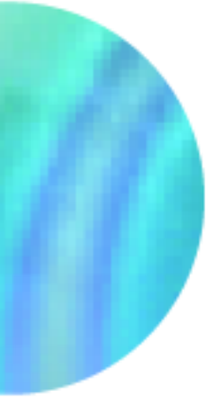
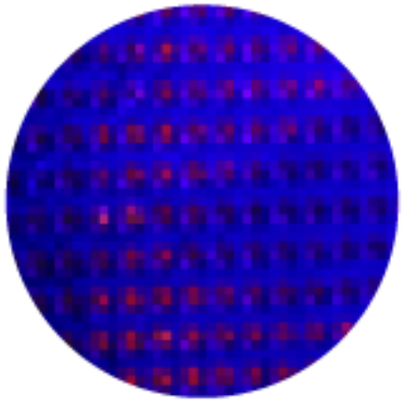
Advanced Air Cooling Technologies





ARPA-e Alternative Power Plant Cooling Workshop, May 12-13, 2014

Michael M. Ohadi, Professor of Mech. Engr.
Advanced Heat/Mass Exchangers Laboratory
A. James Clark School of Engineering

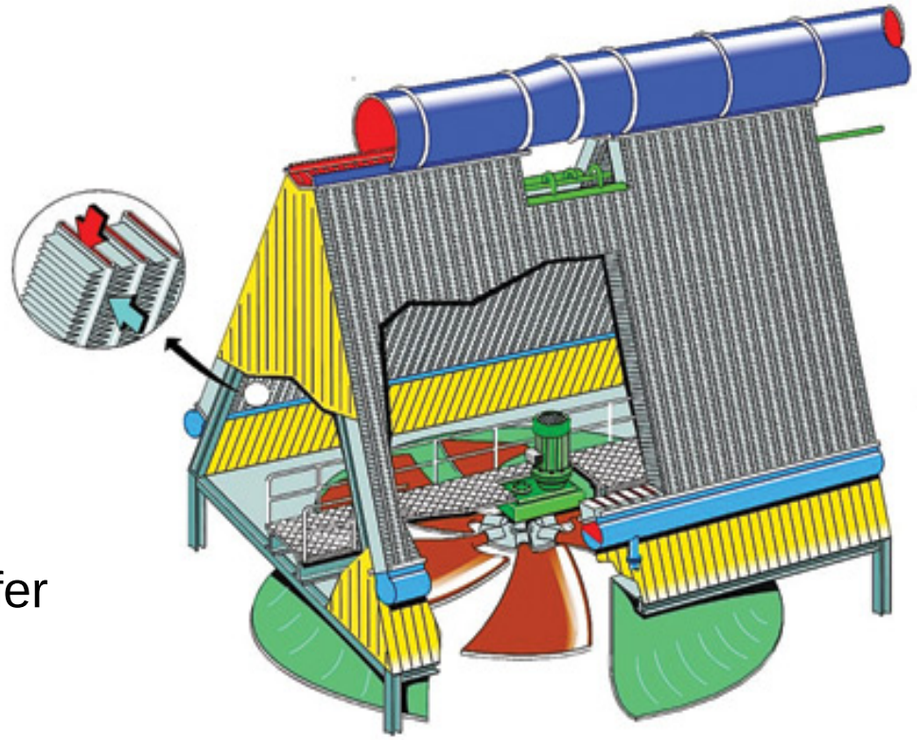
UNIVERSITY OF MARYLAND

Outline of the 15 Minutes presentation

- Quick Review of Most Recent research on air side heat transfer enhancement
- Where are we and where we need to be?
- Possibilities and the thinking forward

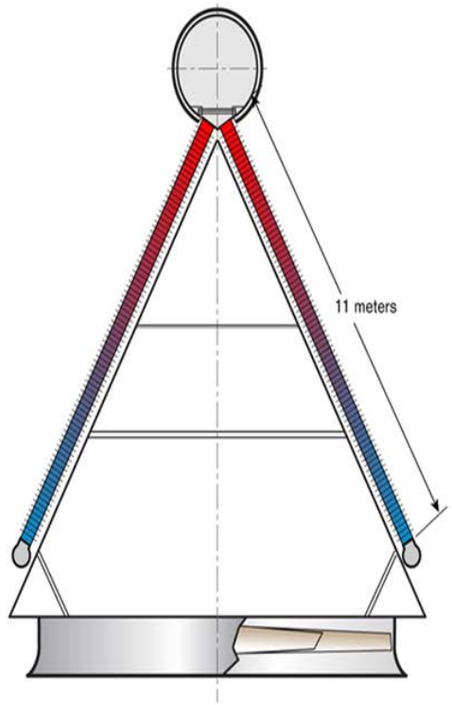
State of the art ACC

Often massive frontal area (typically 30 ft height on each side), yet the low air-side heat transfer coefficients in ACCs (~50 W/m2-K) require large air-side heat transfer surface areas and high pumping power to move the air through relatively long (3–6 ft) finned passages.

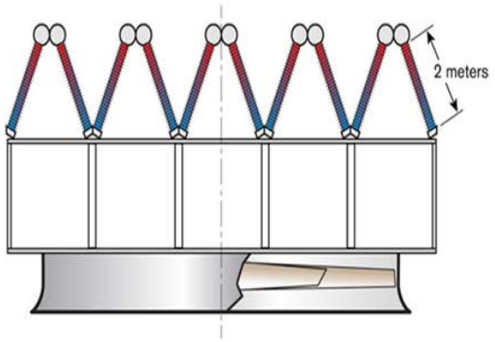


http://www.powermag.com/air-cooled-condensers-eliminate-plant-water-use/

The typical A-frame face accommodating as many as 200 downward flowing conventional tubes with Diameter of 1 1/2 inch (~ 4 cm) equipped with fins of various shapes for improved air-side heat transfer. The air-side heat transfer is often the dominant resistance (~80 - 90%) of total resistance.



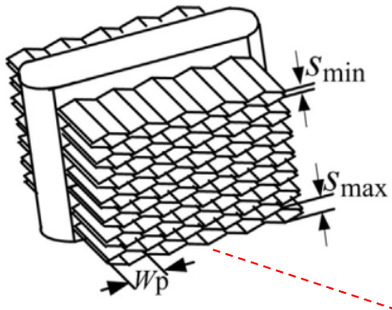
Classic A-frame ACC Module Design



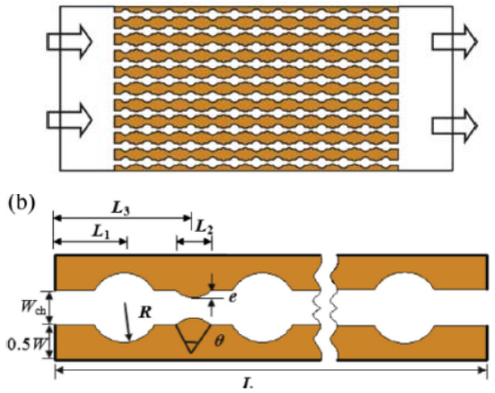
ModuleAir™ A-frame ACC Module Design

http://spxcooling.com/products/moduleair-air-cooled-condenser

$$F = \Delta P \frac{1}{0.5\rho u^2}\frac{D}{L}, \qquad J = \frac{h}{c_p \rho u} Pr^{2/3} = \frac{Nu}{RePr^{1/3}}$$

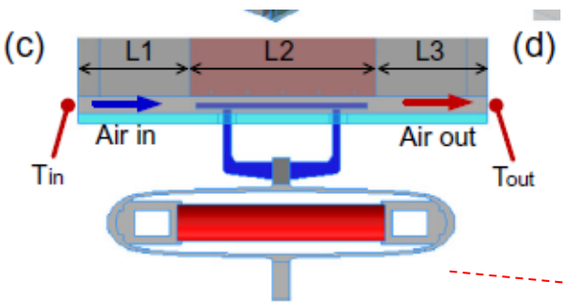


Minichannel Finned HX (2013)



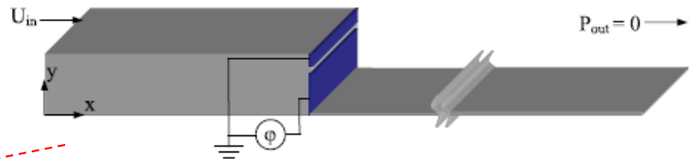
Microchannel Cavities (2013)

Porous Foam (2001, 2006)

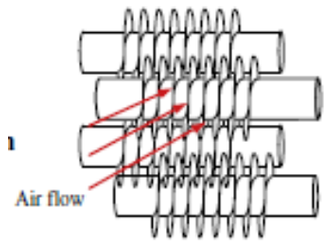


Piezo Agitation (2012)

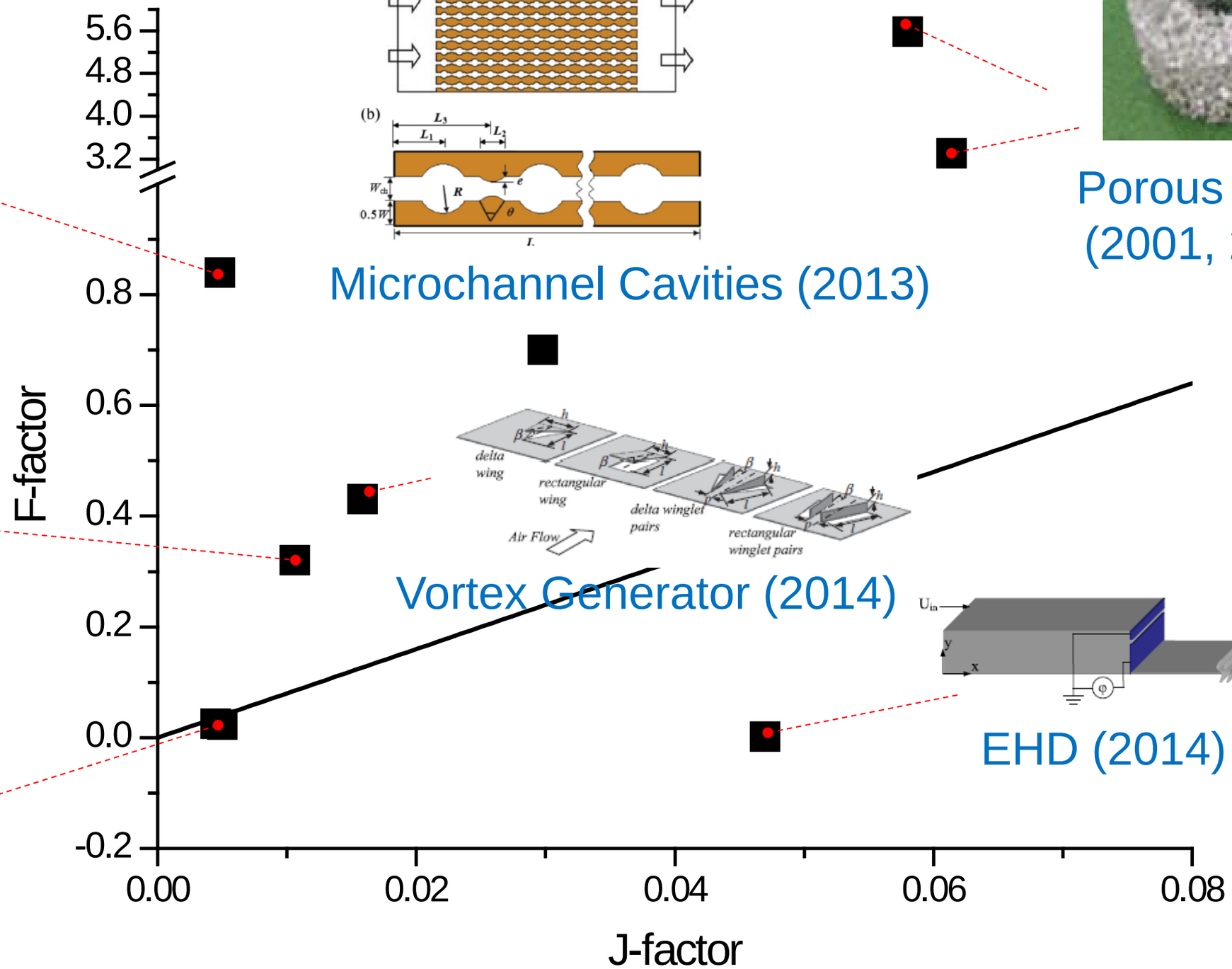
Vortex Generator (2014)



EHD (2014)

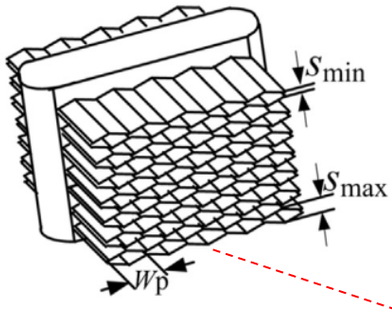


Conventional Finned HX



Recent work in air-side heat transfer enhancement

$$F = \Delta P \frac{1}{0.5\rho u^2}\frac{D}{L}, \qquad J = \frac{h}{c_p \rho u} Pr^{2/3} = \frac{Nu}{RePr^{1/3}}$$



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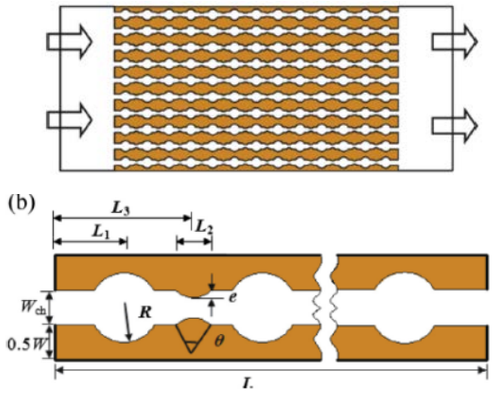

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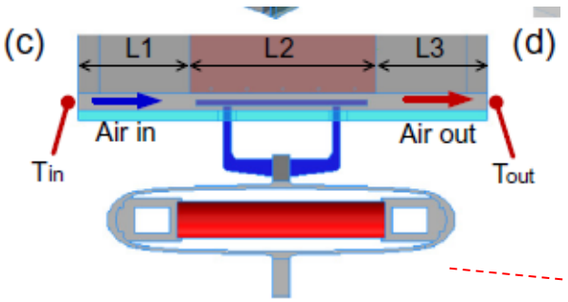

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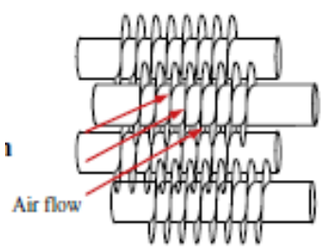

Conventional Finned HX

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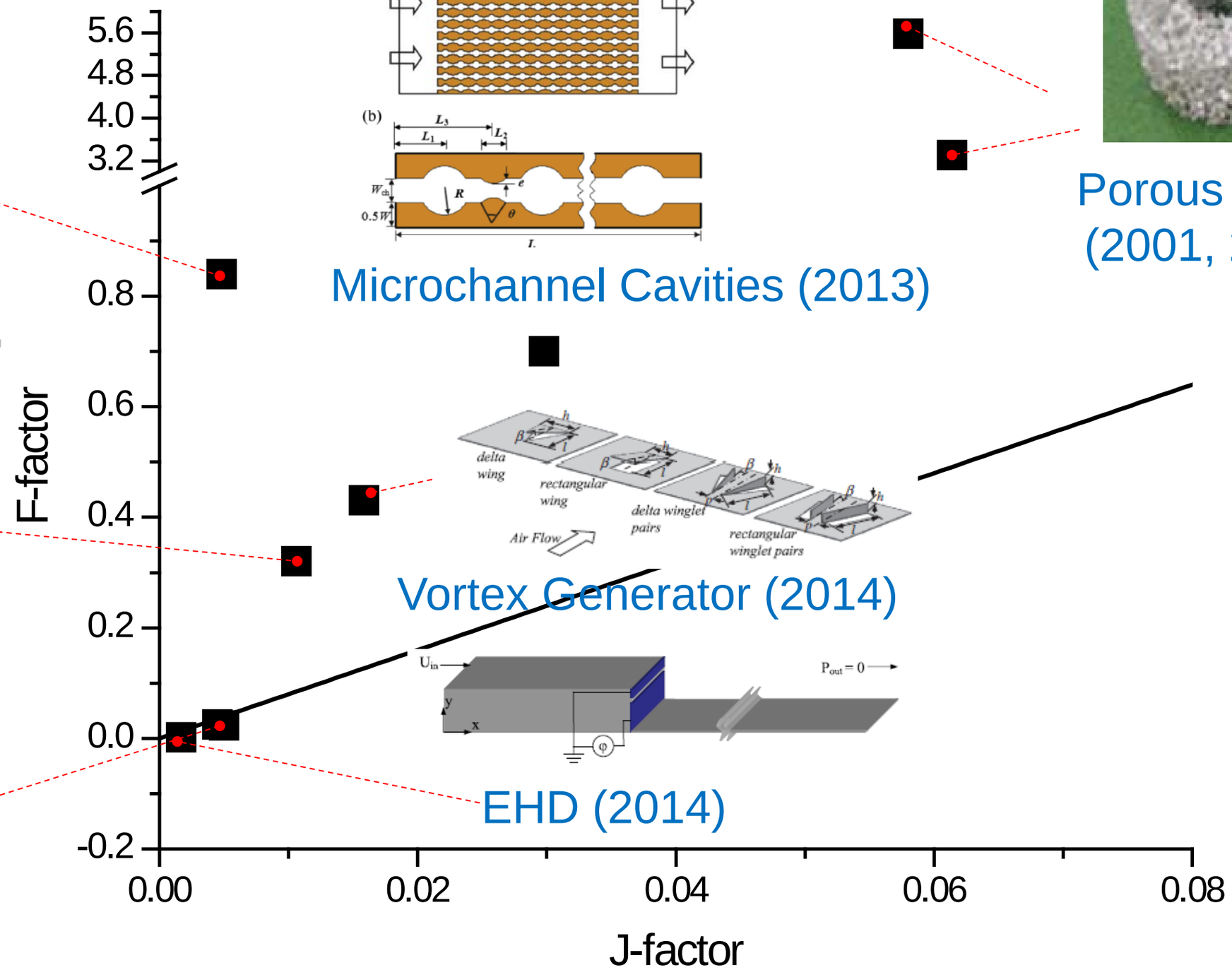
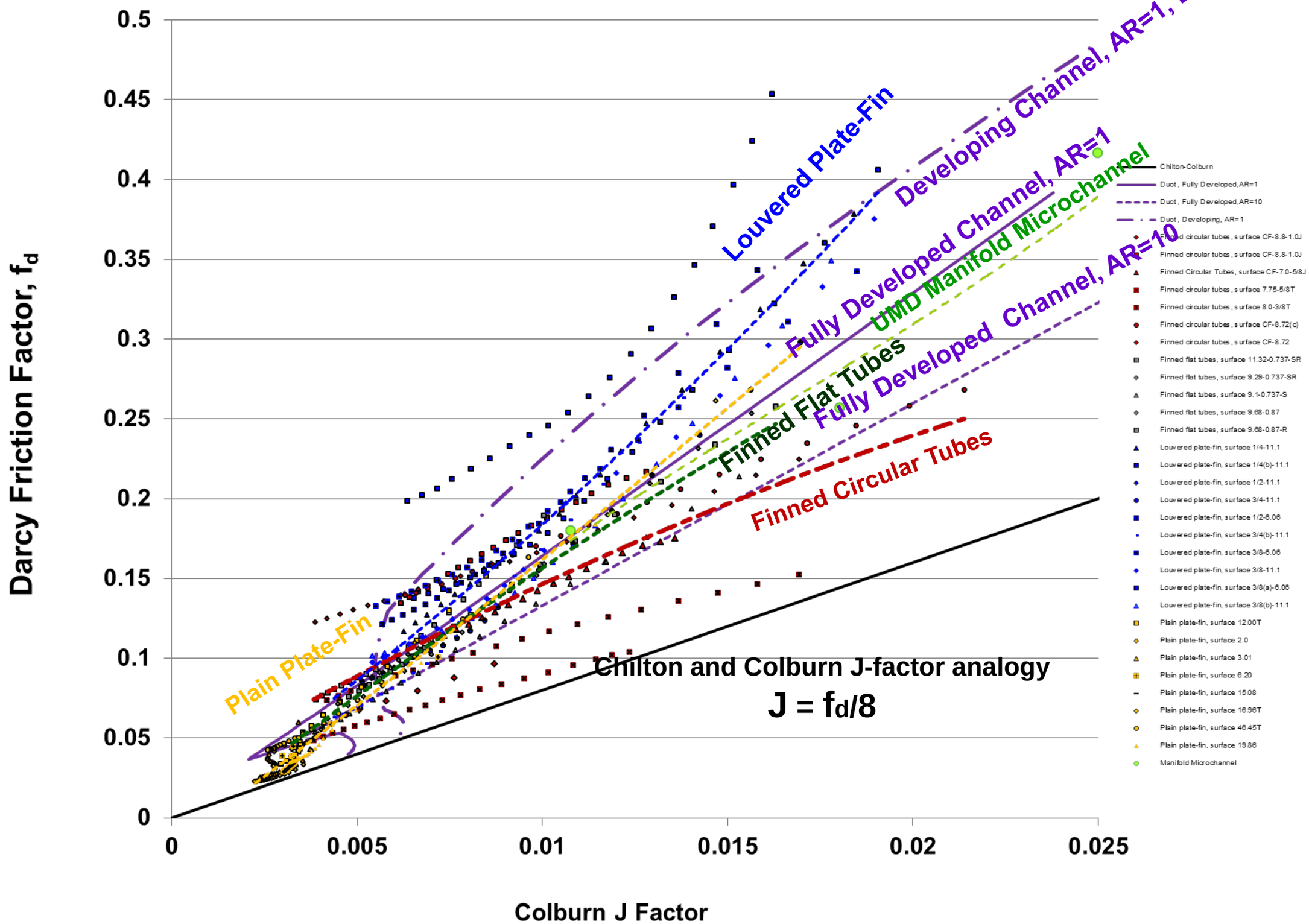


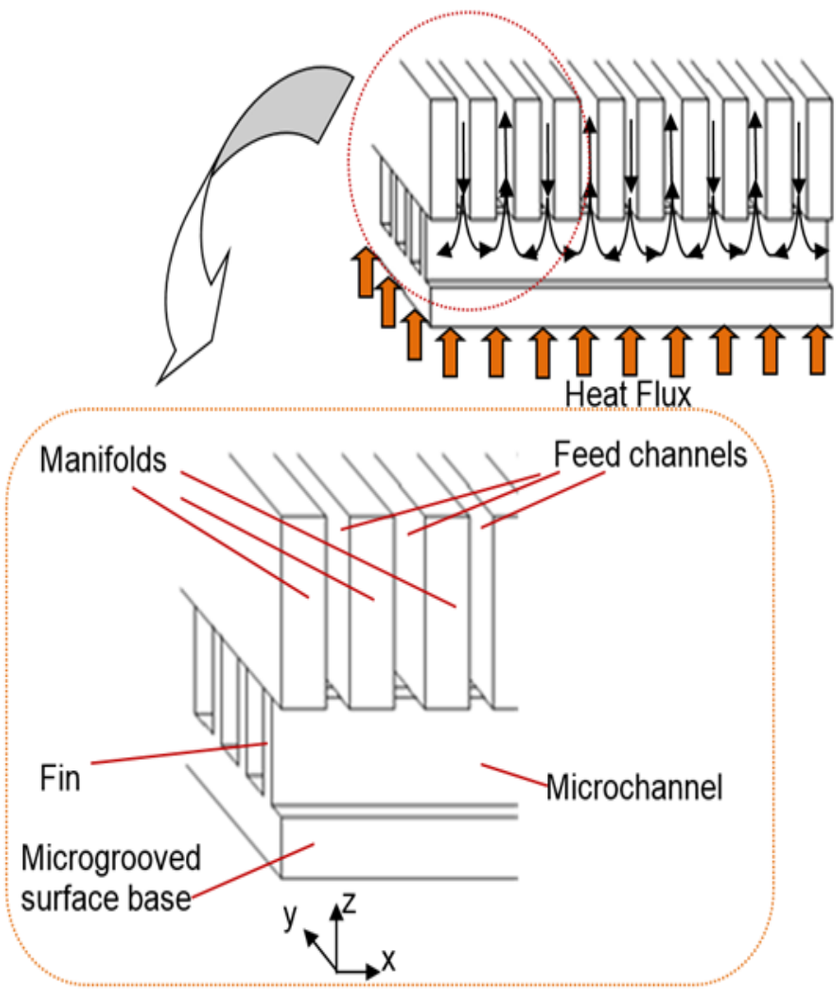
Chilton and Colburn J-factor Analogy for a few surface/fin designs



Chilton and Colburn J-factor analogy (Cont.)

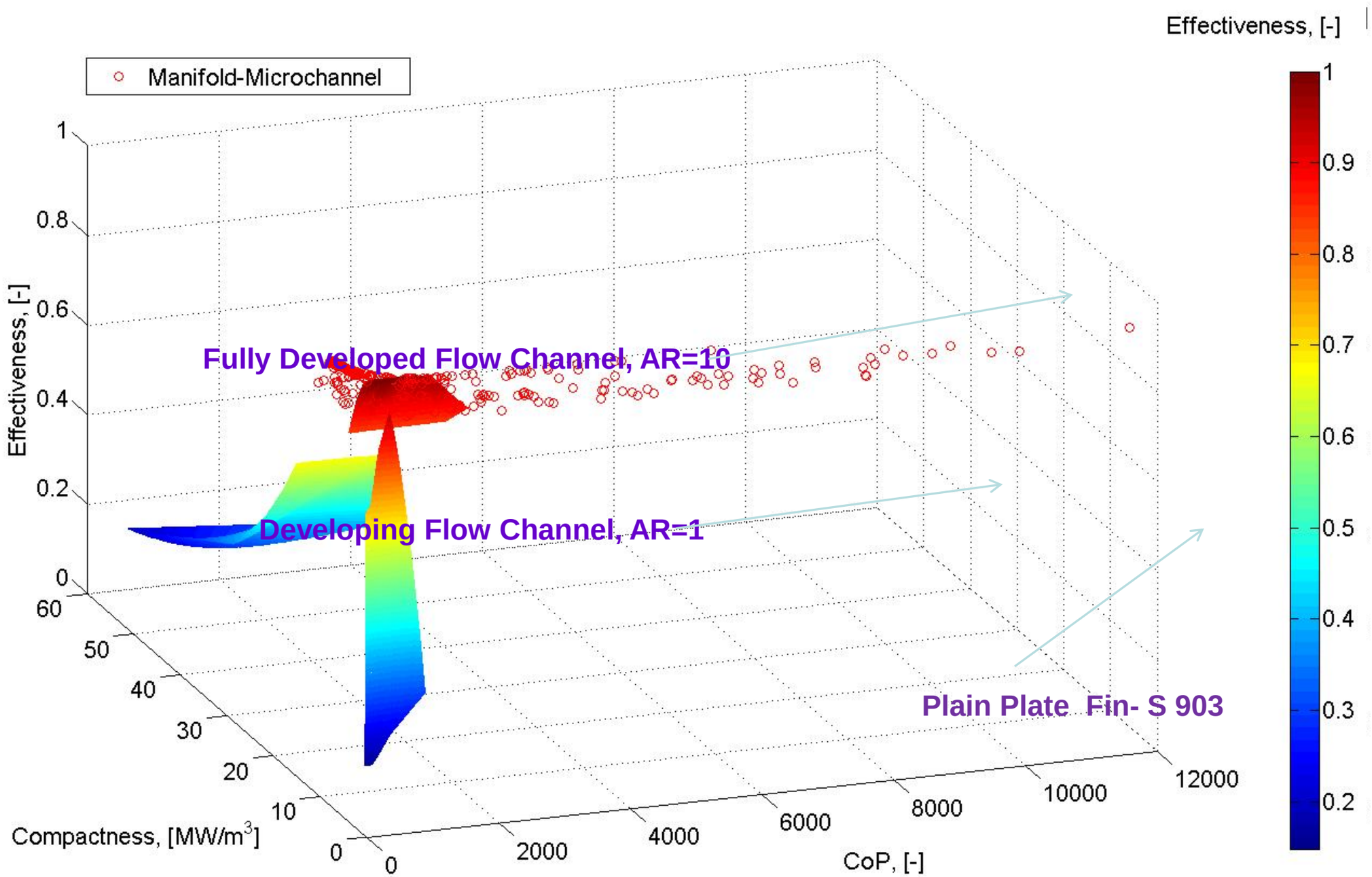
- Colburn J factor analogy (black line in the previous slide) is developed for turbulent flow in smooth tubes. The curve is independent of the working fluid and is given as $J=f_d/8$ for Darcy friction factor (or $J=C_f/2$ for Fanning friction factor).
- For fully developed channel flow curve we can see three sections: A linear part for laminar flow, a hook shape part for turbulent flow and an intermediate part for transition flow.

Normal Flow Heat Exchanger

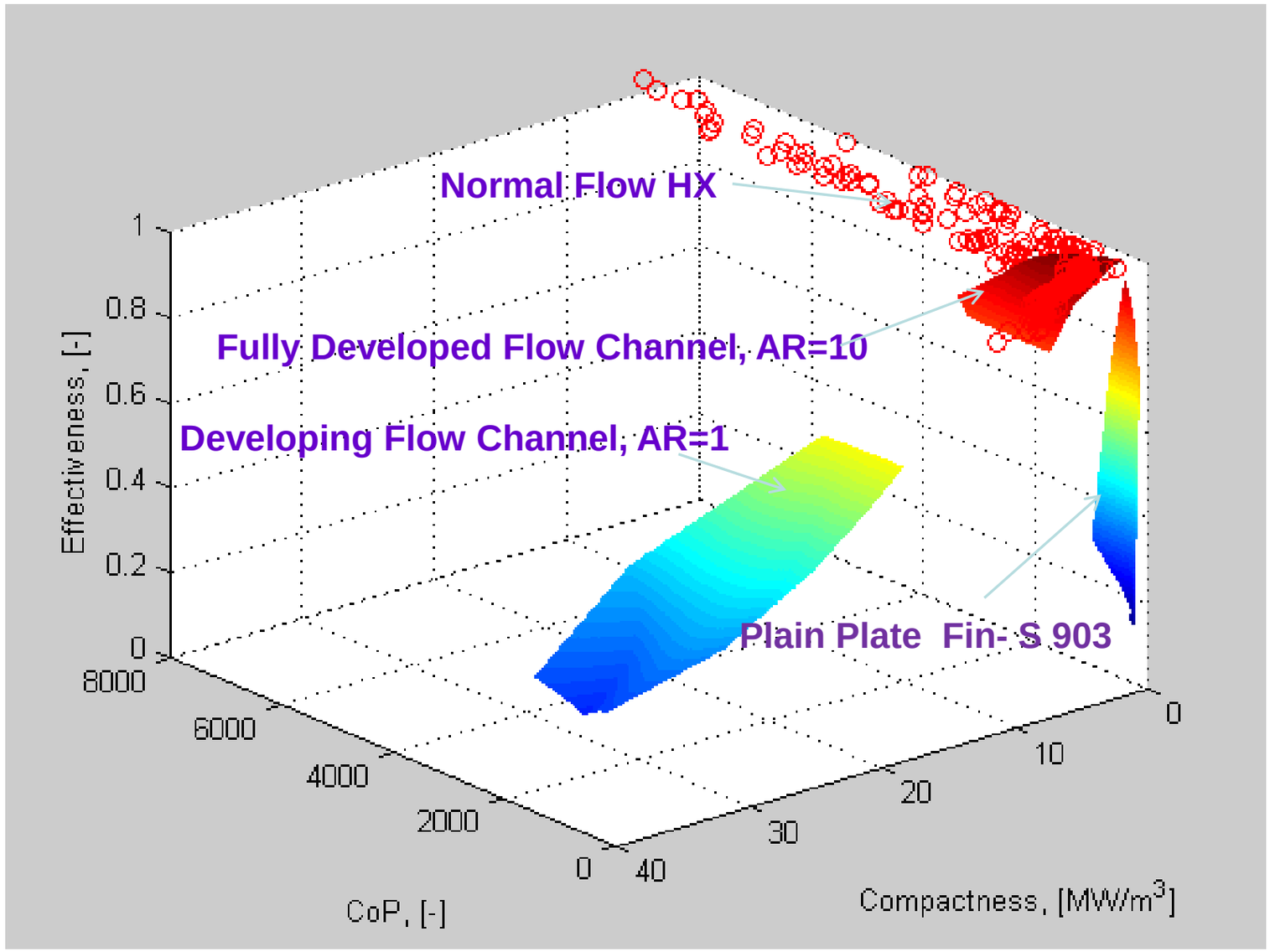


- Compactness of short developing flow microchannels
- Large face area accomplished inside of heat exchanger, therefore actual face area can be kept small
- Short fins are beneficial for Additive Manufacturing while reducing material consumption (potential size and weight reduction)

3-D Metrics

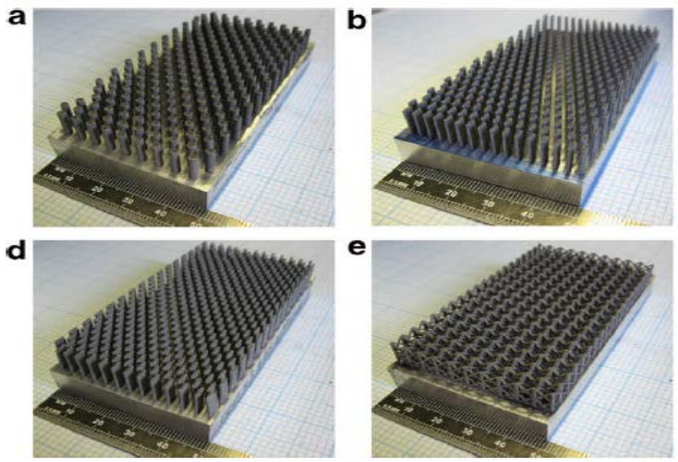

Manifold-Microchannel
Effectiveness, [-]
Fully Developed Flow Channel, AR=10
Developing Flow Channel, AR=1
Plain Plate Fin- S 903
Compactness, [MW/m3]
CoP, [-]
0
0.2
0.4
0.6
0.8
1
0
10
20
30
40
50
60
0
2000
4000
6000
8000
10000
12000
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

3-D metrics

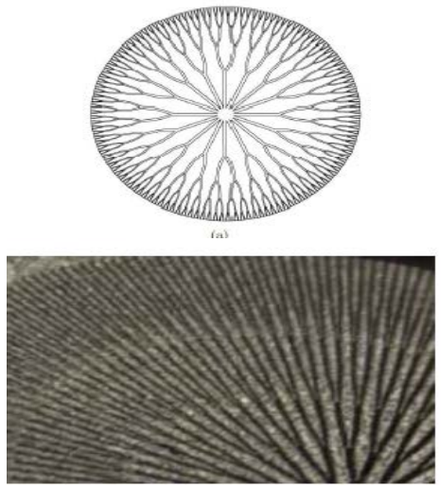


- High f-factor surfaces may be necessary to achieve high compactness and high effectiveness'
- Short developing flow channels promote compactness but the frontal area is large
- Normal flow HXs can utilize advantages of developing flow channels, yet avoiding the large frontal area because now the face area is extended in the direction of HX depth.

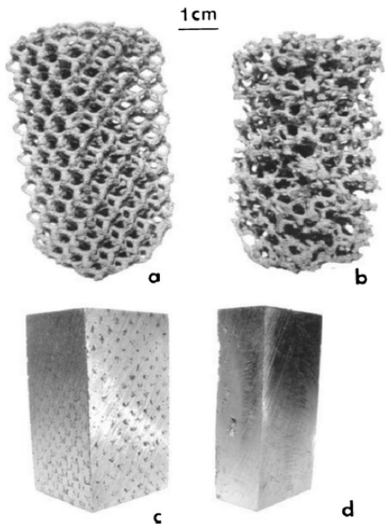
Sample AM-produced heat exchanger surfaces



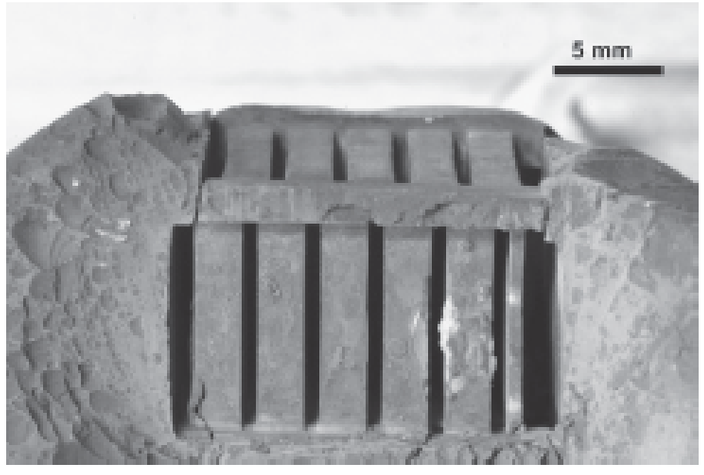
Novel heat sinks by Selective laser melting (SLM)



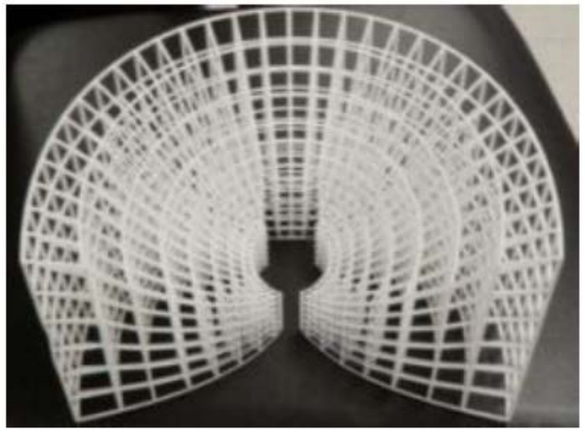
Fractal like heat exchanger by Direct metal laser sintering (DMLS)



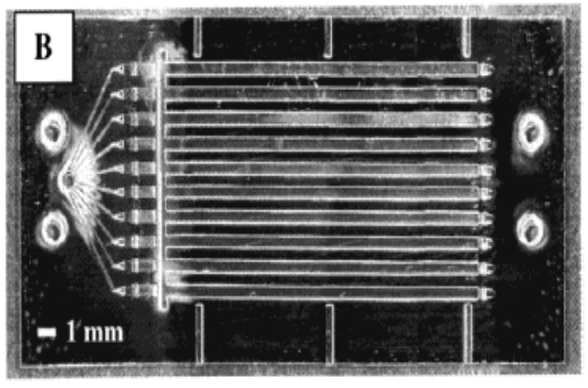
Open-cellular structures by Electron beam melting (EBM)



Microchannel heat exchanger fabricated by Stereolithography (SLA)



Nylon structure by selective laser sintering (SLS)



Multichanel reactor by Deep-RIE

AM Relevant Heat/Mass Exchange Devices

Design	AM Tech	Material	Other Tech	Convection Coefficient or Conductivity	Overall Heat Transfer Coefficient
Heat Sinks[10,11]	SLM	Aluminium 6061	Lattice cell	70W/mK	Assuming 100 W/m^2K
Fractal Like Heat Transfer Device[12,13]	DMLS	Stainless Steel	Micro-channel width of 100 µm	130 W/mK	N/A
Open-cellular Structure[14]	EBM	Copper/Cu_2O	N/A	N/A	N/A
Microchannel Heat Exchanger[15,16, 17]	SLA	SiCN compounds	N/A	N/A	N/A
Unit-Cell-Based Custom Thermal Management Structure[19]	SLS (0.5 mm minimum diameter as the limitation)	Nylon	Electroplating Copper (50.8µm) on nylon structure	7 W/m^2K	N/A

Message 1

F vs. J graphs might be useful in some cases but it may be too simplistic to satisfy optimum design of next generation HXs. For example, it may not address requirements such as heat exchanger shape, aspect ratio, effectiveness , compactness, etc.

Message2

Innovation in air side heat transfer has been modest. Fin/surface designs remain limited by excessive pressure drop penalties. Innovative solutions guided by realistic, but ambitious goals are needed to realize transformative technologies

Message 3

We may need to <u>reorganize</u> our thinking to allow for <u>cross-disciplinary</u> approach—a combination of heat transfer, materials, and manufacturing technologies coupled with component and system level optimization tools to realize next generation HXs.

Message 4

We may want to harvest the power of additive manufacturing to expedite innovation in air side heat transfer Enhancement?

Message 5

As we look for a proper manufacturing technique (ies), we may keep the modularity approach in mind, so as to minimize the scalability issues

M. Ohadi, May 12-2014. ARPA-e Alternative Power plant cooling workshop