TEL AVIV UNIVERSITY אוניברסיטת תל-אביב

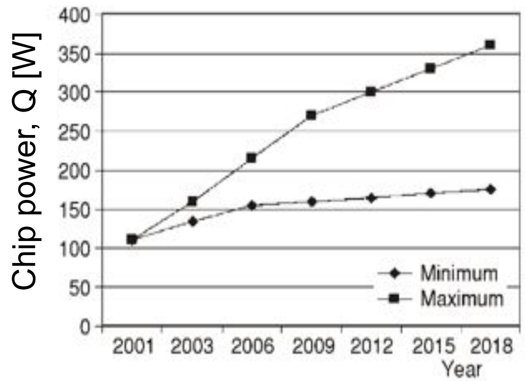
ELECTRONIC COMPONENT STEADY/UNSTEADY AIR COOLING

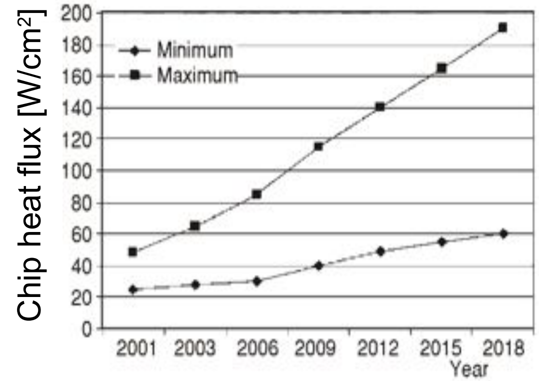
By:
David Altura

Advisors:
Dr. Alex Liberzon
Prof. Neima Brauner

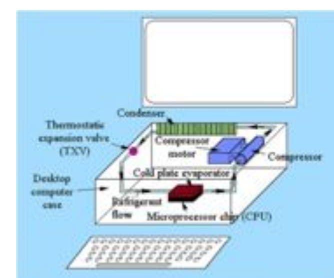
MOTIVATION

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





STATE OF THE ART COOLING TECHNIQUES

~10 W Passive Air	~100 W Forced Air	~200 W Coolant (water)	~300 W Refrigeration
			
-Cheap, quiet	-Inexpensive, noisy	-Expensive, complex	-Expensive, complex
-Low heat loads	-Mid heat loads	-High heat loads	-High heat loads

PRESENTATION OUTLINE

- 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

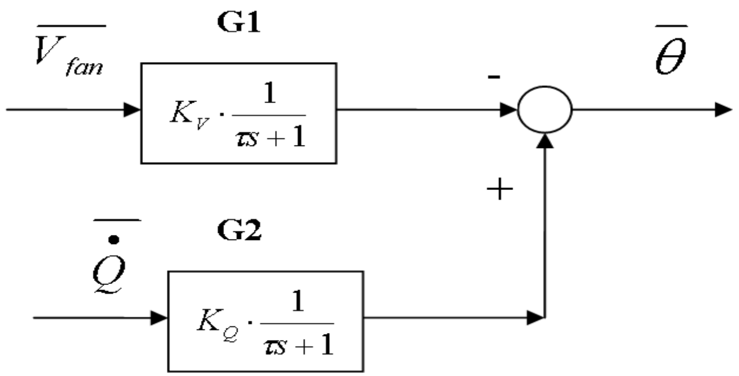
$\text{Control objective: optimize } COP$

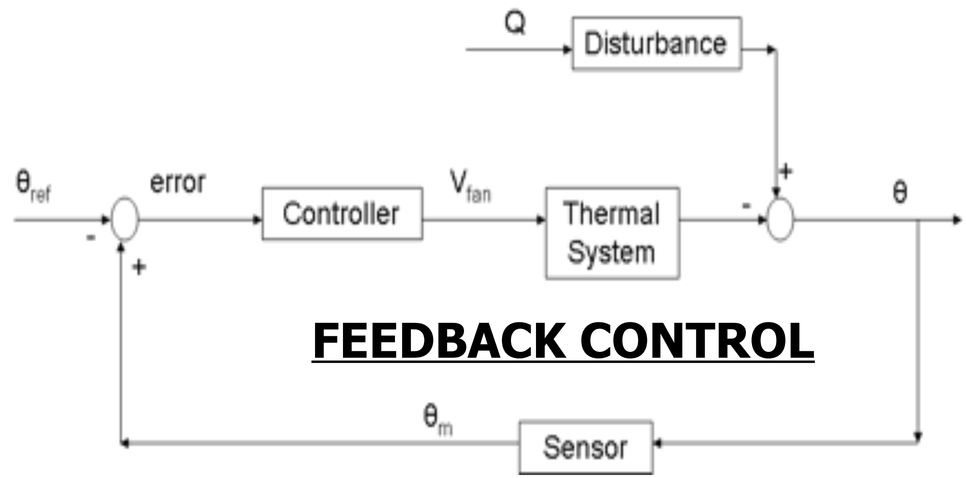
$\text{Specified constrain}: \theta_{SP}$

$\textit{Manipulated parameter}: V_{fan}$

$\textit{Disturbance}: Q$

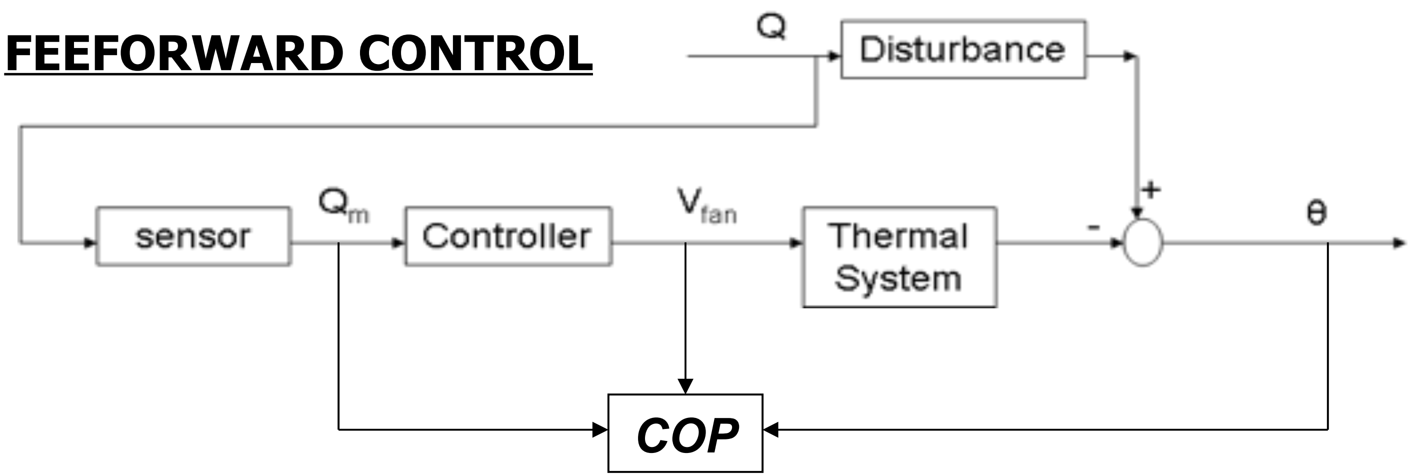
OPEN LOOP





FEEDBACK CONTROL

FEEFORWARD CONTROL

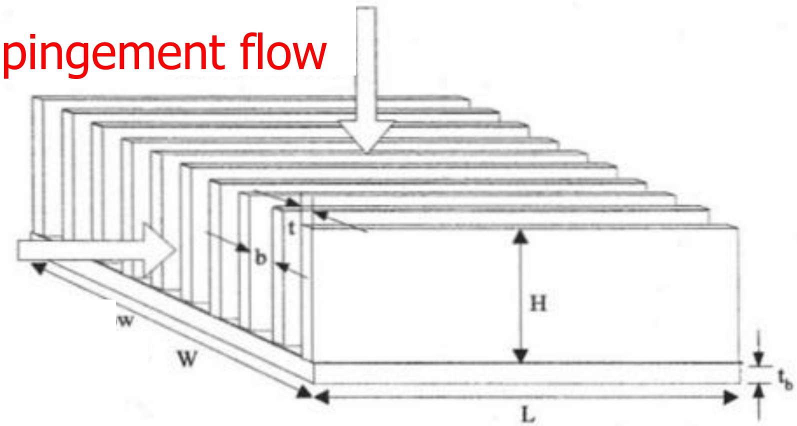


HEAT SINK FLOW ORIENTATIONS

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

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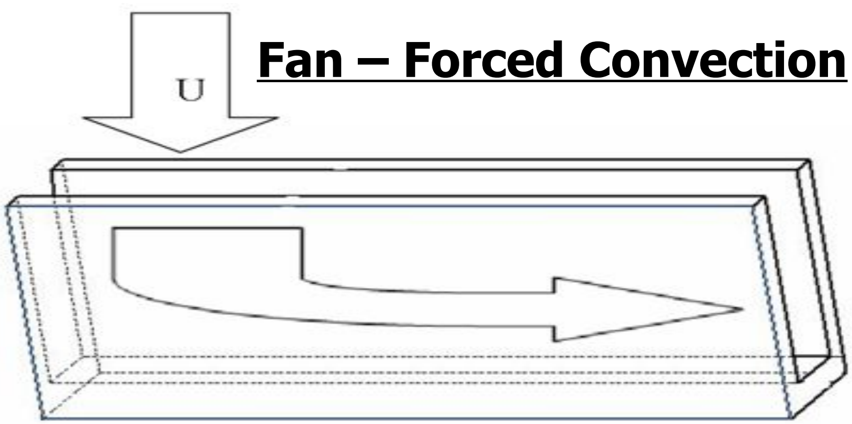
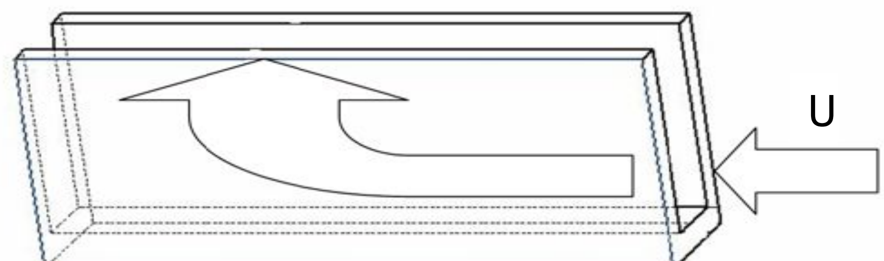
FLOW DIRECTIONS

Fan – Forced Convection



No Fan – Natural Convection

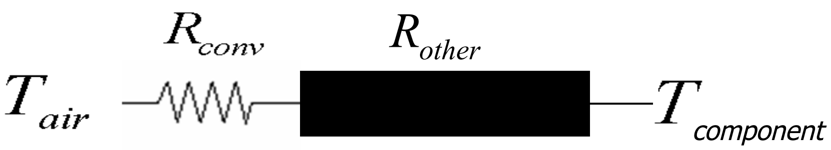


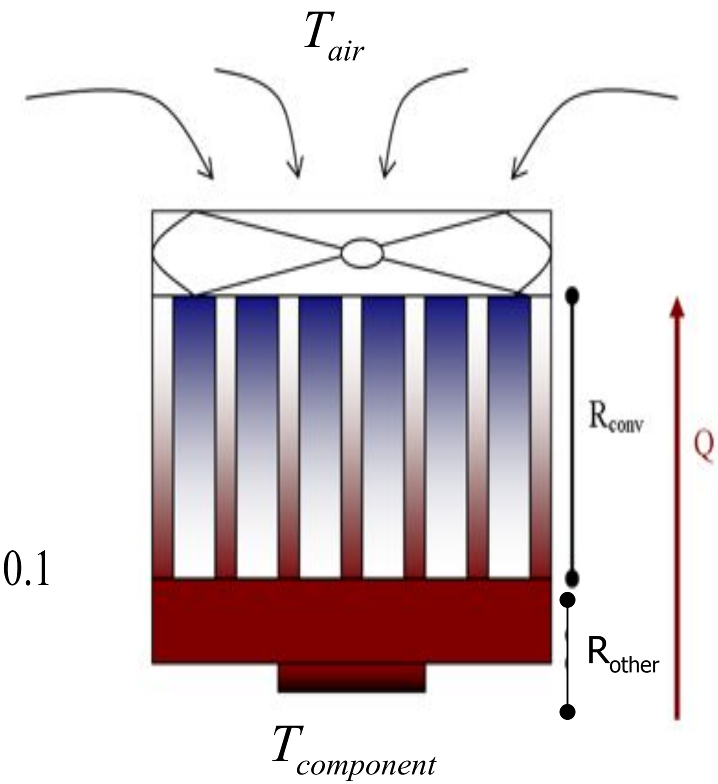
PHYSICAL CONDITIONS & ANALYSIS

- Thermal resistance circuit:

$$\Delta T = R_{th} \cdot Q$$

- Heat sink thermal resistance circuit:





- Lumped system condition (verified experimentally): $Bi = \frac{hx}{k} = \frac{h(V/A)}{k} < 0.1$

- Lumped system thermal resistance:

$$R_{conv} >> R_{other} \rightarrow R_{th} \approx R_{conv} = \frac{1}{hA} = \frac{\Delta T}{Q} \quad \Big| \quad \Delta T = T_{component} - T_{air}$$

$$h = h(G_{air},\ flow\ attributes,\ \Delta T\ for\ NC)$$

COOLING SYSTEM POWER PERFORMANCE

- High power performance $\Longleftrightarrow$ High heat transfer rate @ Low HP_{fan}

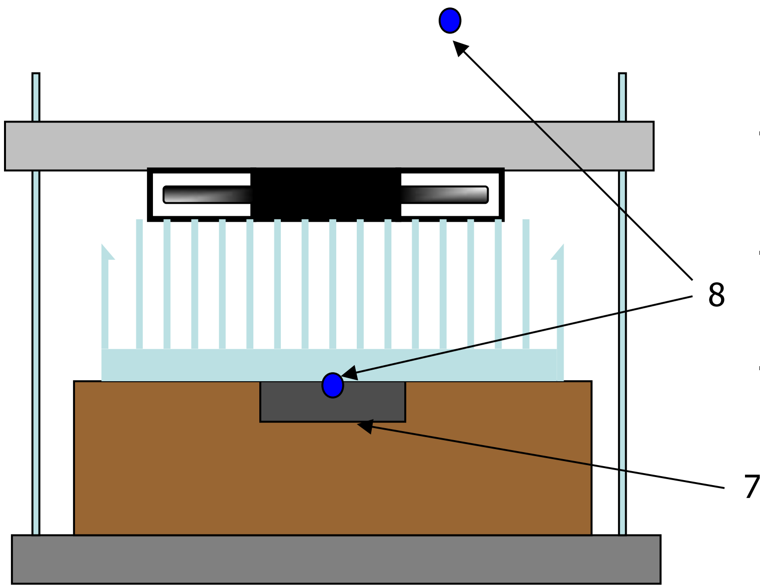
- Fan laws:

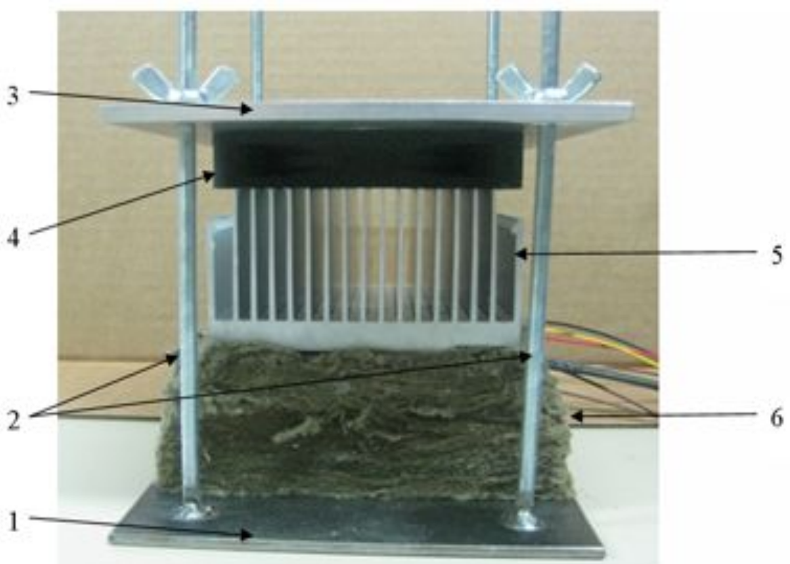
$$\sqrt[3]{\frac{(HP_{fan})_1}{(HP_{fan})_2}} = \frac{(RPM_{fan})_1}{(RPM_{fan})_2} = \frac{(G_{air})_1}{(G_{air})_2} = \frac{(V_{fan})_1}{(V_{fan})_2} = \frac{(U_{air})_1}{(U_{air})_2} = \sqrt[2]{\frac{(\Delta P_{fan})_1}{(\Delta P_{fan})_2}}$$

- Fan power coefficient of performance:

$$COP = \frac{Q_{SP}}{HP_{fan}} \qquad Q_{SP} = R_{th} \cdot \theta_{SP}$$

THERMAL SYSTEM





Legend

1 – lower plate
2 – threaded rods
3 – upper plate
4 – axial fan
5 – heat sink
6 – insulation
7 – heat element
8 – thermocouples

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:

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

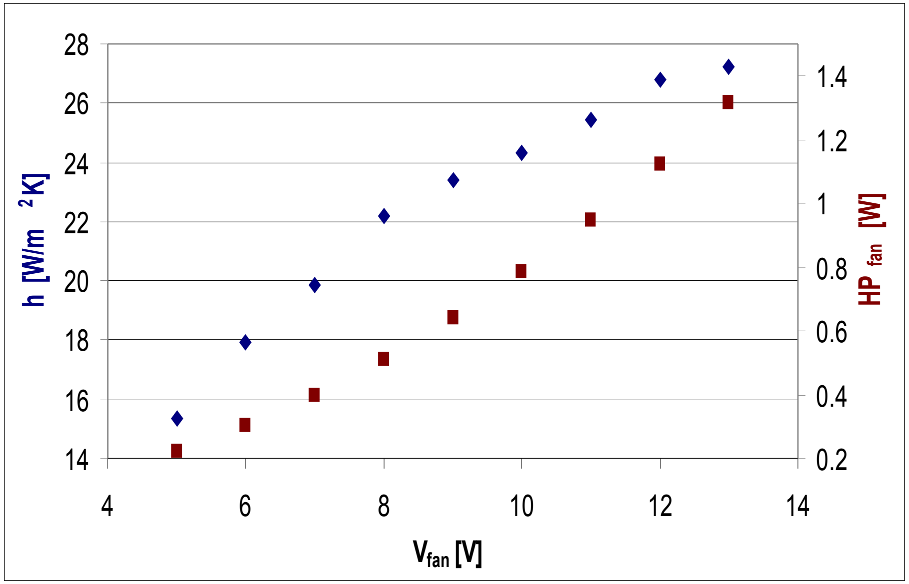
$$HP_{fan} = V_{fan} \cdot I_{fan}$$

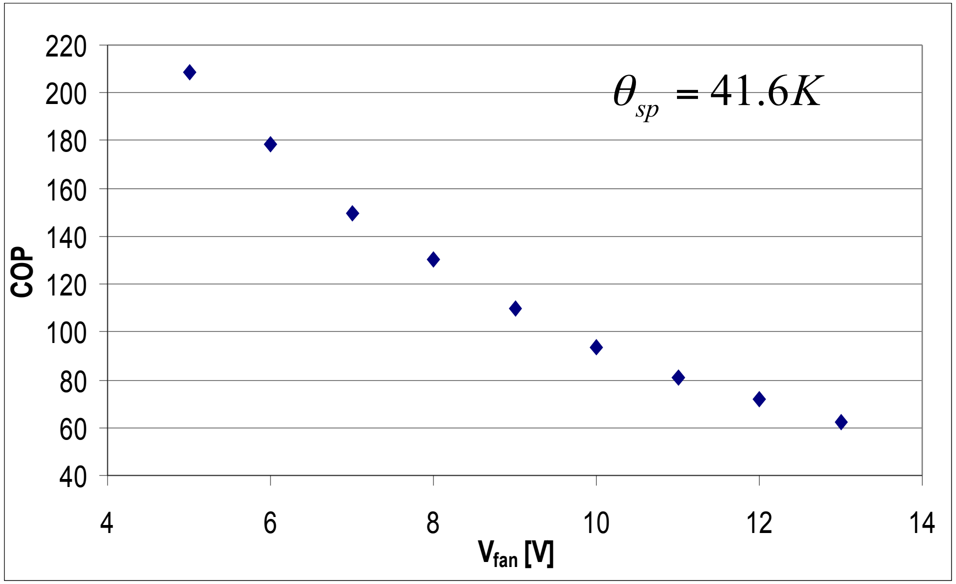
$$Q_{SP} = hA\theta_{SP}$$

$$COP = \frac{Q_{SP}}{HP_{fan}}$$

STEADY FAN OPERATION

$$COP = \frac{Q_{SP}}{HP_{fan}} \qquad Q_{SP} = hA\theta_{SP} \qquad R_{th} = \frac{\Delta T_{\exp}}{Q_{\exp}} \qquad h = \frac{1}{R_{th} \cdot A} = \frac{Q_{\exp}}{\Delta T_{\exp} \cdot A}$$





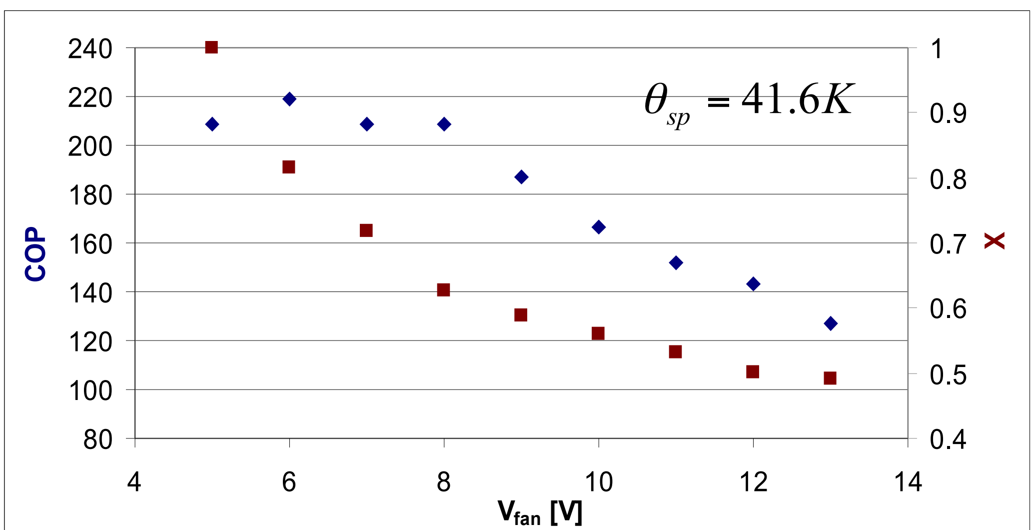
$$HP_{fan} = V_{fan} \cdot I_{fan}$$

$$\sqrt[3]{\frac{(HP_{fan})_1}{(HP_{fan})_2}} = \frac{(RPM_{fan})_1}{(RPM_{fan})_2} = \frac{(G_{air})_1}{(G_{air})_2} = \frac{(V_{fan})_1}{(V_{fan})_2} = \sqrt[2]{\frac{(\Delta P_{fan})_1}{(\Delta P_{fan})_2}}$$

COMBINED FAN/NATURAL CONVECTION

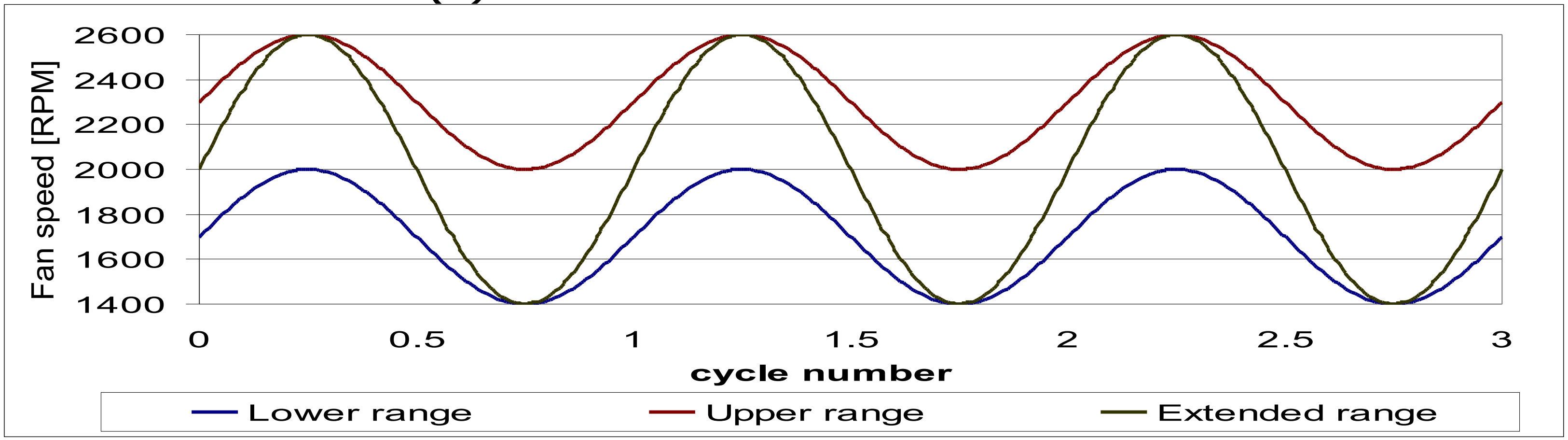
- Fan is **OFF** for part of cycle ⟶ **combined forced/natural convection**
- System time constant is large, theoretically allowing small temperature change within cycle
- Time average heat transfer coefficient (h_{av}) determined by forced/natural convection coefficients and fan operation time fraction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

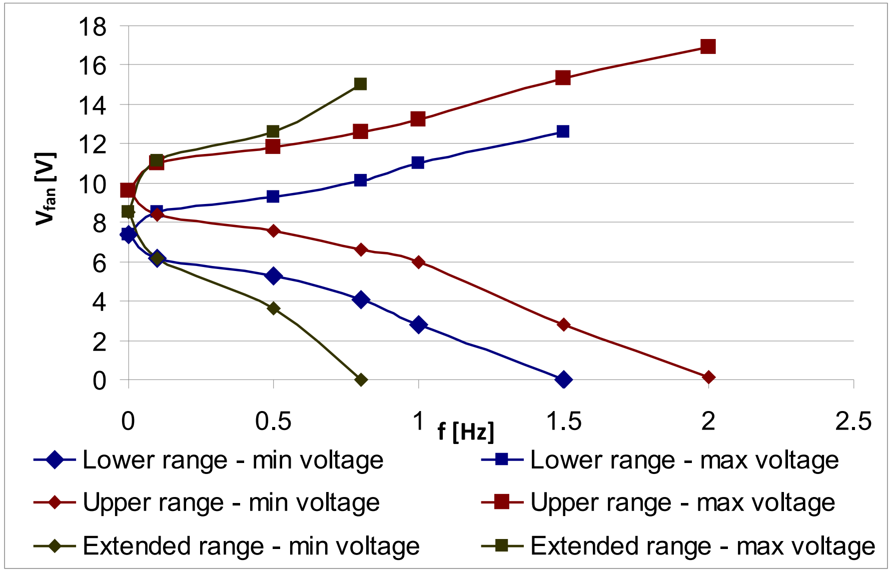
$$h_{av} = x h_{fc} + (1-x) h_{NC} \qquad Q = h_{av} A \theta_{sp} \qquad h_{NC} = 3.9 W/m^2 K, \ @41.6K$$

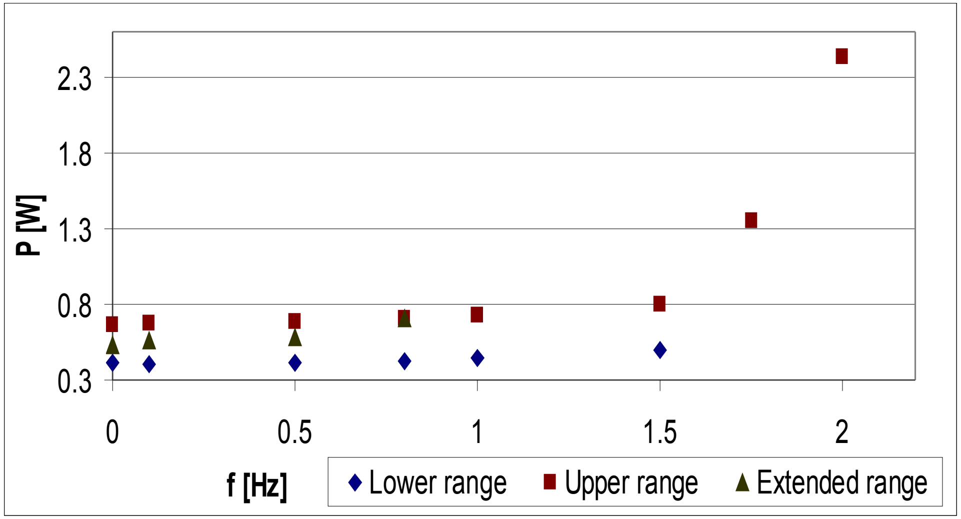


FAN SINUSOIDAL CYCLE RESULTS

- Comparison between steady and fan operation, regarding heat transfer coefficient (*h*) and *COP*







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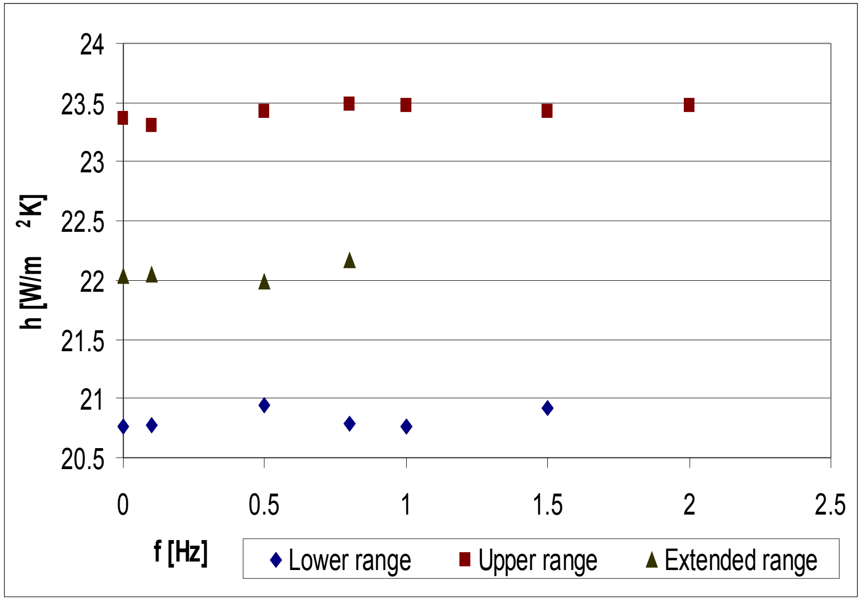
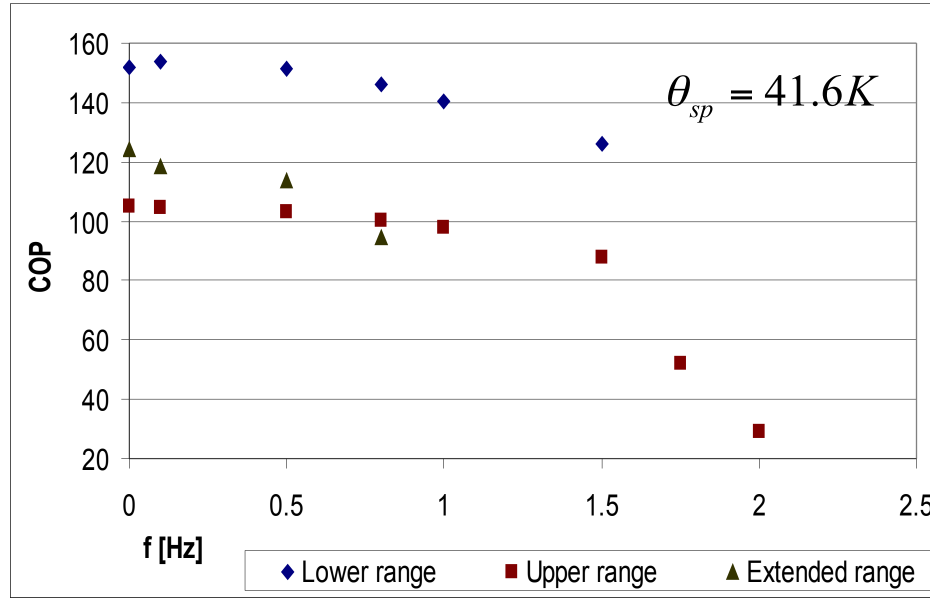
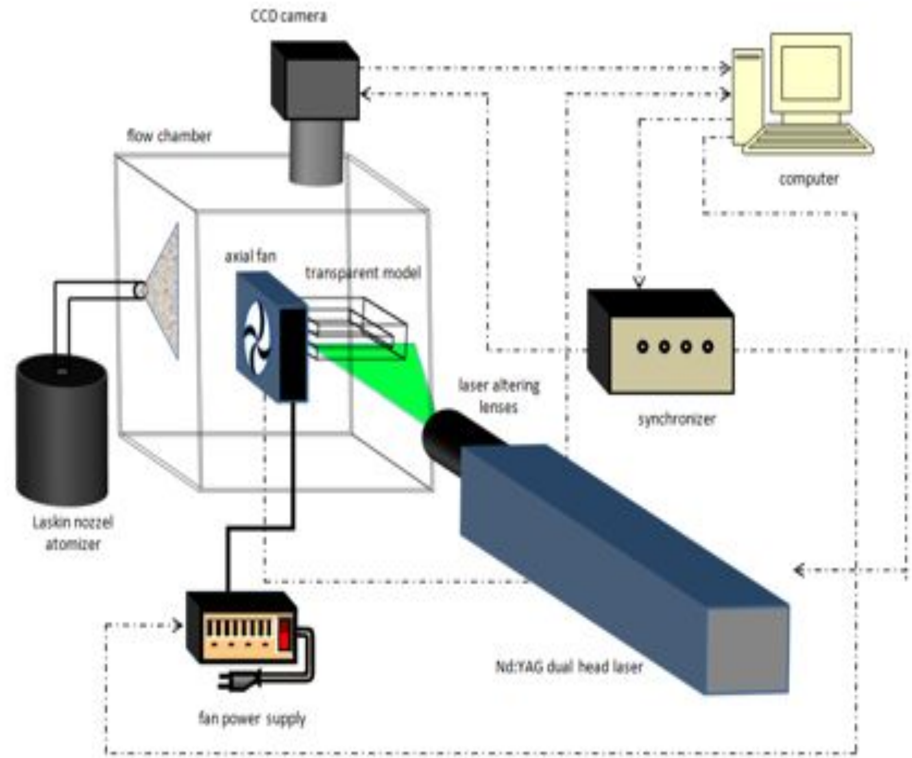
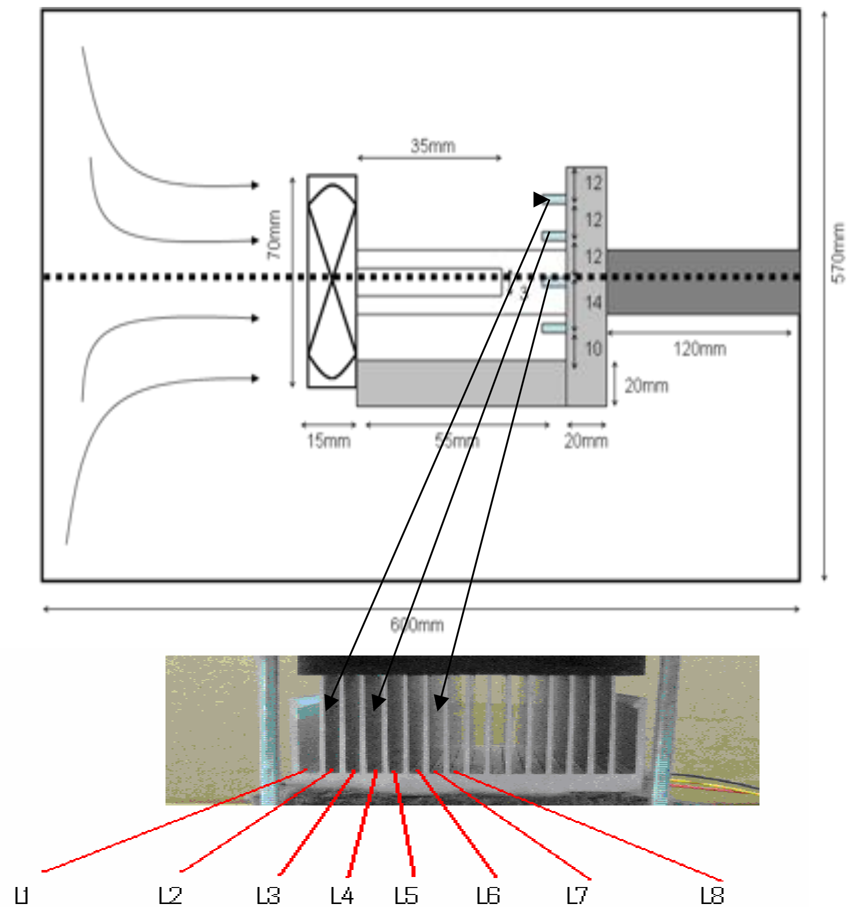




- Axial fan limits maximum frequency to ~2Hz @ tested amplitudes
- Frequency in this range had negligible affect on *h*
- Increasing frequency raises HP_{fan}, and therefore *COP* is reduced

PIV EXPERIMENTAL SYSTEM





PIV technique:

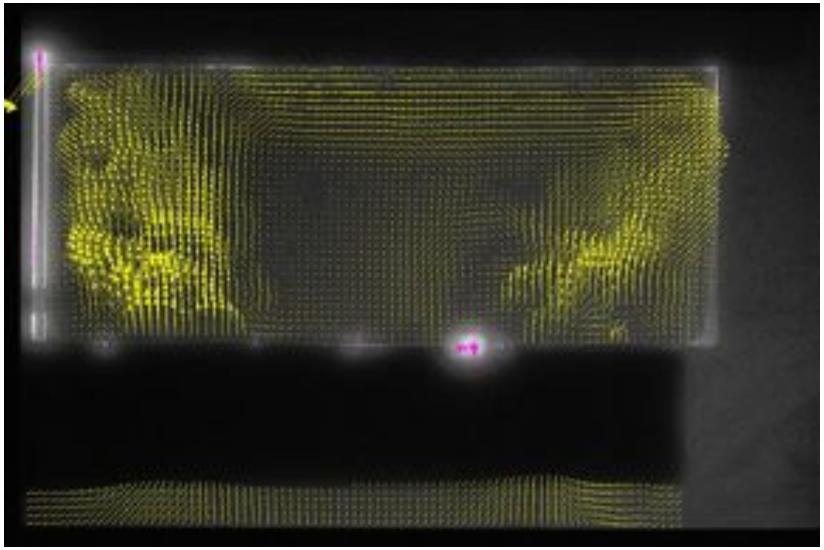
• Two consecutive exposures are taken of flow plane, at set Δt, each illuminated by laser sheet

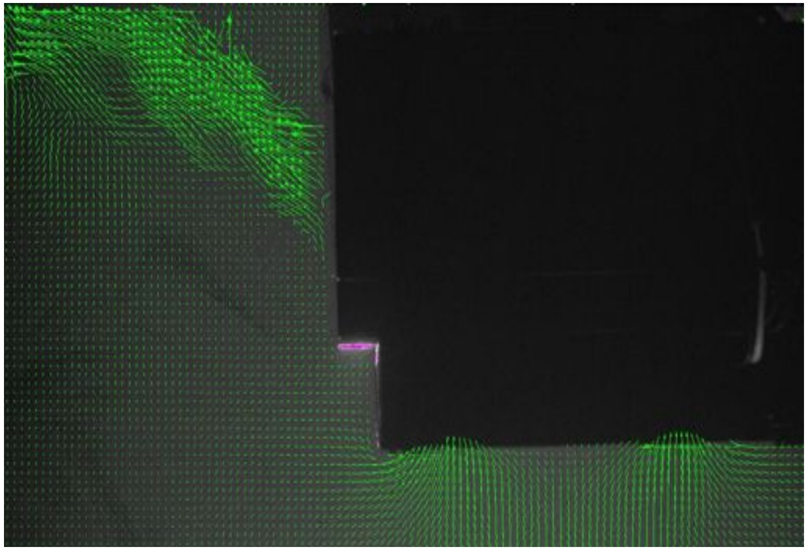
• A 2D velocity vector field is produced by calculating particle translation between the two exposures, using cross-correlation methods

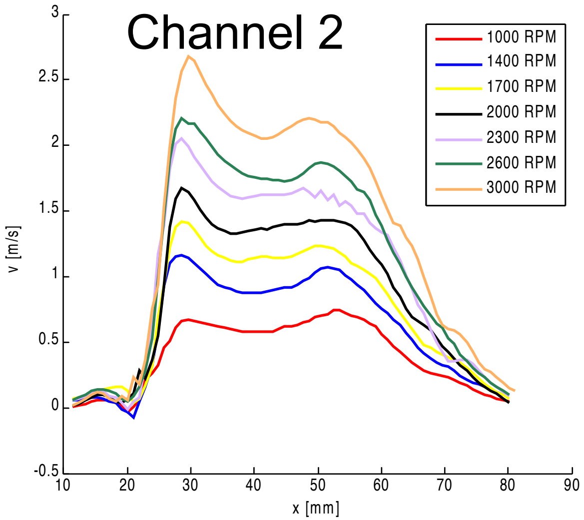
PIV EXPERIMENTAL PARAMETERS

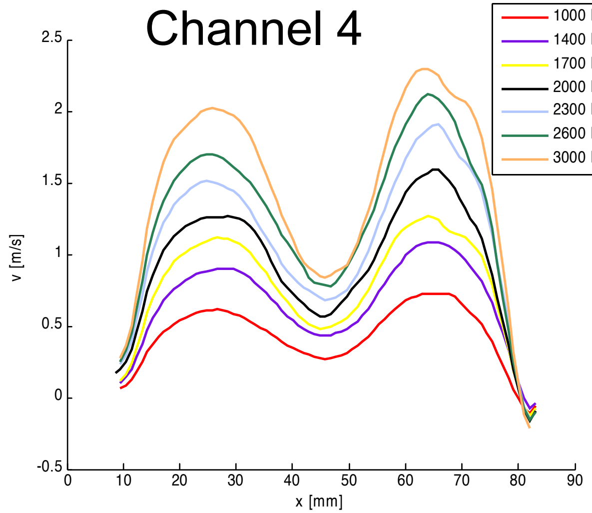
- 11 Megapixel (4008X2672) CCD camera
- 120 mJ Nd:YAG (532nm wavelength) pulse laser
- Insight 3G$_{TM}$ software
- Operation frequency: 2.07 Hz
- Exposure pair Δt: 30-200 μs
- Spot dimensions: 75X75 pixels

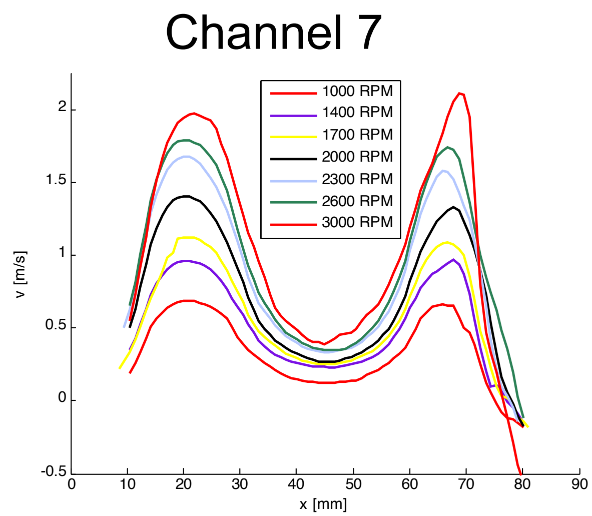
PIV VECTOR FIELDS & FAN INLET PROFILES





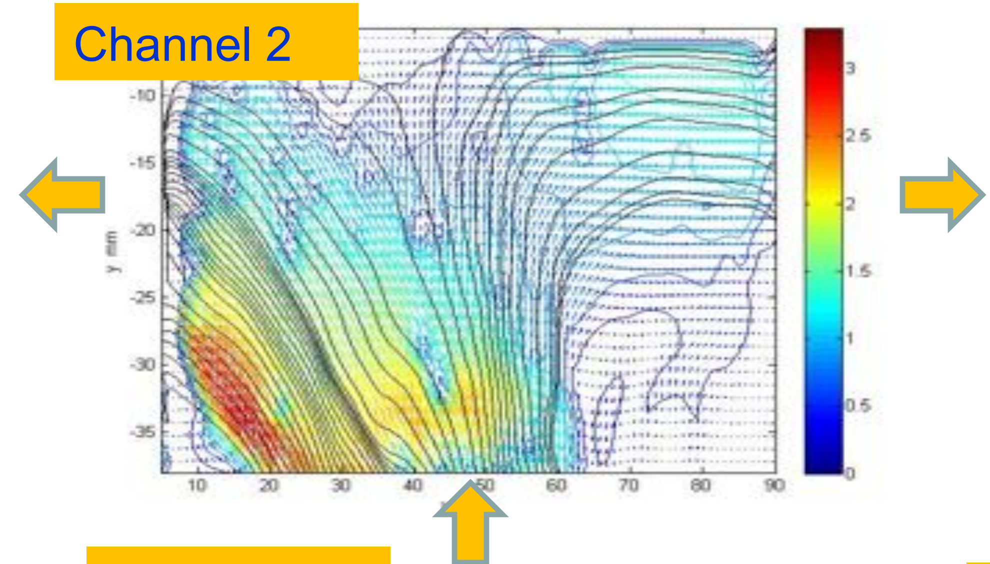


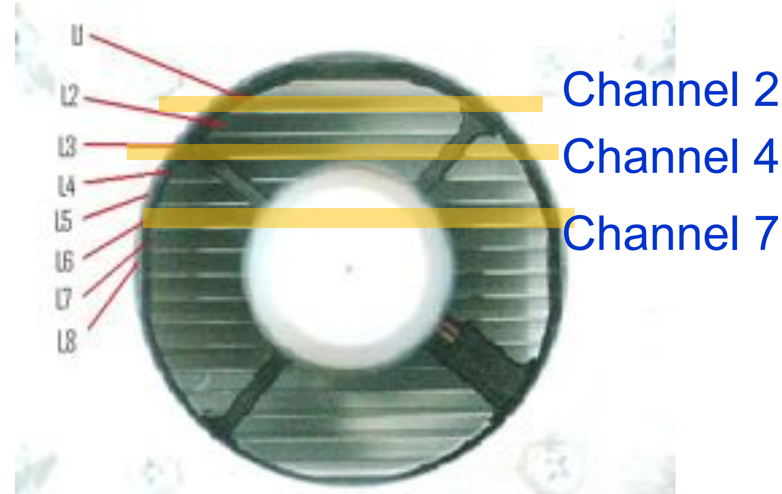




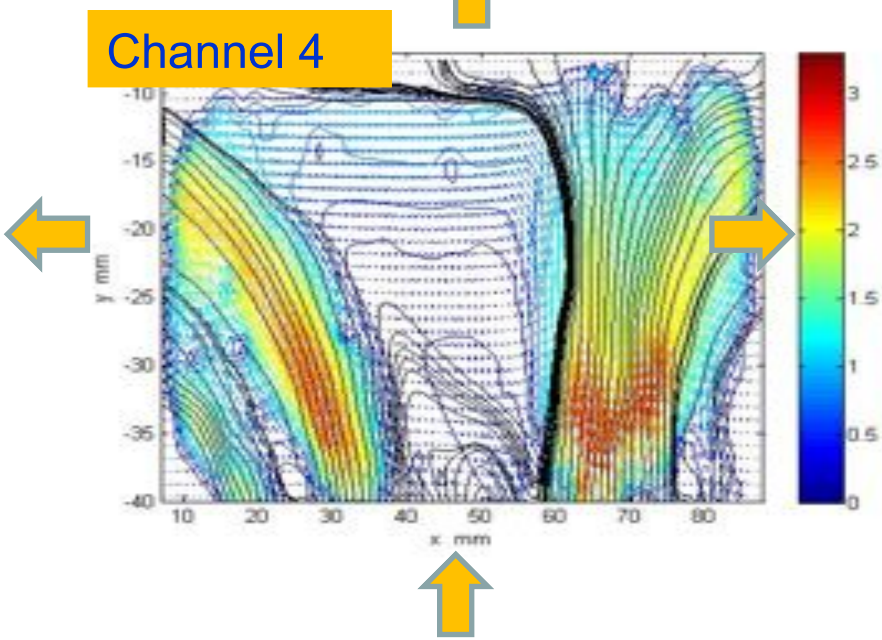
$$\mathrm{Re}_{D_H} = 400U$$

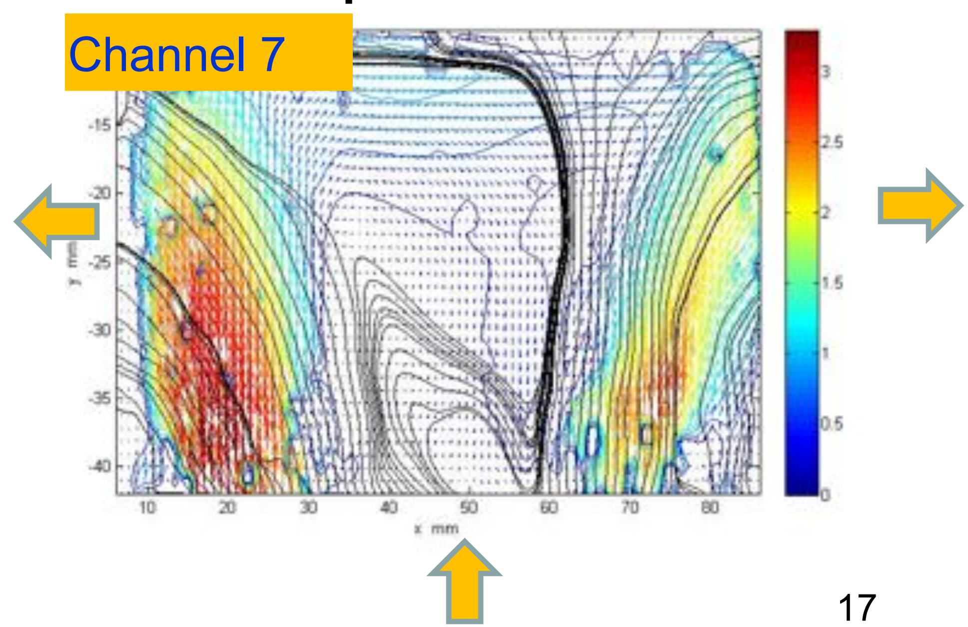
TRANSPARENT CHANNEL MODEL FLOW





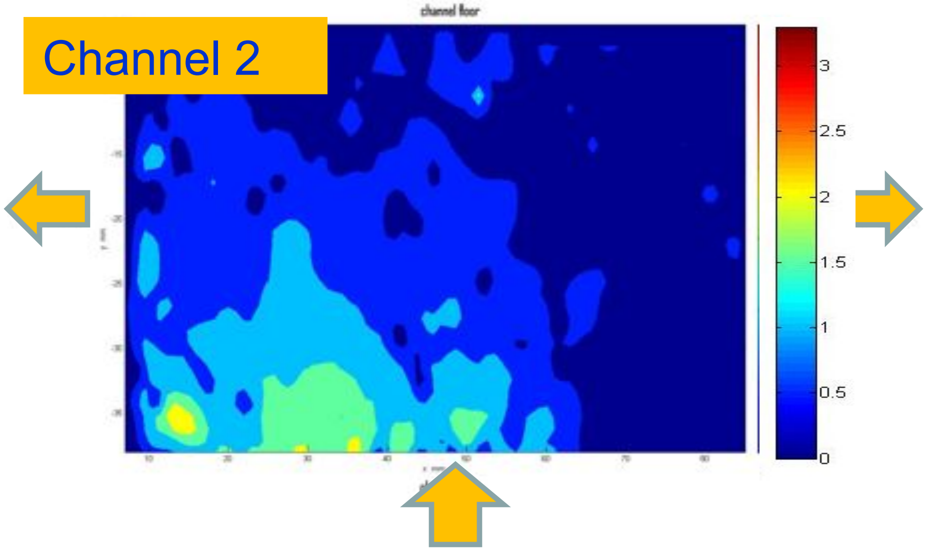
Fan Speed = 1400 RPM

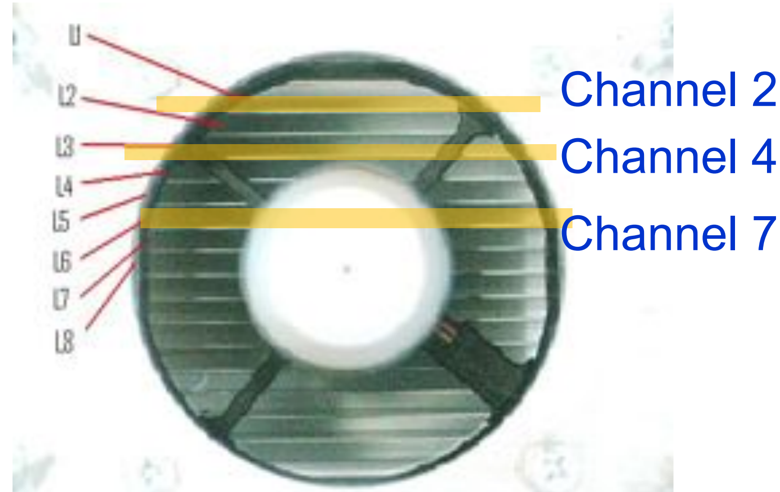




TURBULENCE INTENSITY

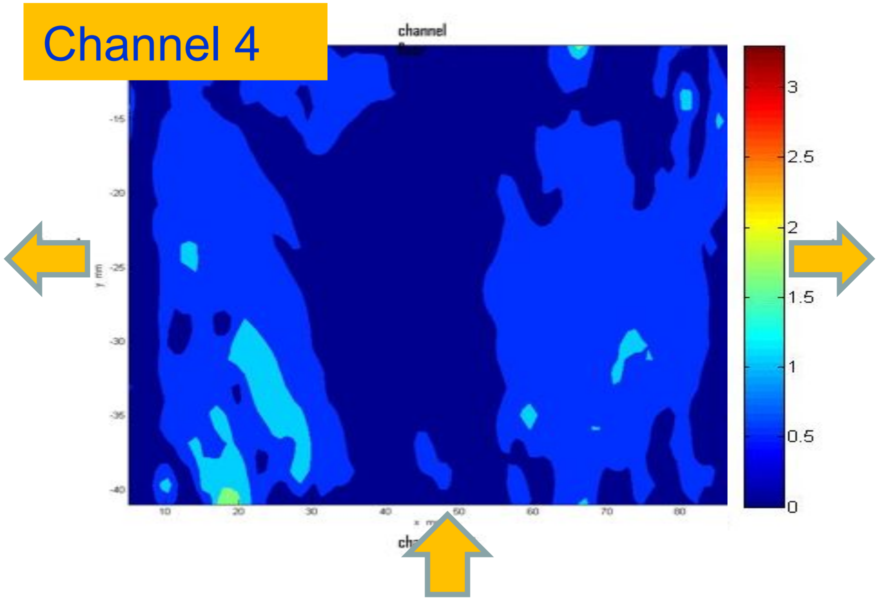
Channel 2



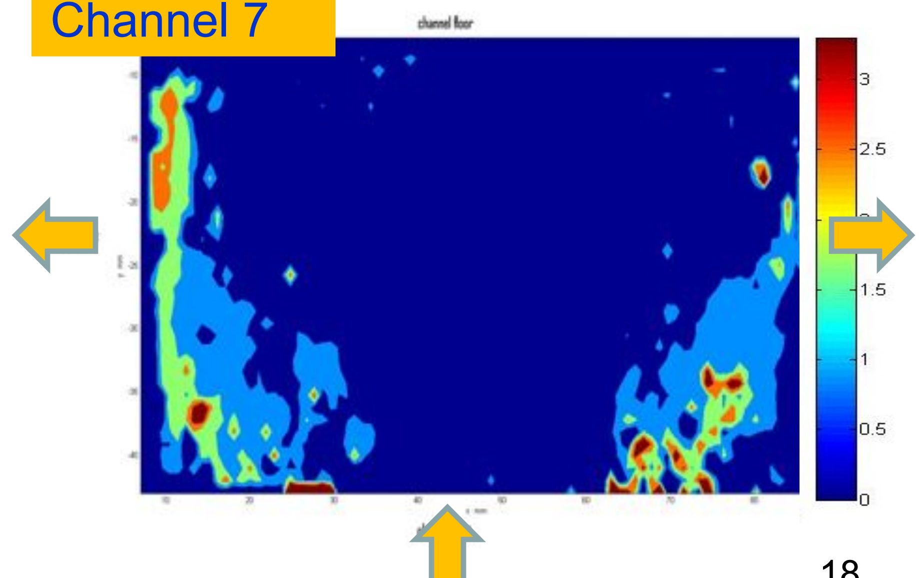


Fan Speed = 1400 RPM

Channel 4



Channel 7



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

$$\tau_{ch} = \frac{x_{streamline}}{v_{average}} \qquad f = \frac{1}{\tau_{ch}}$$

- 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*(30Hz); 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