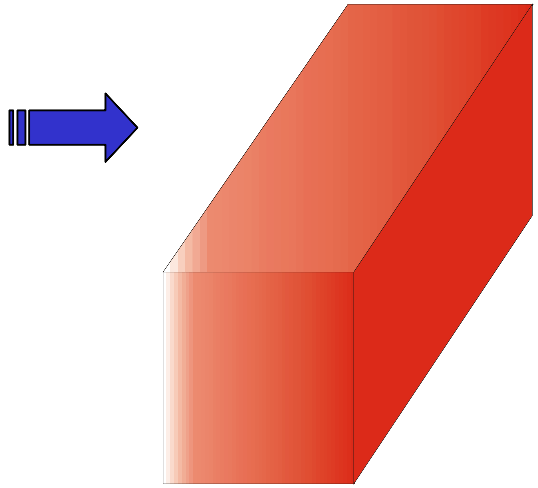
Exterior Surfaces



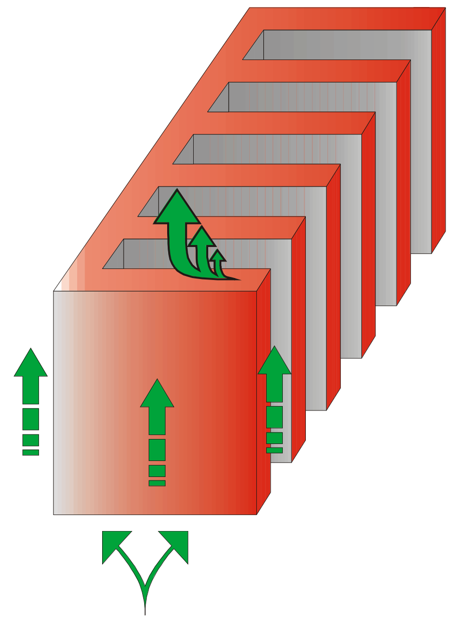


Diffusion

- lower Rayleigh numbers
- thick boundary layers

Boundary Layer Flow

- **higher Rayleigh numbers**
- **thin boundary layers**



Diffusion Model

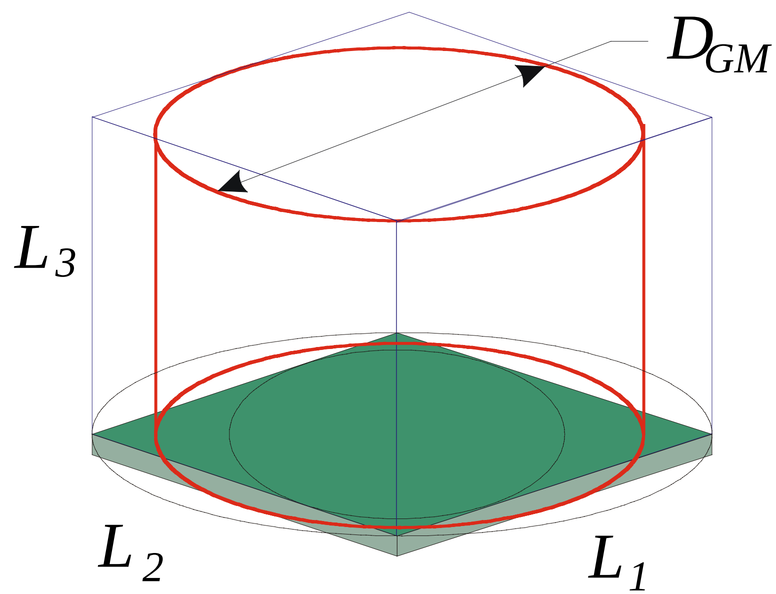
$$Nu_0 = S^*_{\sqrt{A}} = \left(S^*_{\sqrt{A}}\right)_{plate} \left(\frac{1 + 0.8688\left(L_3 / D_{GM}\right)^{0.76}}{\sqrt{1 + 2 L_3 / D_{GM}}} \right)$$

$$1.0 \le L_1 / L_2 \le 5.0$$

$$\left(S^*_{\sqrt{A}}\right)_{plate} = \frac{\sqrt{2/\pi}\left(1 + \sqrt{L_1/L_2}\right)^2}{\sqrt{L_1/L_2}}$$

$$5.0 < L_1 / L_2 < \infty$$

$$\left(S^*_{\sqrt{A}}\right)_{plate} = \frac{2\sqrt{2\pi}\sqrt{L_1/L_2}}{\ln\left(4 L_1/L_2\right)}$$



Parallel Plates Models

- Elenbaas, 1941

$$Nu_b = \frac{1}{24} Ra_b \left[1 - \exp\left(-35/Ra_b\right)\right]^{3/4}$$

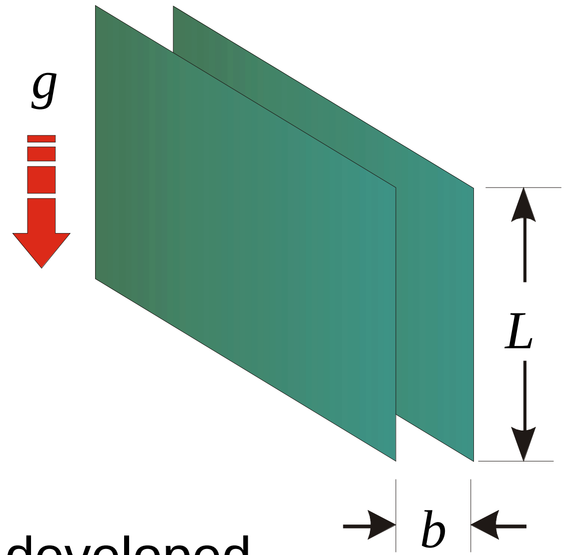
- Churchill, 1977

$$Nu_b = \left[Nu_{fd}^{-m} + Nu_{dev}^{-m}\right]^{-1/m}$$

$$m = 2$$

$$Nu_{fd} = \frac{1}{24} Ra_b$$

$$Nu_{dev} = G_{\sqrt{A}} \cdot F(\Pr) \cdot Ra_b^{1/4}$$

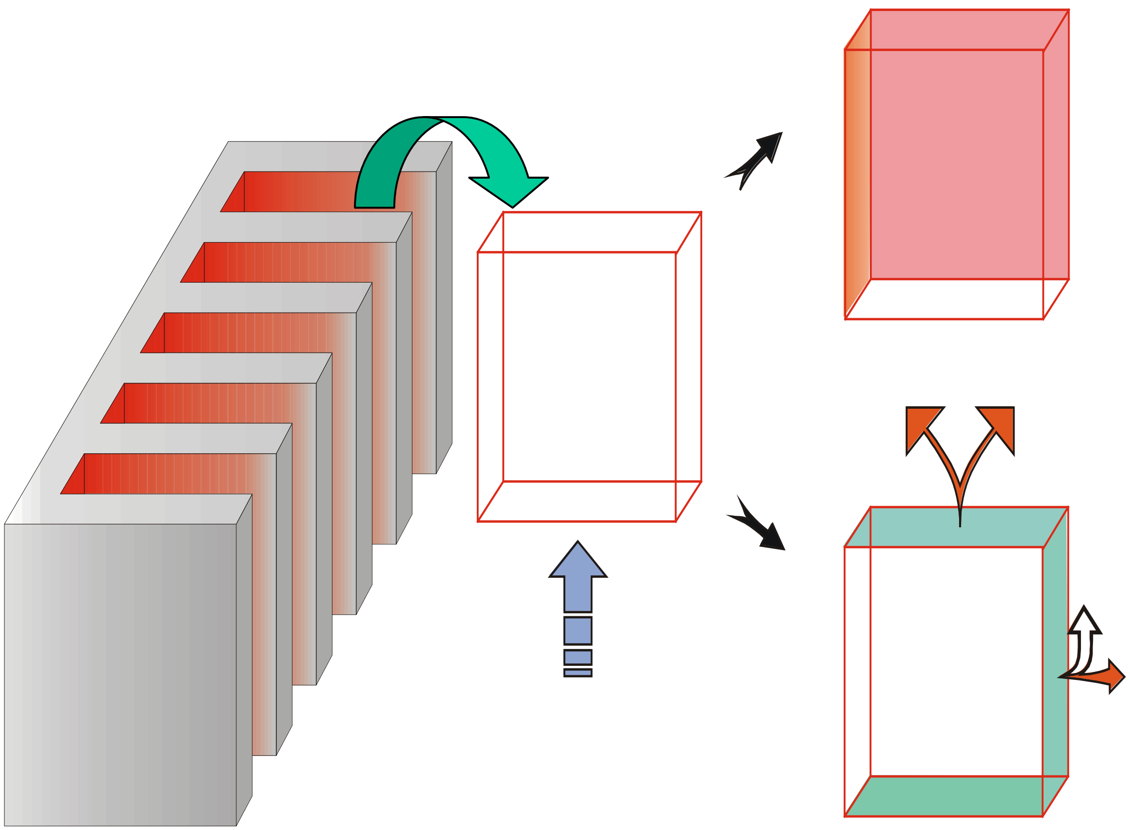


fd - fully developed
dev - developing flow

$G_{\sqrt{A}}$ - body gravity function

$F(\Pr)$ - Prandtl number function

Interior Surfaces



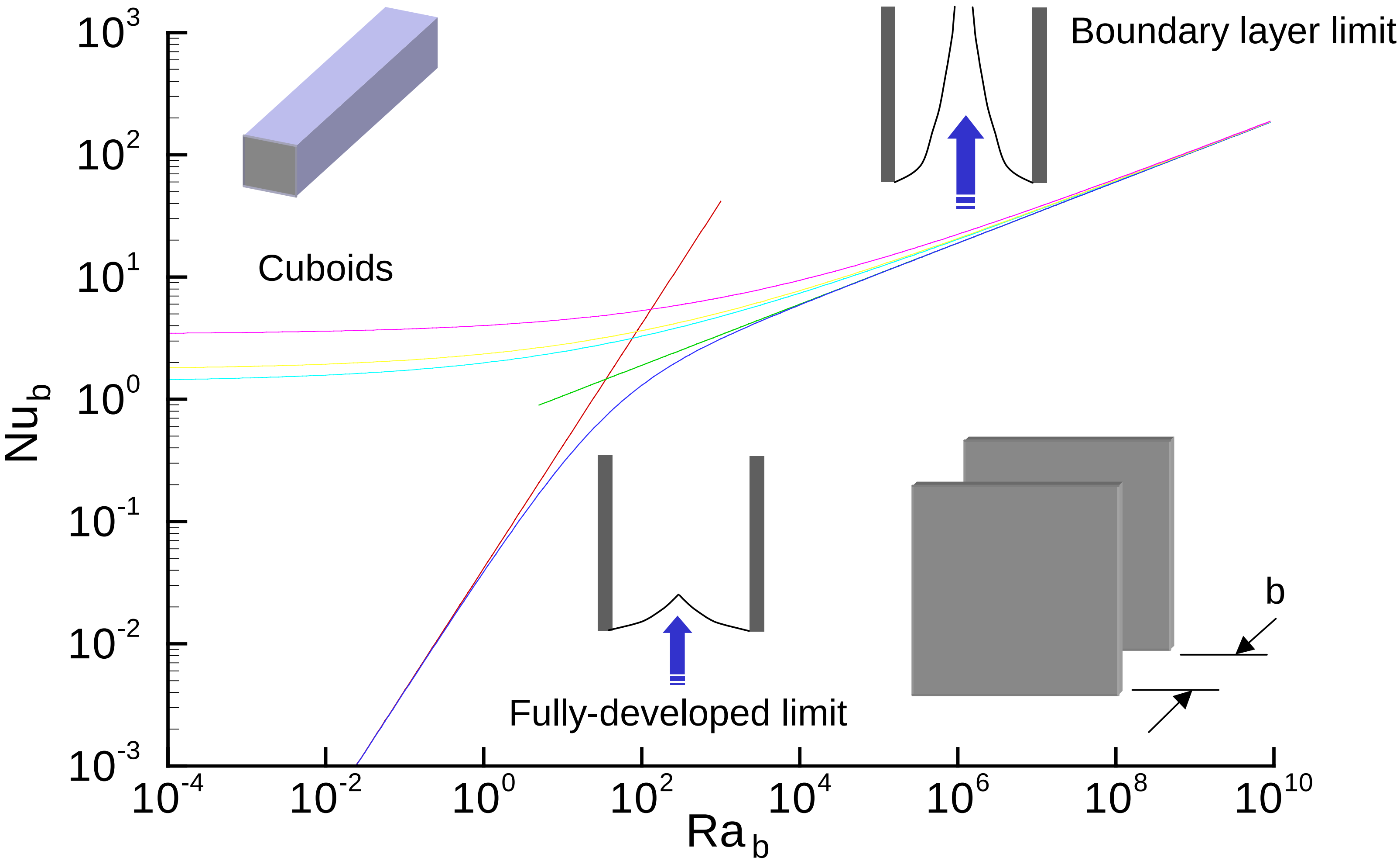
Channel Flow

- Elenbaas model with adjustment for end wall
- combined flow: developing + fully developed

Control Surface

- open surfaces with energy migration

Compact Model Limiting Cases



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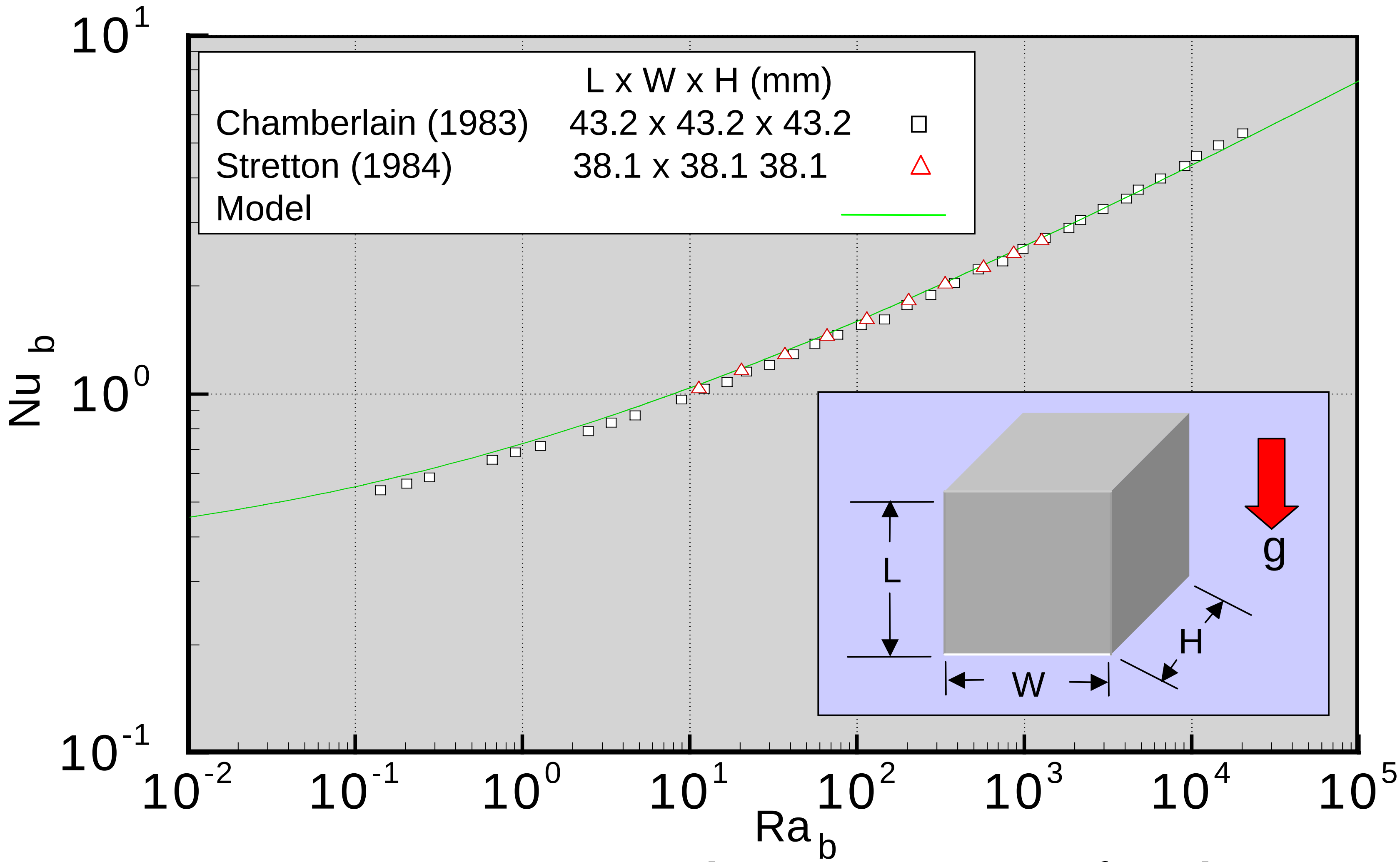
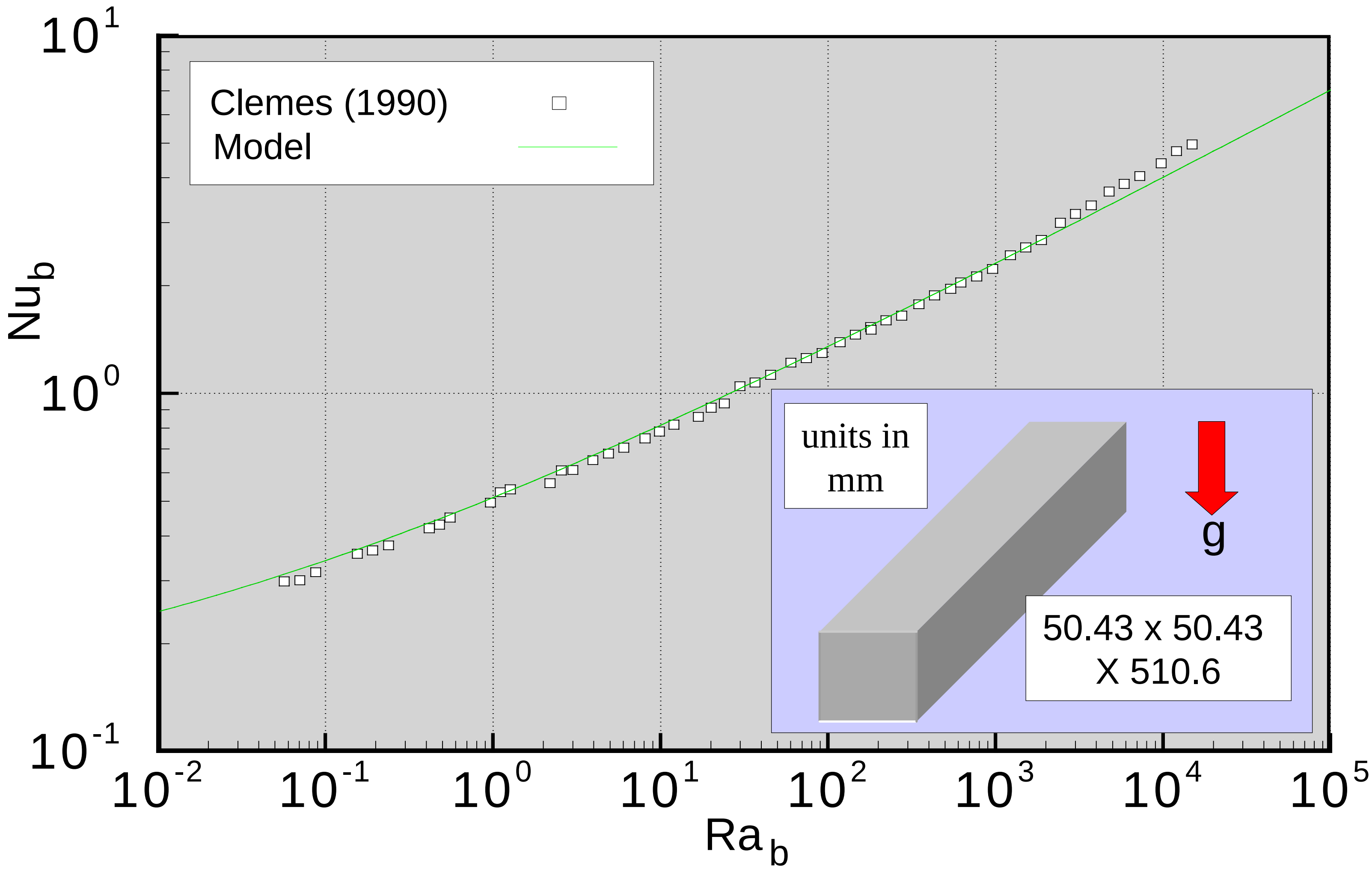
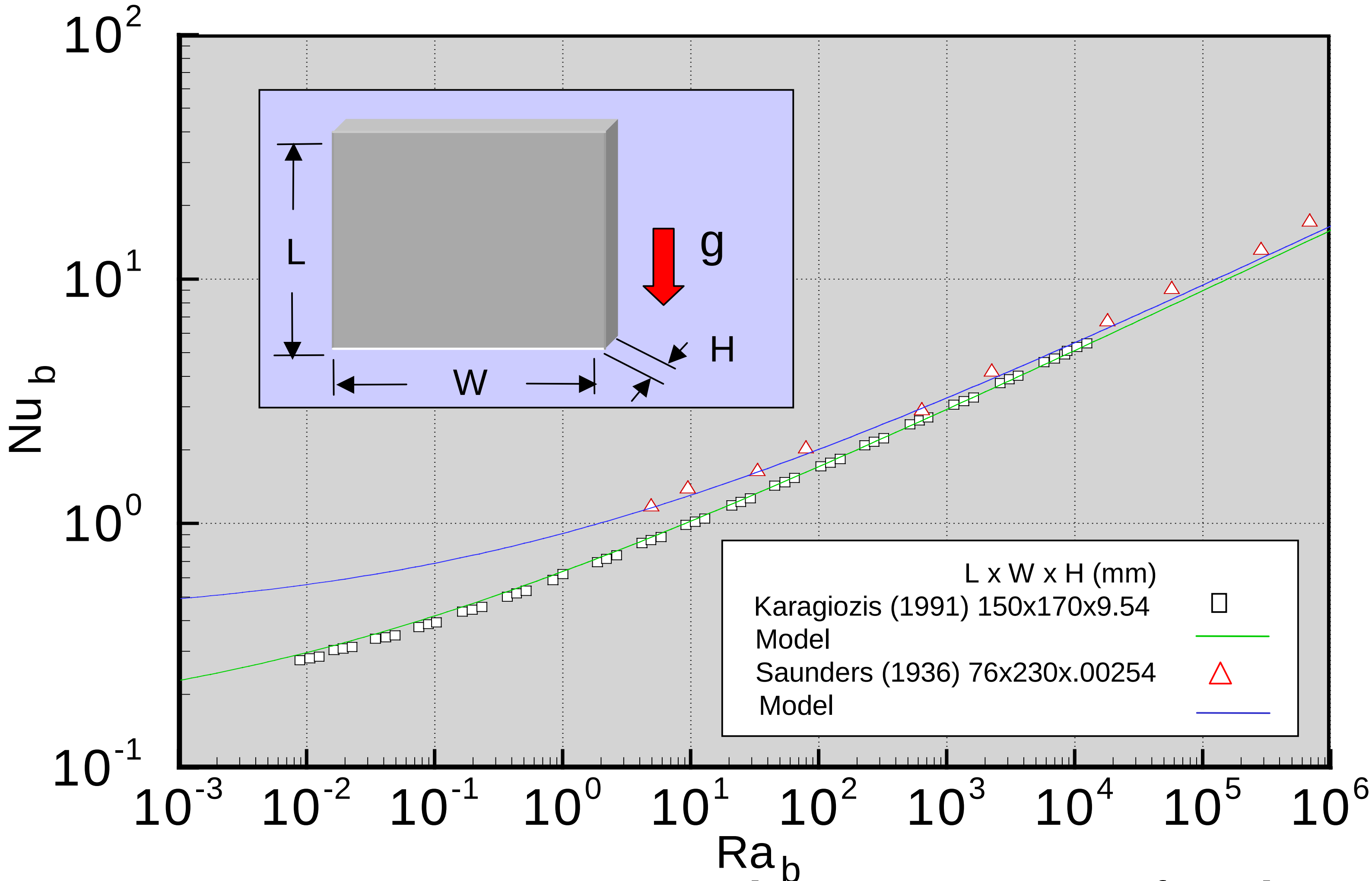
Model Validation: Cube



Model Validation: Cuboid



Model Validation: Vertical Plate



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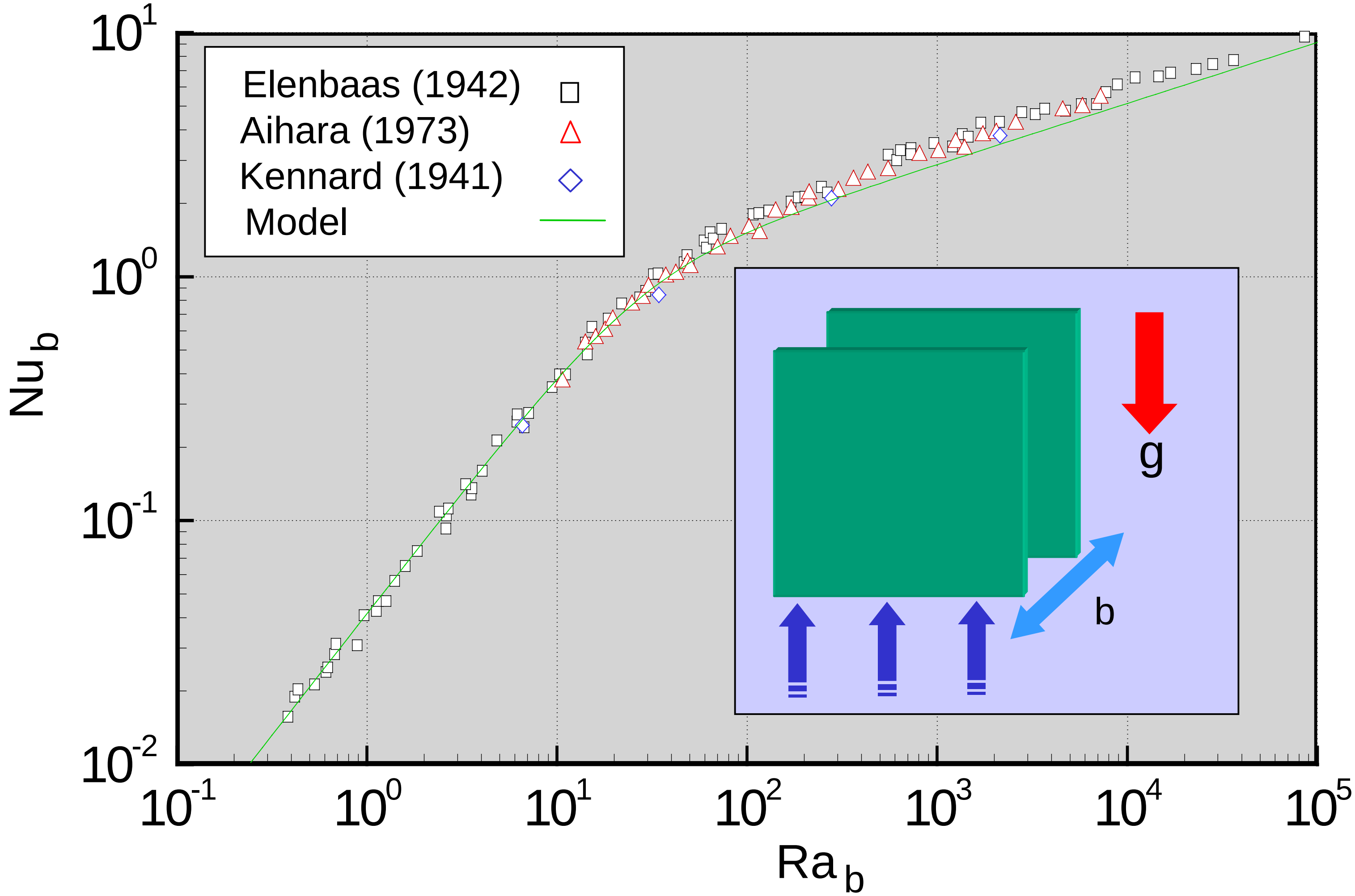
Model Validation: Parallel Plates



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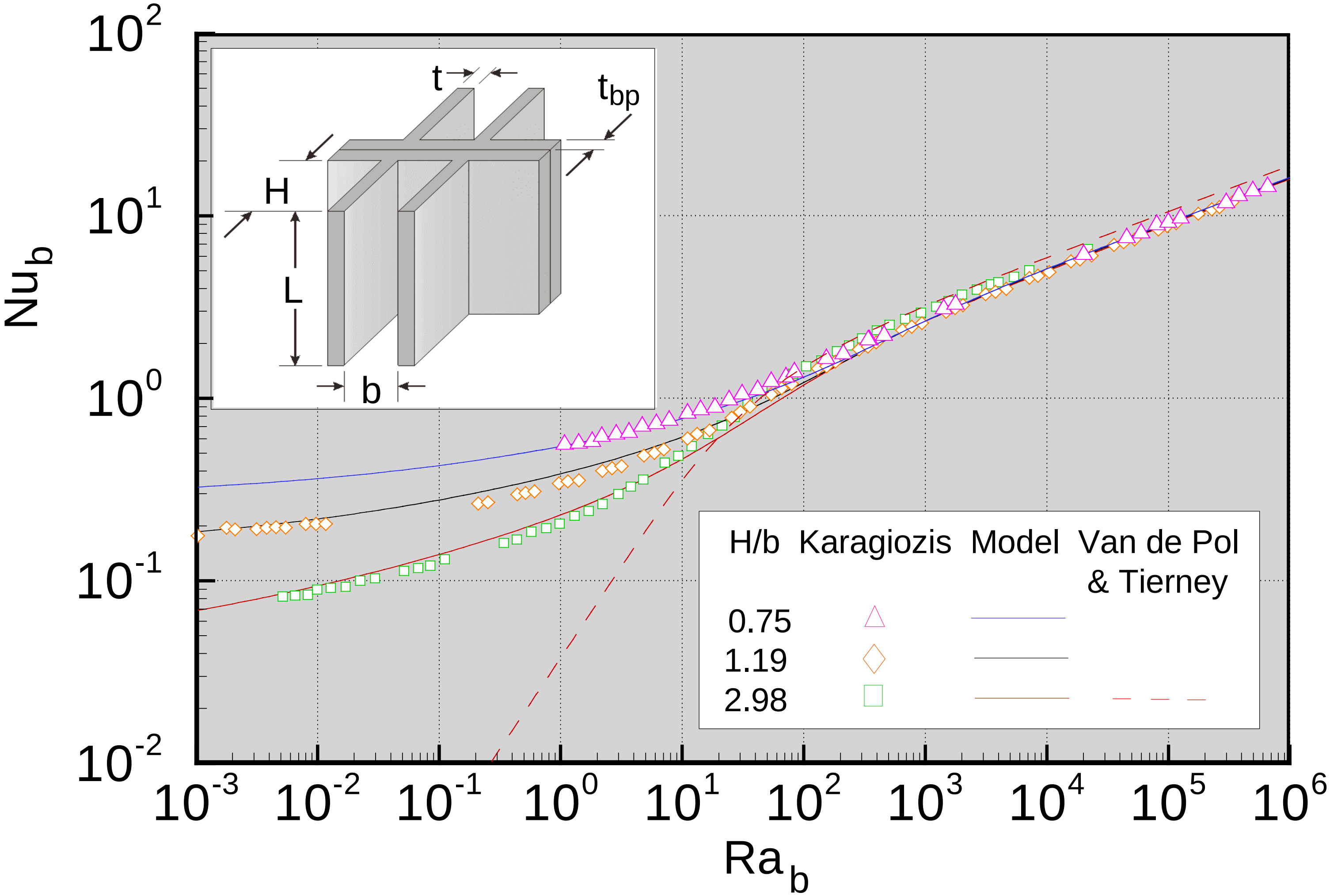
Model Validation: Plate Fin Heat Sinks



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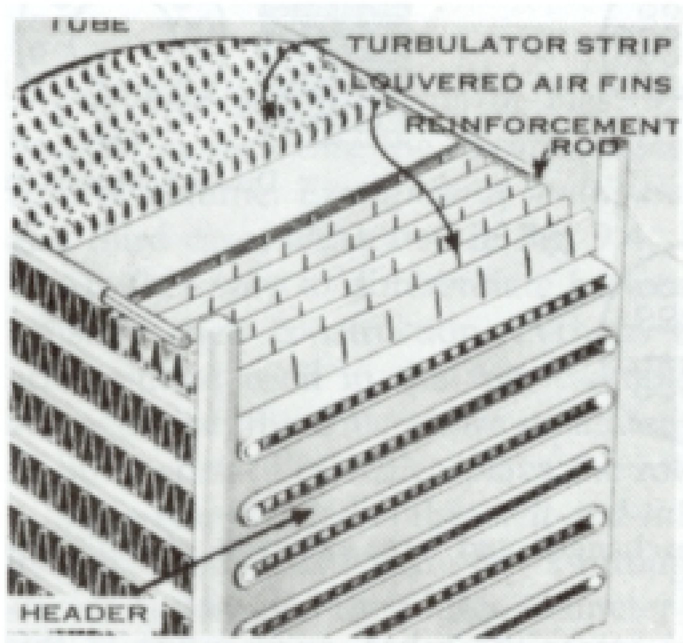
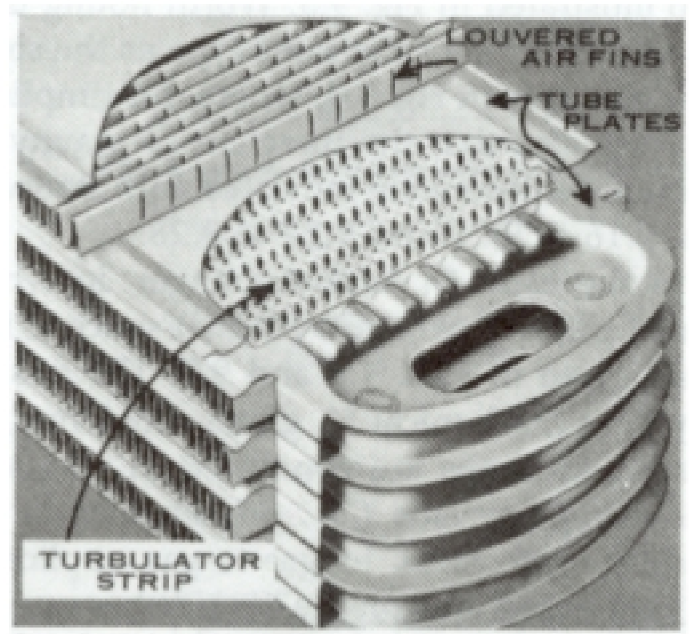
Automotive Heat Exchangers

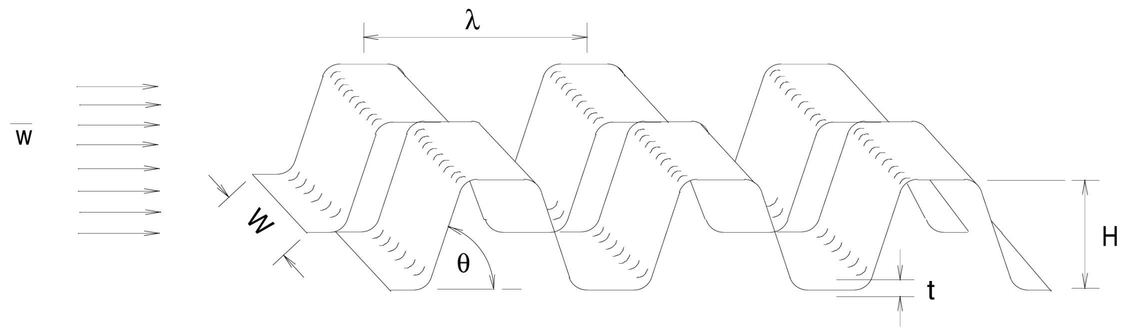




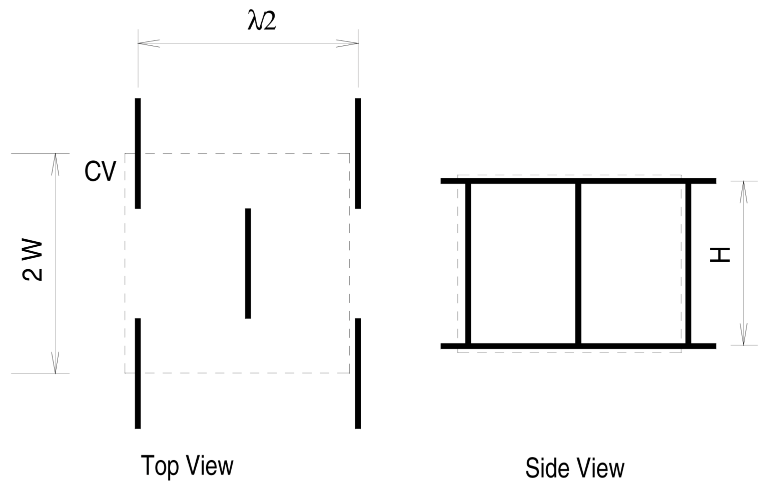
A. Bejan, Heat Transfer, Wiley, New York, 1993.

- Forced convection, internal flow
- Solve for $(\Delta P, \dot{m})$ and $(\Delta T, Q)$
- Requires f and j for wide range of *Re*, *Pr*

System Geometry and Basic Cell



Typical Turbulator Stip Geometry



Unit Cell for Compact Model

Modeling Procedure

- Define system, sub-system and basic cell
- Derive force and energy balances for basic cell
- Develop models for three flow regimes:
  - low Reynolds number (creeping) flow
  - laminar flow
  - turbulent flow
- Combine models using composite solution, valid for full range of *Re*
- Quantify combination parameters using experimental data

Modeling Approach

- Force balance

$$F_{total} = F_{friction} + F_{drag} + F_{losses}$$

$$\bar{f} = \frac{\bar{\tau}}{\frac{1}{2}\rho \overline{U}^2} = f(\ldots) + C_D(\ldots) + K(\ldots)$$

where $(\ldots) =$ geometry from basic cell

- Energy balance

$$Q_{total} = Q_{fins} + Q_{walls}$$

$$\bar{j} = \frac{Nu}{Re\ Pr^{1/3}} = j_{fins(\ldots)} + j_{walls}(\ldots)$$

Modeling Approach

- General form based on composite solution

$$f,\ j = \left[\left\{ \left(y_{cf} \right)^m + \left(y_{lam} \right)^m \right\}^{n/m} + \left(y_{tur} \right)^n \right]^{1/n}$$

where:

y_{cf} = low Reynolds number model (creeping flow)

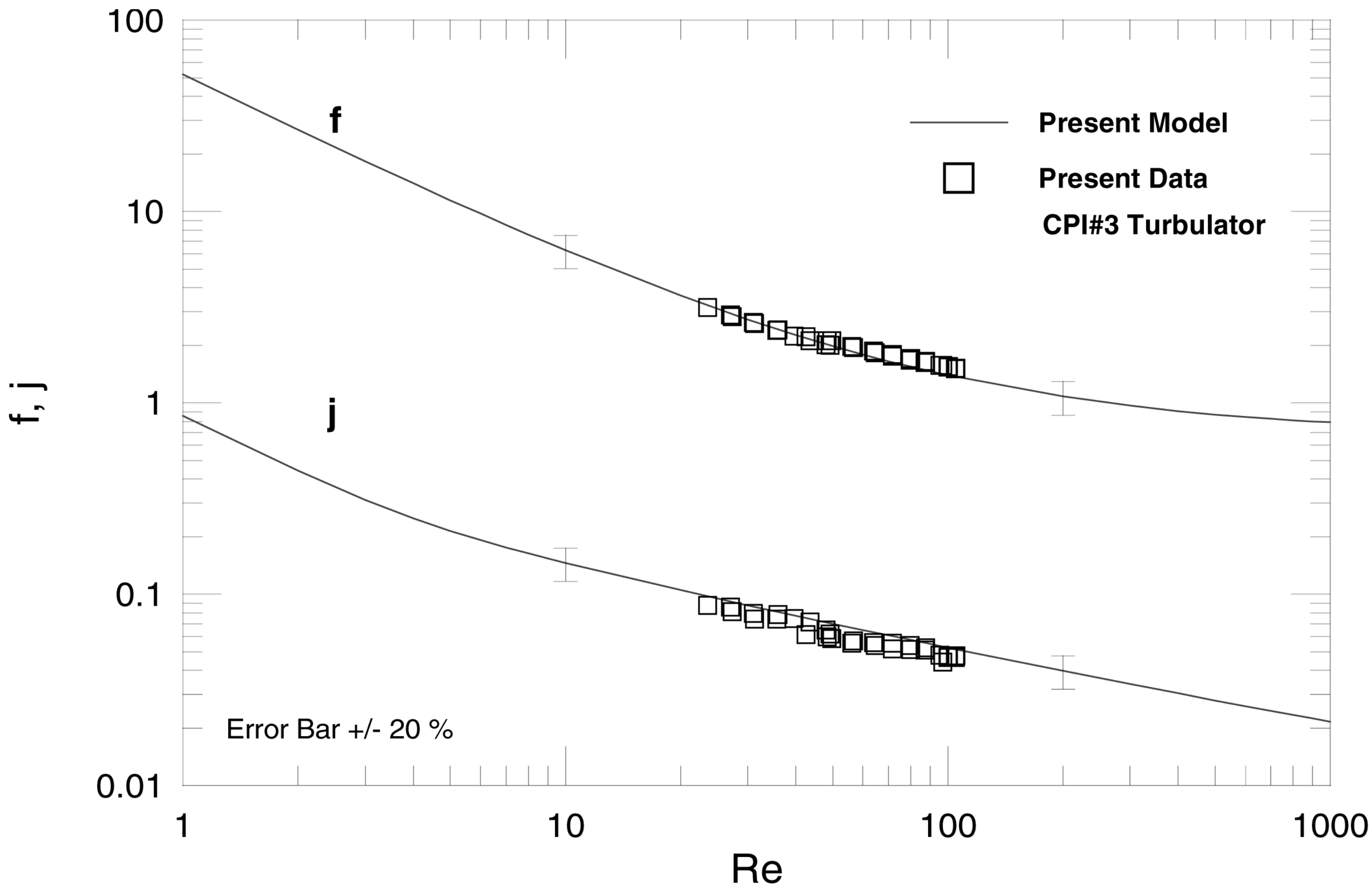
y_{lam} = laminar flow model

y_{tur} = turbulent flow model

m, n = combination parameters

Y. S. Muzychka and M. M. Yovanovich, HTD-Vol. 364-1, 1999, pp. 79-90.

Model Validation



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