Thermal Management for Electronic Packaging

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Outline

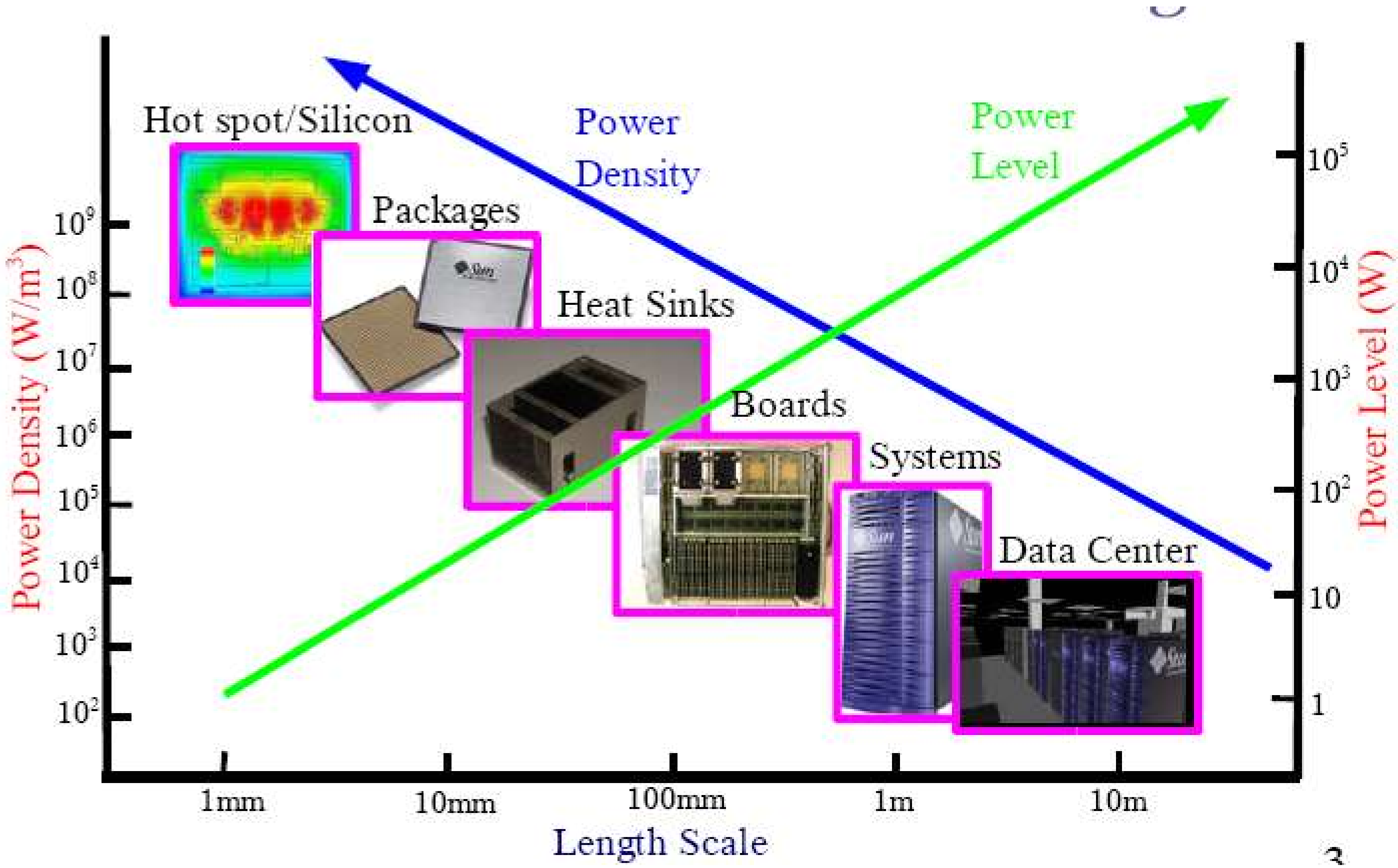
- Introduction
- Heat transfer theory
- Thermal resistance in electronic packaging
- Thermal design
- Thermal modeling
- Thermal measurement

Introduction

- Functions of Electronic Packaging
  - Package protection
  - Signal distribution
  - Power distribution
  - Heat dissipation

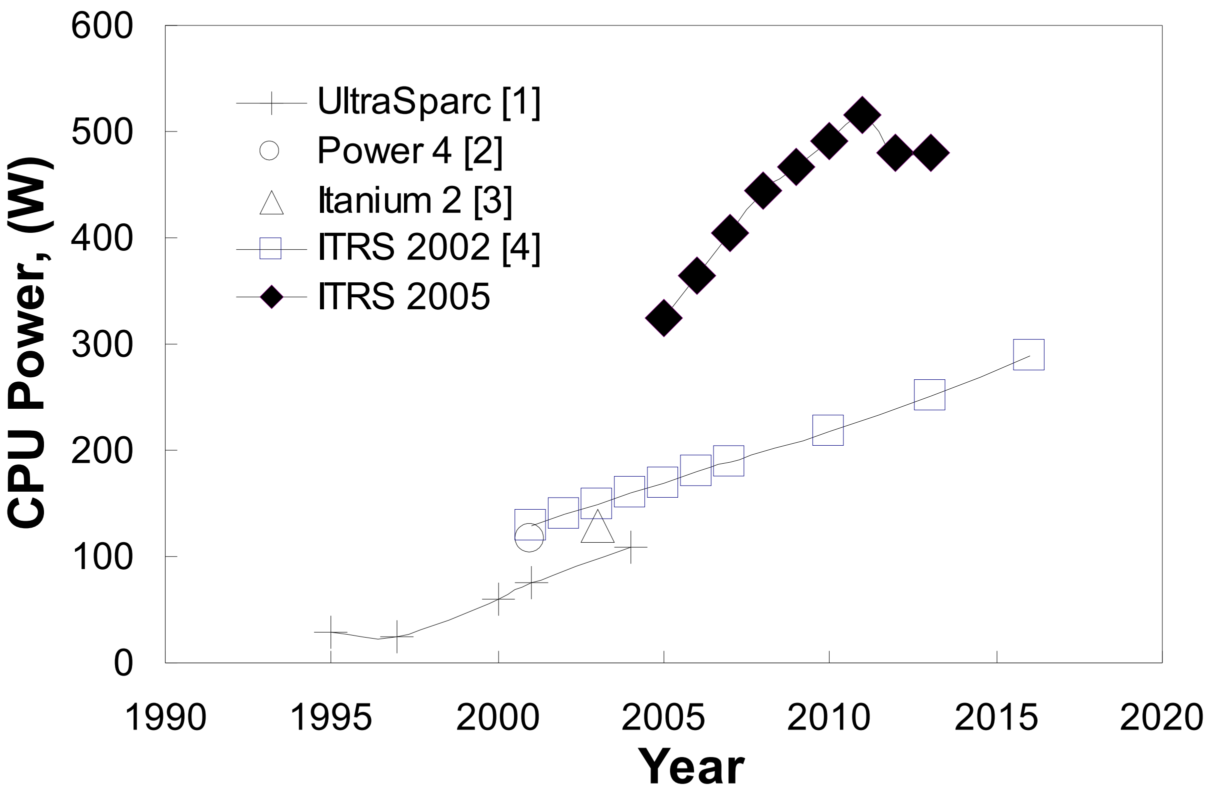
Introduction

- Packaging Hierarchy
  - Chip
  - Package
  - Board
  - System
  - Rack
  - Room



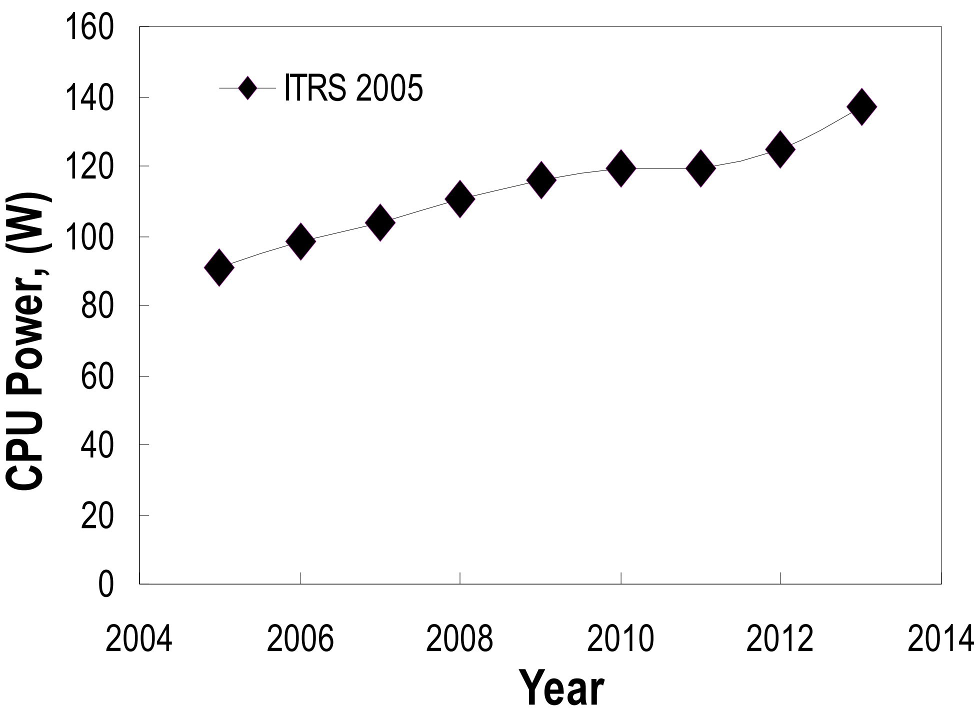
Introduction

- High end chip power trend



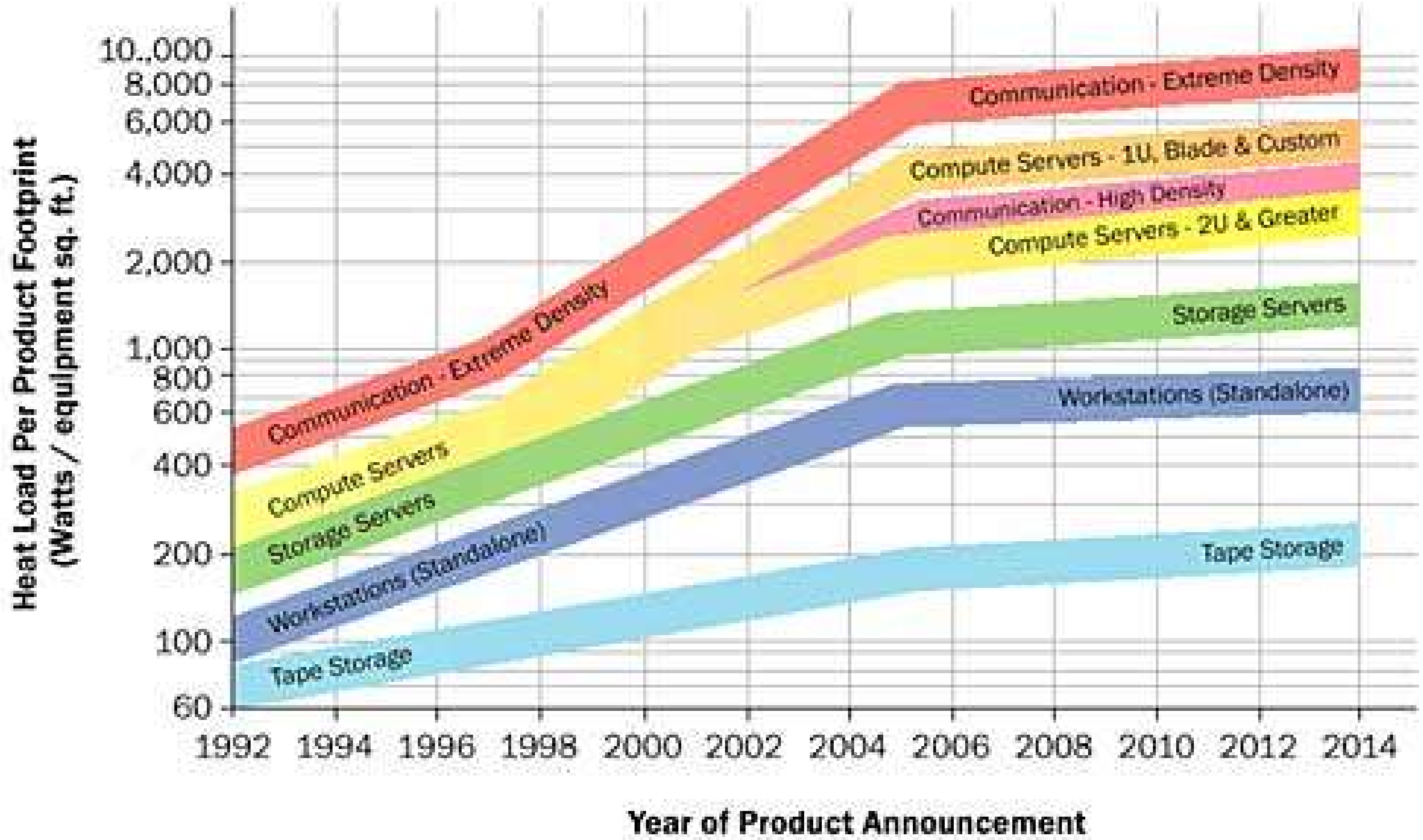
Introduction

- Cost performance chip power trend



Introduction

- Power density in datacom equipment



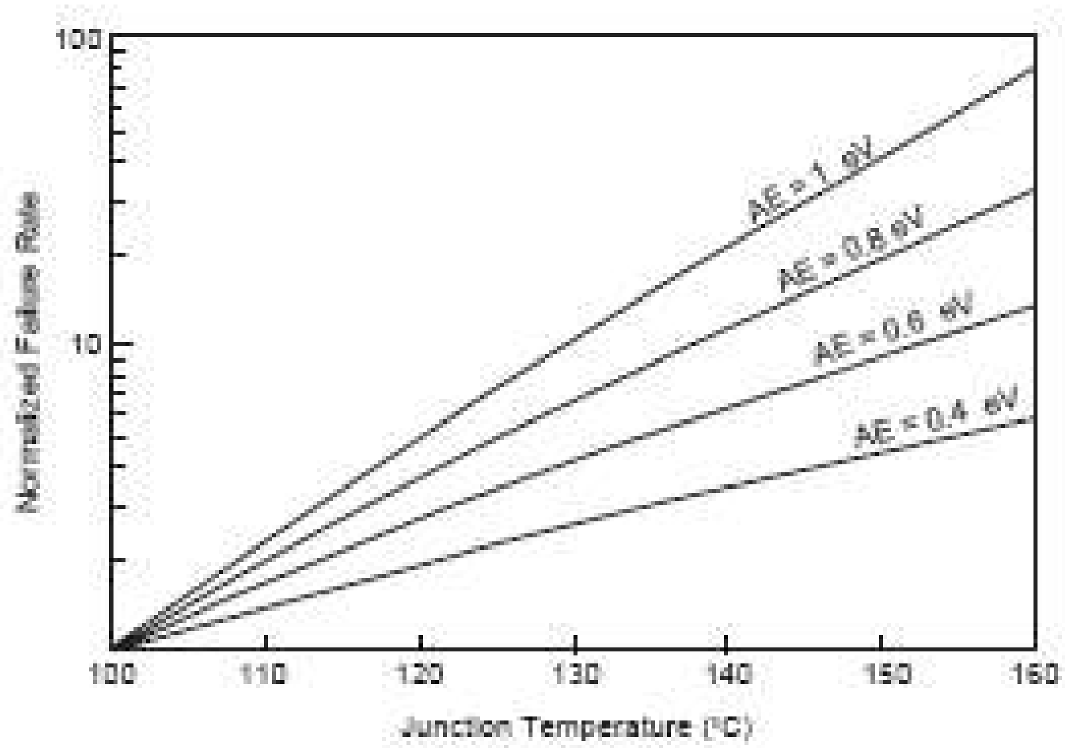
Introduction

- Power density in datacom equipment
  - Total power: 24KW
  - Footprint: 15 sq. ft
  - Power density: 1600W/sq. ft

Sun Fire E25K

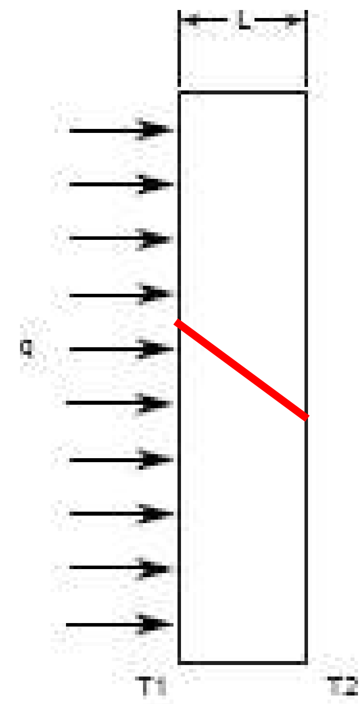
Introduction

- Impact of Device junction temperature
  - Computing performance
  - Reliability
  - Fire hazard and/or Safety issues



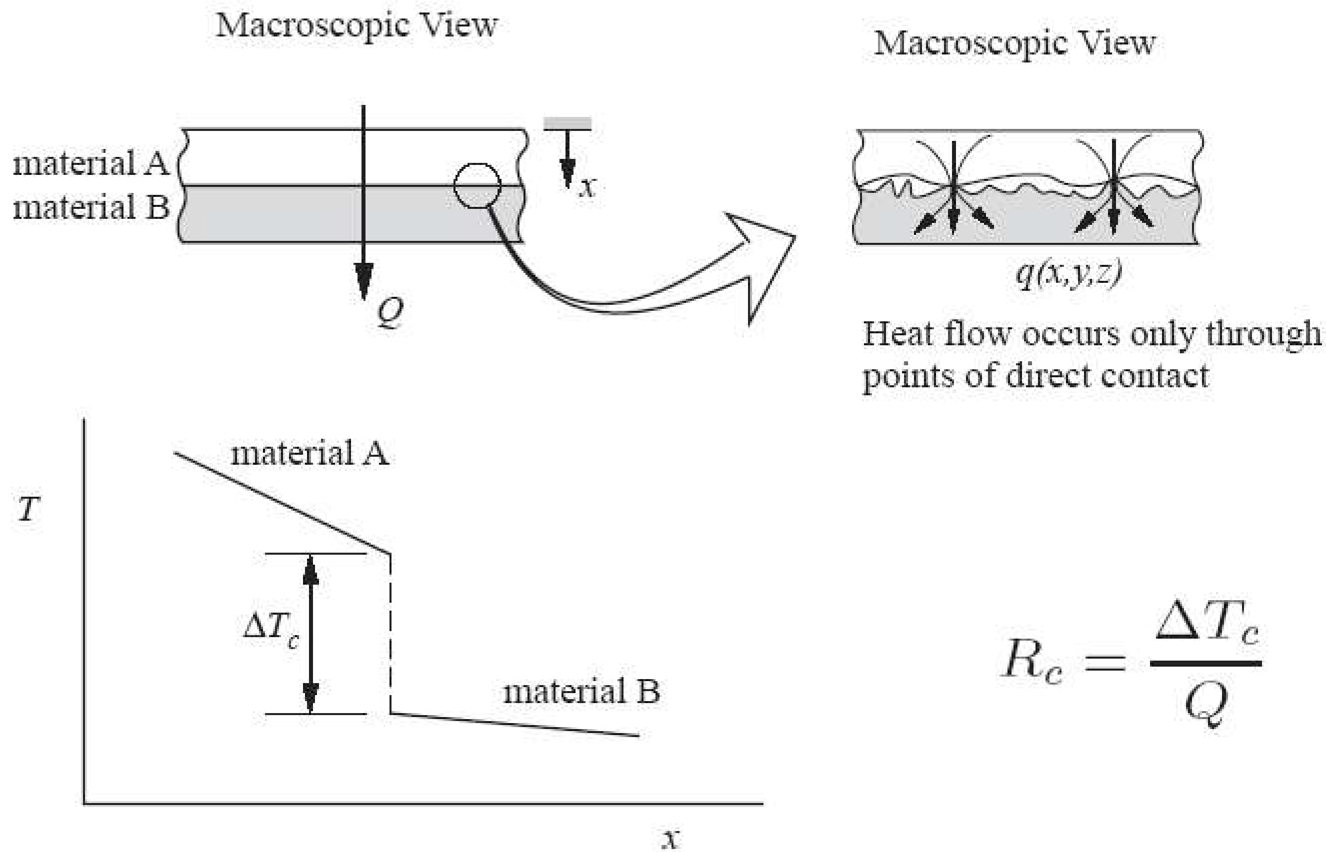
Heat Transfer Theory

- Conduction
  - Definition: Conduction is a mode of heat transfer in which heat flows from a region of higher temperaure to one of lower temperature within a medium (solid, liquid, or gases) or media in direct physical contact
  - Fourier's law: Q = -KA(dT/dX)
  - 1-D conduction: Q = -KA (T1-T2)/L
  - Thermal resistance: R = (T1-T2)/Q = L/(KA)



Heat Transfer Theory

- Conduction
  - Contact thermal resistance



$$R_c = \frac{\Delta T_c}{Q}$$

Heat Transfer Theory

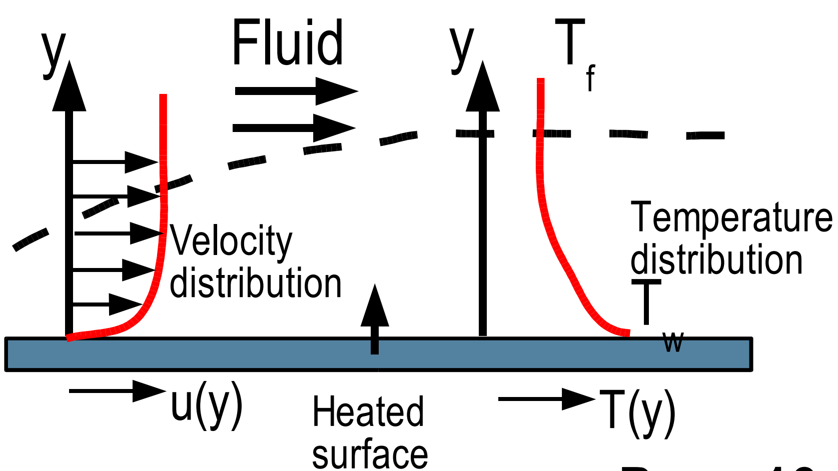
- Thermal conductivity of various packaging materials

Material	W/mK
Aluminum (pure)	216
Aluminum Nitride	230
Alumina	25
Copper	398
Diamond	2300
Epoxy (No fill)	0.2
Epoxy (High fill)	2.1
Epoxy glass	0.3
Gold	296
Lead	32.5
Silicon	144
Silicon Carbide	270
Silicon Grease	0.2
Solder	49.3

Heat Transfer Theory

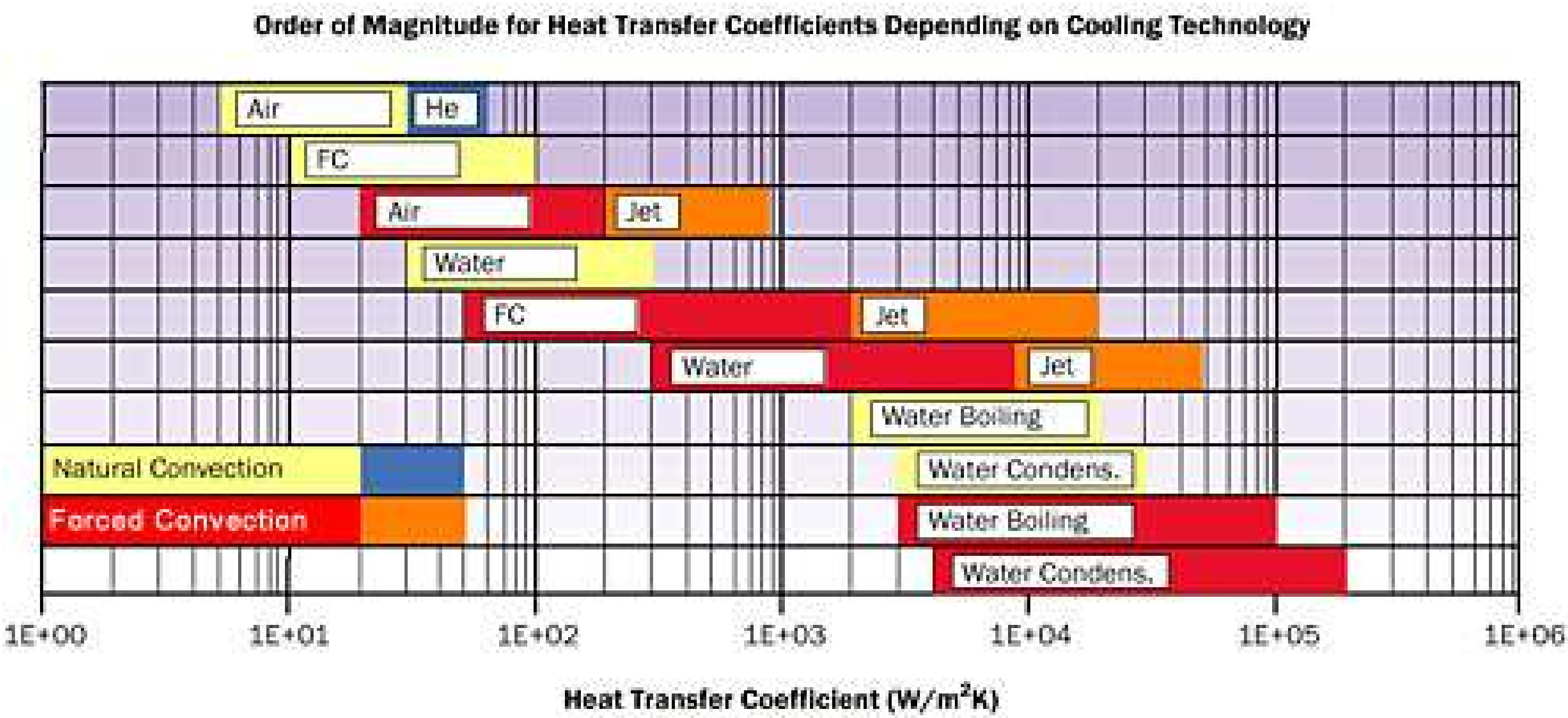
Convection

- Convection: is a mode of heat transport from a solid surface to a fluid and occurs due to the bulk motion of the fluid.
- Newton's law: Q= hA (Tw- Tf)
- Convective thermal resistance: R= 1/(hA)
- Effects of heat transfer coefficient
  - Convetion mode: Natural convection, Foreced convection, phase change
  - Flow regime: Laminar, Turbulent flow
  - Flow velocity
  - Surface condition
  - Fluid



Heat Transfer Theory

- Typical values of the heat transfer coefficient



Heat Transfer Theory

- Radiation
  - Definition: Radiation heat transfer occurs as a result of radiant energy emitted from a body by virtue of its temperature.

$$q = \epsilon \sigma A (T_1^4 - T_2^4) F_{12}$$

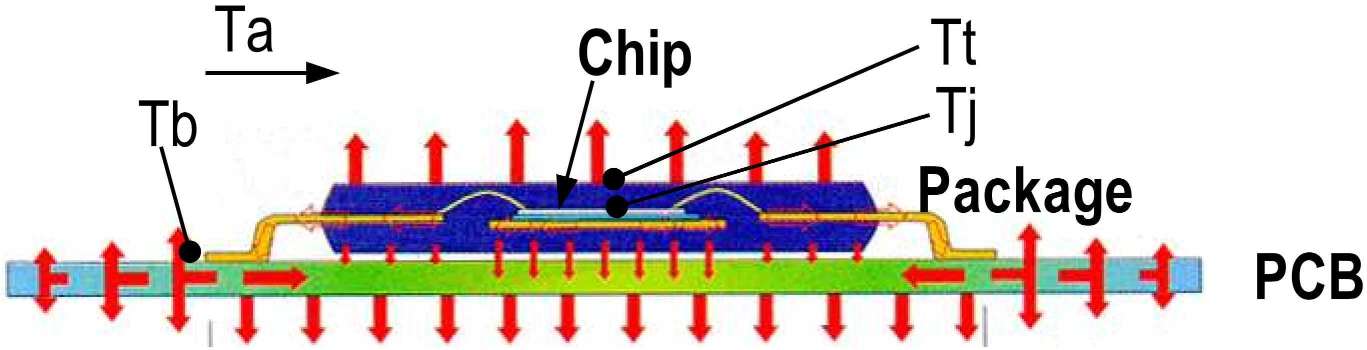
where:

q	=	Amount of heat transfer by radiation (W)
ϵ	=	Emissivity ($0 < \epsilon < 1$)
σ	=	Stefan-Boltzmann constant, 5.67 X 10-8 ($W/m^2 K^4$)
A	=	Area (m^2)
F_{12}	=	Shape factor between surfaces 1 and 2 (A fraction of surface 1 radiation seen by surface 2)
T_1, T_2	=	T_1, T_2 = Surface temperatures (K)

$$h_r = \epsilon \sigma F_{12} (T_1^2 - T_2^2)(T_1 + T_2)$$

Thermal Resistance

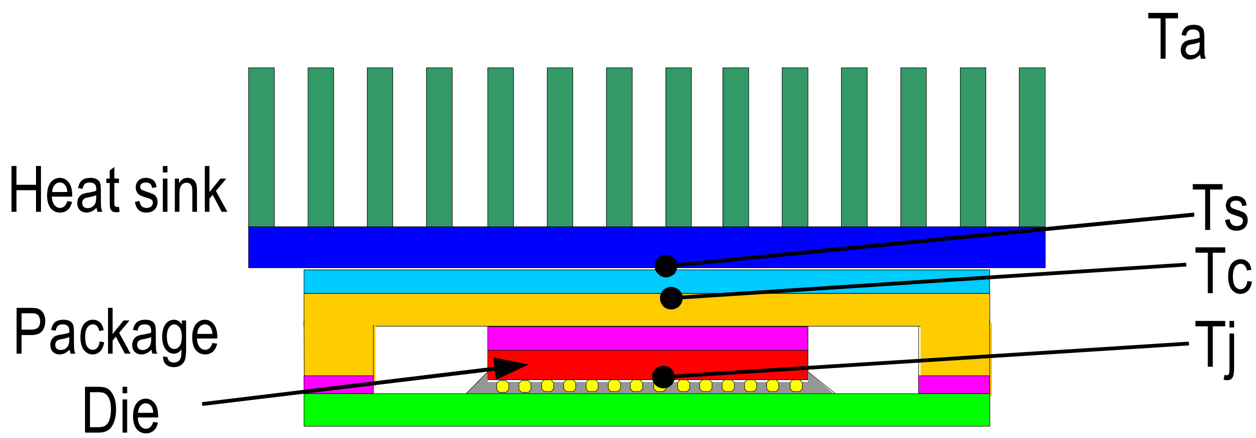
- Package without heat sink



- Rja: Junction to air thermal resistance
  - Rja= (Tj-Ta)/P
  - Low value is good thermal perfromance
- Rjc: Junction to case thermal resistance
  - Rjc = (Tj-Tc)/P
- Ψjt: Thermal characterization parameter: Junction to package top, NOT thermal resistance.
- Ψjb: Thermal characterization parameter: Junction to board

Thermal Resistance

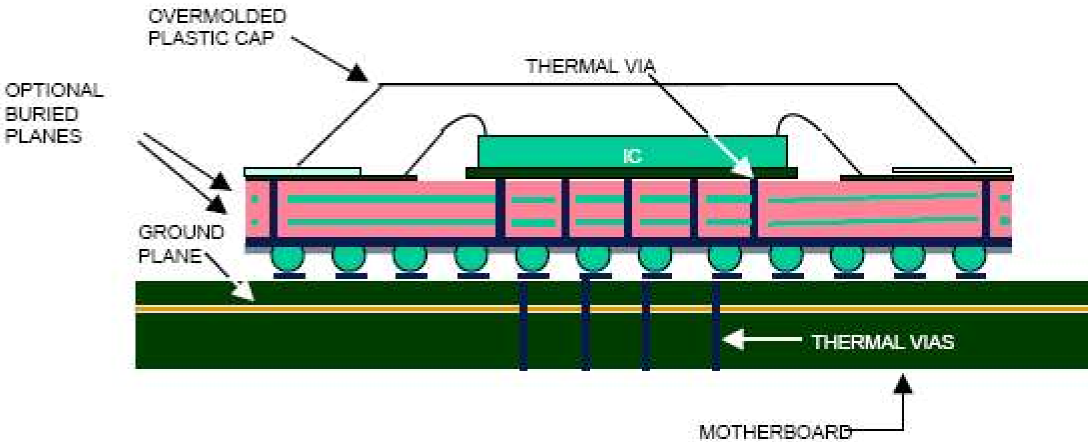
Package with heat sink

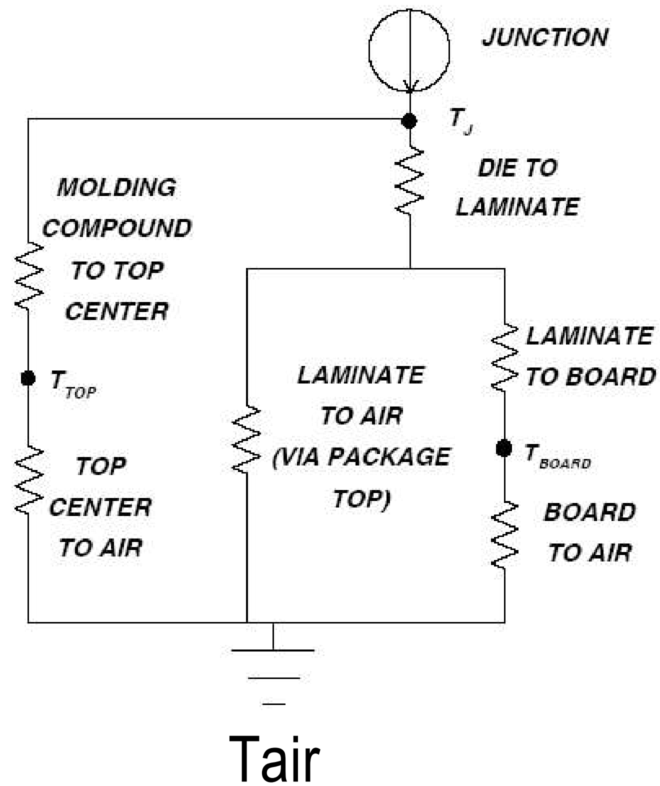


- Rja: Junction to air thermal resistance
  - Rja= (Tj-Ta)/P=Rjc +Rcs+Rsa
- Rjc: Junction to case thermal resistance
  - Rjc = (Tj-Tc)/P
- Rsa: External heat sink thermal resistance
  - Rsa= (Ts-Ta)/P

Thermal Resistance

- PBGA package example





Thermal Resistance

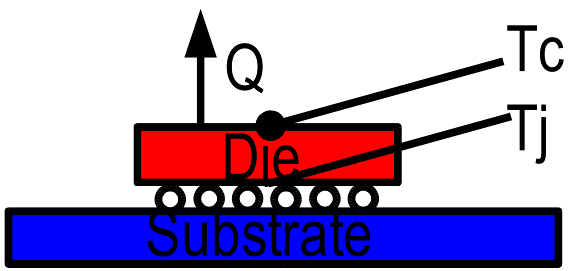
–Impact factors for package without heat sink

- Die size
- Package size, lead count
- Packaging material thermal conductivity
- Material thickness in major heat flow path
- Number of vias
- Heat spreader or heat slug
- Air velocity and temperature
- PC Board size
- Board configuration and material
- Board layout

Thermal Design

- Conduction application

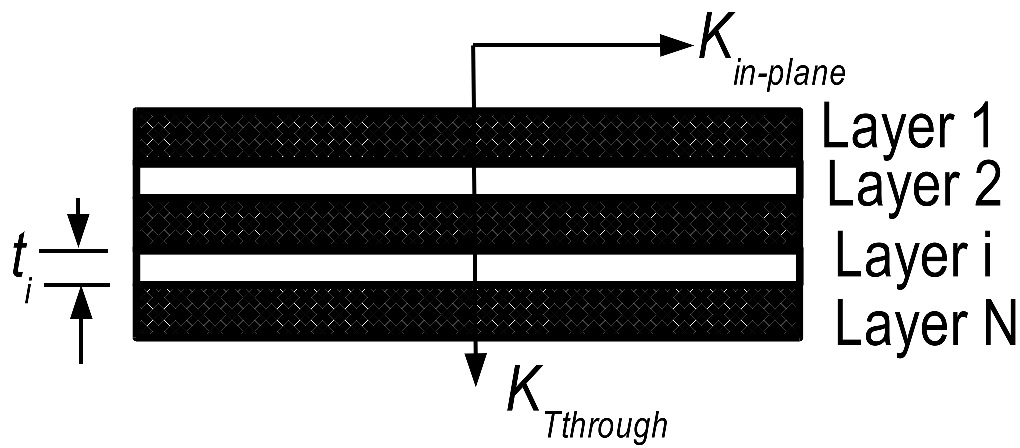
Single material



Tc = Tj - QL/(KA)

Uniform heating on the die

Composite material

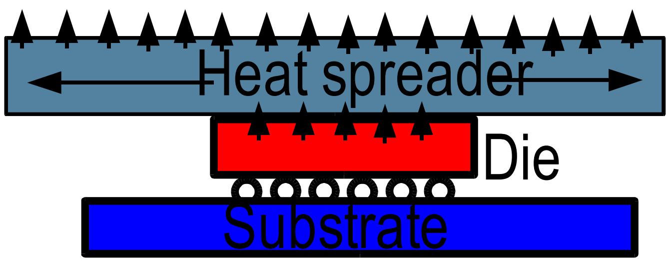


$$K_{\text{IN-PLANE}} = \sum_{i=1}^{N} K_i t_i \Big/ \sum_{i=1}^{N} t_i$$

$$K_{\text{THROUGH}} = \sum_{i=1}^{N} t_i \Big/ \sum_{i=1}^{N} t_i / K_i$$

Thermal Design

- Conduction application



$$R_{sb} = \frac{\sqrt{A_b} - \sqrt{A_s}}{k_b \sqrt{\pi A_b A_s}} \frac{\lambda k_b A_b R_{ba} + \tanh(\lambda H_b)}{1 + \lambda k_b A_b R_{ba} \tanh(\lambda H_b)}$$

$$\lambda = \frac{\pi^{2/3}}{\sqrt{A_b}} + \frac{1}{\sqrt{A_s}}$$

A_b: Heat spreader base area

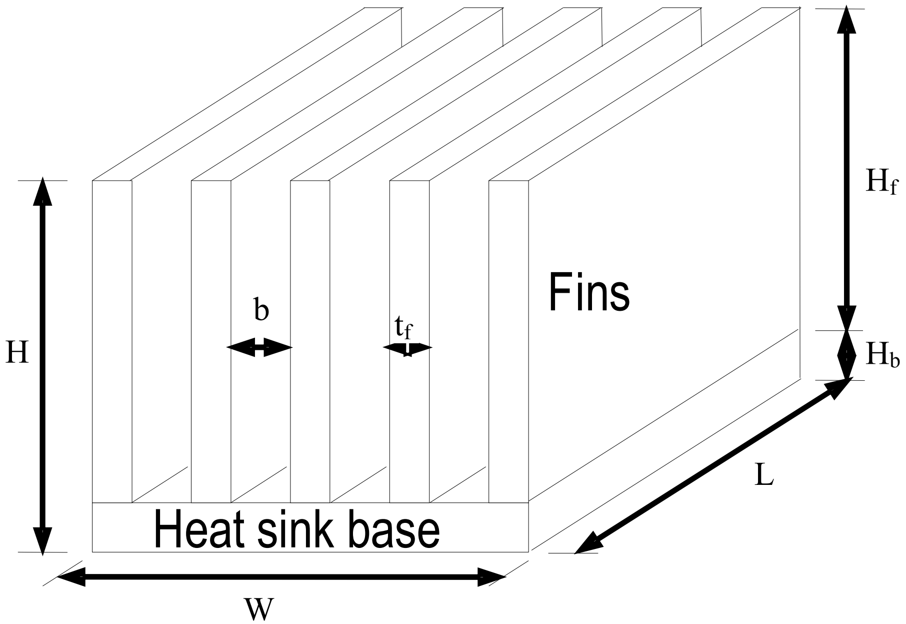
A_s: Heat source area

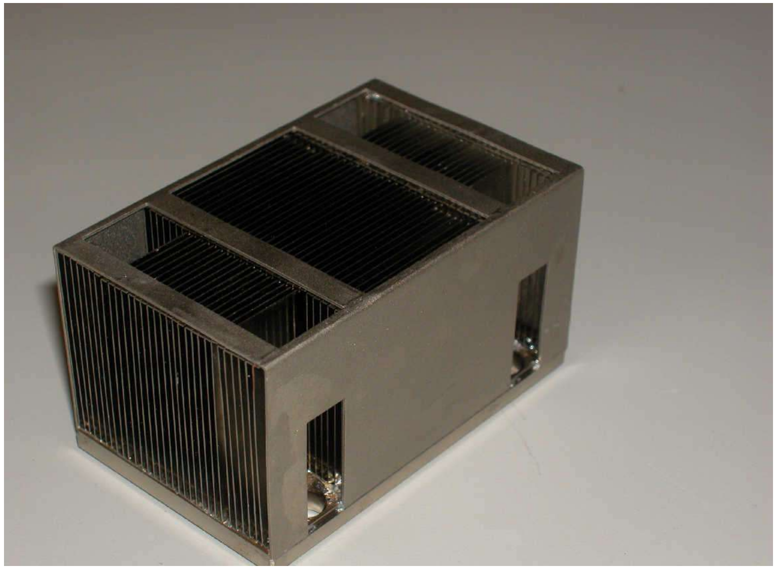
H_b: Heat spreader thickness

K_b: Heat spreader thermal conductivity

Thermal Design

- Convection application-Heat sink design





Thermal Design

- Convection application-Heat sink design
  - Thermal resistance: $$R_{ba} = \frac{T_b - T_{inlet}}{Q} = \frac{1}{\dot{m} c_p (1 - e^{-hA_t \eta_o / \dot{m} c_p})}$$
  - Heat transfer: $$Nu = \frac{hD_h}{k_{air}} = 7.54$$ Laminar flow

    $$Nu = \frac{hD_h}{k_{air}} = 0.024 \,\mathrm{Re}^{0.786} \,\mathrm{Pr}^{0.45}$$ Turbulent flow
  - Fin efficiency: $$\eta_o = 1 - \frac{A_f}{A_t}\left(1 - \eta_f\right) \qquad \eta_f = \frac{\tanh(mH_f)}{mH_f}$$

Thermal Design

Convection application-Heat sink design

- Total static pressure loss:

$$\Delta P = \left(K_c + 4 f_{app} \frac{L}{D_h} + K_e \right) \rho \frac{U_{ch}^{\ 2}}{2}$$

	Culham and Muzychka (2001)	David Copeland (2000)
Apparent friction factor f_{app} calculation	$f_{app}\,\mathrm{Re} = \left\{ \left[3.44 \left(L^* \right)^{-0.5} \right]^2 + \left(f\,\mathrm{Re} \right)^2 \right\}^{1/2}$	$f_{app}\,\mathrm{Re} = \left\{ \left[3.2 \left(L^* \right)^{-0.57} \right]^2 + \left(f\,\mathrm{Re} \right)^2 \right\}^{1/2}$
Fully developed flow friction factor f	$f\,\mathrm{Re} = 24 - 32.527 (b/H_f) + 46.721 (b/H_f)^2 - 40.829 (b/H_f)^3 + 22.954 (b/H_f)^4 - 6.089 (b/H_f)^5$	$f\,\mathrm{Re} = 4.7 + 19.64 \frac{(b/H_f)^2 + 1}{(b/H_f + 1)^2}$
Contraction loss coefficient K_c	$K_c = 0.42 (1 - \sigma)$	$K_c = 0.8 - 0.4 \sigma^2$
Expansion loss coefficient K_e	$K_e = (1 - \sigma)^2$	$K_e = (1 - \sigma)^2 - 0.4 \sigma$

$$L^* = \frac{L}{D_h \mathrm{Re}}$$

$$\sigma = 1 - \frac{N t_f}{W} \approx \frac{b}{t_f + b}$$

Thermal Design

- Convection application- Heat sink design Impact factors
  - Air flow rate
  - Available space
  - Heat sink base and fin material
  - Fin pitch and fin thickness
  - Heat flux
  - Heat sink technologies

Thermal Design

- Design methodology
  - Define requirements
  - Analyze given package design
  - Identify major heat paths and paths for improvements
  - Consider and assess potential improvements
  - Detail analysis/modeling
  - Build prototypes
  - Thermal testing

Modeling

- Finite Element Method (FEM)
  - Software: ANSYS
  - Solve conduction problem within package or board
  - Require input data: material propoerties, package/board construction/geometry
  - Boundary conditions:
    - Heat source distribution on the die or board
    - Effective convective heat transfer coefficient on the surface of the package or board

Modeling

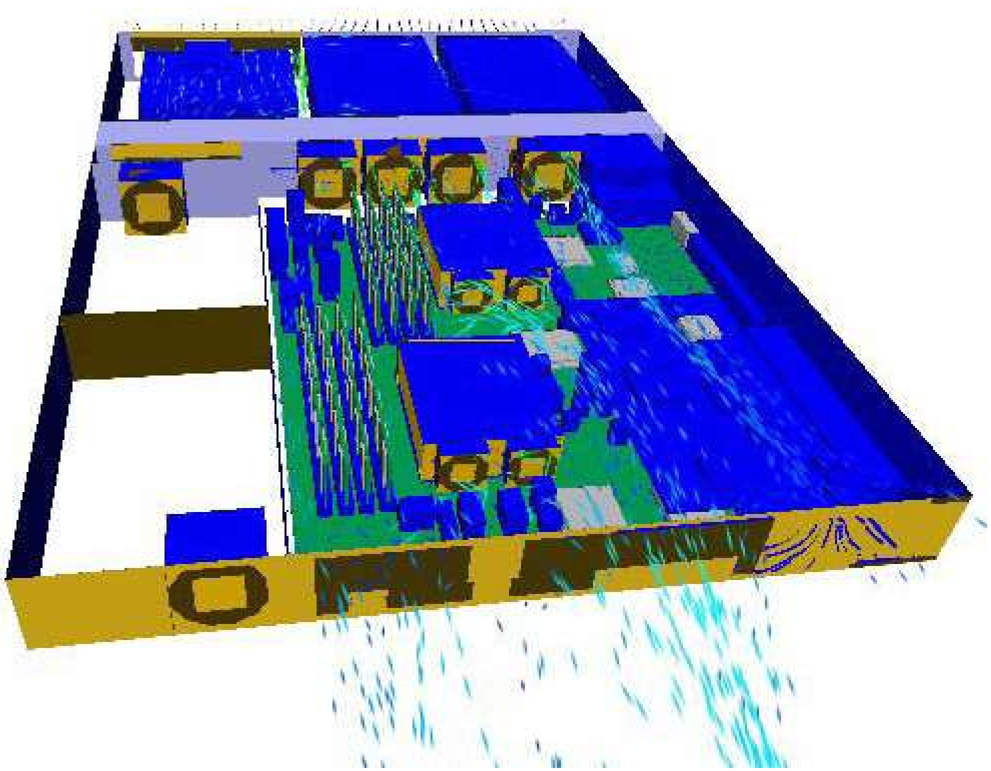
- Finite Element Method
  - Procedure:
    - Create package/board geometry or import from CAD file
    - Mesh
    - Input material properties and assign boundary conditions
    - Solve
    - Post-process

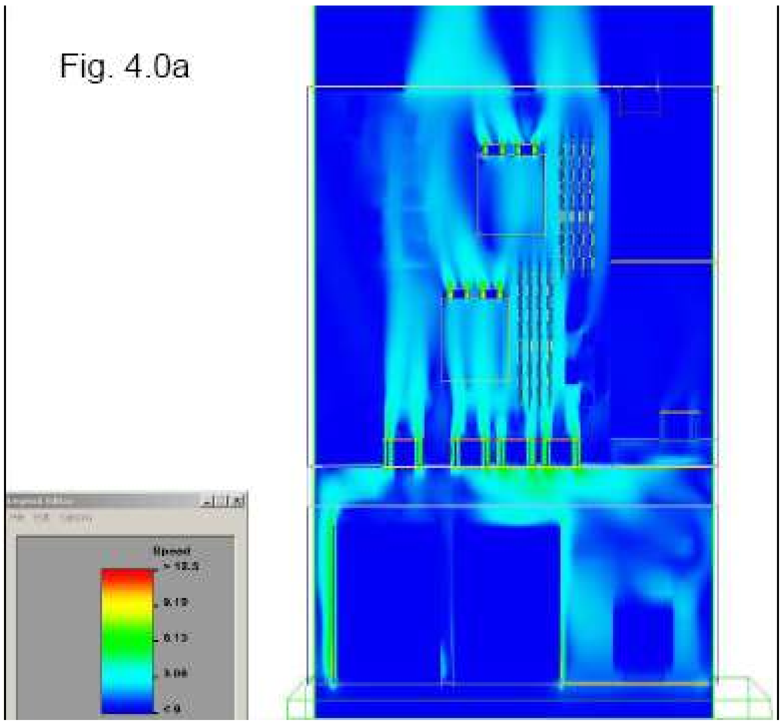
Modeling

- Finite Difference Method (FDM)
  - Computational Fluid Dynamics (CFD)
  - Commercial software: Flotherm, Fluent
  - Solve the temperature field and flow field
  - Not only solve the conduction, also on convection, radiation and phase change
  - Required input: Geometry, flow conditions, material properties including fluid
  - Mesh dependent on the chosed model

Modeling

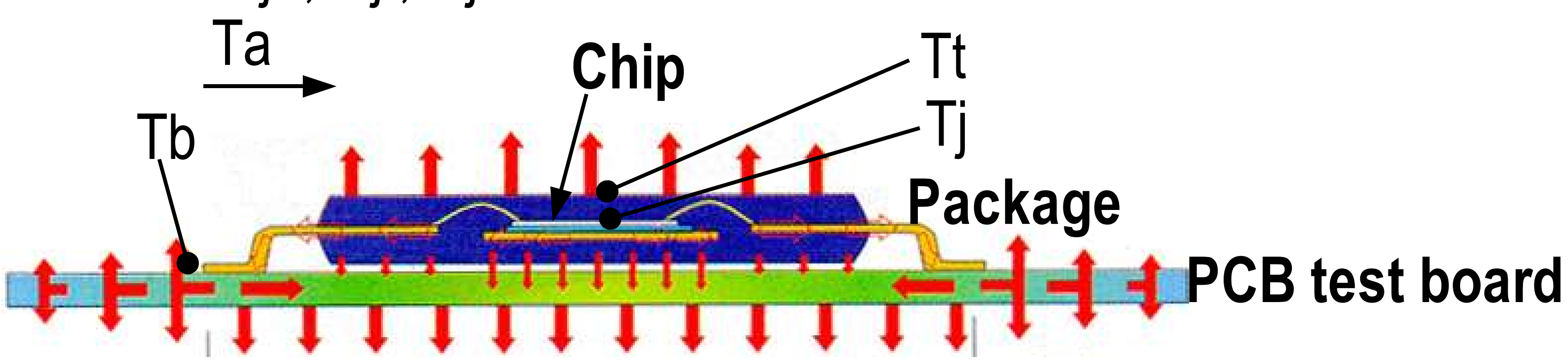
- Finite Difference Method (FDM) Example





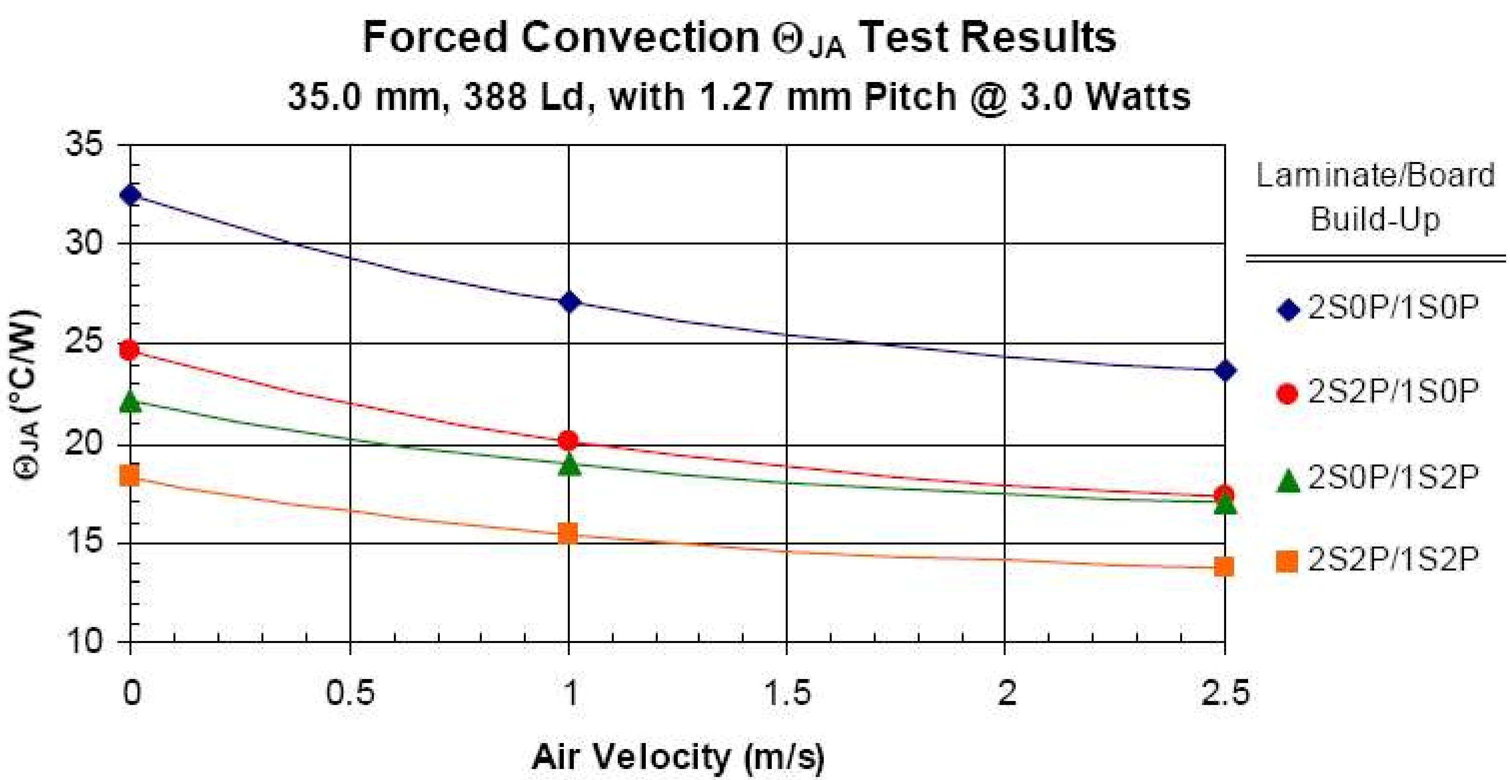
Measurement

- Packaging thermal parameters
  - Mount package on a standard test board
  - Mount thermocouple on top of the package center
  - Mount thermacouple on board at the edge of package
  - Put package in a standard test environment
    - Wind tunnel to vary the air speed
  - Apply known amount of power
  - Measure temperature of Tj, Ta, Tb, Tt
  - Calculate Rja, Ψjt, Ψjb



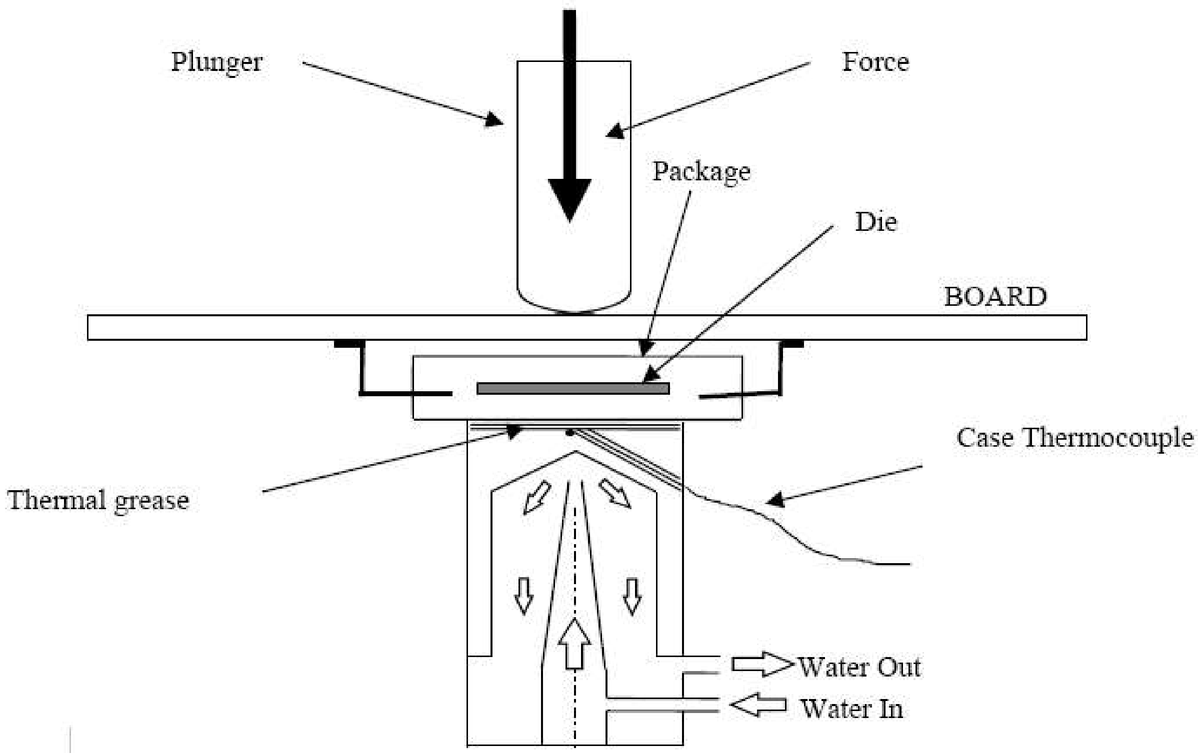
Measurement

- Packaging thermal parameters



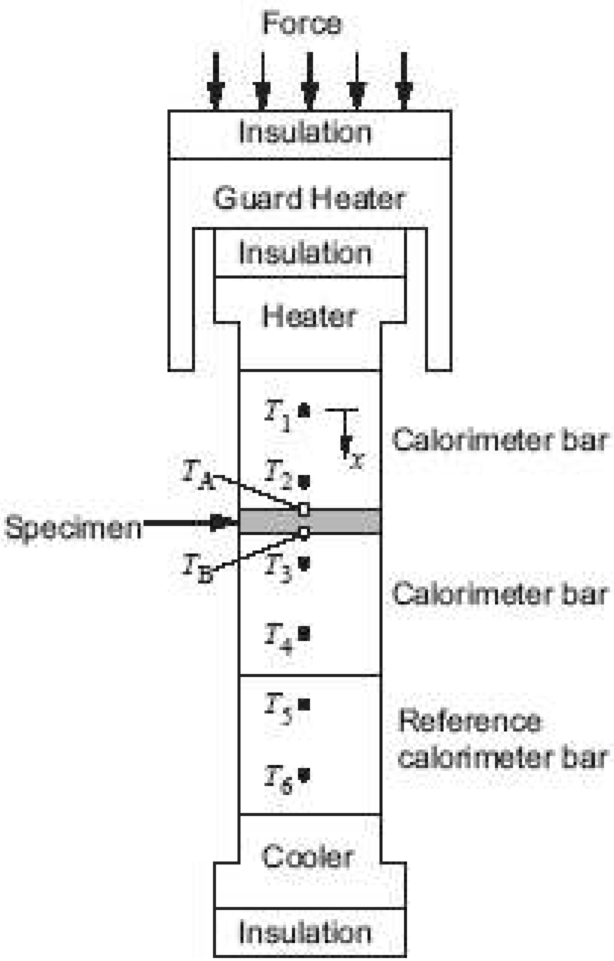
Measurement

- Packaging thermal resistance Rjc
  - All heat is removed from top of the package



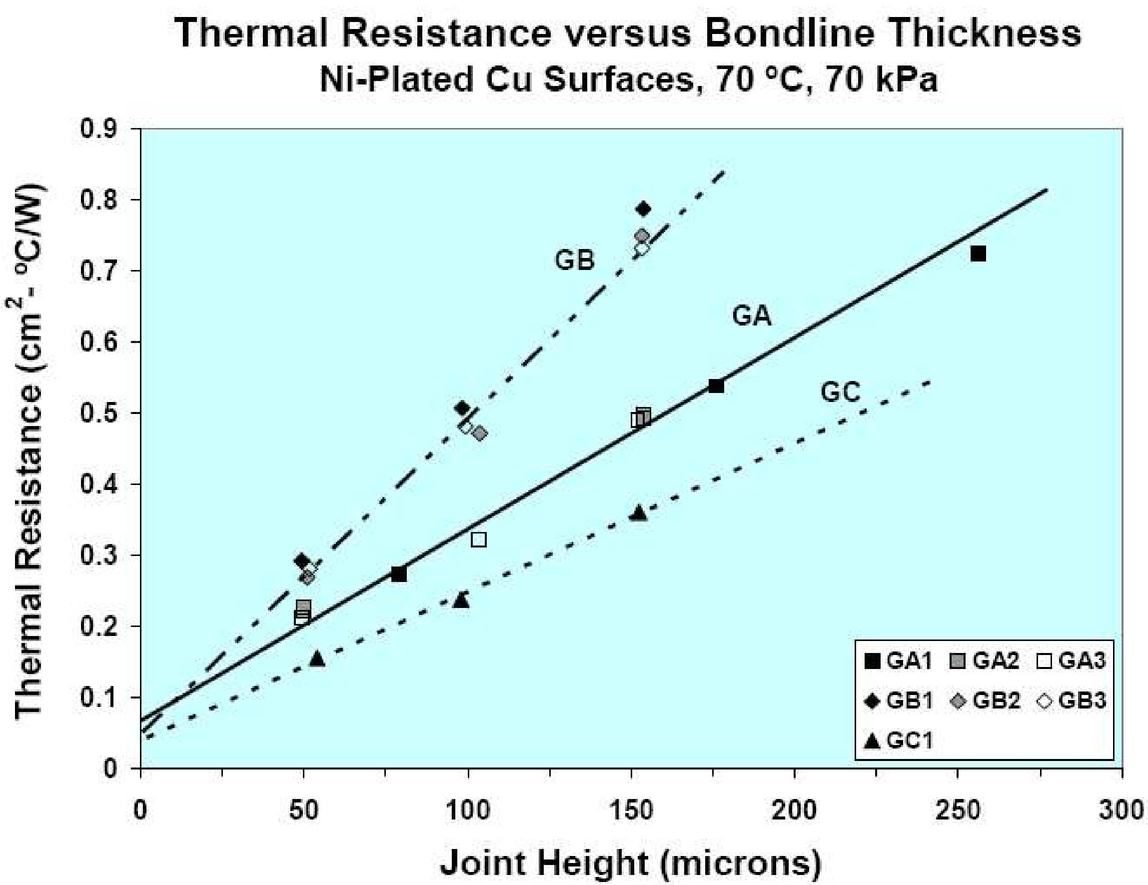
Measurement

- Thermal interface material resistance Rcs



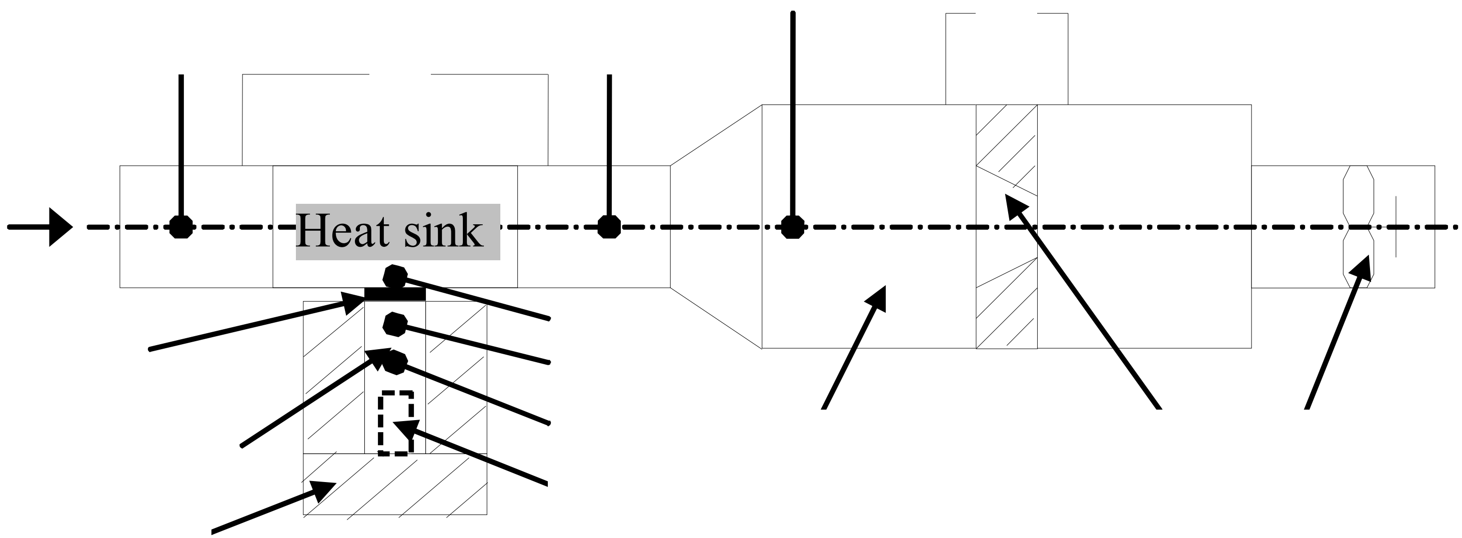
Measurement

- Thermal interface material resistance Rcs



Measurement

- Heat sink thermal resistance Rsa

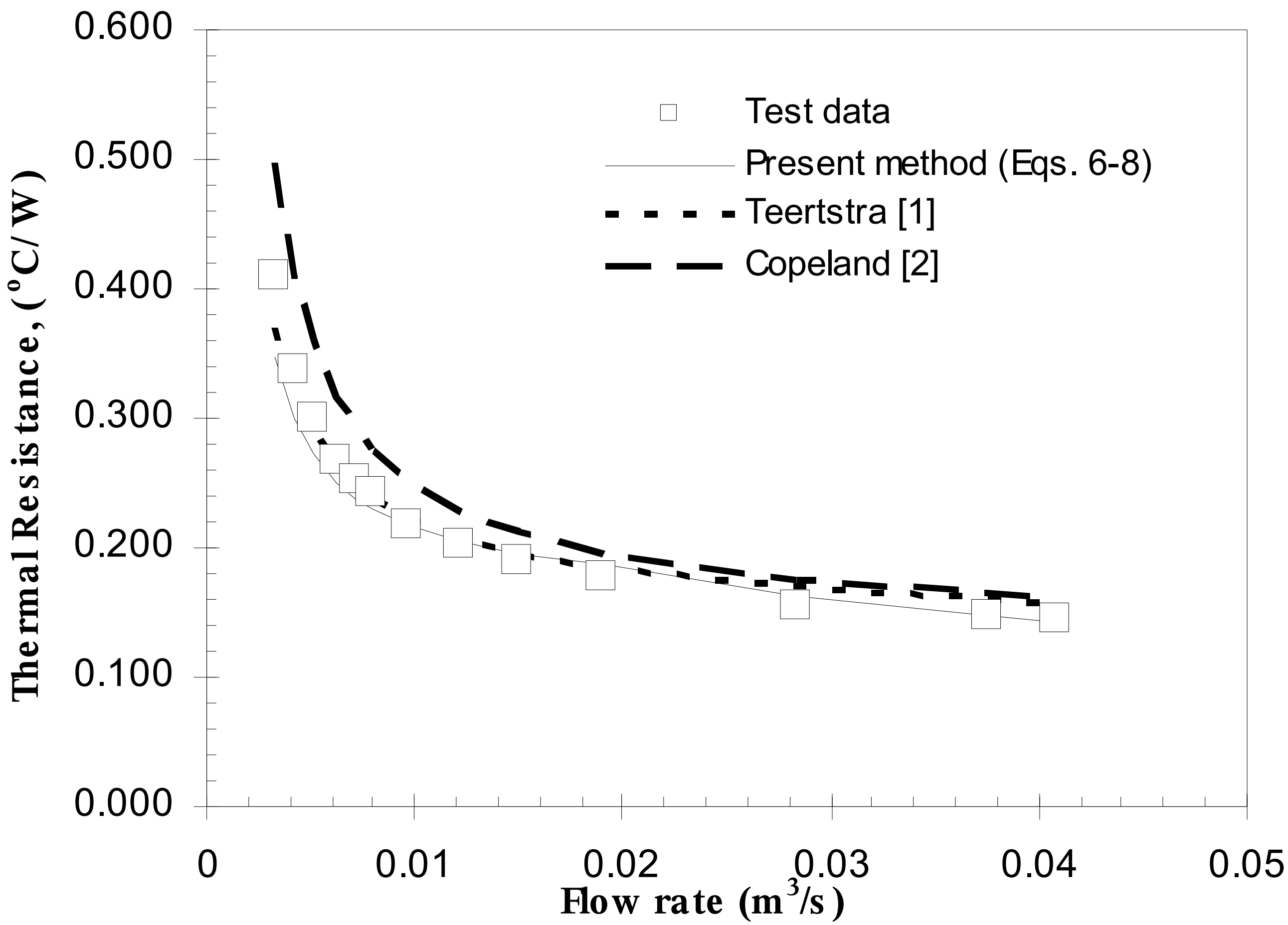


$$R_{sa} = \frac{T_s - T_{inlet}}{Q} \qquad Q = k_s A_s \frac{T_3 - T_2}{\Delta L}$$

Heat source size: 25 mm x 25 mm

Measurement

- Heat sink thermal resistance Rsa



Q & A

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