ELECTRONIC COMPONENT
STEADY/UNSTEADY AIR COOLING

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MOTIVATION

Microprocessor chip power and heat flux trends Anandan & Ramalingam (2008)

STATE OF THE ART COOLING TECHNIQUES

- ~10 W
  - Passive Air
    - Cheap, quiet
    - Low heat loads
  
- ~100 W
  - Forced Air
    - Inexpensive, noisy
    - Mid heat loads
  
- ~200 W
  - Coolant (water)
    - Expensive, complex
    - High heat loads

- ~300 W
  - Refrigeration
    - Expensive, complex
    - High heat loads
• Research objectives
• Control system
• Cooling system physical conditions
• Thermal & power performance (COP)
• Experimental cooling system
• Fan operation schemes: thermal & power performance
• PIV optical measurement system & results
• Conclusions
RESEARCH OBJECTIVES

• Using **controllable and measurable forced air cooling system** for heat generating element - the “thermal system” – to **optimize power performance**, in terms of *COP* parameter, for the following possible fan operation conditions:
  
  – **Steady** fan speed operation
  – **Combined** fan/natural convection (constant thermal performance)
  – **Sinusoidal** fan operation

• **Understand** channel flow behavior using PIV technique

• **Control** of thermal system, via manipulation of fan speed constantly maximizing *COP*, while operating within the thermal system θ specified limit.
CONTROL SYSTEM

Control objective: optimize $COP$

Specifyed constrain: $\theta_{SP}$

Manipulated parameter: $V_{fan}$

Disturbance: $Q$

**OPEN LOOP**

$$V_{fan} \rightarrow G1 \cdot \frac{1}{\alpha s + 1} \rightarrow - \bar{\theta}$$

$$\dot{Q} \rightarrow G2 \cdot \frac{1}{\alpha s + 1}$$

**FEEDBACK CONTROL**

**FEEFORWARD CONTROL**
HEAT SINK FLOW ORIENTATIONS

PARALLEL PLATE HEAT SINK

Impingement flow

Parallel/duct flow

Duan (2003)

- Impingement flow: very widespread use in microprocessor cooling, more effective than parallel flow; used in this research

FLOW DIRECTIONS

Fan – Forced Convection

No Fan – Natural Convection
PHYSICAL CONDITIONS & ANALYSIS

- **Thermal resistance circuit:**
  \[ \Delta T = R_{th} \cdot Q \]

- **Heat sink thermal resistance circuit:**

- **Lumped system condition (verified experimentally):**
  \[ Bi = \frac{h_x}{k} = \frac{h(V / A)}{k} < 0.1 \]

- **Lumped system thermal resistance:**
  \[ R_{th} \approx R_{conv} = \frac{1}{hA} = \frac{\Delta T}{Q} \]
  \[ \Delta T = T_{component} - T_{air} \]

\[ h = h(G_{air}, \text{ flow attributes}, \Delta T \text{ for NC}) \]
High power performance $\Leftrightarrow$ High heat transfer rate @ Low $HP_{fan}$

\[
\left( \frac{HP_{fan}}{HP_{fan}} \right)_1^{\frac{3}{2}} = \left( \frac{RPM_{fan}}{RPM_{fan}} \right)_2 \left( \frac{G_{air}}{G_{air}} \right)_1 = \left( \frac{V_{fan}}{V_{fan}} \right)_1 = \left( \frac{U_{air}}{U_{air}} \right)_1 = 2 \left( \frac{\Delta P_{fan}}{\Delta P_{fan}} \right)_2
\]

Fan laws:

Fan power coefficient of performance: $Q_{SP} = R_{th} \cdot \theta_{SP}$
System operation:
- Heat flow $Q_{exp}$ is set at heat element power supply
- Fan voltage/speed is set at programmable fan power supply
- Thermocouple and fan power data are acquired at steady or dynamic conditions

Calculations:

$$R_{th} = \frac{\Delta T_{exp}}{Q_{exp}}$$

$$h = \frac{1}{R_{th} \cdot A} = \frac{Q_{exp}}{\Delta T_{exp} \cdot A}$$

$$HP_{fan} = V_{fan} \cdot I_{fan}$$

$$Q_{SP} = hA\theta_{SP}$$

$$COP = \frac{Q_{SP}}{HP_{fan}}$$
STEADY FAN OPERATION

\[
COP = \frac{Q_{SP}}{H_P_{fan}} \quad Q_{SP} = h A \theta_{SP} \quad R_{th} = \frac{\Delta T_{exp}}{Q_{exp}} \quad h = \frac{1}{R_{th} \cdot A} = \frac{Q_{exp}}{\Delta T_{exp} \cdot A}
\]

\[HP_{fan} = V_{fan} \cdot I_{fan}\]

\[
\sqrt[3]{\left(\frac{HP_{fan}}{RPM_{fan}}\right)_2} = \frac{\left(\frac{HP_{fan}}{RPM_{fan}}\right)_2}{\left(\frac{G_{air}}{V_{fan}}\right)_2} = \frac{\left(\frac{G_{air}}{V_{fan}}\right)_2}{\left(\frac{\Delta P_{fan}}{V_{fan}}\right)_2} = \frac{\left(\frac{\Delta P_{fan}}{V_{fan}}\right)_2}{\left(\Delta P_{fan}\right)_2}
\]

\[\theta_{SP} = 41.6K\]
Fan is **OFF** for part of cycle → **combined forced/natural convection**

- System time constant is large, theoretically allowing small temperature change within cycle
- Time average heat transfer coefficient ($h_{av}$) determined by forced/natural convection coefficients and fan operation time fraction ($x$)
- **COP** is compared between different $V_{fan}$ at common $h_{av}$

$$h_{av} = xh_{fc} + (1 - x)h_{NC}$$

$$Q = h_{av}A\theta_{sp}$$

$$h_{NC} = 3.9W/m^2K, \text{ @ 41.6K}$$

![Graph](image-url)
FAN SINUSOIDAL CYCLE RESULTS

• Comparison between steady and fan operation, regarding heat transfer coefficient \( (h) \) and \( COP \)
• Axial fan limits maximum frequency to ~2Hz @ tested amplitudes

• Frequency in this range had negligible affect on $h$

• Increasing frequency raises HP_{fan}, and therefore COP is reduced
PIV technique:

- Two consecutive exposures are taken of flow plane, at set $\Delta t$, each illuminated by laser sheet
- A 2D velocity vector field is produced by calculating particle translation between the two exposures, using cross-correlation methods
11 Megapixel (4008X2672) CCD camera

120 mJ Nd:YAG (532nm wavelength) pulse laser

Insight 3G™ software

Operation frequency: 2.07 Hz

Exposure pair Δt: 30-200 μs

Spot dimensions: 75X75 pixels
\[ \text{Re}_{D_H} = 400U \]
TRANSPARENT CHANNEL MODEL FLOW

Channel 2

Channel 4

Channel 7

Fan Speed = 1400 RPM
TURBULENCE INTENSITY

Channel 2

![Channel 2 Image]

Channel 4

![Channel 4 Image]

Channel 7

![Channel 7 Image]

Fan Speed = 1400 RPM
CHANNEL RETENTION TIME & TURNOVER RATE

- Definition: amount of time a characteristic air particle remains in a heat sink channel, and the reciprocal of that time

\[
\tau_{ch} = \frac{x_{\text{streamline}}}{v_{\text{average}}} \quad f = \frac{1}{\tau_{ch}}
\]

- Characteristic values, based on PIV flow measurements:

\[
\tau_{ch} = O\left(\frac{0.035m}{1m/s}\right) = O(0.035s)
\]

\[
f = O\left(\frac{1}{0.35s}\right) = O(30Hz)
\]

- Sinusoidal fan cyclic operation at frequency lower than the turnover rate may be regarded as a sum of steady speed operations
CONCLUSIONS

The following important information regarding power performance was obtained in this research, which will be used in control system design:

- **COP** highest at low fan speed, for steady and forced/natural convection fan operation

- Sinusoidal fan cyclic operation did not show heat transfer improvement, and increasing frequency lowered COP in the range examined

- Channel retention time is $O(0.035s)$ and turnover rate is $O(30\text{Hz})$; sinusoidal fan cyclic operation may or may not improve heat transfer at frequency above turnover rate

- PIV results show stagnation area in some channels; flow is influenced by fan hub; asymmetry between left & right in channel flow; relatively low turbulence intensity
FUTURE WORK

- Control system design based on the present experimental conclusions
- PIV analysis for sinusoidal cyclic fan operation for current tested frequency range
- PIV/thermal system analysis for sinusoidal cyclic fan operation at higher frequency
- Attempt to find solution for stagnation area in selected channels
THANKS FOR LISTENING