Extending the Limits of Air Cooling for Microelectronic Systems

CMAP Year 1 Project Review

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Presentation Outline

- Review of project goals and deliverables
- Progress reports:
  - Optimization models for air cooled heat sinks
  - Impact of surface conditions on thermal joint resistance with TIMs
- Plan for project completion
Motivation

• Current trend in industry of applying air cooling as long as possible – rapidly approaching the limits of air cooling

• 2005 power dissipation projections:
  • 100 $W$ for office systems
  • 250 $W$ for large systems

• Alternatives to air cooling:
  • Liquid cooling
  • Refrigeration
  • Thermoelectric coolers
  • Significant cost, time required to implement

Air Cooling Limits

- Air cooling limit = when fan-driven convection is insufficient to maintain temperature levels necessary for reliable operation
- Previous air cooling limits often based on system-wide air temperature rise, i.e. Telcordia specs
- Air cooling limit for particular component / location / application function of:
  - Available space and airflow
  - Heat sink geometry and materials
  - Quality of thermal contact between heat sink and package
Project Descriptions

- Extend knowledge base for air cooling limits through two part research study
- Predict air cooling limits
  - Develop and validate tools to predict air cooling limits for specific component / location / application
- Extend air cooling limits
  - Optimize surface roughness of contacting surfaces with thermal interface materials (TIMs) to minimize thermal contact resistance
Optimization Models for Air Cooled Heat Sinks in Variable By-pass Conditions
Objective

- Use entropy generation minimization (EGM) technique to develop analysis tools for predicting air cooling limits as a function of:
  - Conduction heat transfer
    - Spreading resistance
    - Thermal joint resistance
  - Forced convection heat transfer
    - Plate fin, folded fin, pin fin heat sinks
  - Hydrodynamic behaviour
    - Pressure drop, side and top by-pass
Model Development

- EGM model developed based on available sub-models:
  - Spreading resistance
  - Thermal joint resistance
    - TIMs (Savija, 2002; Smith, 2004; Banik, 2005)
  - Forced convection heat transfer for shrouded heat sinks
    - Plate fins (Teertstra et al, 2000)
    - Pin fins (Khan, 2004)
  - Flow bypass models
    - Plate fins, top by-pass only (Leonard, 2002)

- No analytical models available to predict top and side by-pass for plate fin, pin fin heat sinks
Methodology

- Analytical modelling of by-pass is complex problem
  - Behaves as both flow between parallel plates (internal) and flow over a plate (external)
  - Many independent variables required to describe geometry
- Preliminary experimental measurements
  - Aid in understanding the physics of the problem
  - Identify key parameters, simplifying assumptions, physical relationships
  - Leads to development of more effective analytical model
  - Validation
- Experimental measurements performed in two parts:
  - By-pass measurements - pressure drop and local velocity for heat sinks with variable top and side bypass.
  - Thermal measurements – validation data for EGM model
By-pass Measurements

- 150 cfm airflow test chamber
- Test section with movable top and side walls
- Pitot tubes, differential pressure transducer for velocity measurement
- Labview / Keithley DAQ system for data management
By-pass Measurements

- Heat sink geometry
  - Width (B): 4”
  - Length (L): 4”
  - Height (H): 2”
  - Fin spacing (s): 1/8”
  - Fin thickness (t): 1/8”
  - No of fin (n): 16

- Duct Bypass
  - Side bypass (CB): 4” (2+2”)
  - Top bypass (CH): 2”
  - Ratio of Bypass CB:B=1; CH:H=1
Flow Network Model

- Static pressure measured for $4000 < \text{Re}_{Dh} < 30000$.
- Total flow rate $Q$ from integration of pitot tube measurements.
- Flowrate through heat sink
  \[ Q_{\text{heatsink}} = Q_{\text{total}} - (Q_1 + Q_2 + Q_4 + Q_5 + Q_6) \]
  where $Q_{\text{total}}$ from orifice plate.

\[ \Delta P_1 \quad \Delta P_2 \quad \Delta P_4 \quad \Delta P_5 \quad \Delta P_6 \]

\[ Q_1 \quad Q_2 \quad Q_4 \quad Q_5 \quad Q_6 \]

\[ \Delta P_{\text{heatsink}} \]

\[ \Delta P_{\text{heatsink}} \]

Honeycomb → Honeycomb → Orifice → Fan
Drag Coefficient ($C_d$)

\[ C_d = \frac{\Delta P}{(1/2 \rho V_{app}^2)} \]
Velocity Coefficient \((C_v)\)
Future Work

- **Experimental**
  - By-pass measurements
    - Bypass: CB/B = .75, .5, 0  CH/H = .75, .5, 0
    - Heat sink geometry: s = 1/16”- 1/8”; t = 1/16”
  - Heat transfer measurements
    - Wind tunnel testing of forced convection for different heat sink geometries with variety of bypass conditions
    - Validation data for analytical models

- **Analytical modelling**
  - By-pass modelling for heat sinks
  - Incorporate by-pass, spreading and contact resistance models into EGM analysis
Study of Contact Resistance for Flycut Aluminum 2024 Surfaces
Objectives

- Experimental study of thermal contact resistance for face-milled (flycut) aluminum 2024 joints
  - Microscopic study of surface parameters
    - Surface roughness
    - Mean asperity slope
    - Asperity height distribution
    - Micro hardness
  - Experimental measurements of thermal contact resistance for a wide range of loads
- Comparison with existing conforming rough surface contact models
Motivation

- Typical contact between heat sink and component with TIM compound
  - TIM fills voids, air gaps
  - Bondline thickness (BLT) supports load, prevents direct surface contact
- Maximize contact conductance by minimizing BLT, leading to direct surface contact
- Analytical models of contact resistance problem for conforming rough surfaces with TIM compounds
Motivation

• Experimental measurements for conforming rough surfaces with TIM compounds:
  • Total joint resistance $R_j$
  • In-situ BLT thickness
• If surfaces are in contact the bulk resistance of the TIM determined by reducing contact resistance from total joint resistance

$$\frac{1}{R_b} = \frac{1}{R_j} - \frac{1}{R_c}$$

$$R_b = \frac{BLT}{k_{TIM} A_a}$$

• Need to determine $R_c$ experimentally, analytically
Surface Analysis: SEM

Feed rate 12mm/min, Magnification 20X
Feed rate 75mm/min, Magnification 20X

Feed rate 12mm/min, Magnification 50X
Feed rate 75mm/min, Magnification 50X
Asperity Heights Distribution

- Gaussian distribution of asperity heights is a common assumption made in contact resistance models
- As feed rate increases, surface roughness increases and height distribution no longer Gaussian
Vicker’s Microhardness Testing

Vickers Micro-Hardness of Al2024 Ground and Polished Surface

\[ H_v = 1.5269d_v^{0.0074} \]

Indentation Diagonal, \( d_v (\text{mm}) \)

Vickers Micro-Hardness, \( H_v (\text{GPa}) \)
TIM Test Apparatus
TIM Test Apparatus Schematic

- Linear Electric Actuator to apply load
- Load Cell
- Spring
- Heat Out
- Measure \( \Delta T / \Delta x \) with RTDs
- Heat In
- Vacuum Bell Jar
- Keithly 2700 D.A. system
- Position Sensing Detectors
- 635 nm Diode Lasers
- Keithly 2700 D.A. system
- TIM Test Apparatus Schematic
Contact Resistance Test Results

![Graph showing contact resistance test results.](image)

- Flycut 1, $\sigma/m = 14.00$
- Flycut 2, $\sigma/m = 14.66$
- Flycut 3, $\sigma/m = 15.69$
- Flycut 4, $\sigma/m = 18.59$
- Flycut 5, $\sigma/m = 20.67$

**Best Fit (Power)**
Comparison with Existing Model

- Modified CMY model: (Cooper, Mikic, Yovanovich, 1969)

\[ h_c = 1.25 \frac{m}{\sigma} k_s \left( \frac{P}{Hc} \right)^{0.95} \]

- 22% RMS difference
Future Work

- Laser-scan micrometer to measure BLT
- Thermal joint resistance, bulk resistance and thermal conductivity measurements for variety of TIM compounds
- Analysis of optimum surface roughness as function of BLT, TIM properties, load, etc.