Thermal Design of Liquid Cooling System for Electronic Cooling

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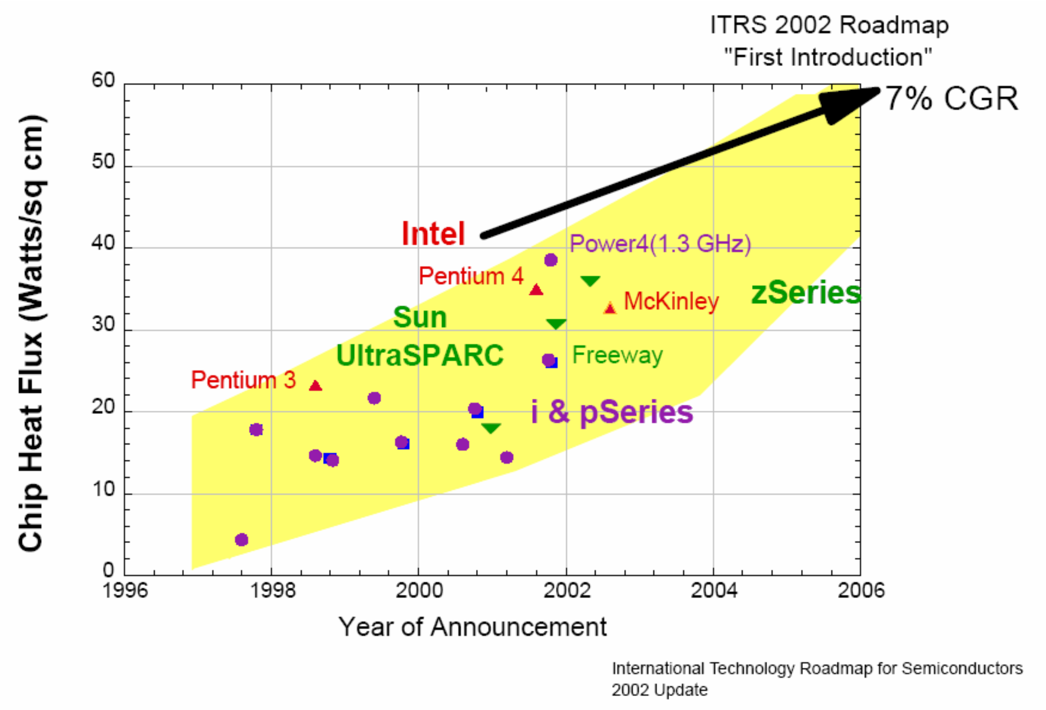
Outline

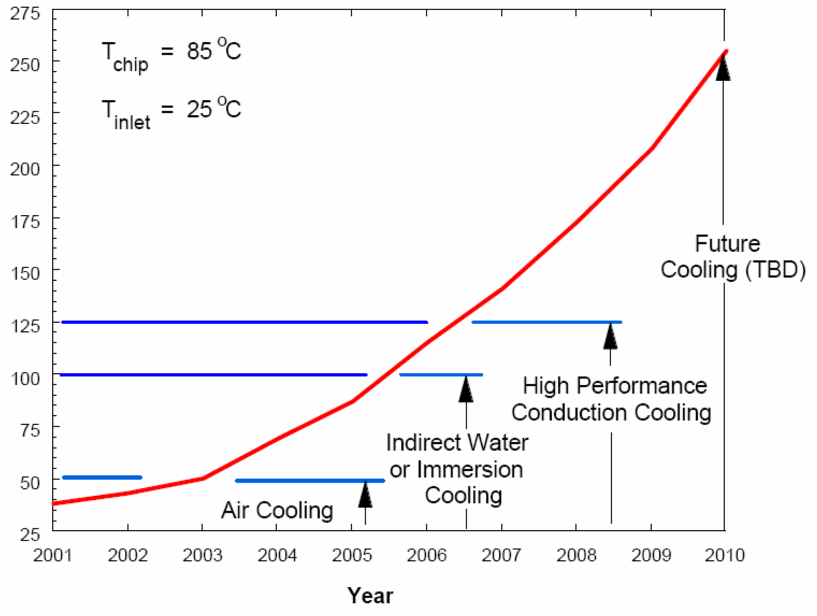
- Background
- Fundamentals of Augmentation
- Micro-channel HXs
- Liquid Cooling – Maldistribution
- Liquid Cooling – Radiators
- Summary

Limits of cooling technology



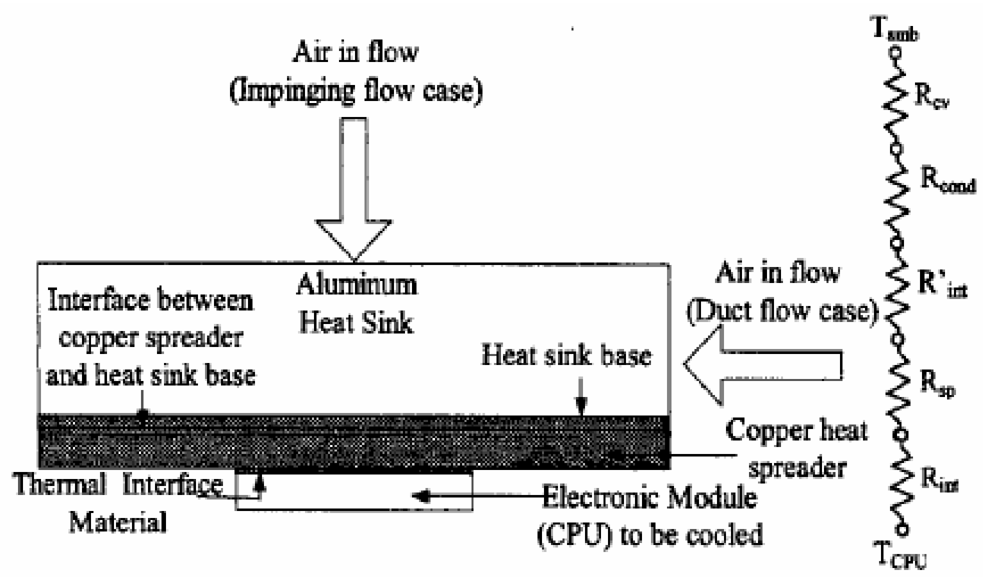
ITRS 2002 Roadmap
"First Introduction"

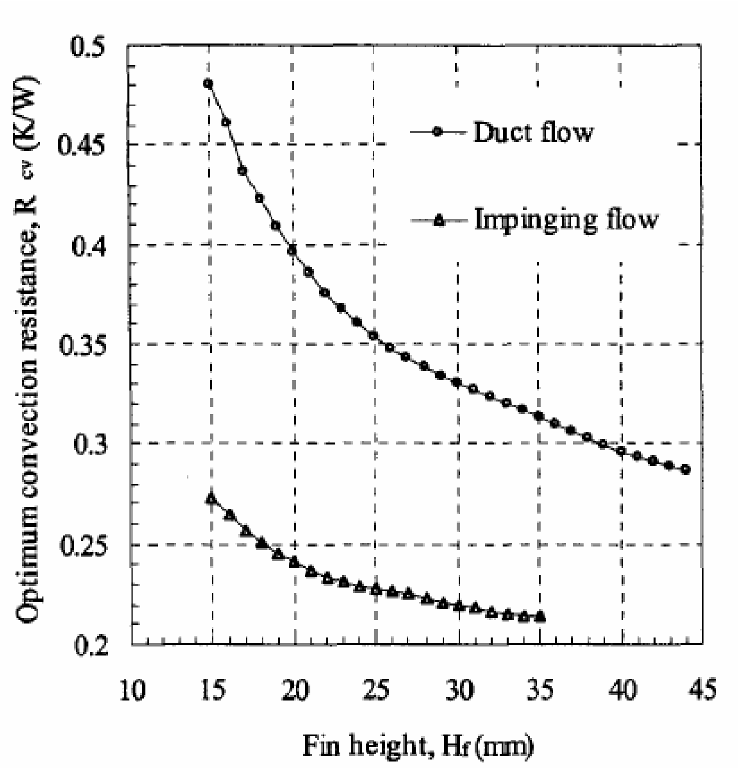
International Technology Roadmap for Semiconductors
2002 Update



Richard. C. Chu - IBM

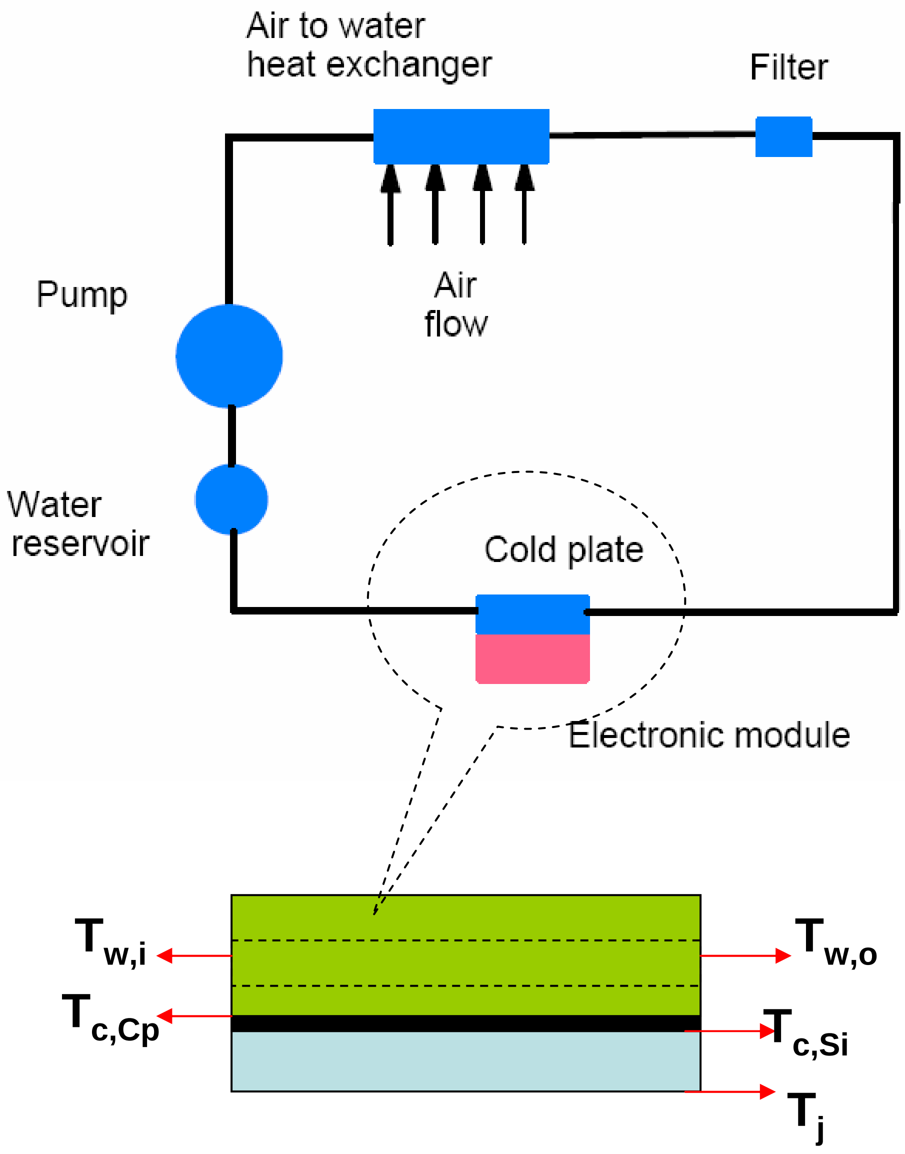
Limits of Air-cooled Design

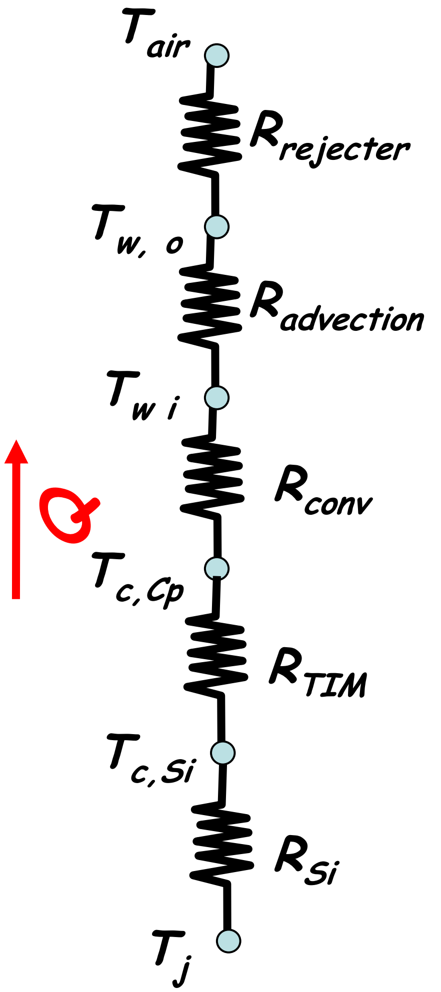




Saini et al., 2002 Inter Society Conference on Thermal Phenomena

Water-cooled System





$R_{rejecter}$: Heat Transfer bewteen water and HX

$$R_{advection} = \frac{1}{\rho \dot{V} C_p}$$

$$R_{convection} = \frac{1}{hA_{ch}}$$

$$R_{TIM} = 0.05 \sim 0.1\,W/°C$$

$$R_{Si} = \frac{d}{kA}$$

Fundamentals:

Heat Transfer Augmentation of Cold-Plate

- Heat Transfer Augmentation ($Q = UA\Delta T_m$)

Q : heat transfer rate,

U: overall heat transfer Coeff.

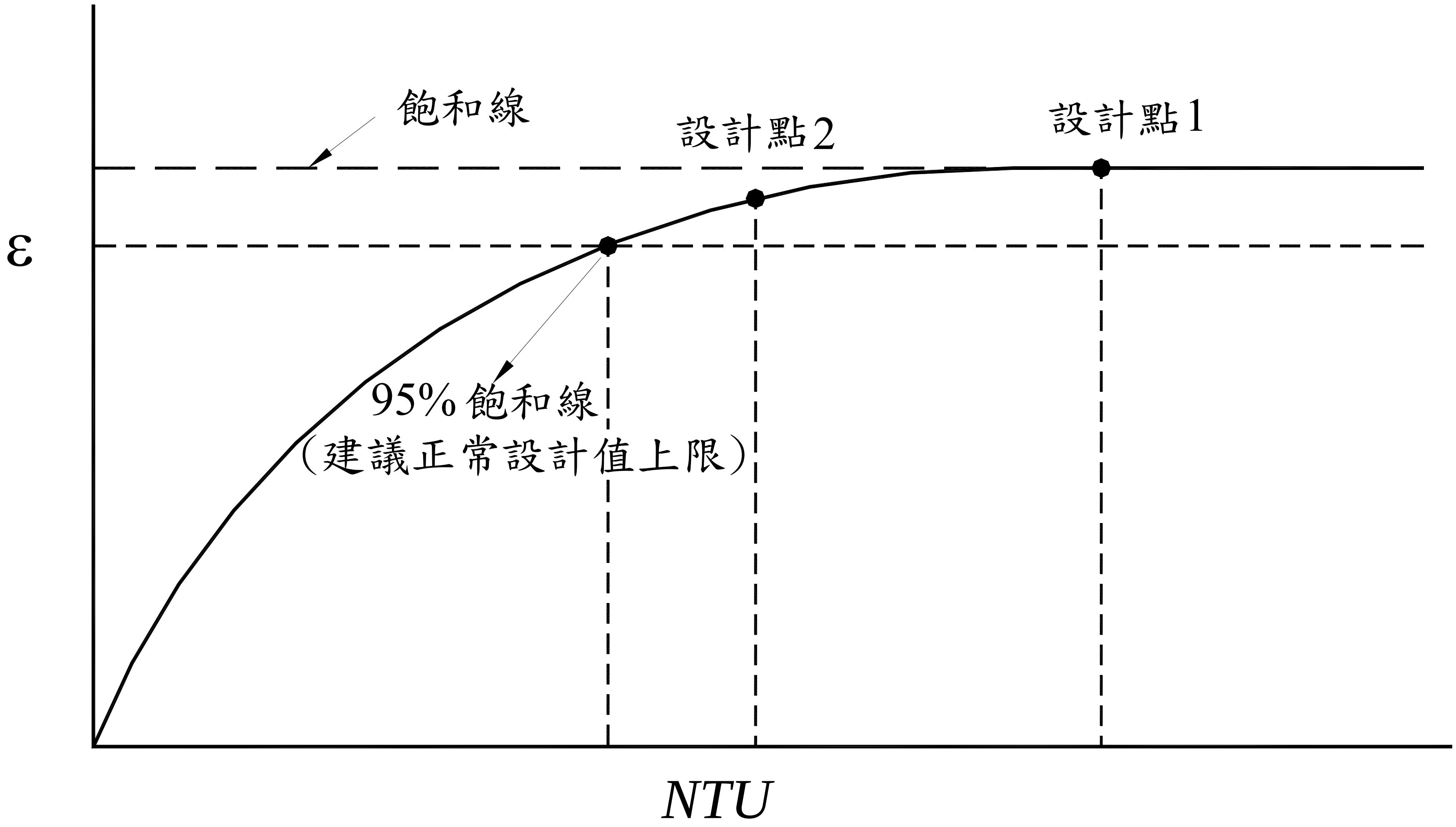
A: Area

ΔT_m: mean temperature difference

- Increase A
- Increase U
- Reduce ΔP at fixed Q

Fundamentals

- Why enhancement? Do you really need enhancement?



Do you really need enhancements?

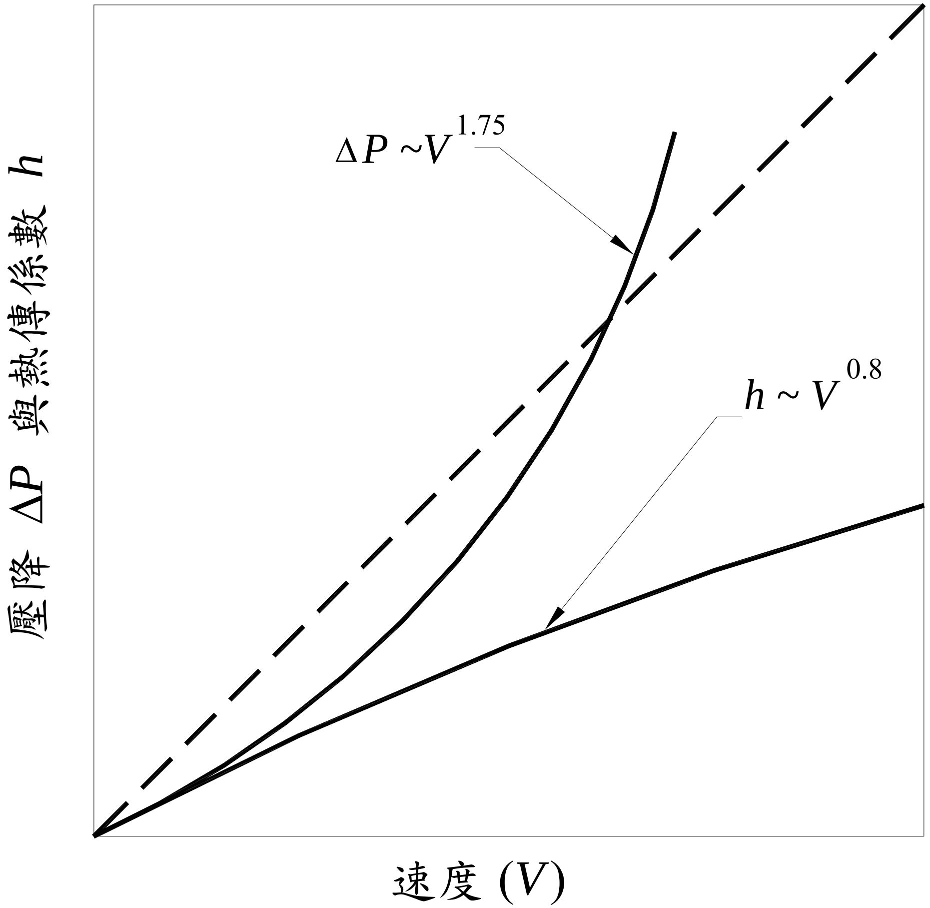
h: heat transfer coeff.

A: area

η: fin efficiency

$$\frac{1}{UA} = \frac{1}{\eta_i h_i A_i} + \frac{1}{\eta_o h_o A_o} + R_w$$

How you can do about enhancement – Q is not the sole objective.

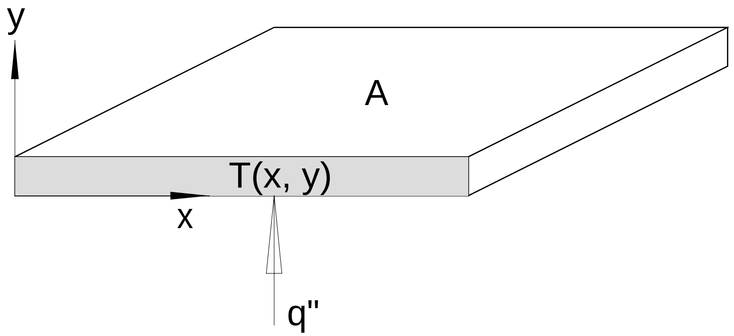


Some objectives for enhancements.

- Maintain Q and ΔP, reduce A
- Maintain Q and A, reduce effective temperature difference
- Increase Q subject to same A
- Maintain Q and A, reduce pumping power

Fundamentals:

- **Conduction** $q = -kA\frac{dT}{dy}$

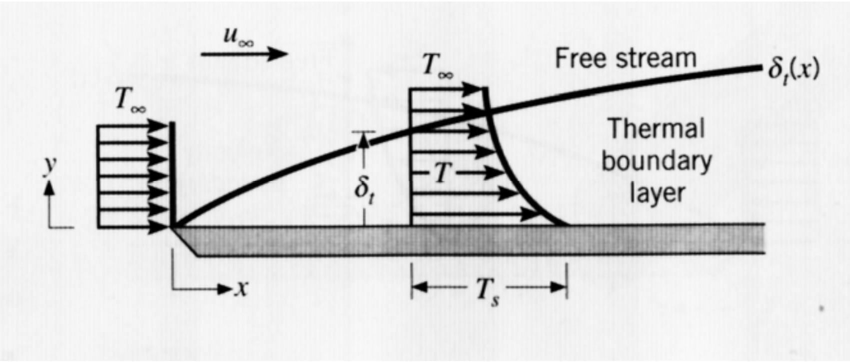


  - Increase A
  - Use high k materials
  - Increase temperature gradient?

    $dT/dy = (T_2 - T_1)/(y_2 - y_1)$

- **Convection**

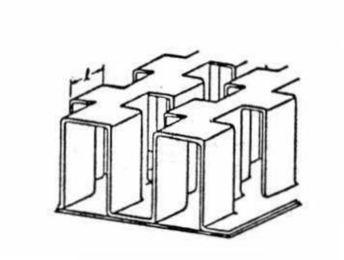
$$q = hA(T_s - T_\infty) = -kA\frac{dT}{dy}\Big|_{y=0}$$

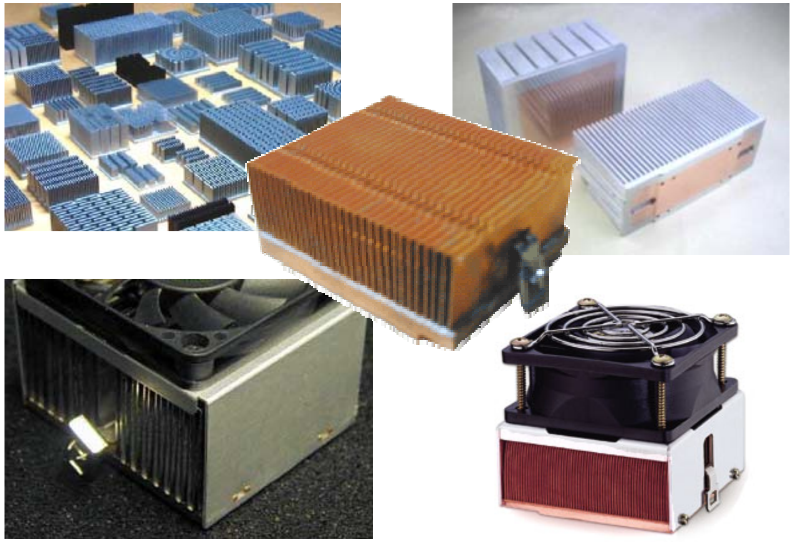


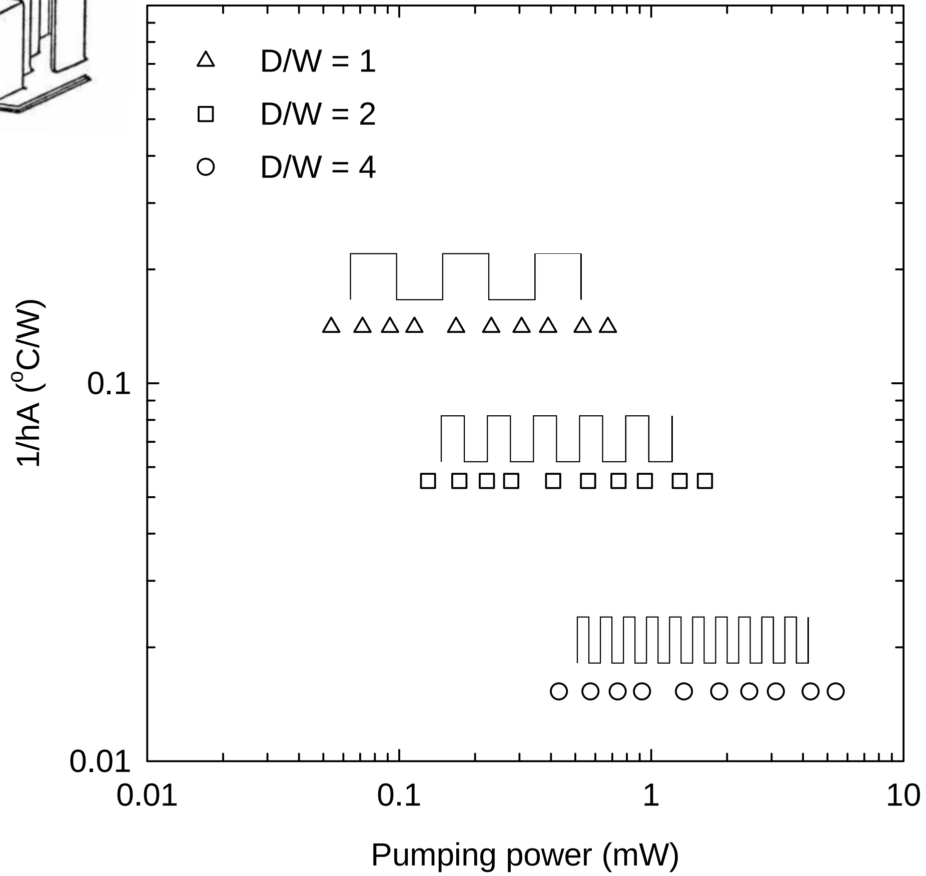
  - Increase A
  - Increase h (convective heat transfer coeff.)

Example of Increased A

- Increase aspect ratio
  - Limit to manufacturing
  - Mal-distribution is likely
- Increase fin type

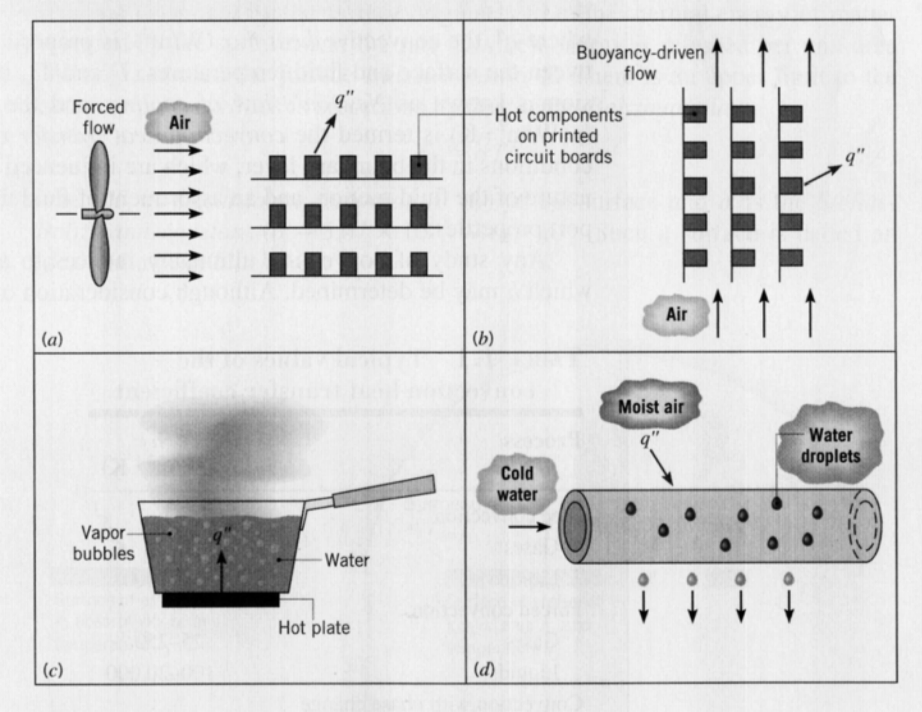






Increased heat transfer coeff.

- Air cool to liquid cool, single-phase to two-phase
- Augmentation



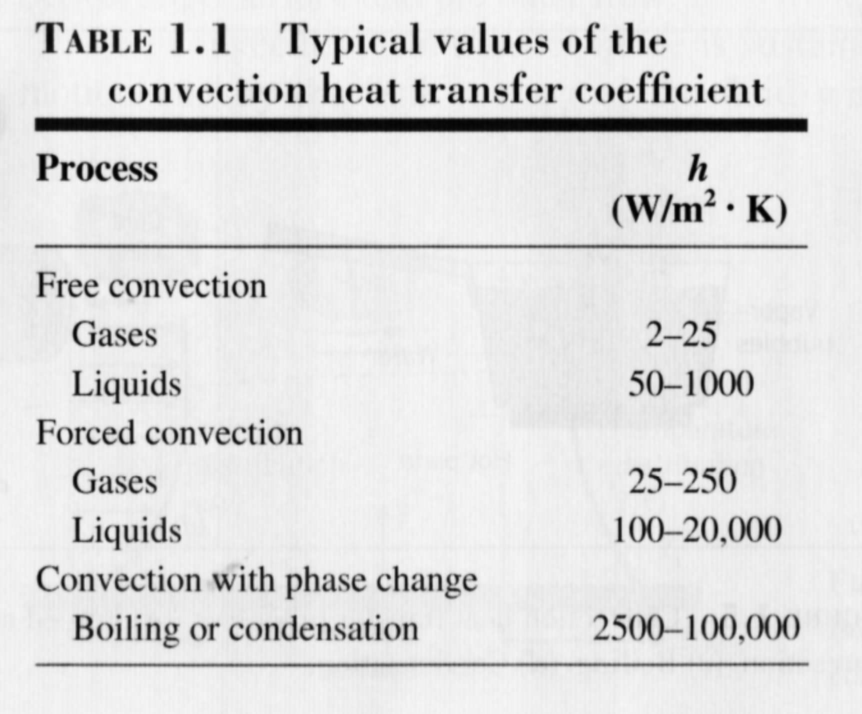


TABLE 1.1 Typical values of the convection heat transfer coefficient

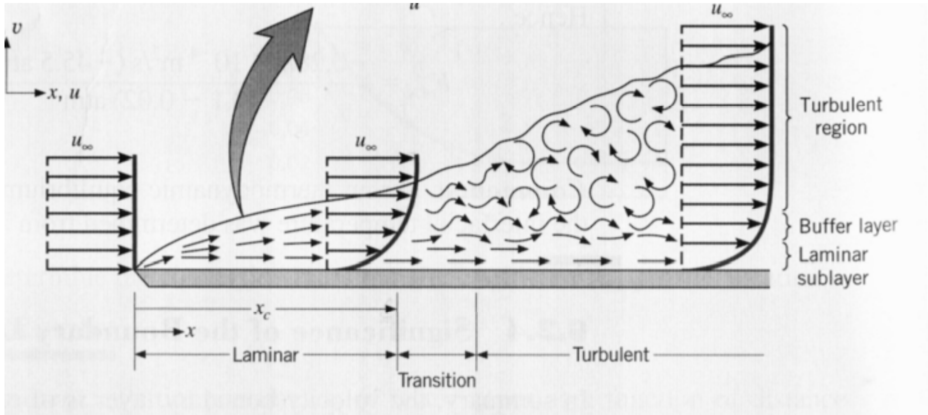
Process	h $(W/m^2 \cdot K)$
Free convection	
Gases	2–25
Liquids	50–1000
Forced convection	
Gases	25–250
Liquids	100–20,000
Convection with phase change	
Boiling or condensation	2500–100,000

Single phase flow pattern

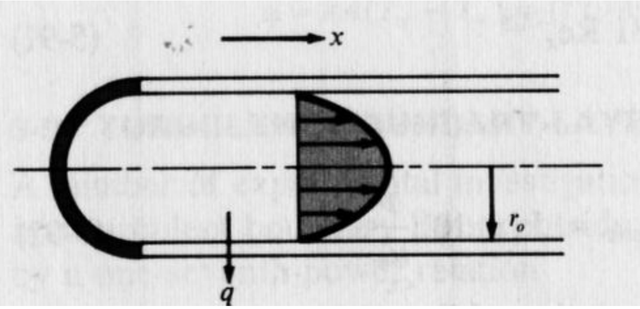
$$q = hA(T_s - T_\infty) = -kA\frac{dT}{dy}\Big|_{y=0}$$

- $Re_D = \rho uD/\mu$

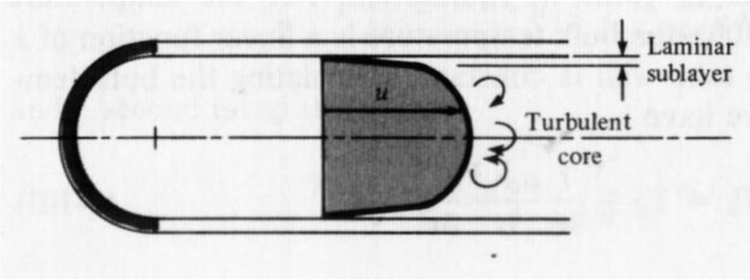
For smaller diameter tube (or micro tube) flow pattern is mostly operated at laminar flow



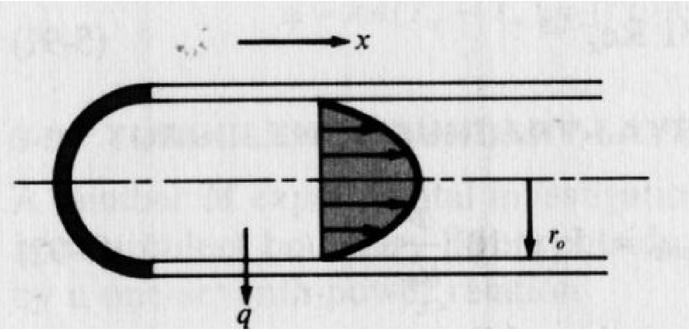
$Re_D < 2{,}300$ laminar flow

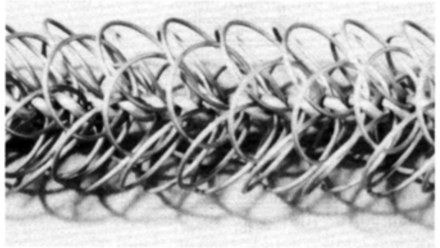


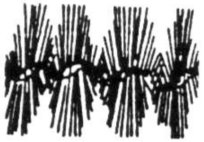
$Re_D > 2{,}300$ turbulent flow

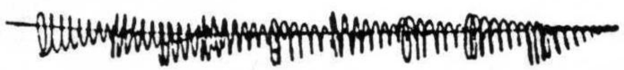


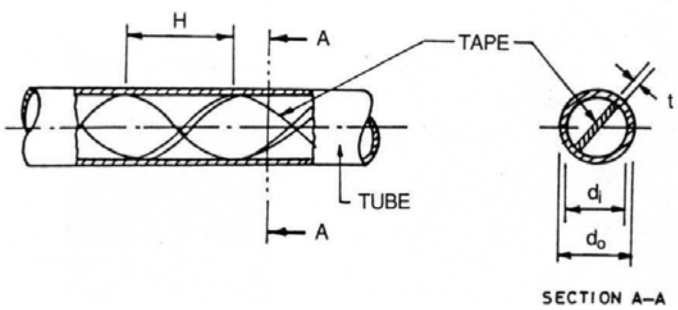
Augmentation of single-phase flow

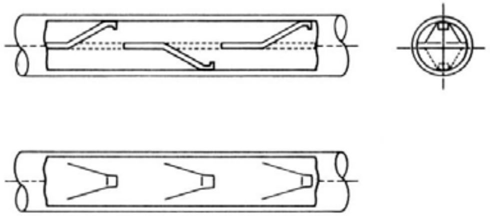


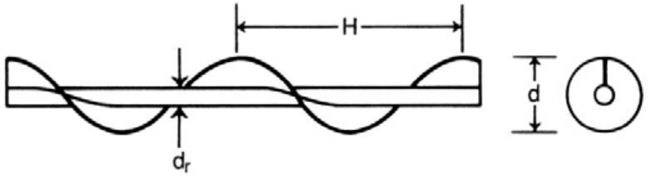


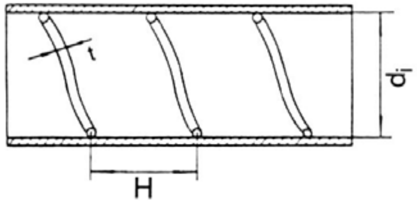




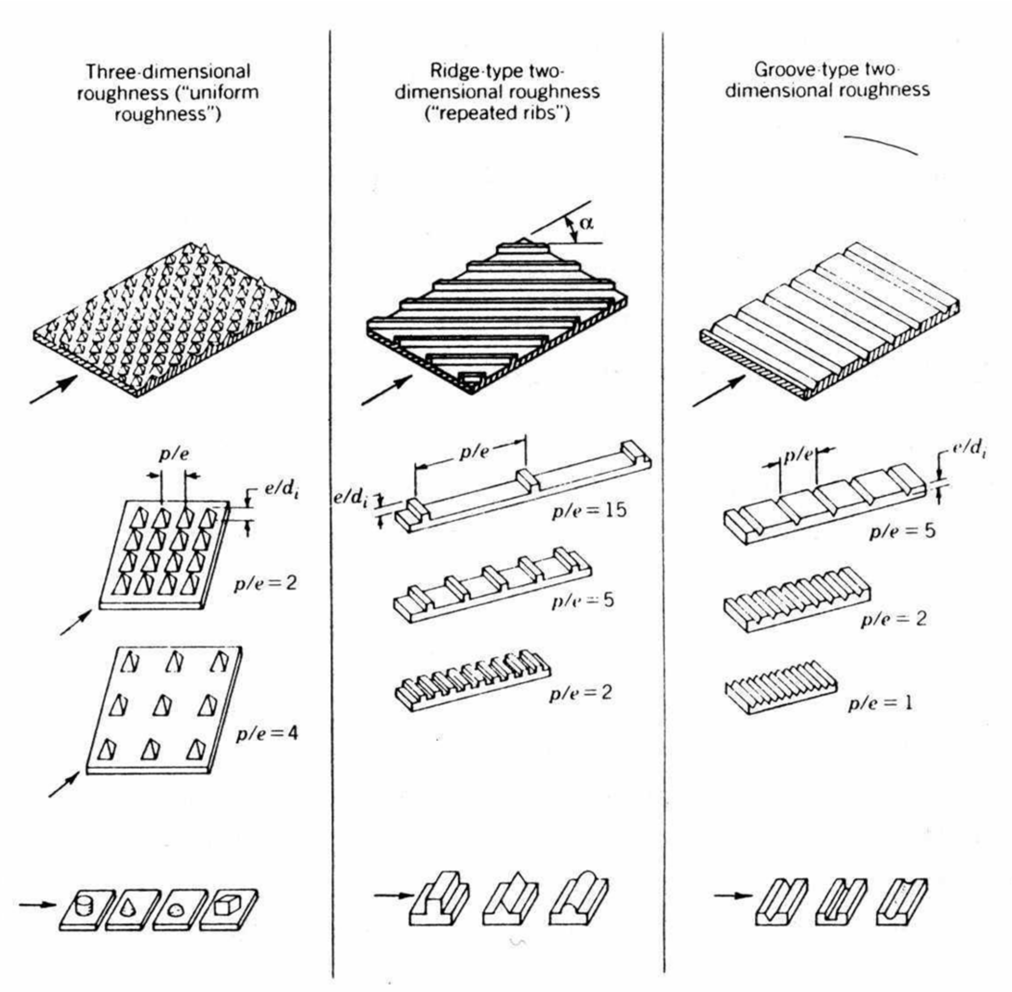


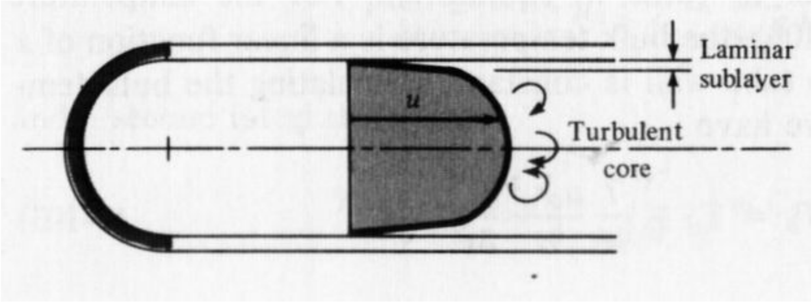


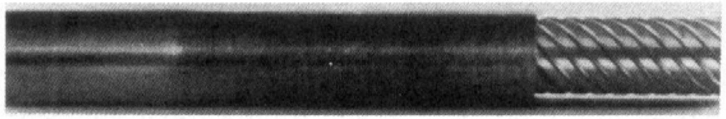


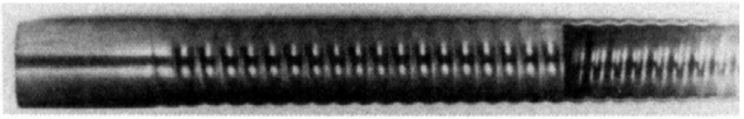


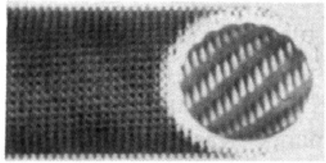
Augmentation in turbulent flow

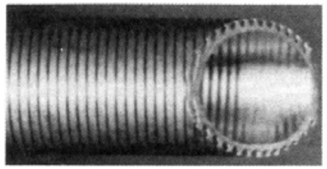






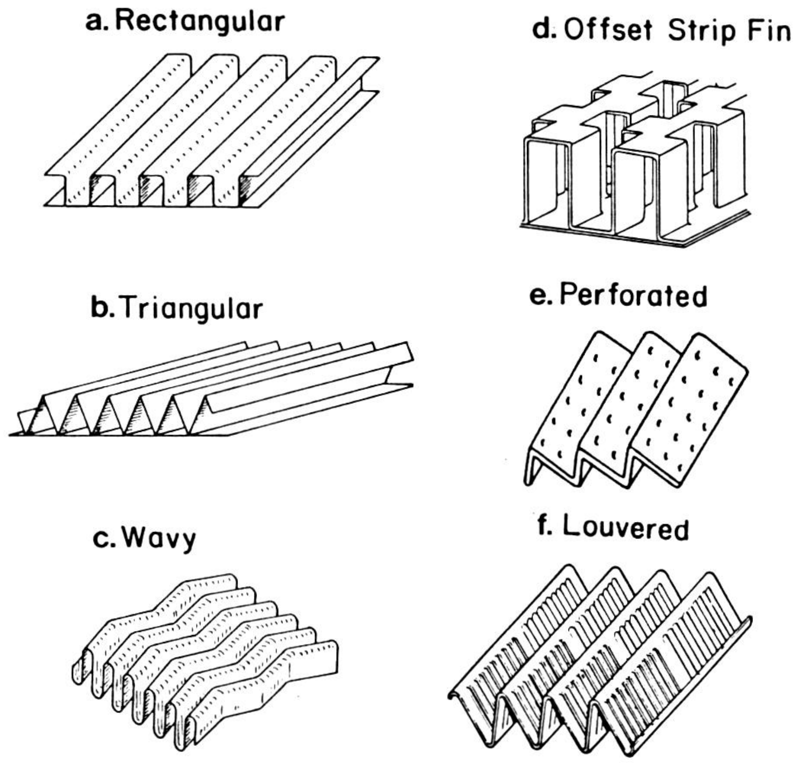


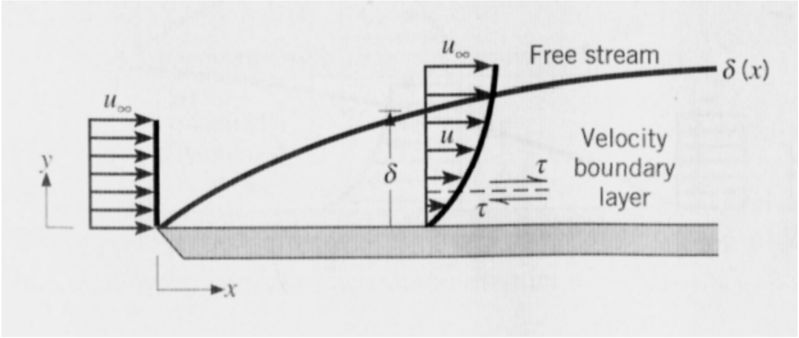


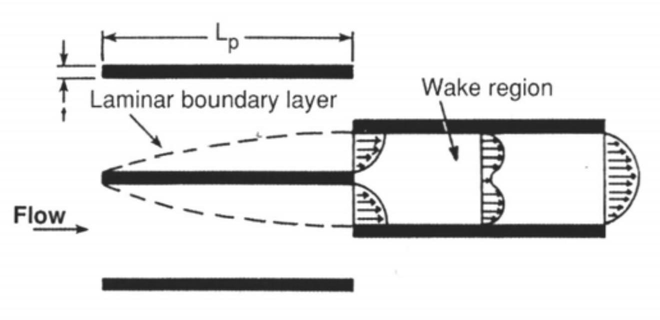


Augmentation – with the presence of fins

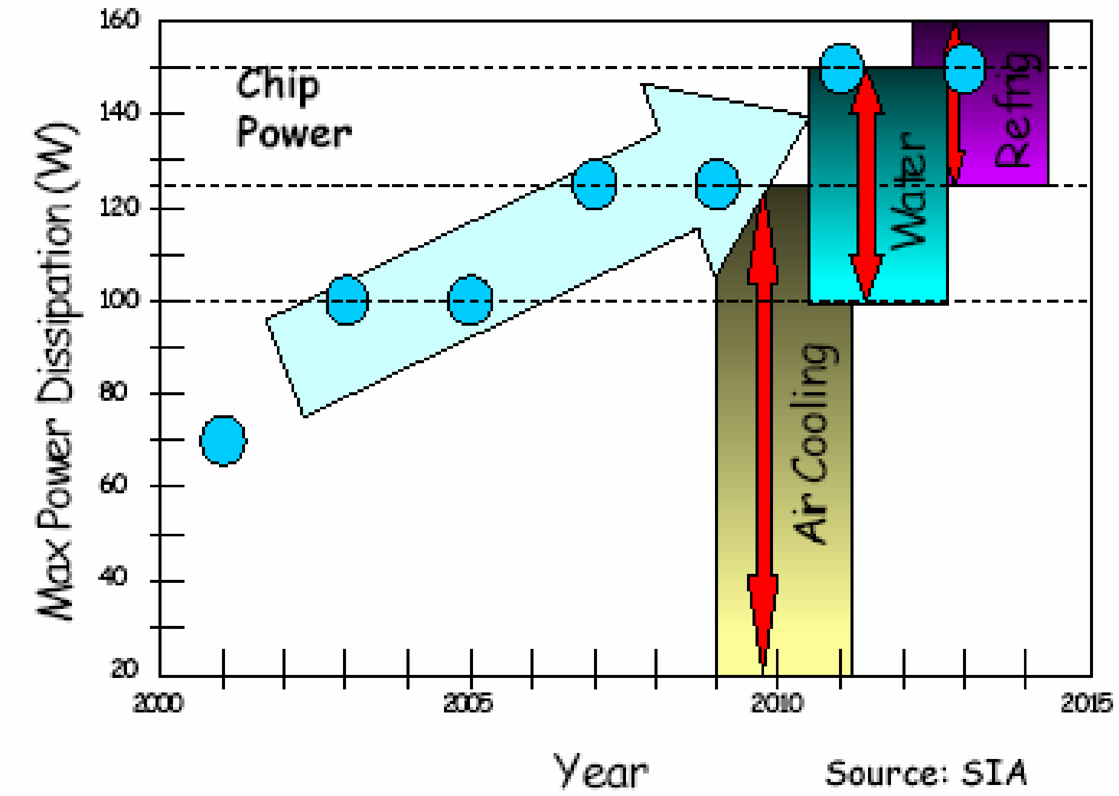
- OSF interrupted surface
- Boundary layer re-starting



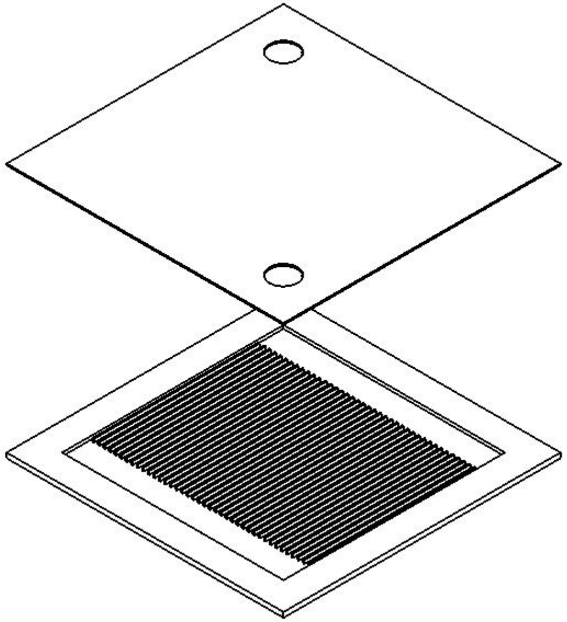




Water-cooled Micro-channel HXs Usually with micro-channels



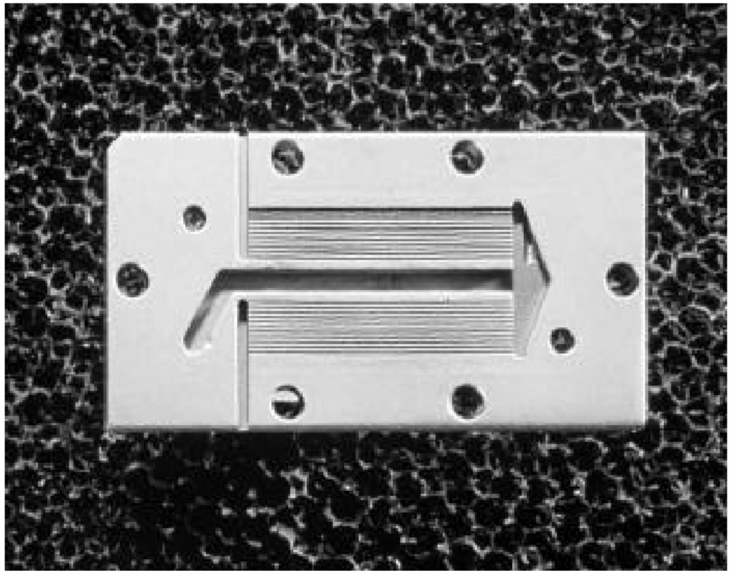
Source: SIA

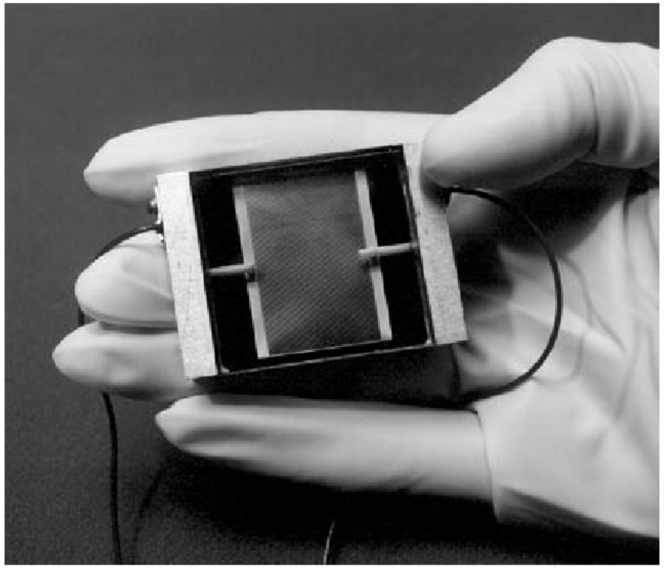


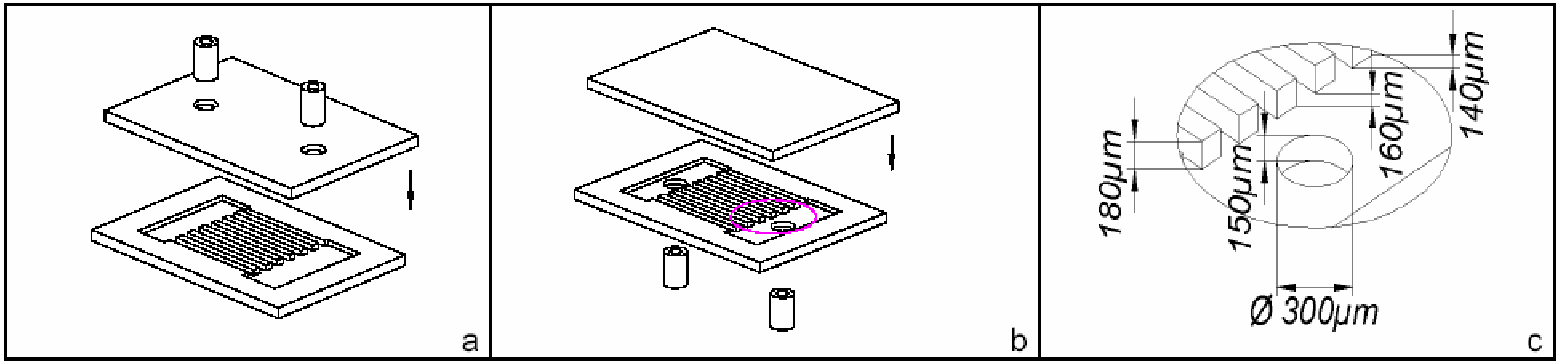
Coolermaster: AQUAGATE Mini:

Hitachi Water Cooling Laptop (Prototype Model)

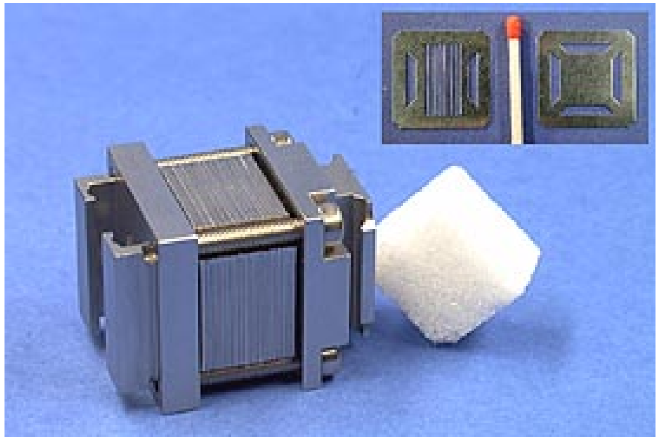
Micro-channel HXs - Examples

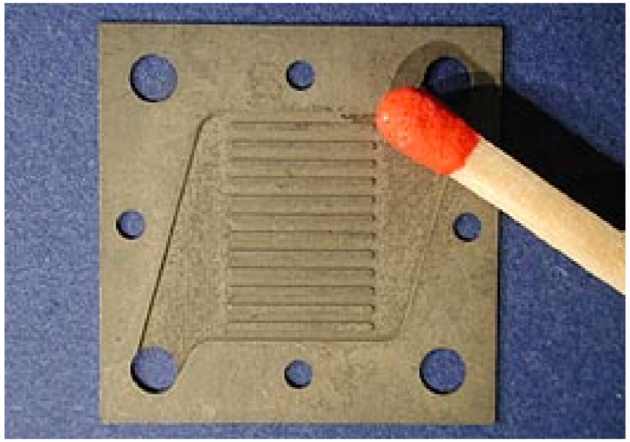


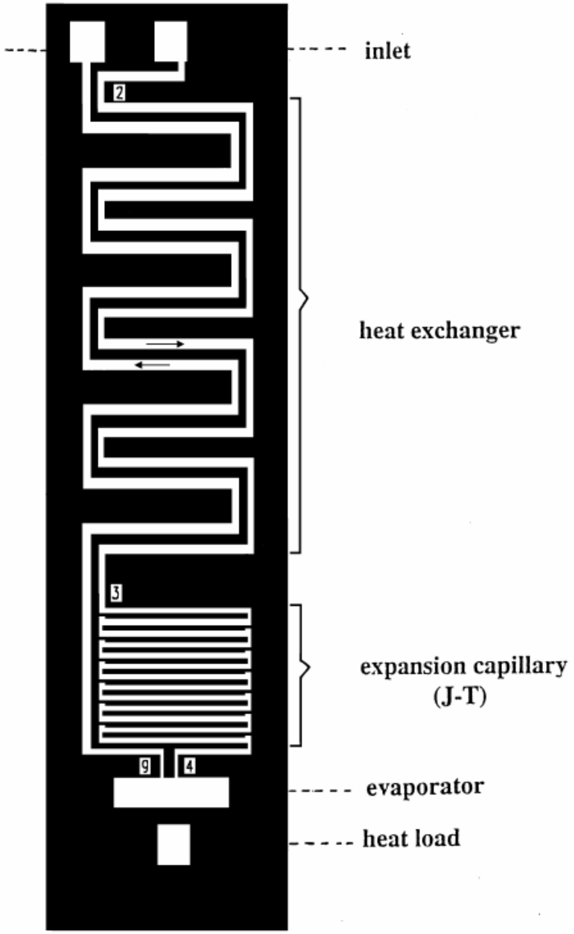




Micro-channel HXs - Examples

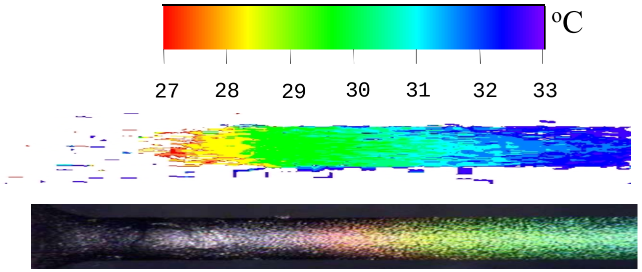


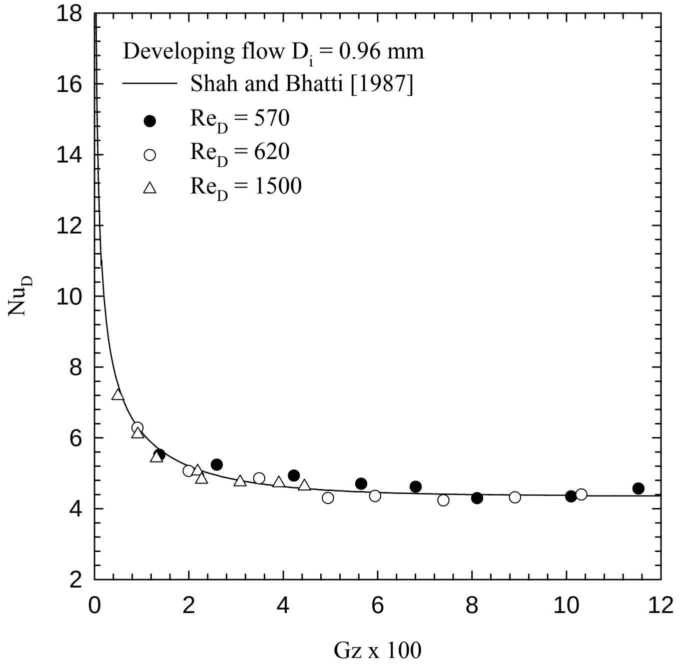


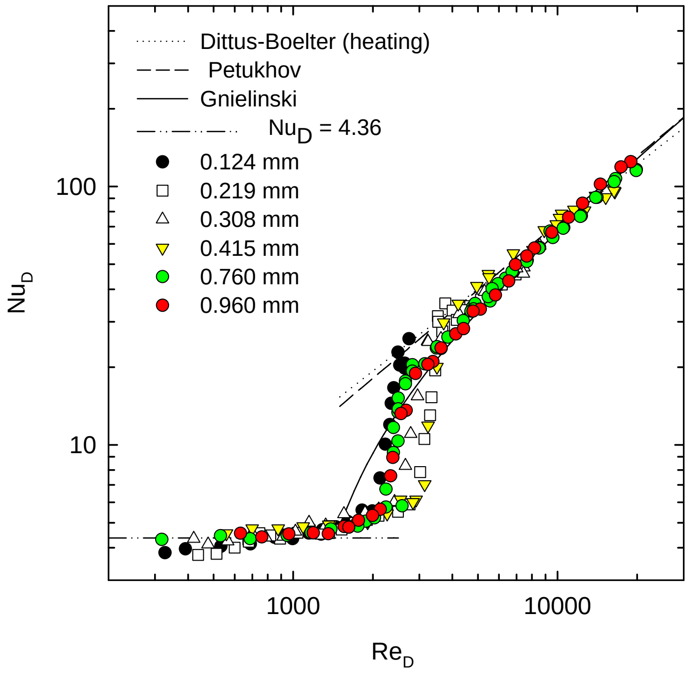


Does the heat/flow characteristics in micro channel behaves like macro channel?

- Nu_D (= hD/k)
- For single-phase fluid in the range of 0.1 to 1.0 mm, heat transfer behaves just like macro-channels

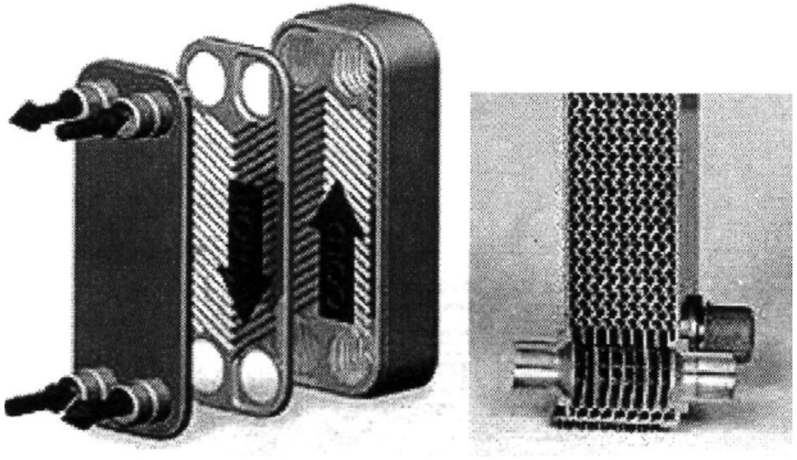


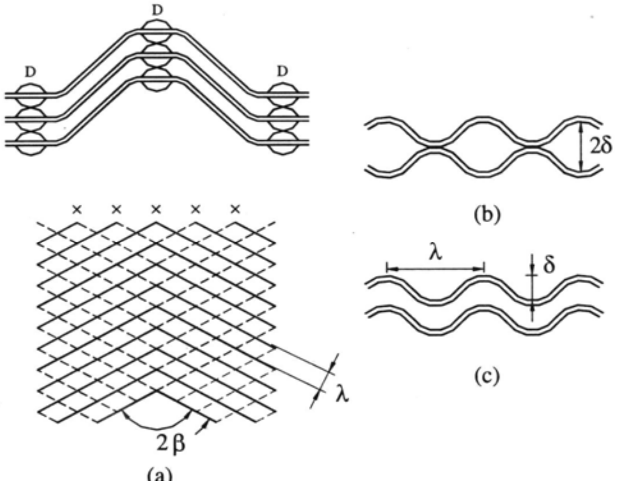


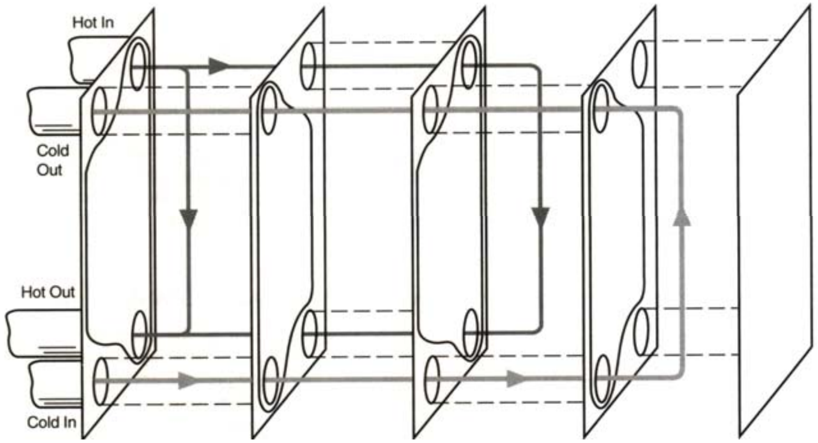


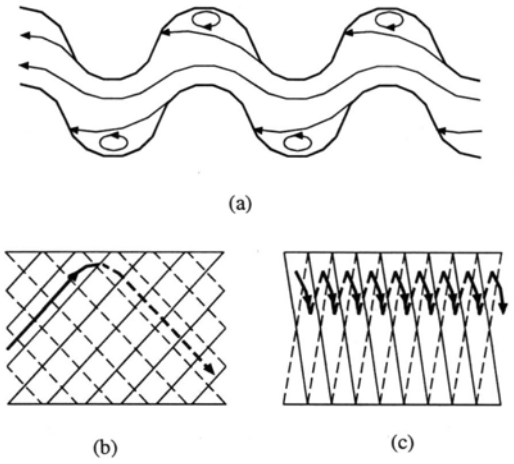
Courtesy of Prof. C.Y. Yang, Department of Mechanical Engng., NCU

Apply the conventional Plate HX





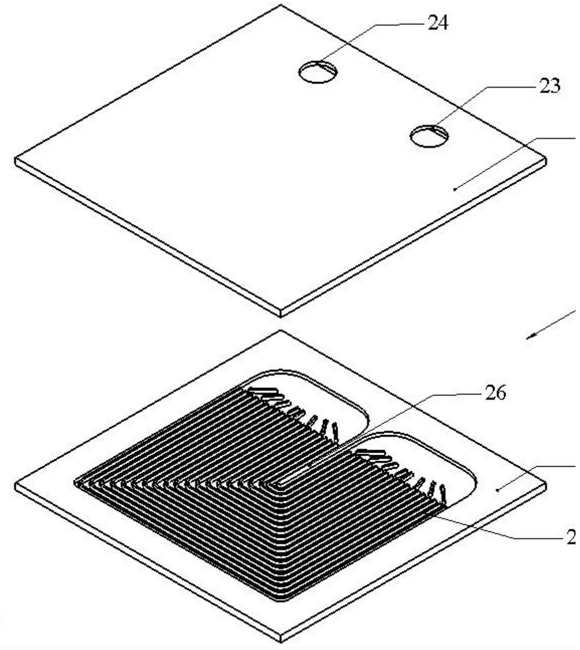




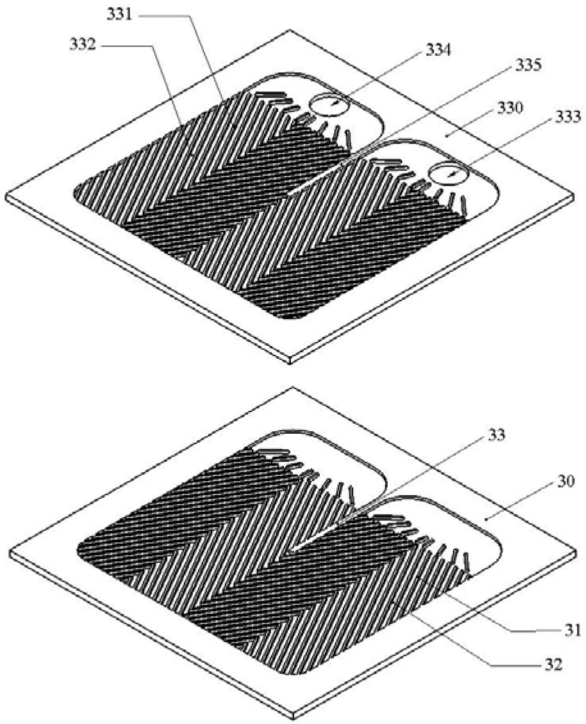
Augmentation based on plate HXs

dimension: 50 mm x 50 mm x 2 mm

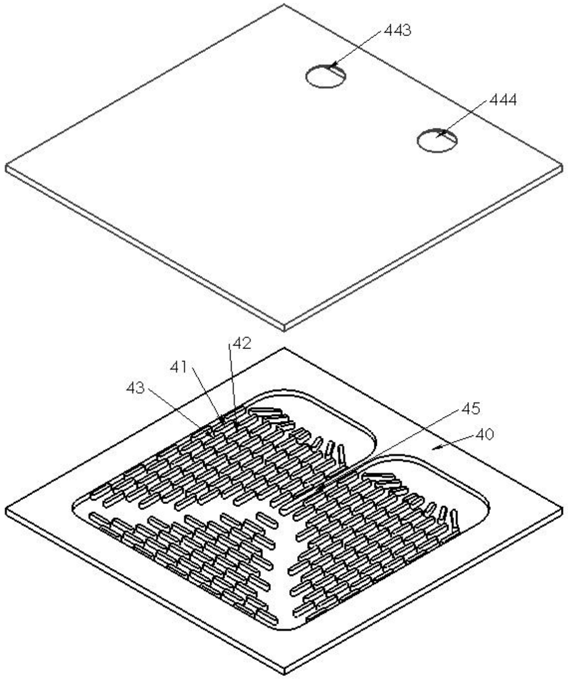
U - type



Chevron (V)

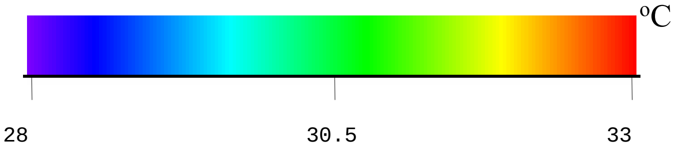


(OSF)

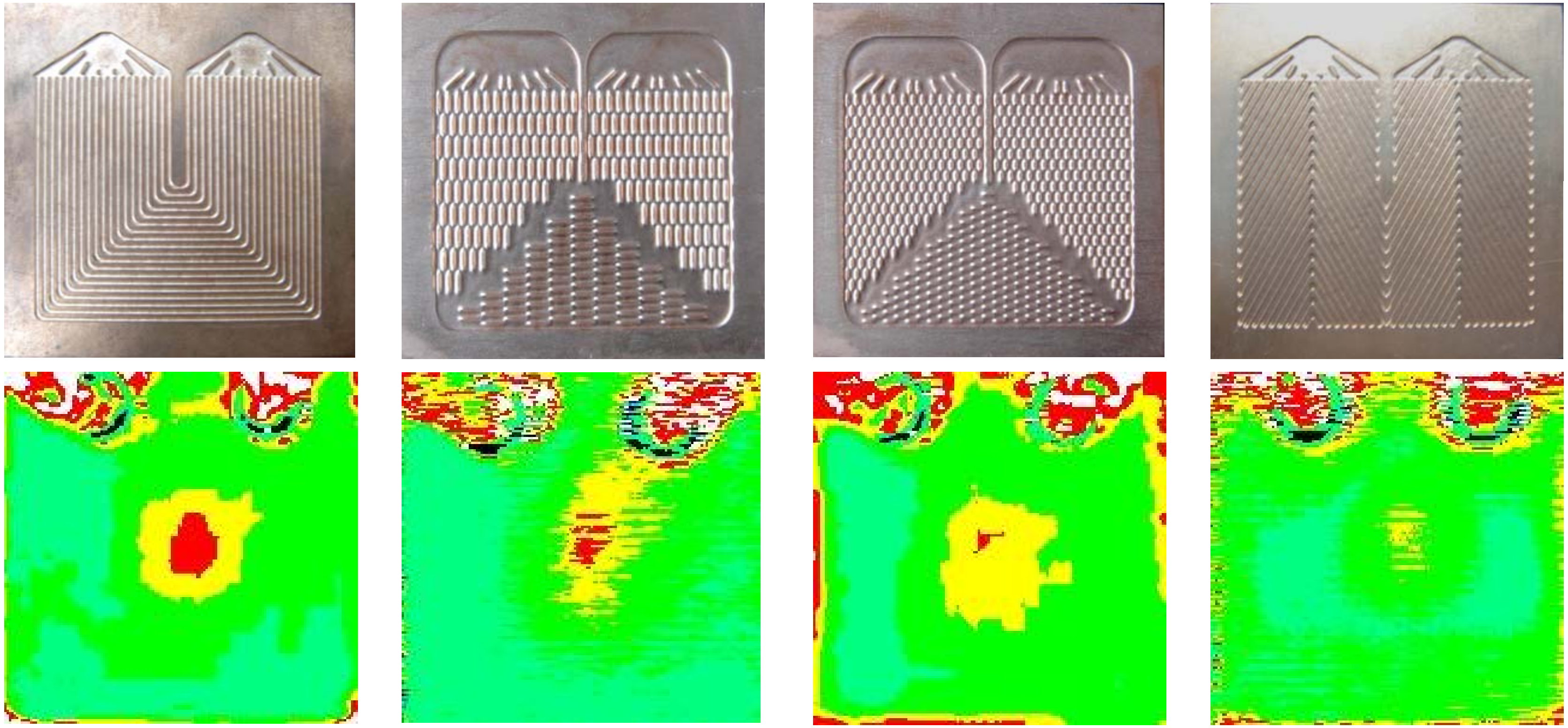


Courtesy of Prof. C.Y. Yang, Department of Mechanical Engng., NCU, cyyang@ncu.edu.tw

Temperature Distribution ..



	Power	Flowrate (mL/min)	Inlet Temp.
	20	230	30 ^oC



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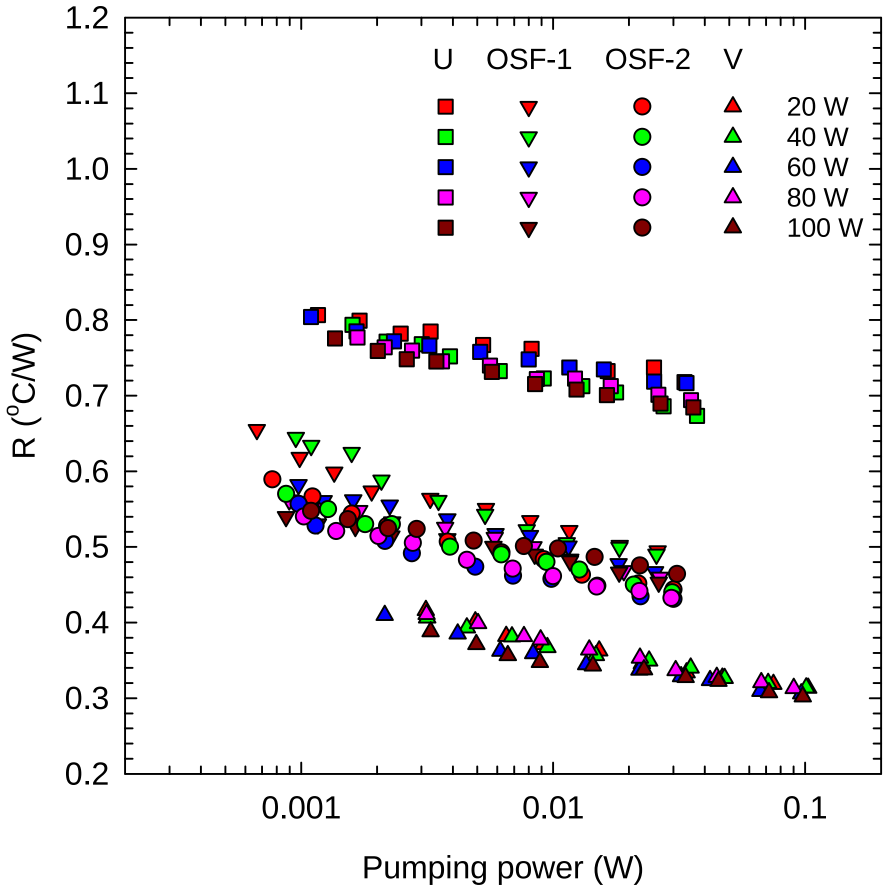
A comparison of Thermal Resistance vs. pumping power



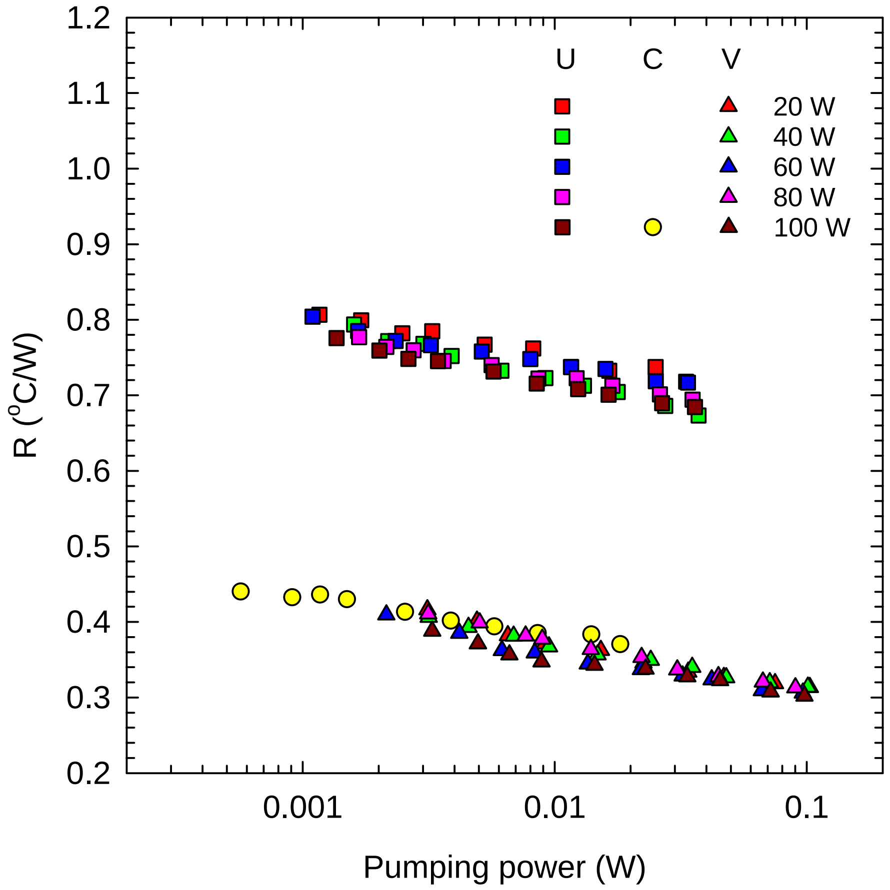
$$R = \frac{T_c - \frac{1}{2}(T_{wi} + T_{wo})}{q}$$

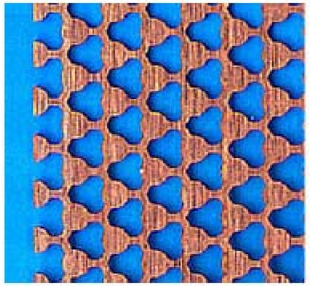
Courtesy of Prof. C.Y. Yang, Department of Mechanical Engng., NCU, cyyang@ncu.edu.tw

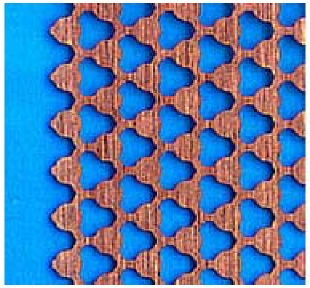
A comparison with some existing commercial products

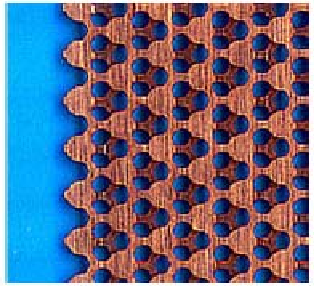
Dimension: U, V: 50 x 50 x 2 mm^3

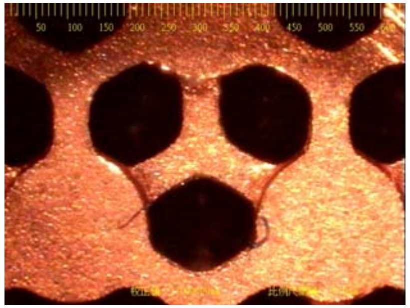
C: 40 x 40 x 4 mm^3

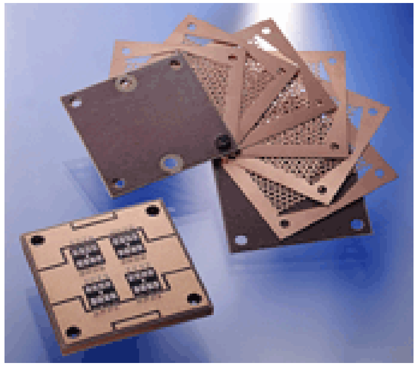


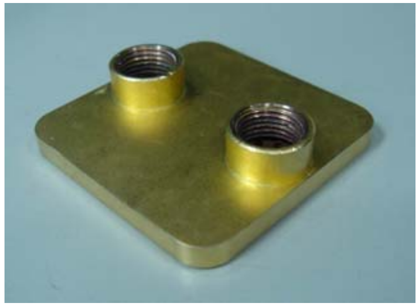








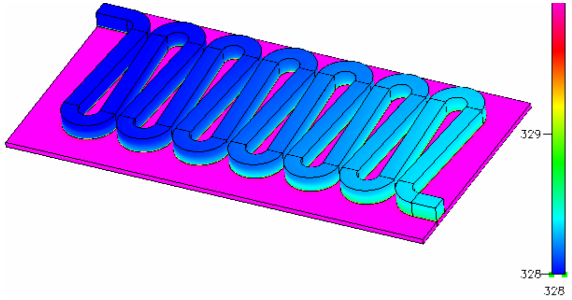




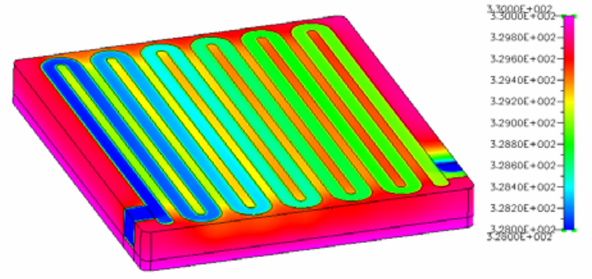
Courtesy of Prof. C.Y. Yang, Department of Mechanical Engng., NCU, cyyang@ncu.edu.tw

Cold Plate

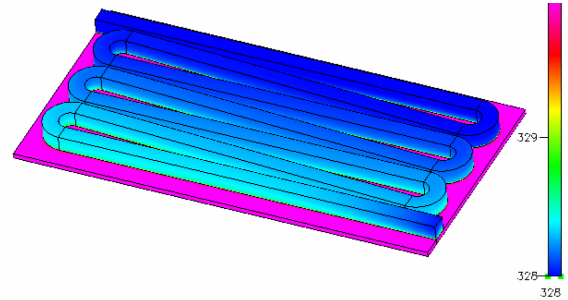
Serpentine vs. multi-port design



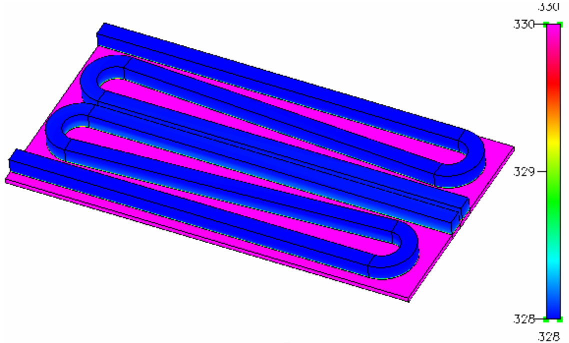
ΔP = 4.9 kPa
Q = 47.94 W



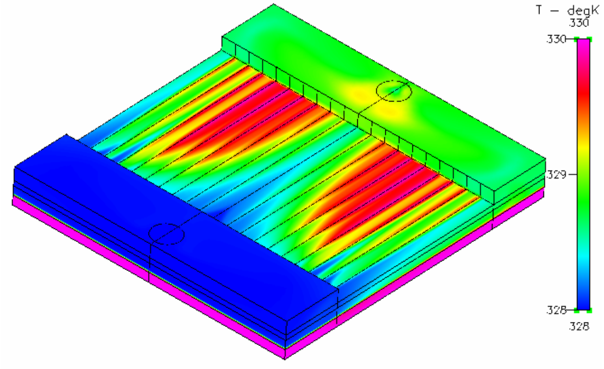
ΔP = 3.4 kPa
Q = 48.72 W



ΔP = 1.2 kPa
Q = 13.73 W

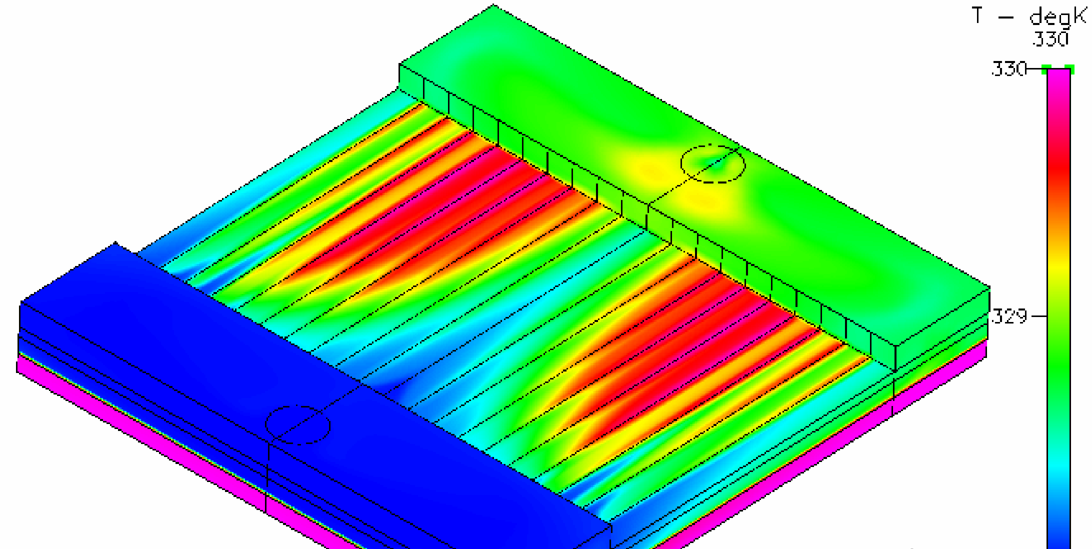


ΔP = 45.2 kPa
Q = 199.93 W



ΔP = 2.17 kPa
Q= 126.91 W

Multi-port HX



ΔP = 2.17 kPa

$\dot{Q}$ *= 126.91 J/s*

$\dot{Q}$ X 2.7

ΔP X 0.5

(1) *ΔP = 4.9 kPac*

$\dot{Q}$ *= 47.94 J/s*

V_{in} = 1.0 (m/s):

Flow mal-distribution:

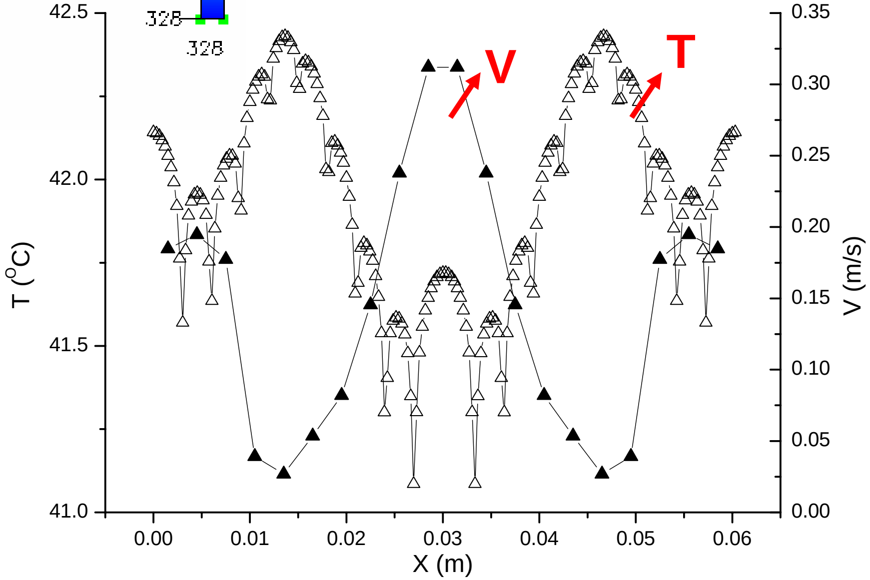
ΔV_{MAX} = 0.2852 (m/s)

Non-uniformity of Temperature field:

ΔT_{MAX} = 1.345 (°C)

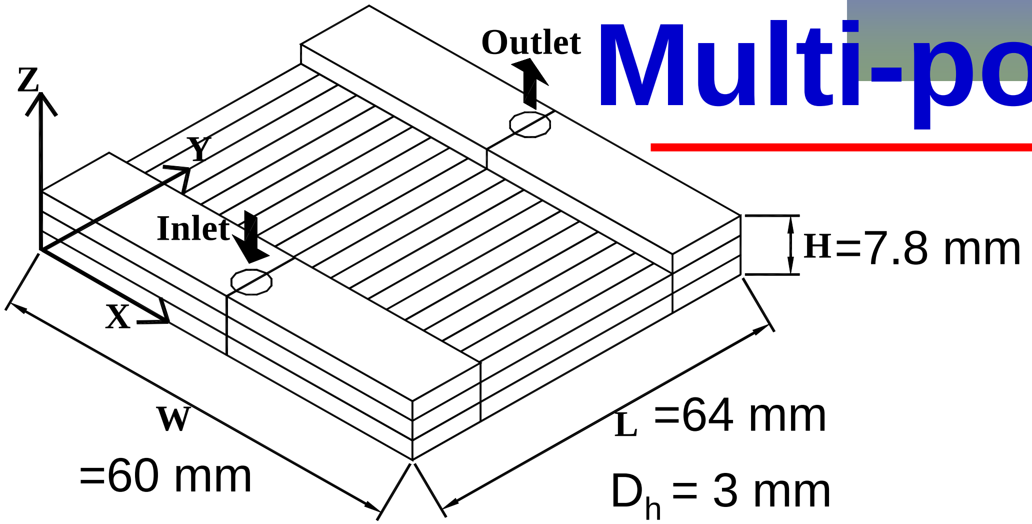
⇩

ΔQ_{MAX} = 148 (W)



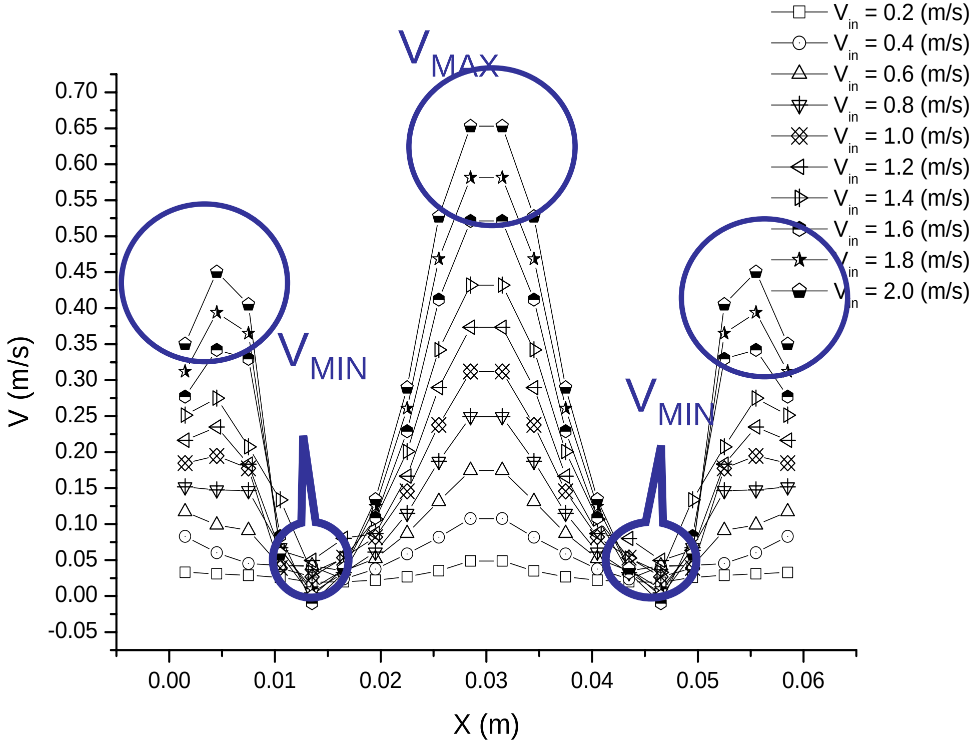
MC Lu et al., (2004)

Multi-port Cold Plate

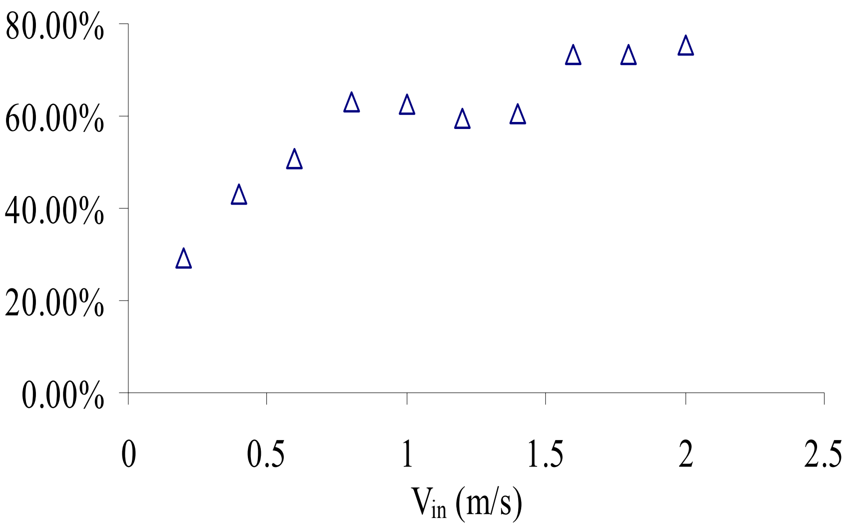


$$V_{STD} \equiv \sqrt{\frac{n\sum_i v_i^2 - (\sum_i v_i)^2}{n(n-1)}}$$

Transverse Velocity Distribution



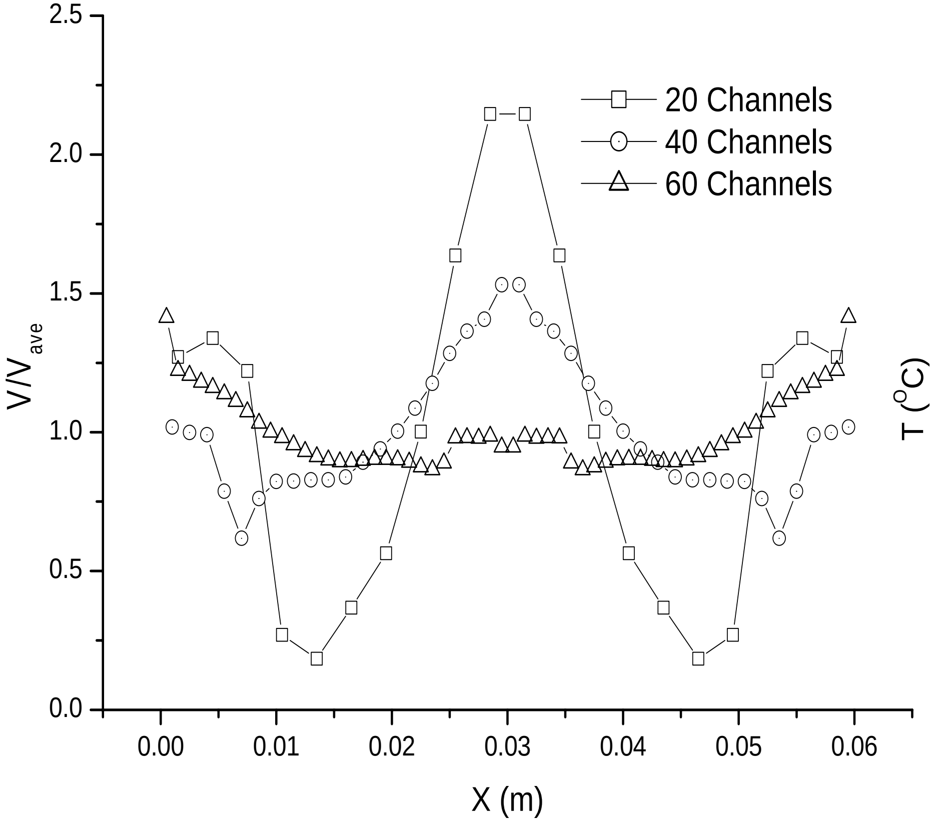
Flow Mal-distribution V_{STD}/V_{ave}



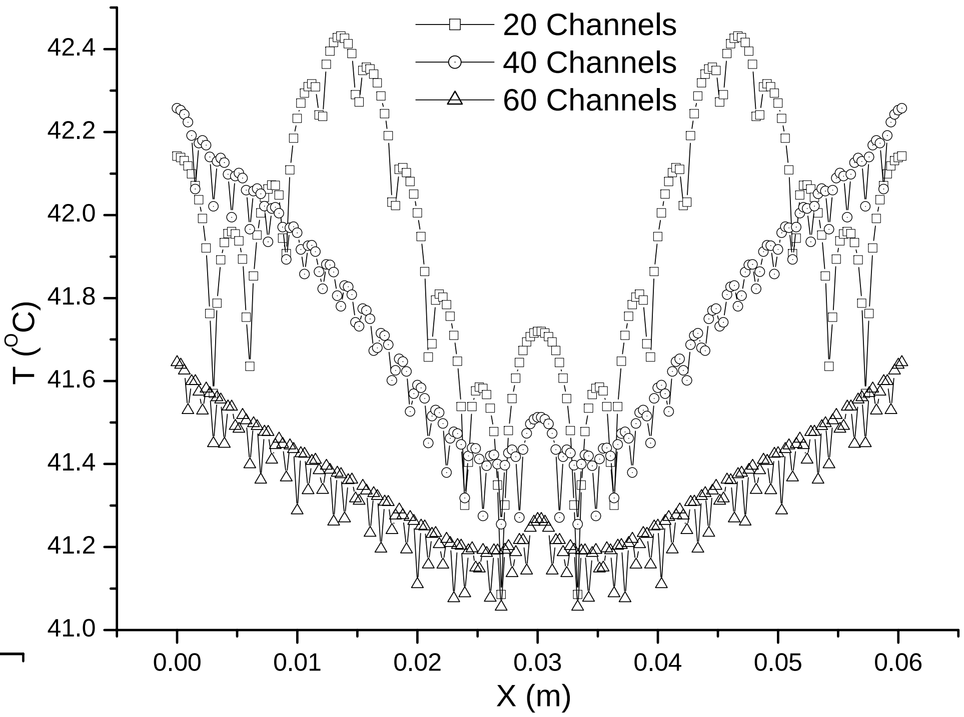
MC Lu et al., (2004)

Effect of number of port (20, 40, 60)

Velocity profiles of 20(☐), 40(O) and 60(Δ) channels for Vin =1.0 m/s.

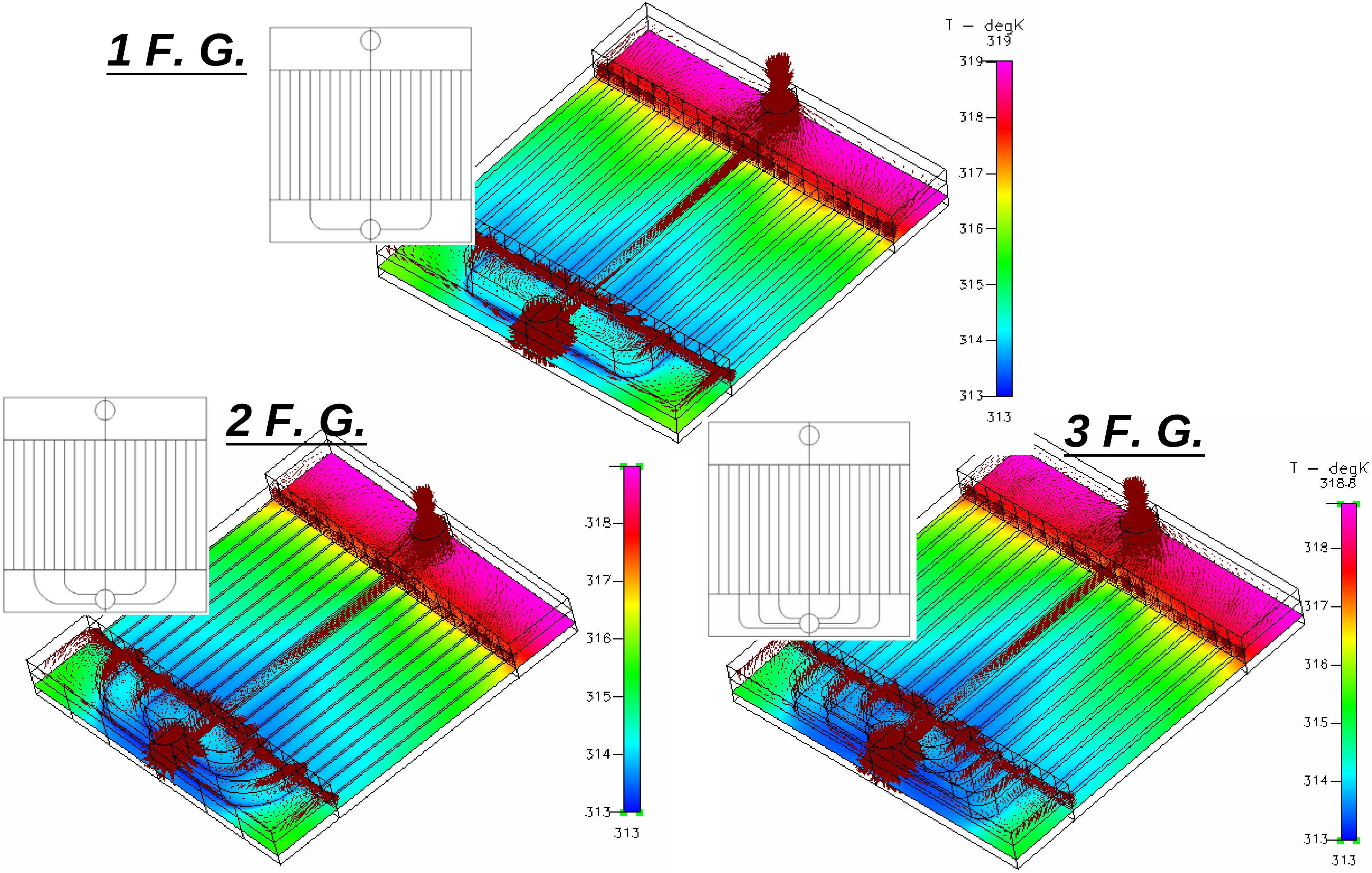


Temperature distribution of 20 (☐), 40 (O)and 60 (Δ) channels cold-plates for Vin = 1.0 m/s.



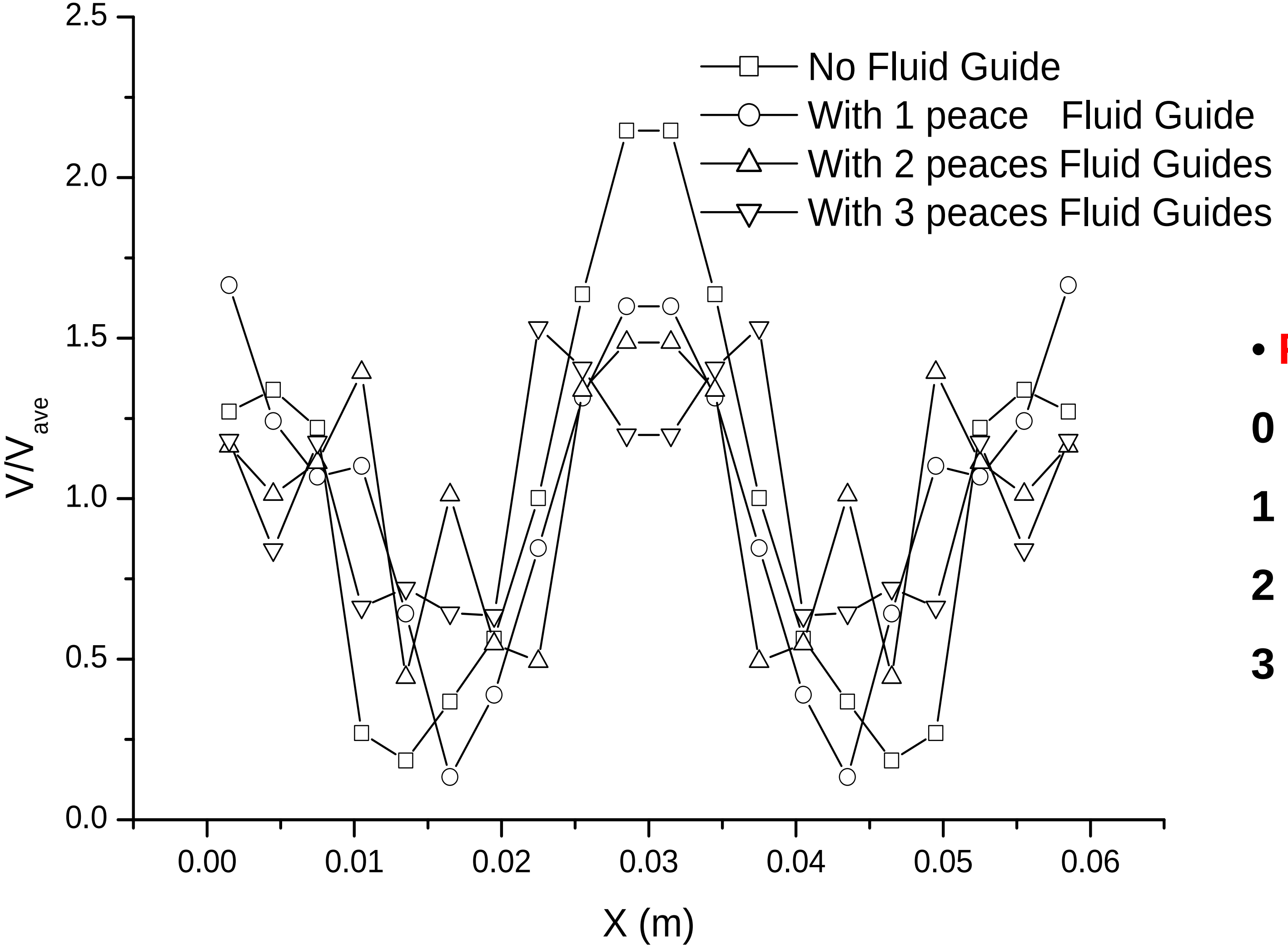
MC Lu et al., (2004)

Influence of Guide-plate



MC Lu et al., (2004)

Influence of Guide Plate, Conti.



- **Flow Mal-dis.**

0 F.G. : 62.7 %

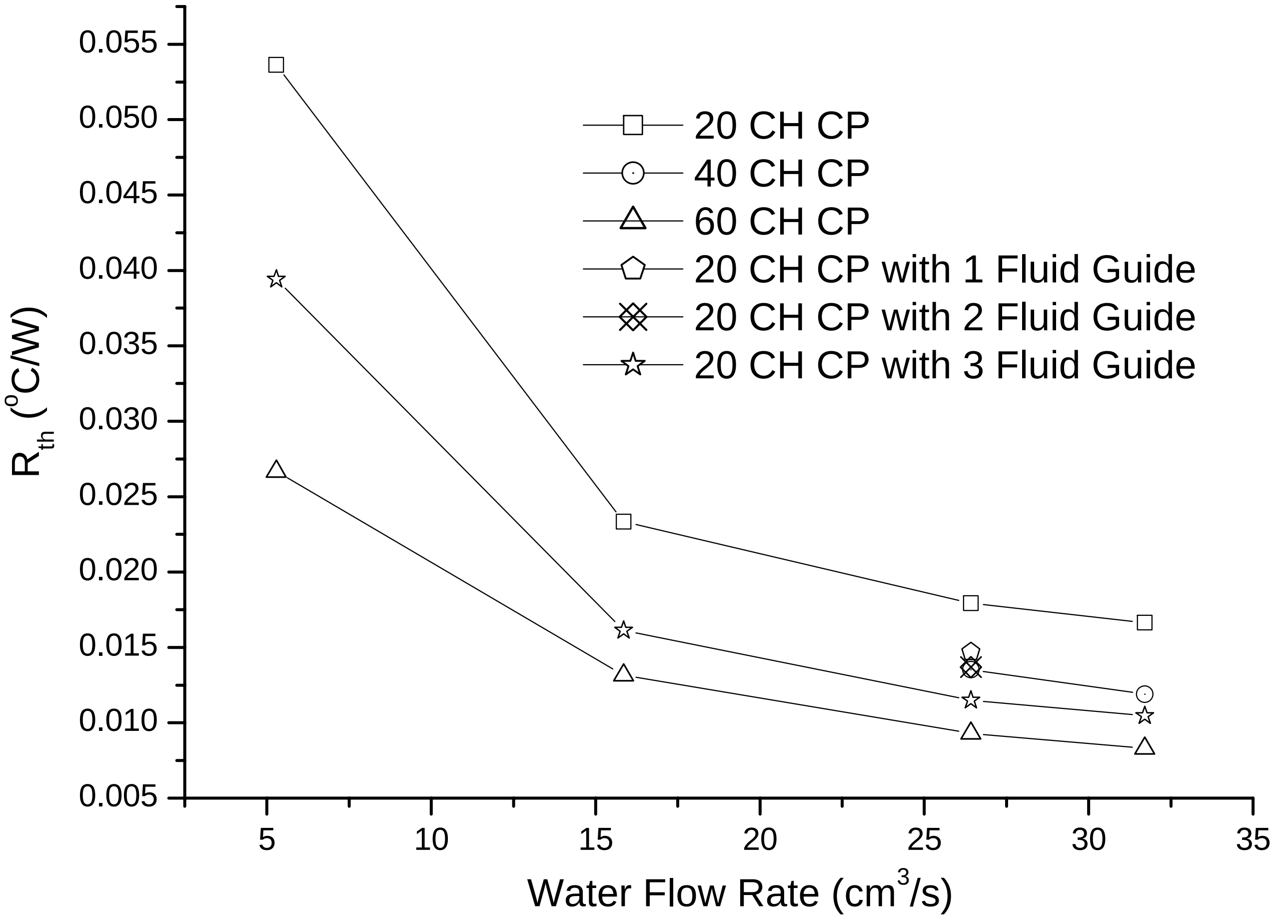
1 F.G. : 48.7 %

2 F.G. : 37.2 %

3 F.G. : 32.3 %

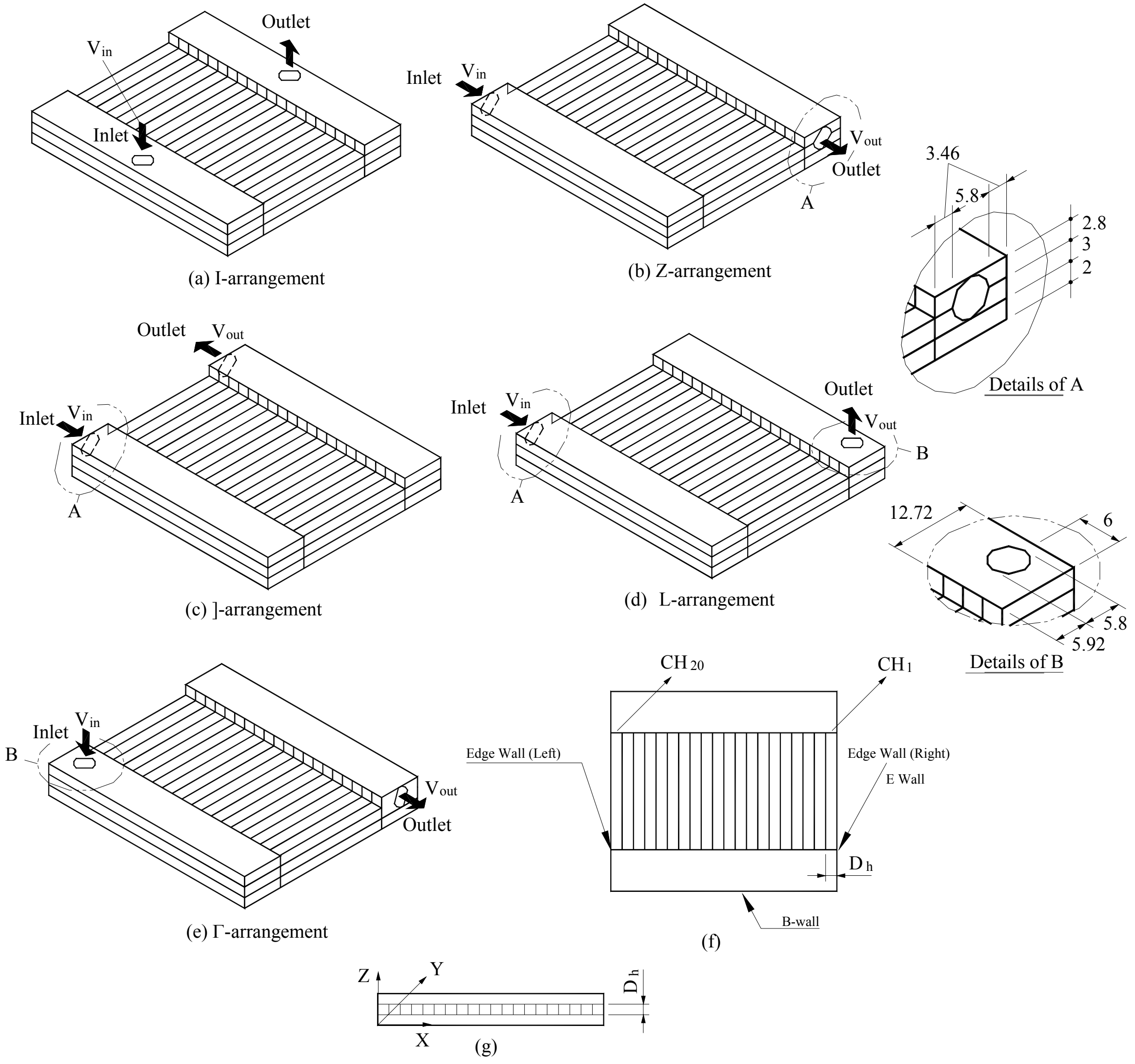
MC Lu et al., (2004)

Effect of Guide Plate – R_{th}



MC Lu et al., (2004)

Effect of Inlet locations



(a) I-arrangement

(b) Z-arrangement

(c)]-arrangement

(d) L-arrangement

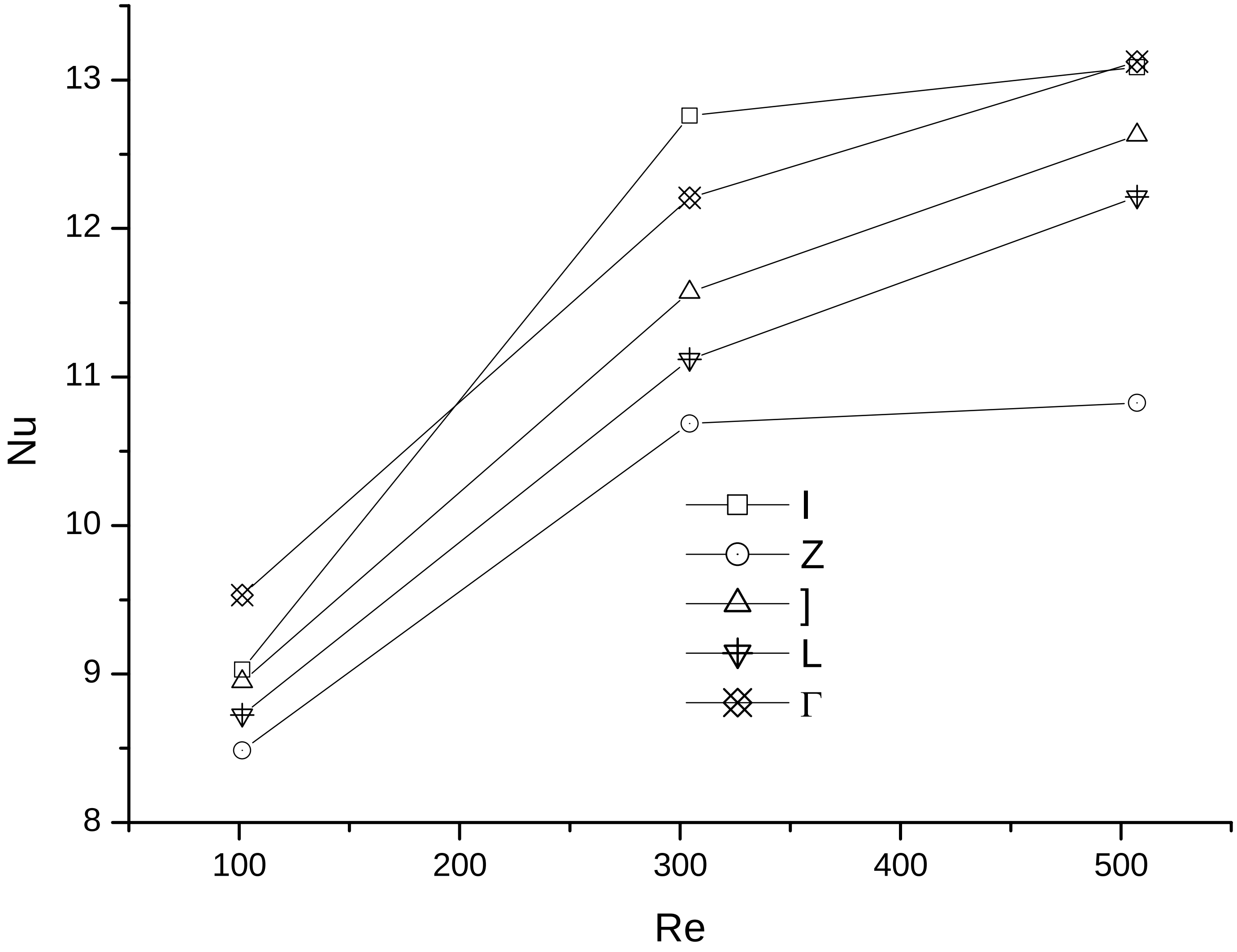
(e) Γ-arrangement

(f)

(g)

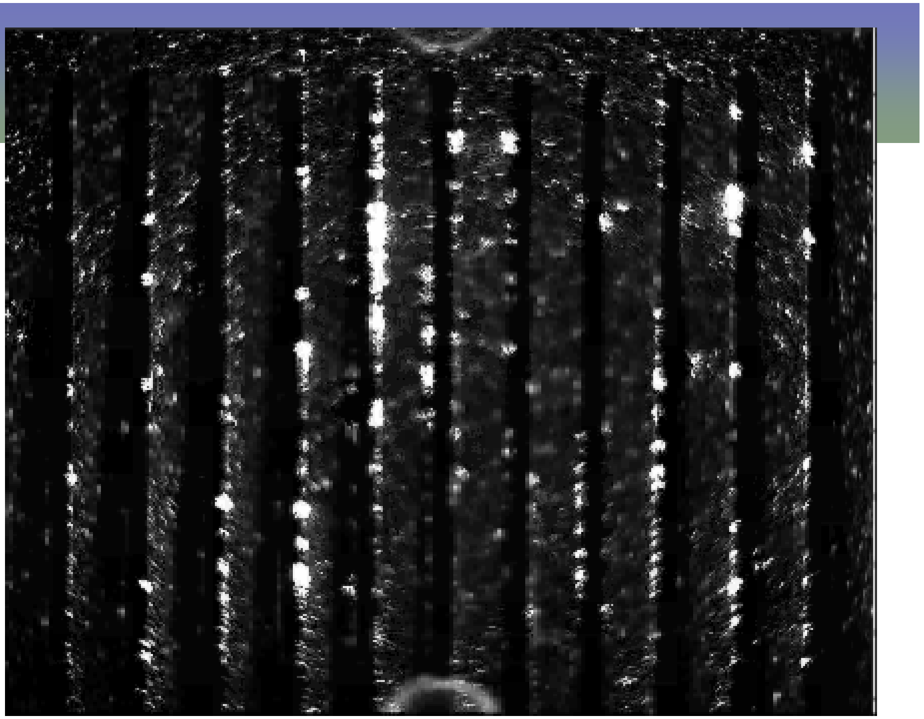
Lu and Wang, (2005)

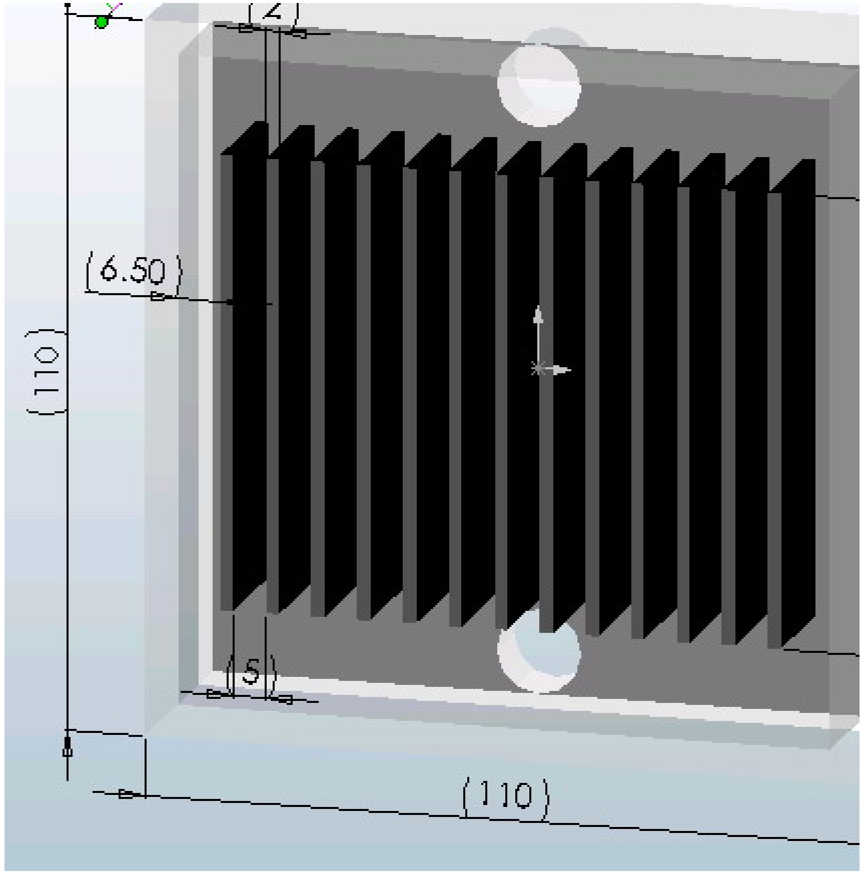
Effect of Inlet locations, Conti..

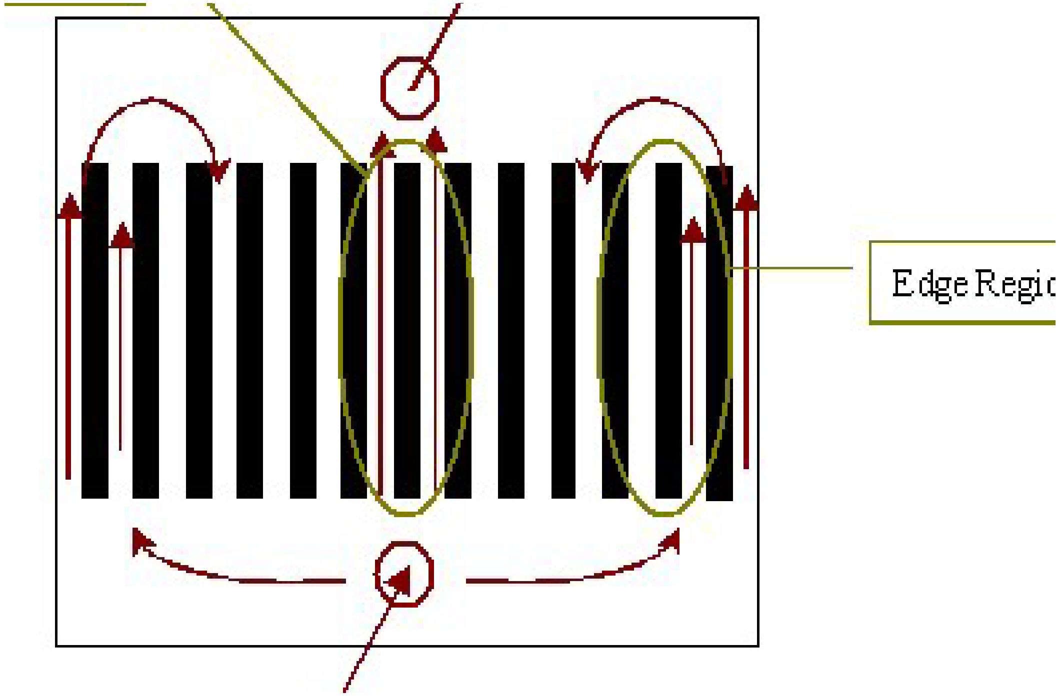


Lu and Wang, (2005)

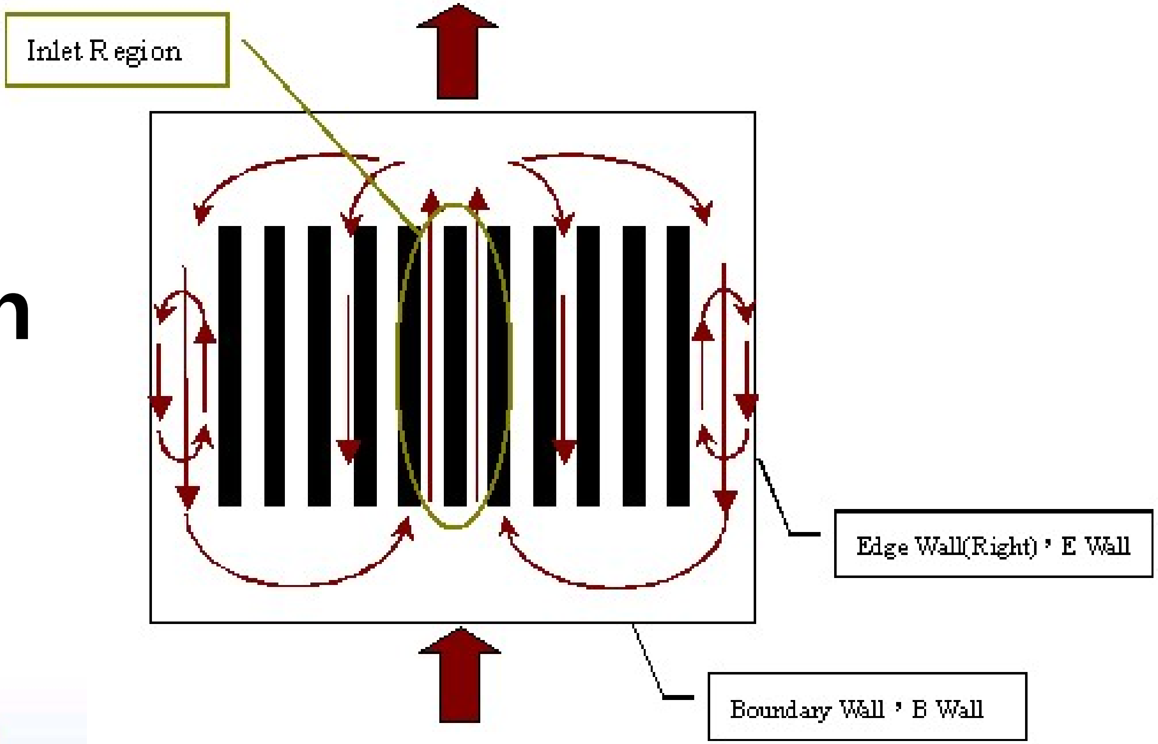
PIV Flow Visualization : I Arrangement – Uniform Gap

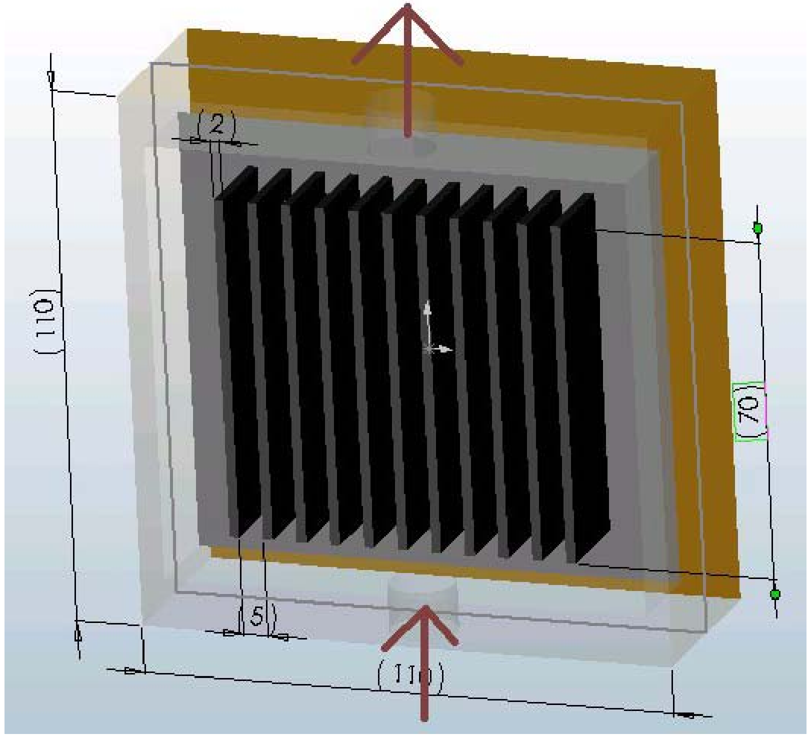


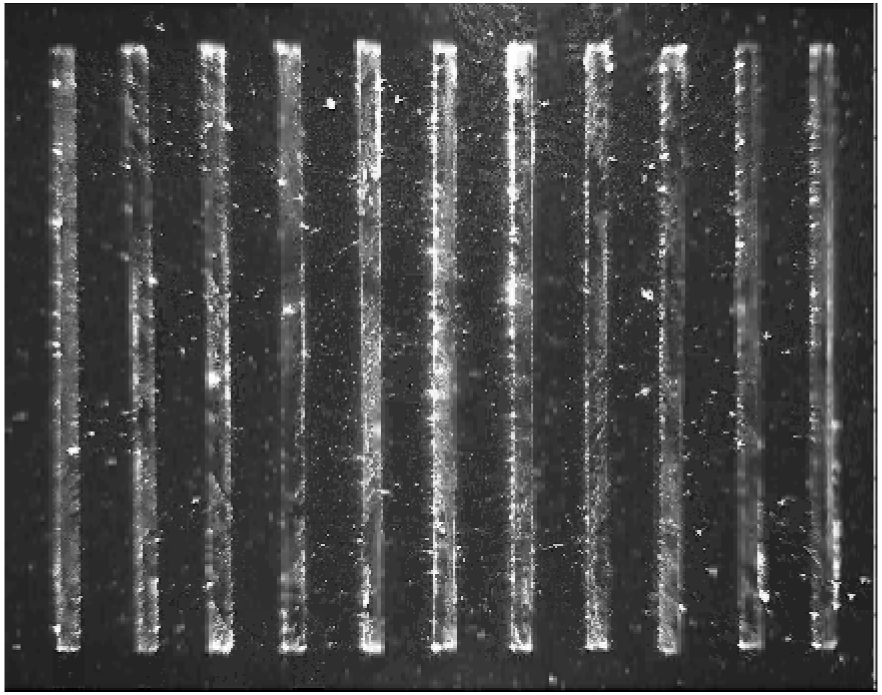




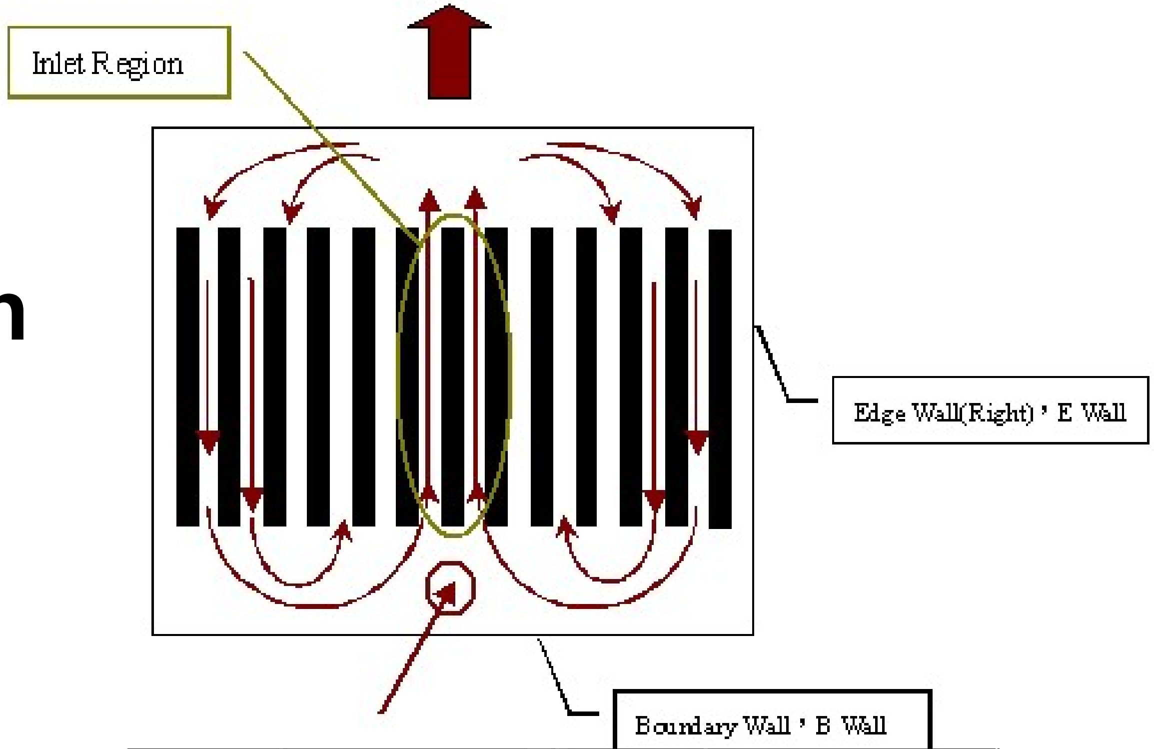
PIV
Flow Visualization

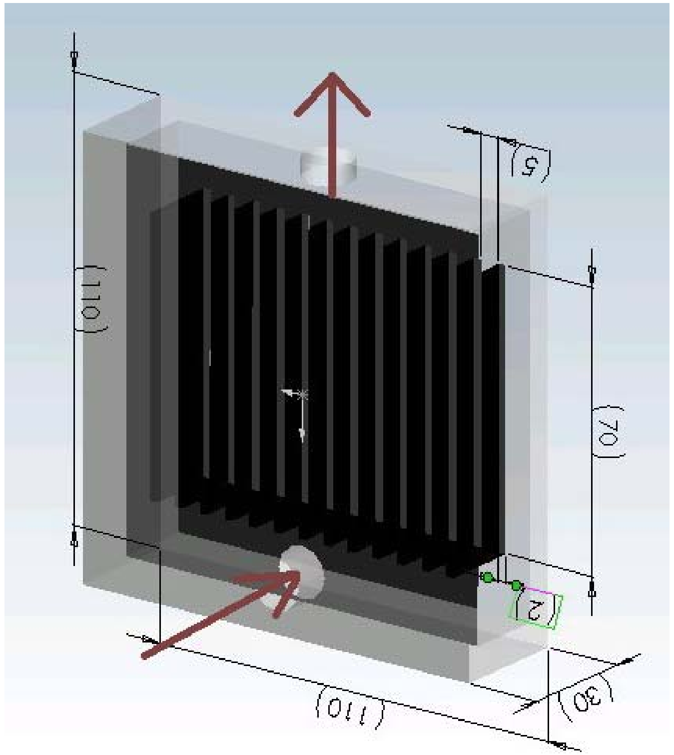


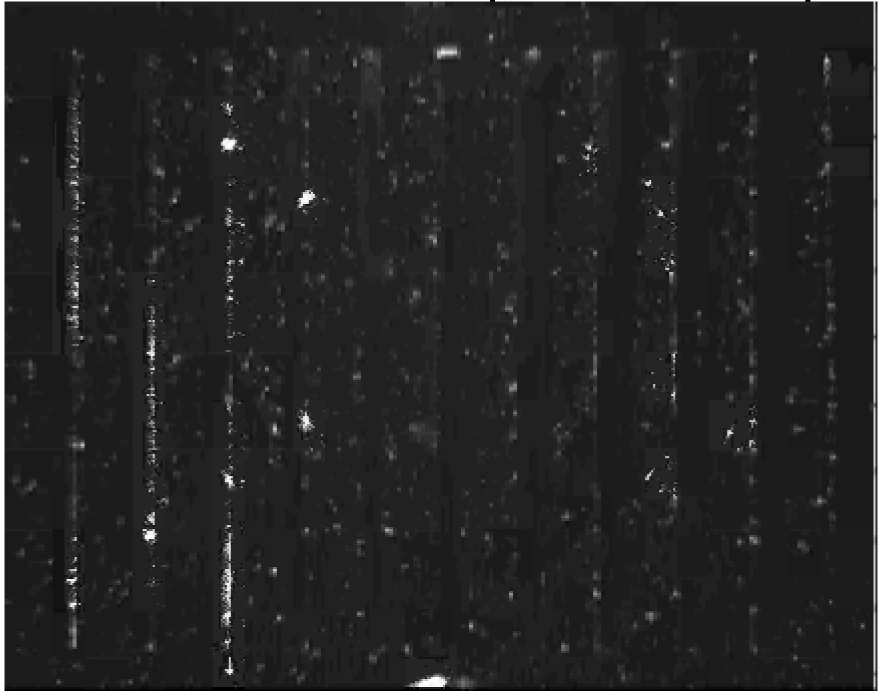




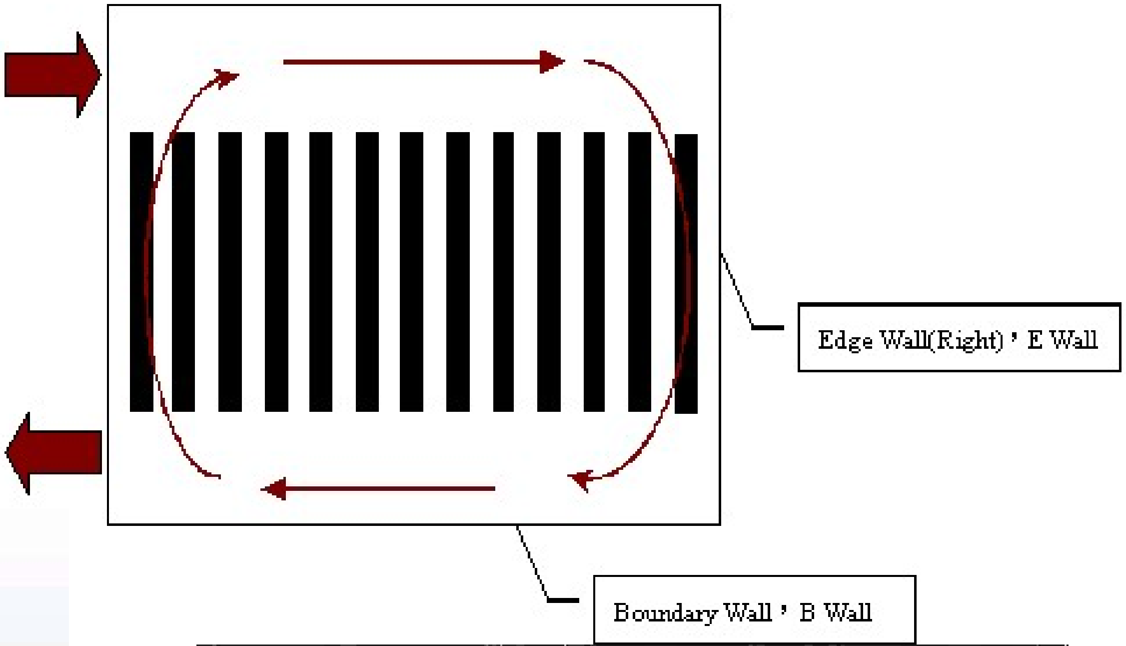
PIV
Flow Visualization

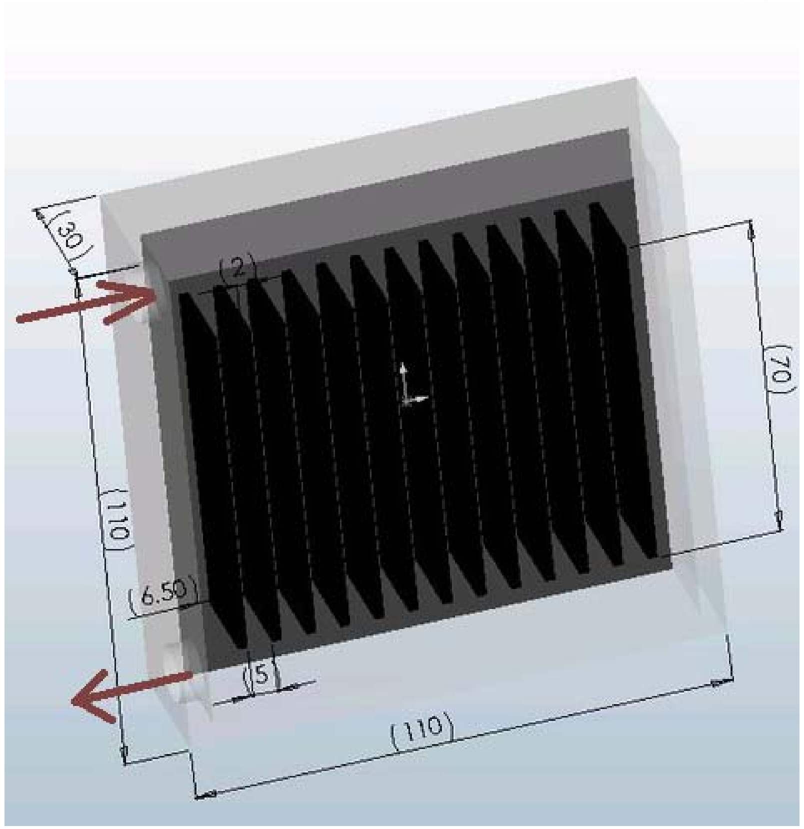


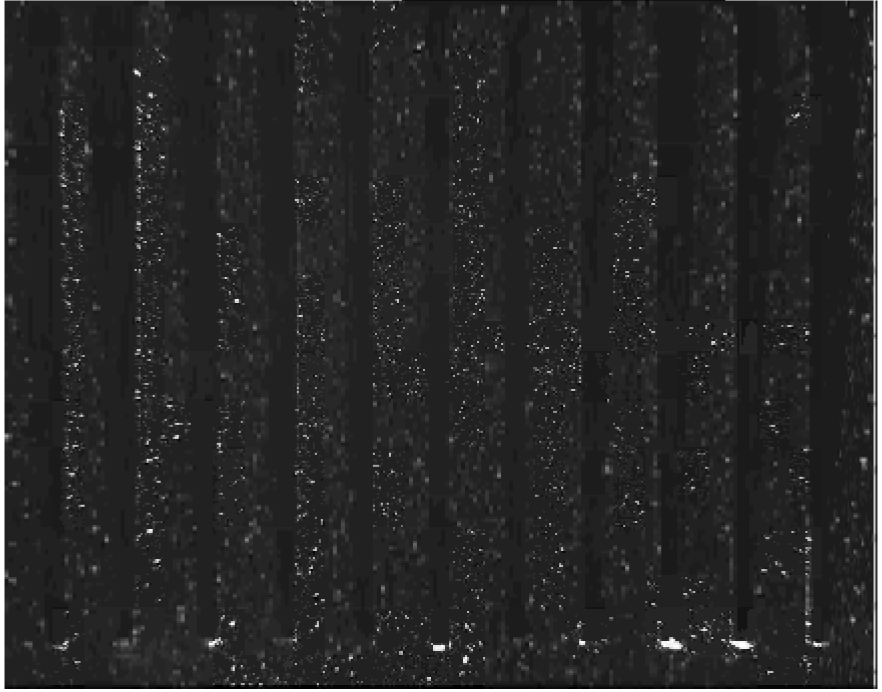




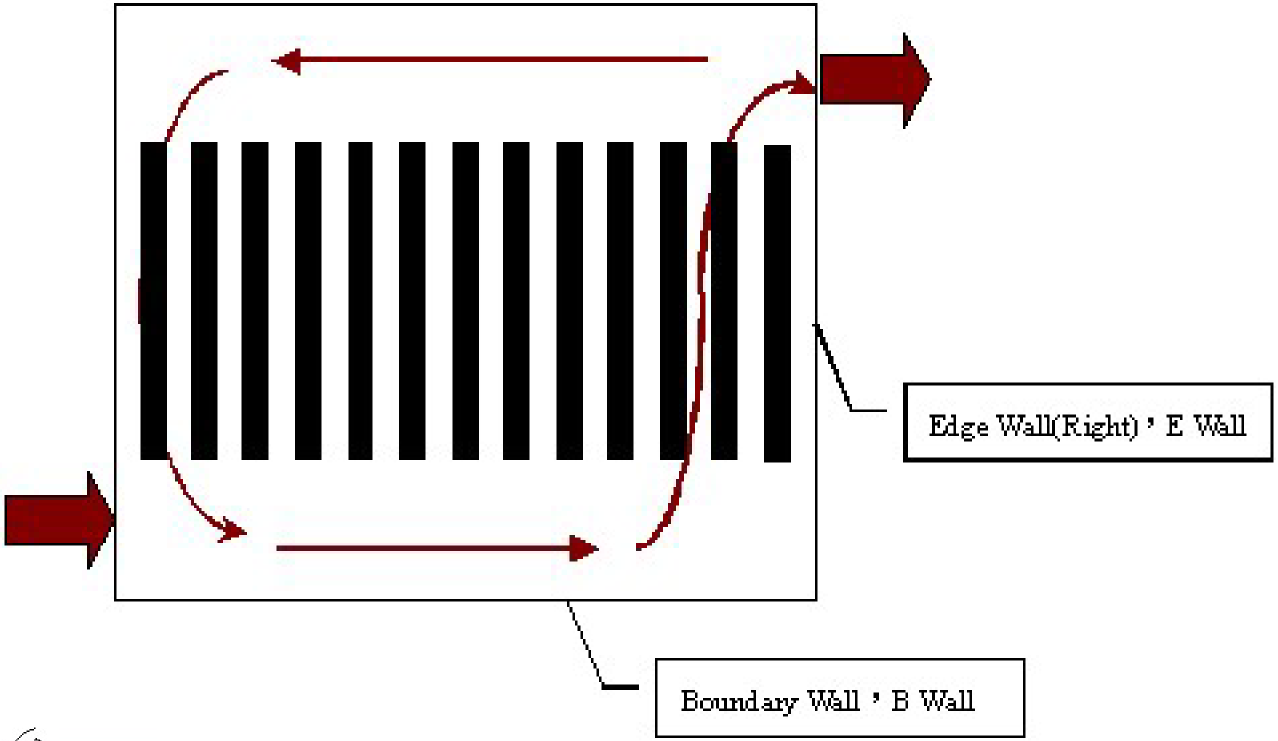
PIV
Flow Visualization

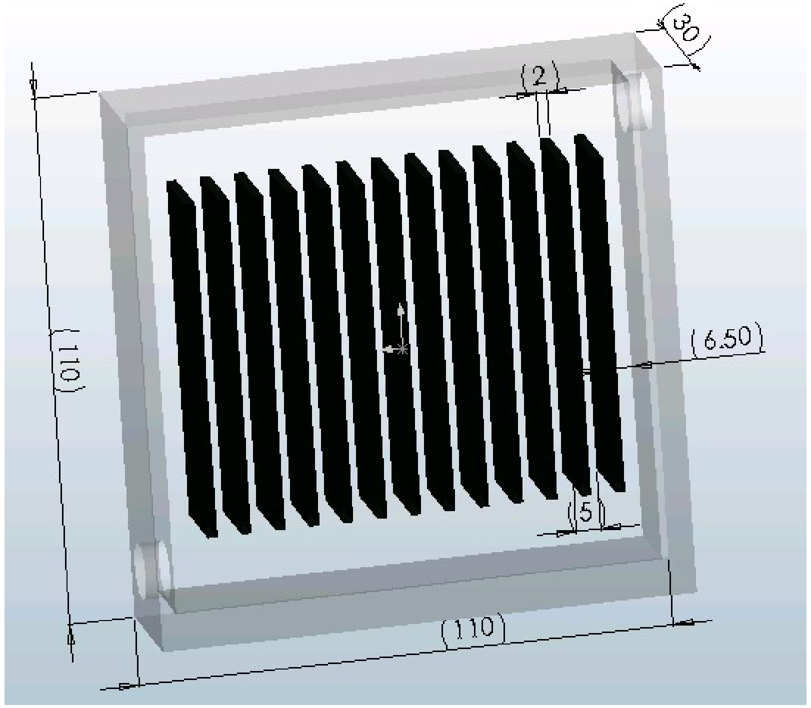


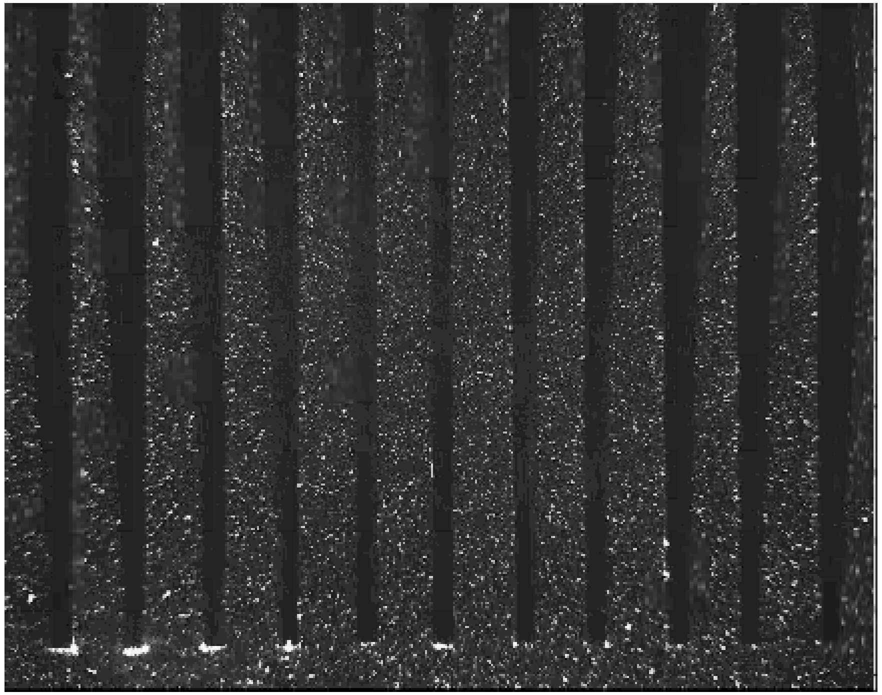




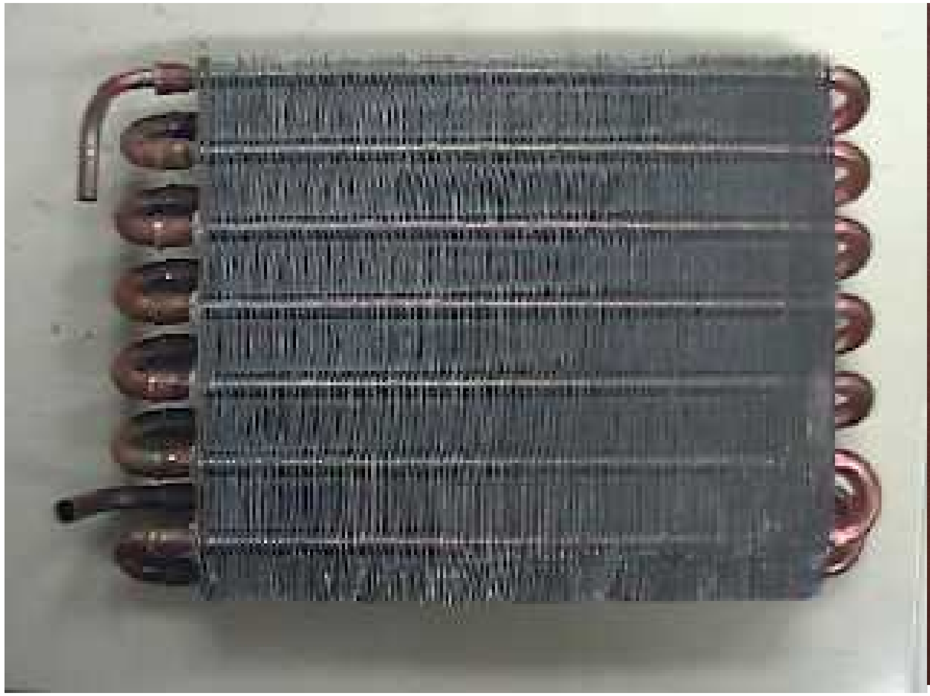
PIV Flow Visualization



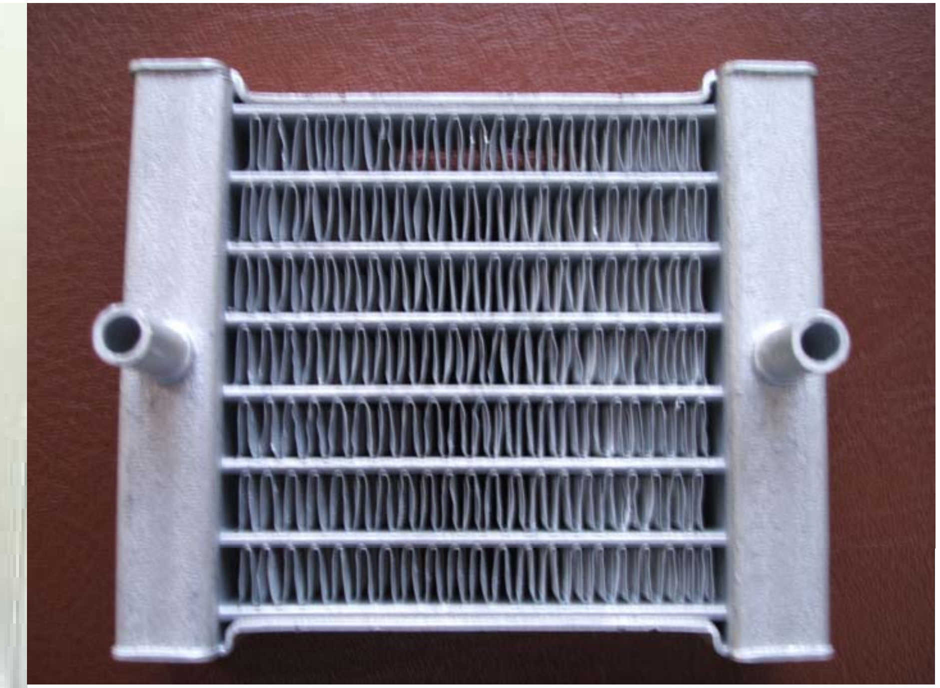




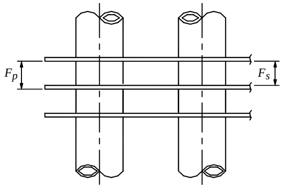
Radiator – air-cooled HX



Copper Fin-and-tube HX

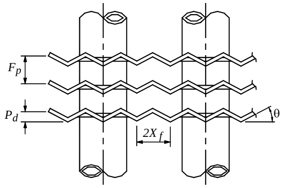


Aluminum Brazed Heat Exchanger



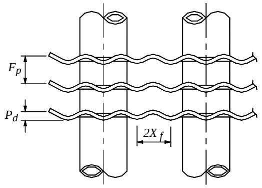
(a) 平板型

Plain fin



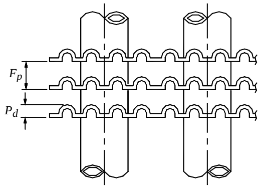
(b) 波浪型

Herringbone wavy fin



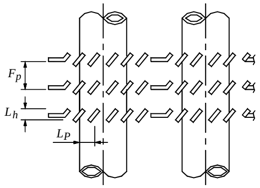
(c) 平滑波浪型

Smooth wavy fin, type (I)



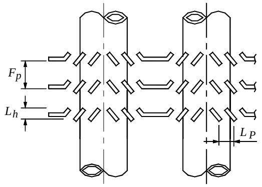
(d) 平滑波浪+平板型

Smooth wavy fin, type (II)



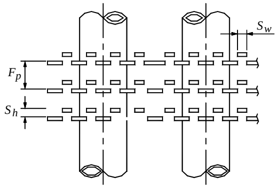
(e) 單向百葉窗型

Louver fin, one-sided



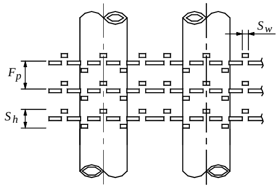
(f) 雙向百葉窗型

Louver fin, with re-direction louver



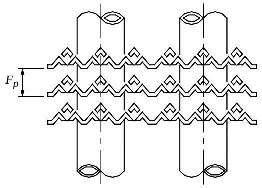
(g) 單向裂口型

Slit fin, one-sided



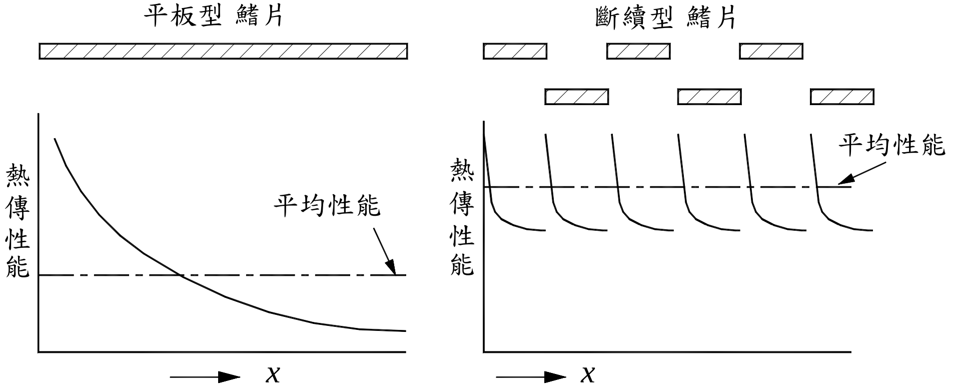
(h) 雙向裂口型

Slit fin, double-sided

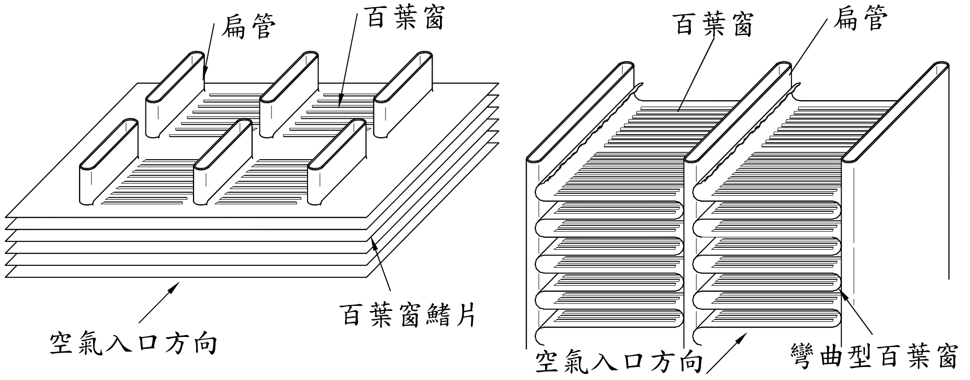


(i) 複和百葉窗型

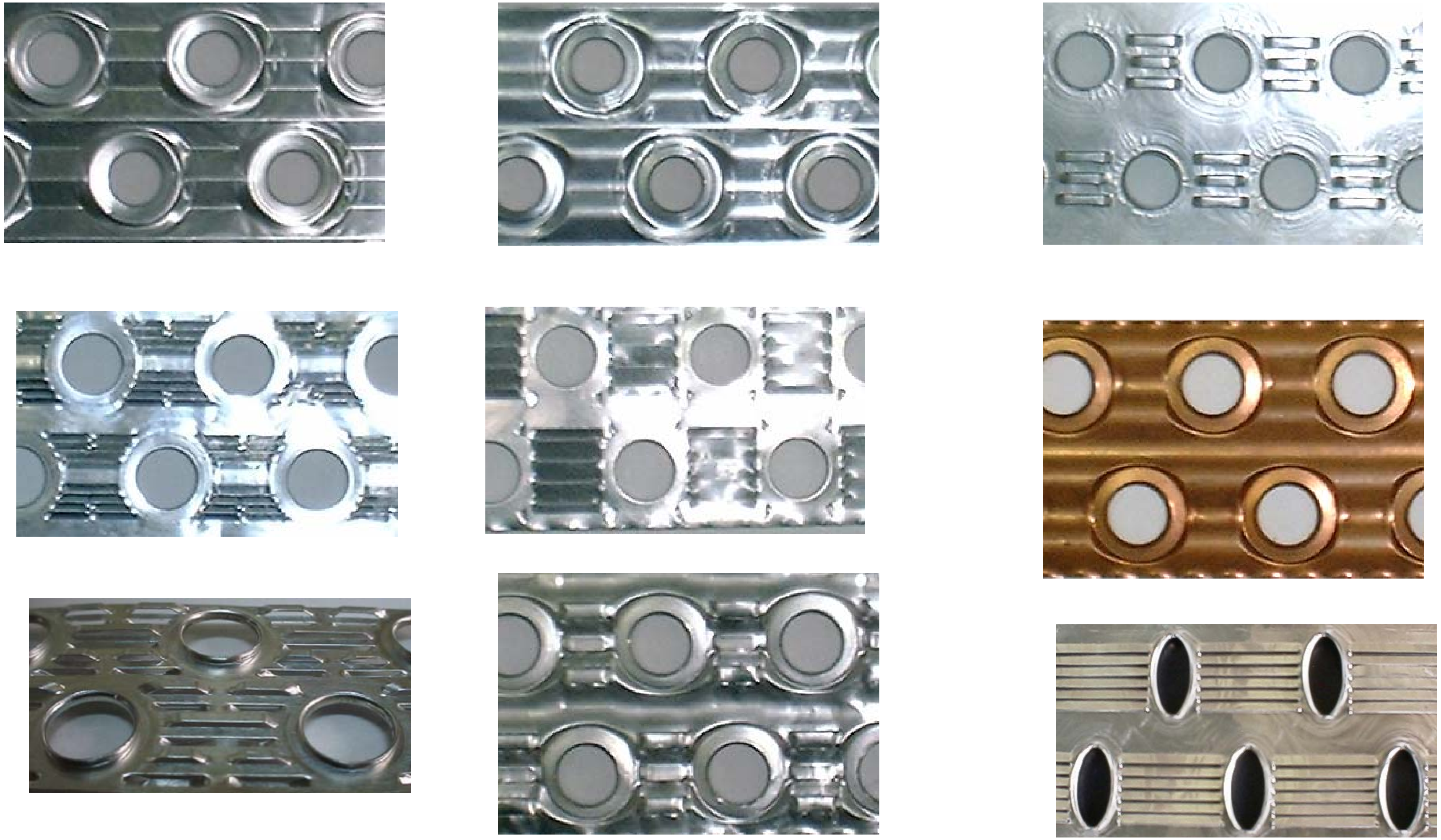
Convex-louver fin



Various Fin Patterns



扁管式百葉窗型熱交換器



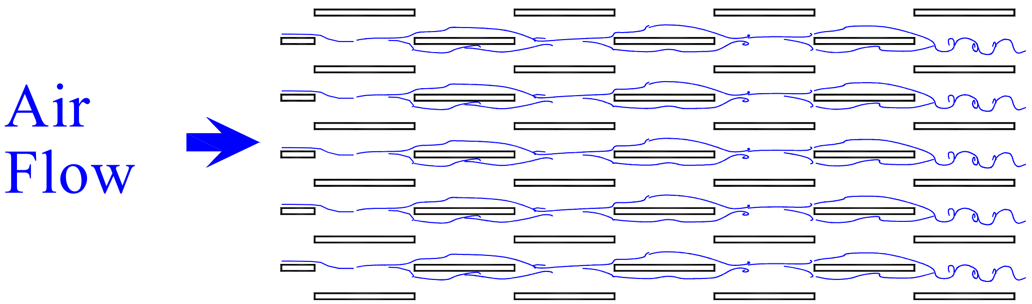
Various Fin Patterns

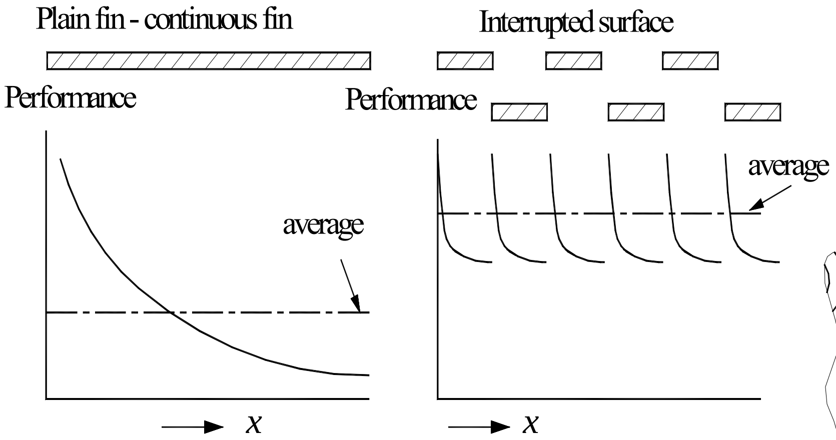
Note: ERL has the biggest database for all kinds fin patterns

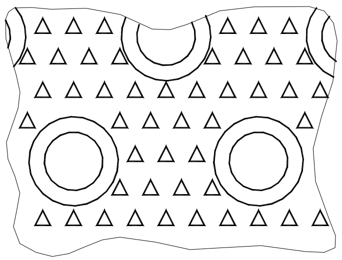
Design software are available (please call, Mr. J.S. Liaw at 03-5914220; jsliaw@itri.org.tw)

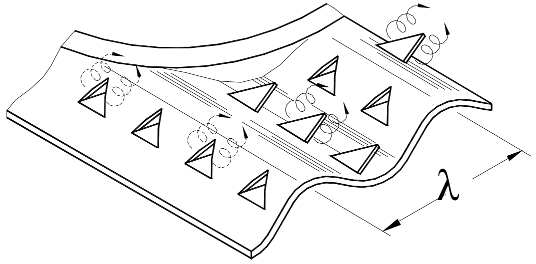
Passive method to improve airside performances - Technology Evolution

- Thermal Boundary Layer Restart
- Instability
- Thermal Wake Management
- Swirl





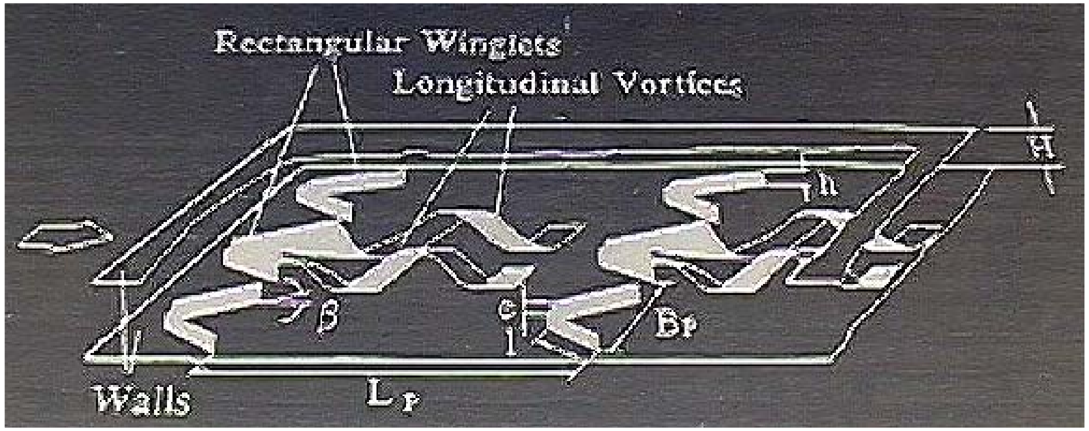




US patent 4817709

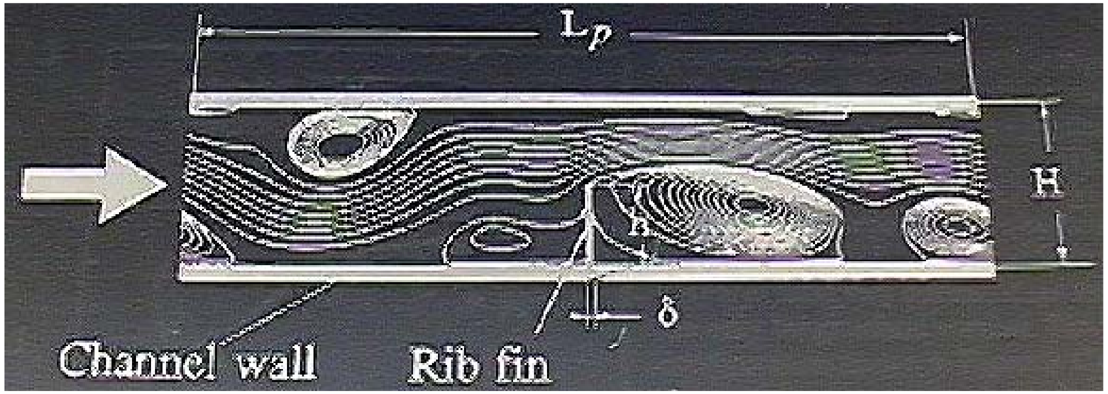
Type of vortex generators

Longitudinal vortex outperforms the transverse vortex



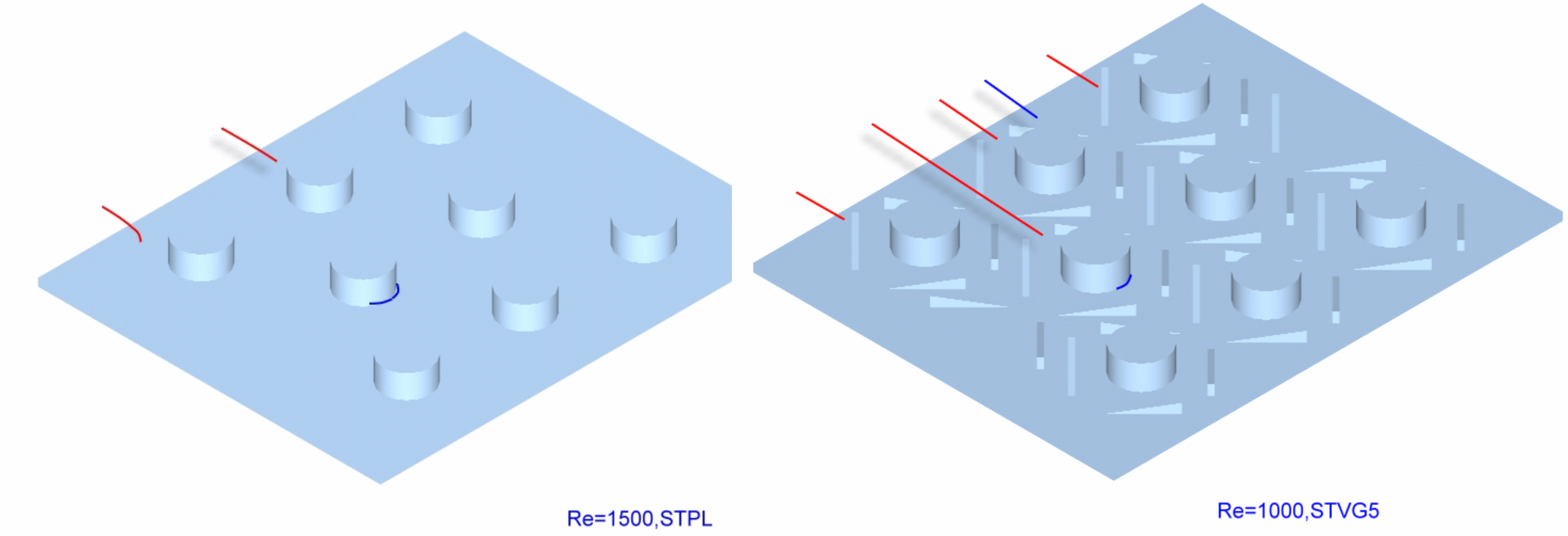
Longitudinal vortex

Transverse vortex



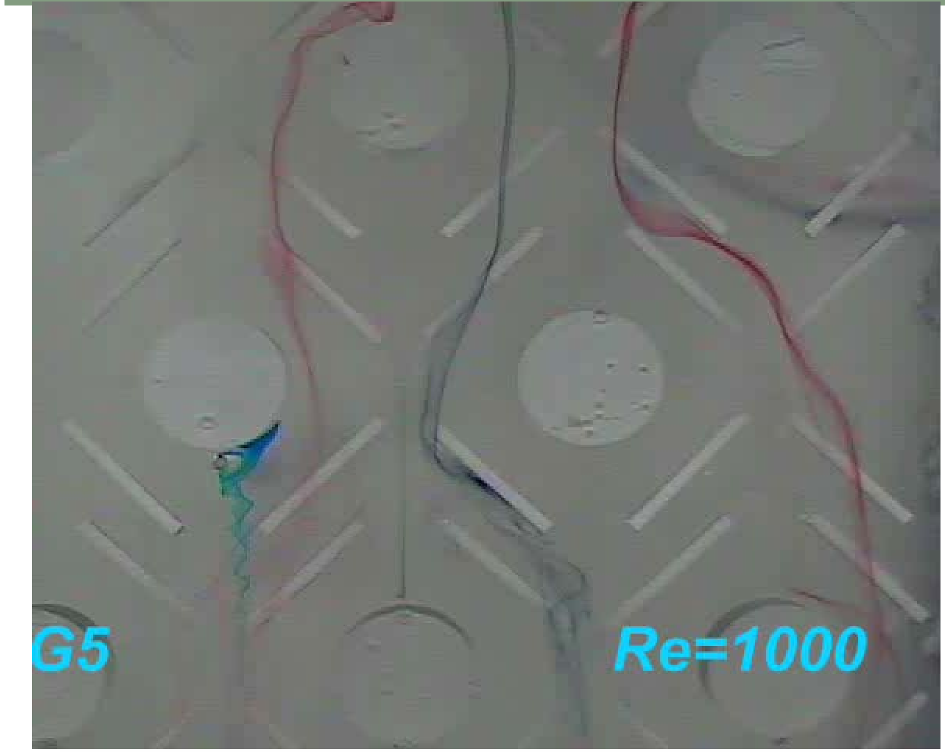
Benefits of vortex generator

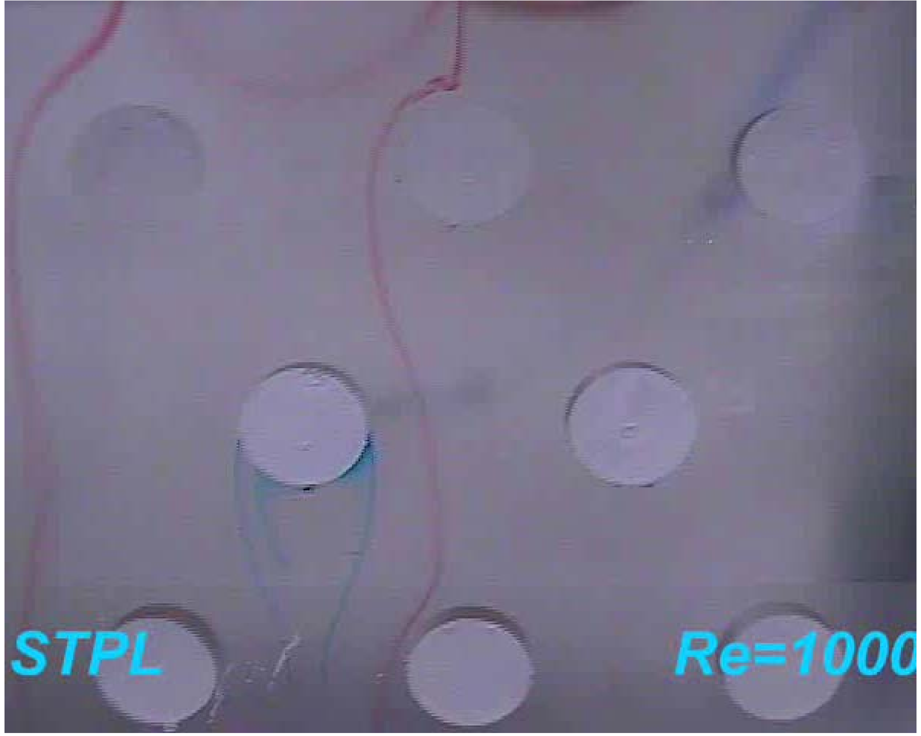
- Prevent Boundary Layer separation
- Improve heat transfer performance with acceptable pressure drop

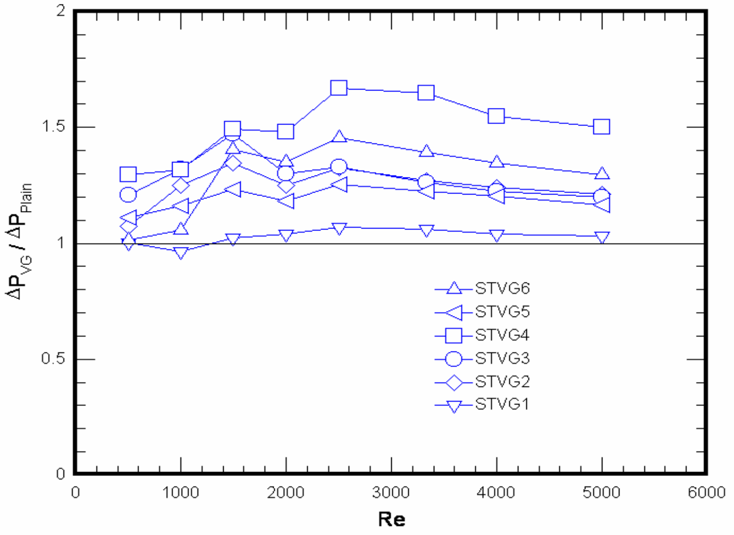


Int. J. of Heat and Mass Transfer, **Vol. 45, pp. 1933-1944.**
Int. J. of Heat and Mass Transfer, **Vol. 45, pp. 3803-3815.**

Influence of vortex generator on flow field







__Int. J. of Heat and Mass Transfer__, **Vol. 45, pp. 1933-1944.**
__Int. J. of Heat and Mass Transfer__, **Vol. 45, pp. 3803-3815.**

Summary

- Liquid Cooling is considered as an alternative for high-flux electronic cooling applications.
- Heat Transfer augmentation is an effective way for laminar flow cold-plate
- Mal-distribution could be a concern for multiple port channel cold-plate
- Radiator is the final place to dump heat – it is very crucial to choose suitable fin pattern

That's for all now.

Questions?