Pool boiling on metal-foam enhanced tube bundle: heat transfer characteristics and flow visualization

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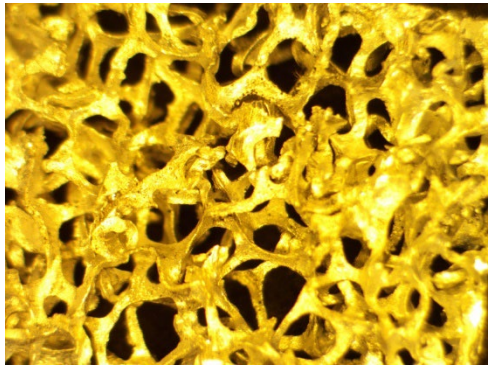
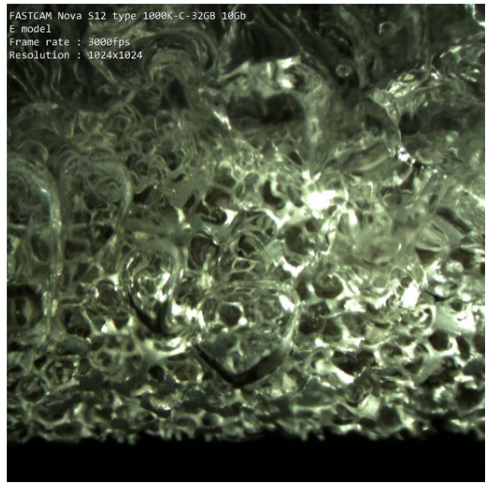
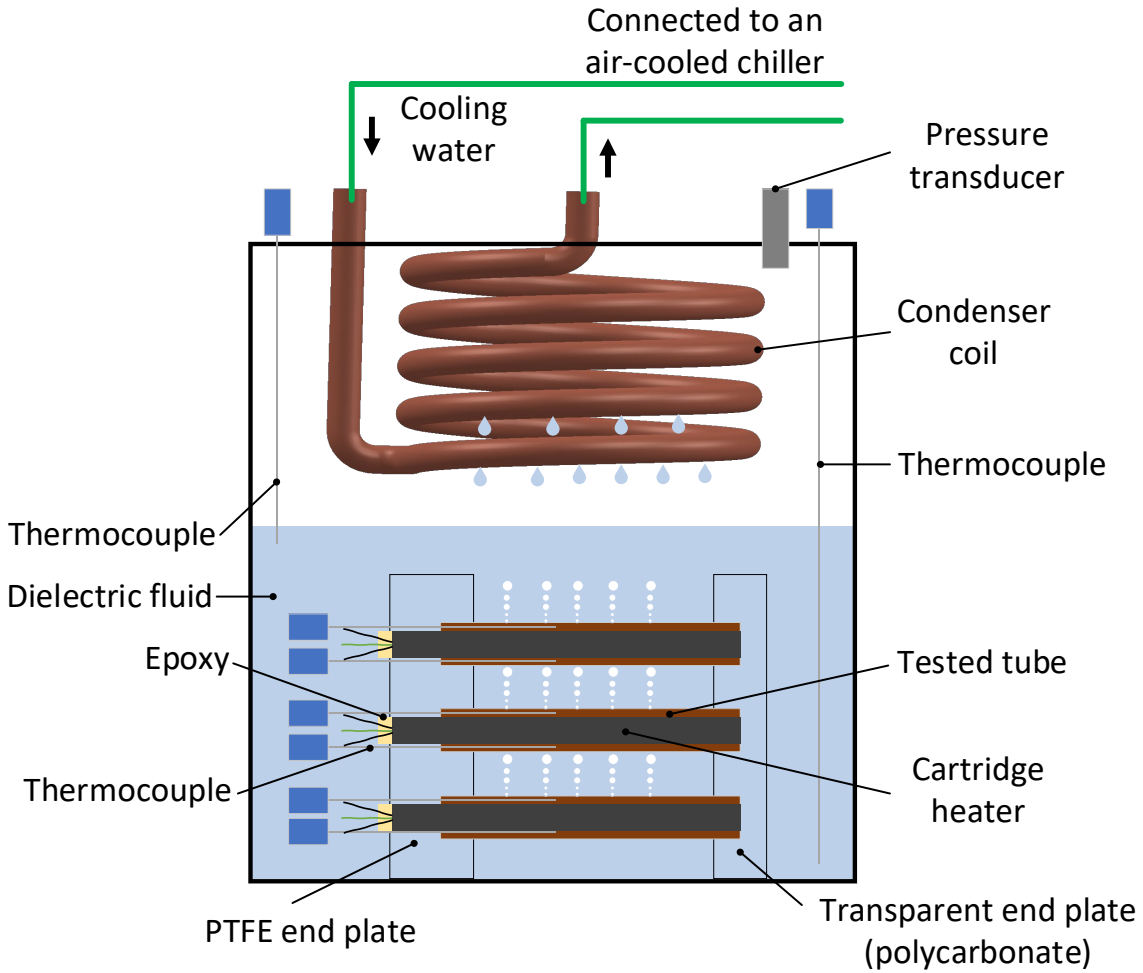
Introduction

- Pool boiling on a tube bundle
  - One of the most effective heat transfer modes in several industrial applications
  - Widely employed in flooded evaporators for air-conditioning and refrigeration, desalination, and absorption chiller industries
  - Extreme high heat transfer rates can be attained at relatively low temperature differences
- Enhance pool boiling heat transfer through porous metal foam structure
  - High-porosity metal foam, which is lightweight, high strength and rigidity and large surface-area-to-volume-ratio
- Limited research into using porous structures to enhance the pool boiling heat transfer for tube bundles in the literature
- Improve the shell-side heat transfer rate by the enhanced tube bundle
- Provide a better understanding of the role of the metal foam

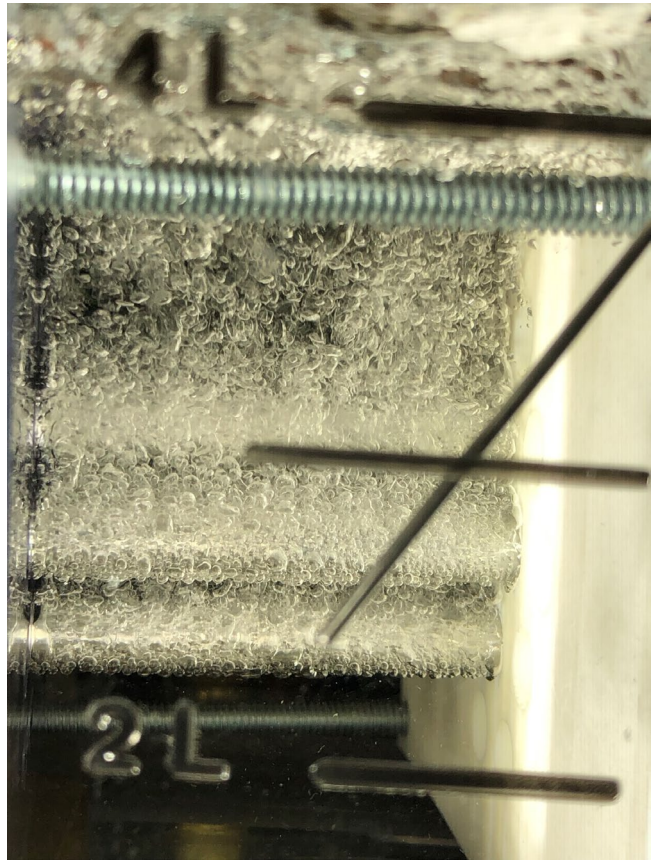




Experimental setup

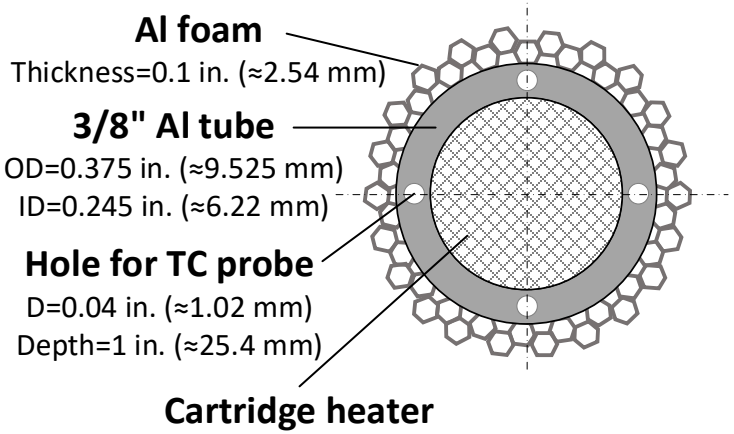


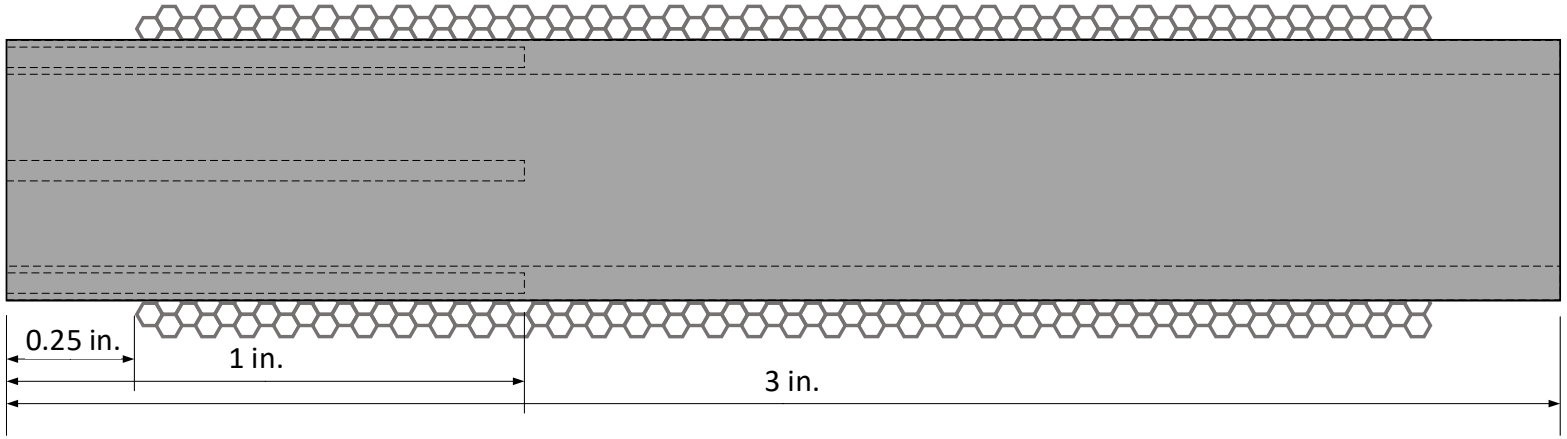
Front view

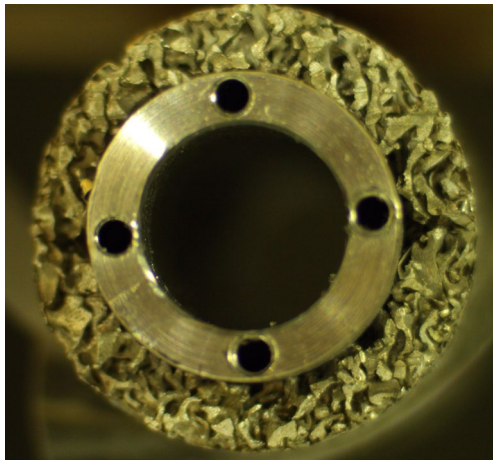


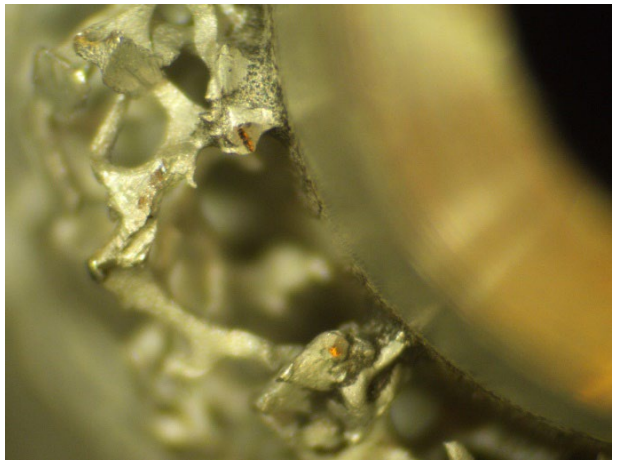
Side view

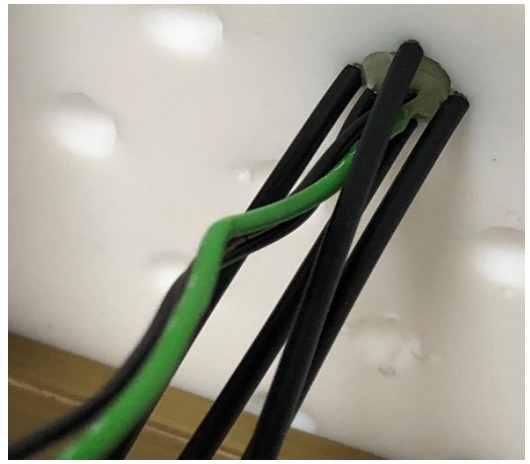
Heat transfer test section



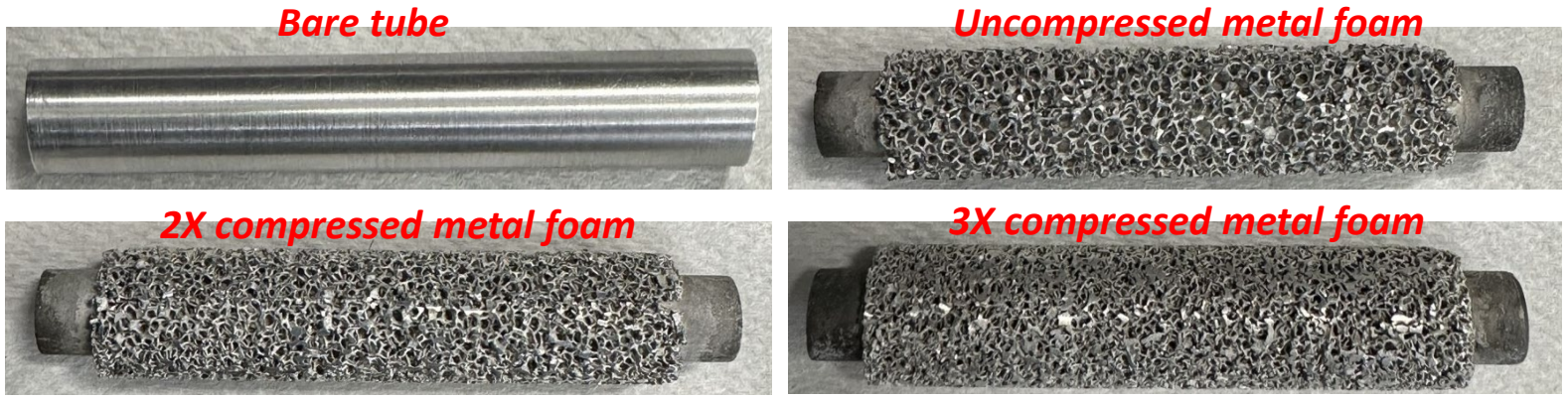


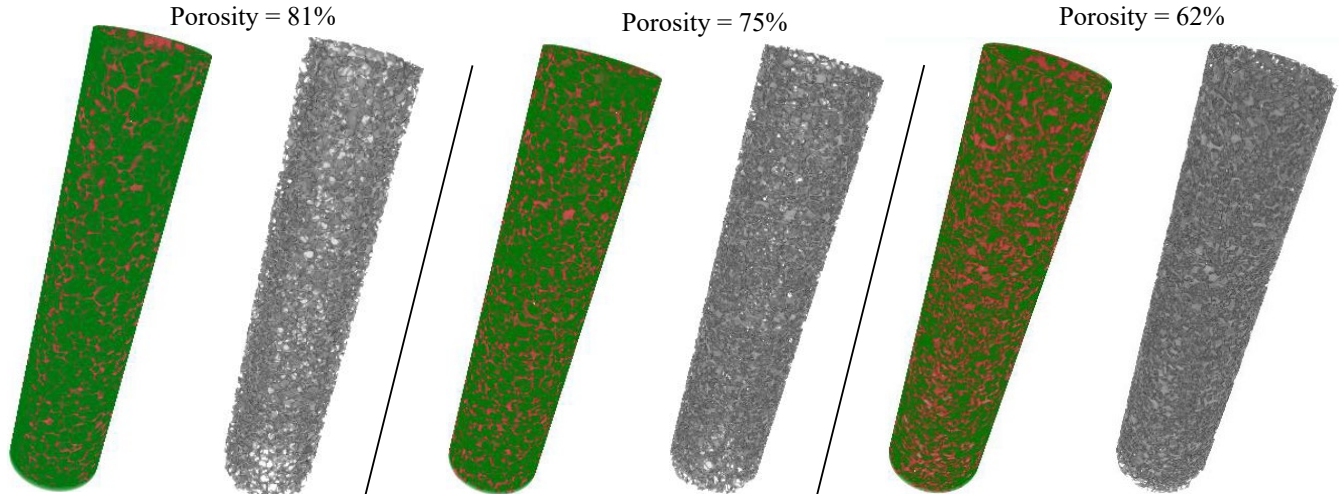






Metal foam tubes





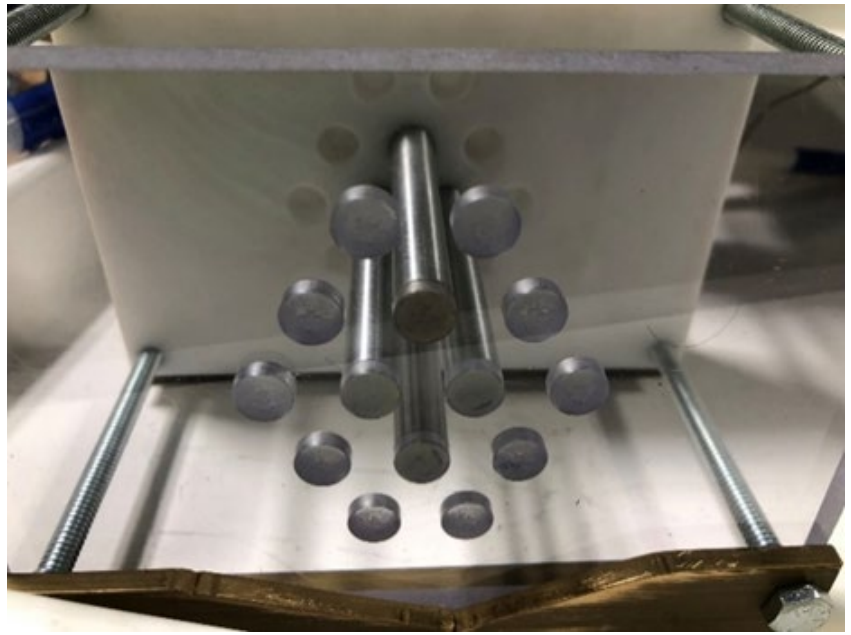
X-ray computed tomography (3D scanning) for metal foam enhanced tubes

- Al tube: OD=9.52 mm, L=76.5 mm
- Aluminum (6101) foam: 40 PPI, thickness=2.54 mm
- Metal foam was brazed around the outer surface of the tube.
- Uncompressed, 2X compressed, and 3X compressed metal foams

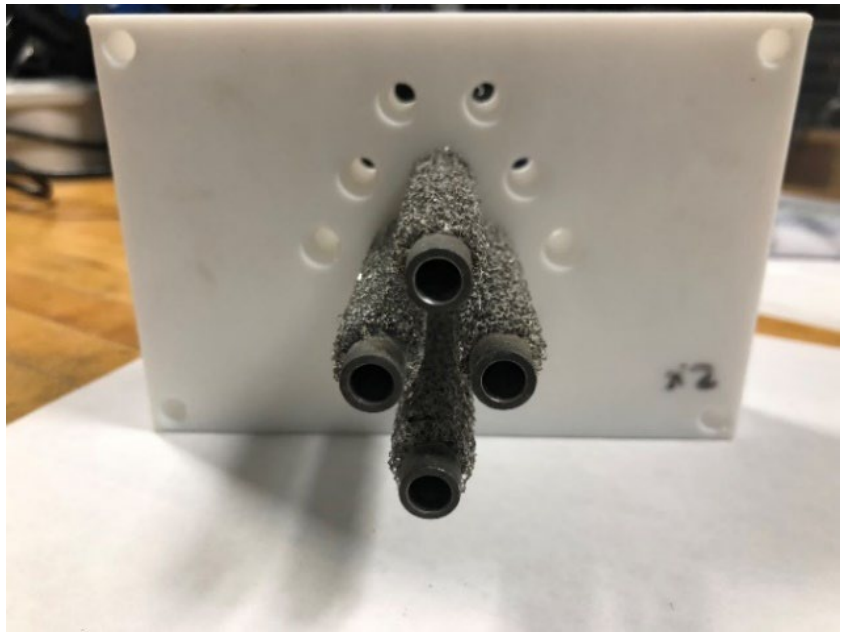
Metal foam porosities

Metal foam enhaced tube	Porosity
Uncompressed metal foam	81%
2X compressed metal foam	75%
3X compressed metal foam	62%

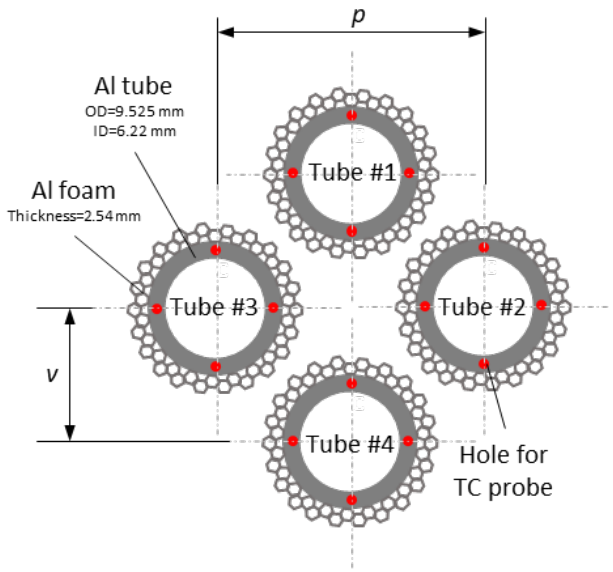
Tube bundle arrangement



Bare tube bundle



Metal foam tube bundle



- Tube bundles with four aluminum tubes
- Horizontally placed in a staggered tube arrangement

	Case 1	Case 2
Tube pitch *p*	19.05 mm	25.4 mm
Vertical distance between tubes *v*	16.5 mm	22.0 mm

Data reduction-heat transfer coefficient

$$HTC = \frac{q''}{\Delta T_{sup}} = \frac{(Q_{elec} - Q_{loss})}{(\pi D_o L_h)(T_{wall} - T_{sat})}$$

Based on heating power of cartridge heater

$$Q_{loss} = kA_{cs}\frac{T_{wall,R} - T_{wall,L}}{\Delta x}$$

Average bath temperature

Based on outer diameter of bare tube

Heated length

Estimated based on 1-D heat conduction eq.

$$T_{wall} = T_{m,avg} - \left(\frac{Q}{2\pi k L_h}\right)\ln\left(\frac{r_o}{r_m}\right)$$

HTC of tube bundle is estimated based on the average value of four single-tube HTCs.

Validation of experimental setup

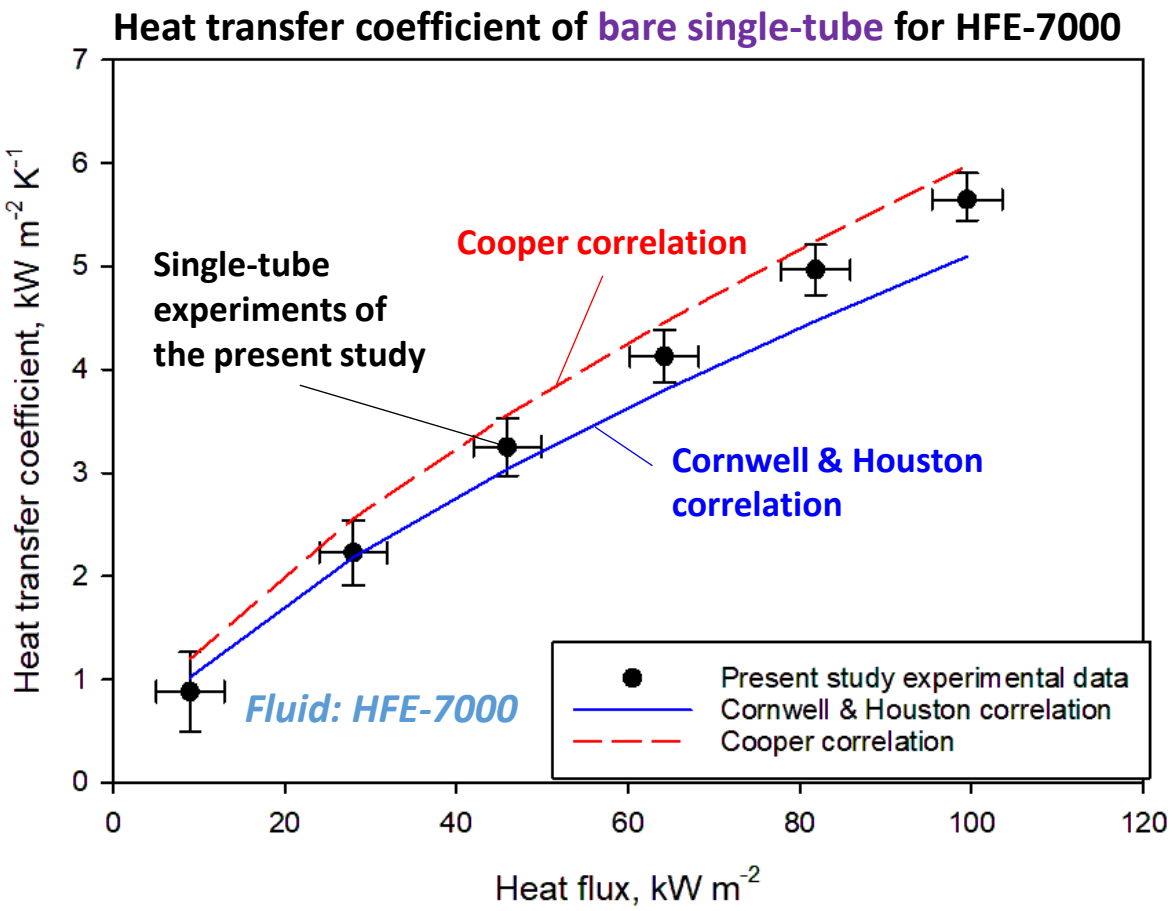
- Single-tube experiments:
  - Bare aluminum tube
  - HFE-7000
  - Heat flux: 8-100 kW/m^2
- Comparison with correlations
  - Cooper correlation:

$$HTC_{Cooper} = 90M^{-0.5}\left(q''\right)^{0.67}\left(-\log\left(P_r\right)\right)^{-0.55}\left(P_r\right)^{\left(0.12-0.2\log\left(R_p\right)\right)}$$

  - Cornwell & Houston correlation:

$$HTC_{Cornwell-Houston} = 9.7P_c^{0.5}\,\mathrm{Re}_b^{0.67}\,\mathrm{Pr}^{0.4}\left(1.8P_r^{0.17}+4P_r^{1.2}+10P_r^{10}\right)\left(\frac{k_l}{D_o}\right)$$

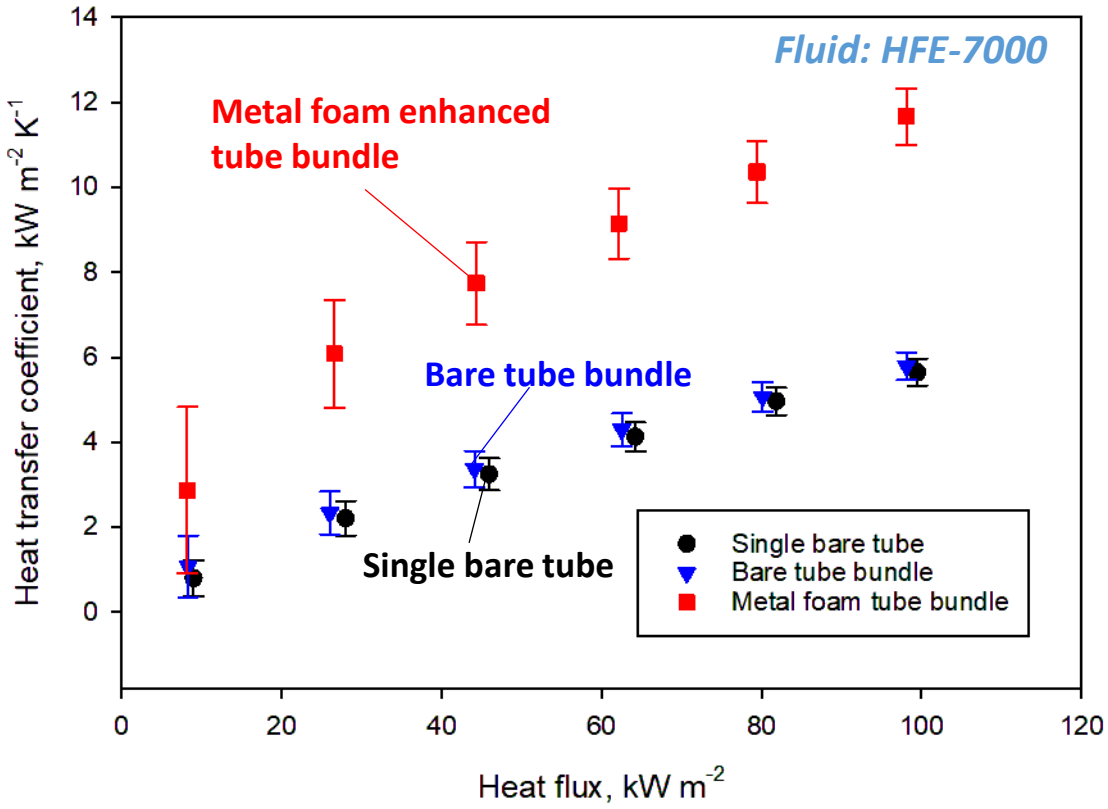
- The results show good agreement.



Performance of tube bundles

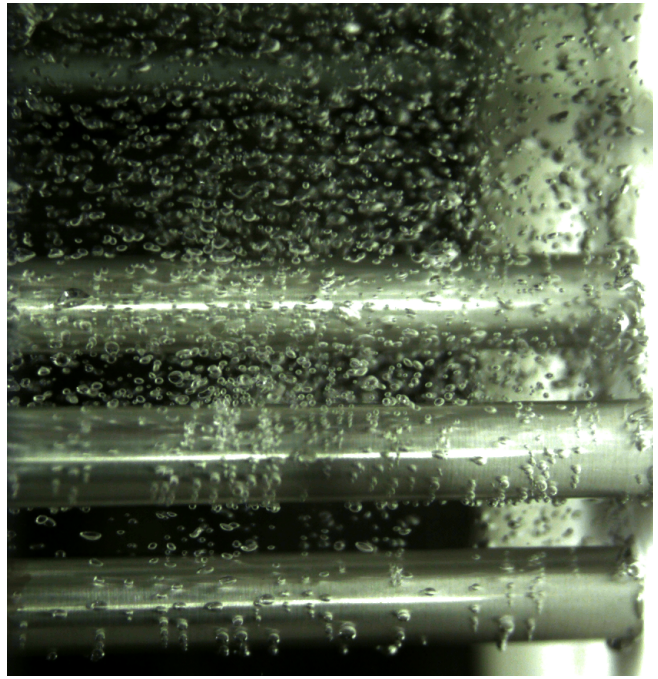
- Tube bundle experiments:
  - Fluid: HFE-7000
  - Tube pitch: 19 mm
  - Uncompressed metal foam tube (ϕ=81%)
- Bare tube bundle is 3-5% higher than that of the single bare tube.
- HTC of the metal foam enhanced tube bundle is 100-160% higher than that of the bare bundle.
- Larger surface area and a greater number of nucleation sites causes an increased HTC in metal foam tubes.

Comparison of single tube, bare bundle, and metal foam bundle

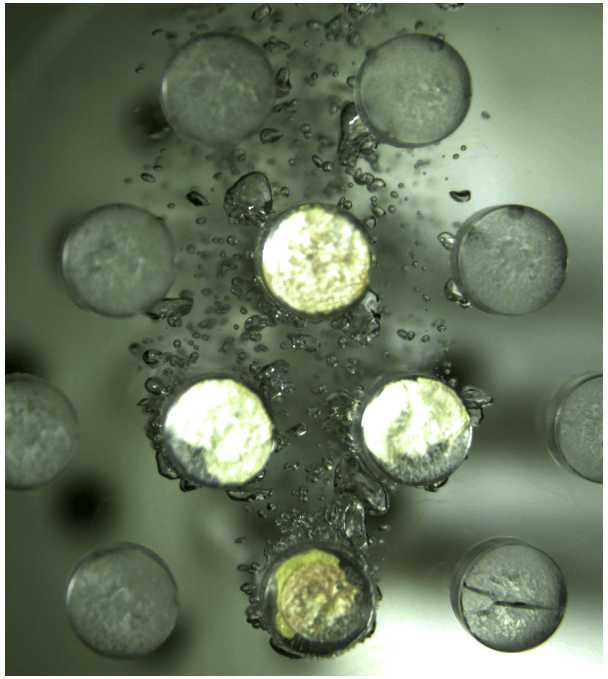


Visualization of boiling process (q=8 kW/m^2)

Bare tube bundle

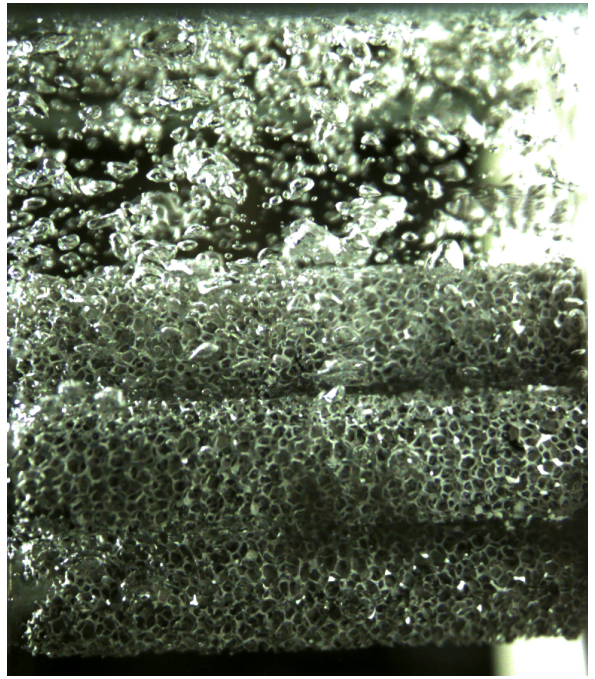


Side view

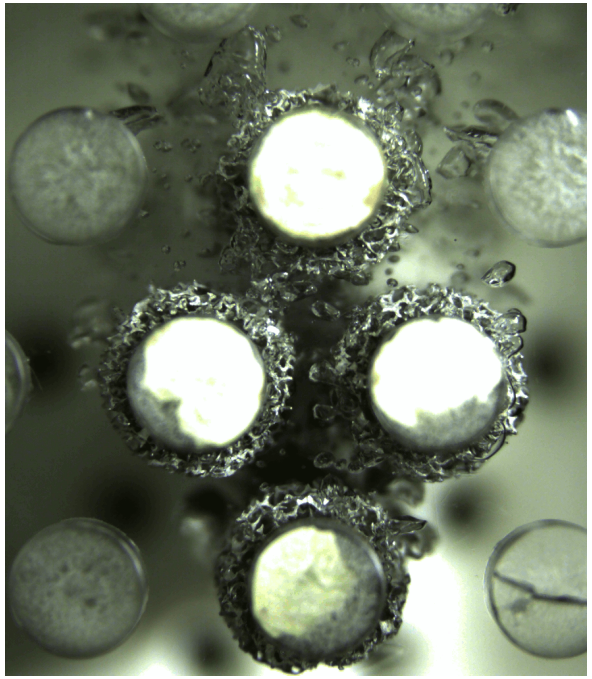


Front view

Metal foam enhanced tube bundle



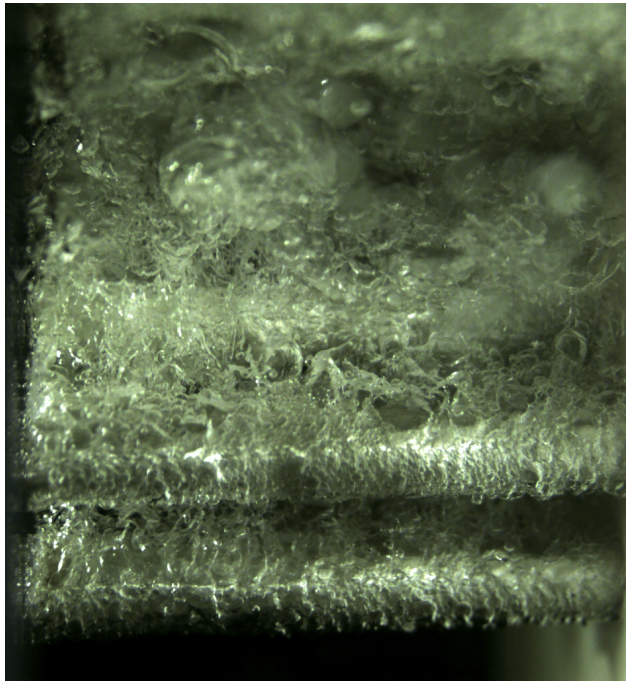
Side view



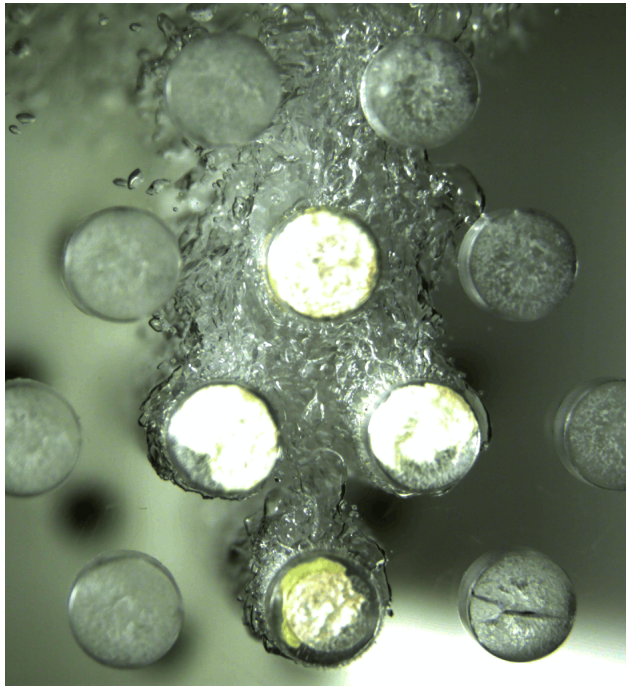
Front view

Visualization of boiling process (q=98 kW/m^2)

Bare tube bundle

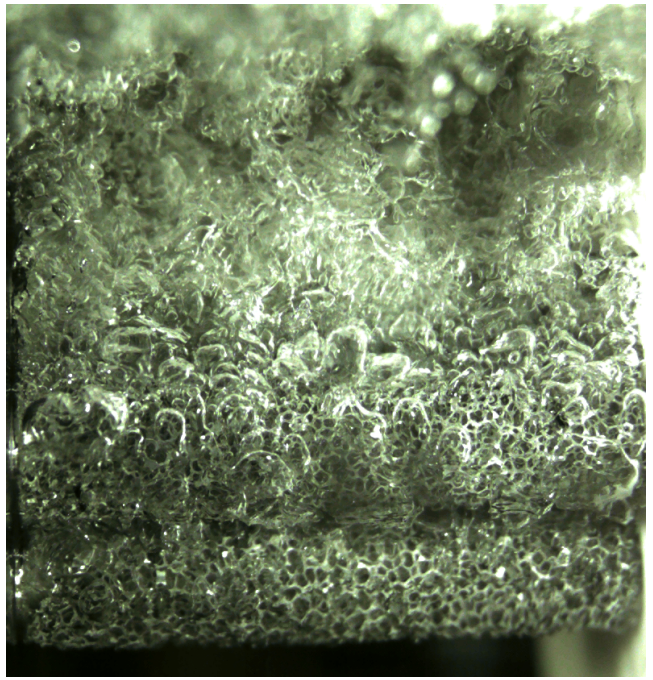


Side view

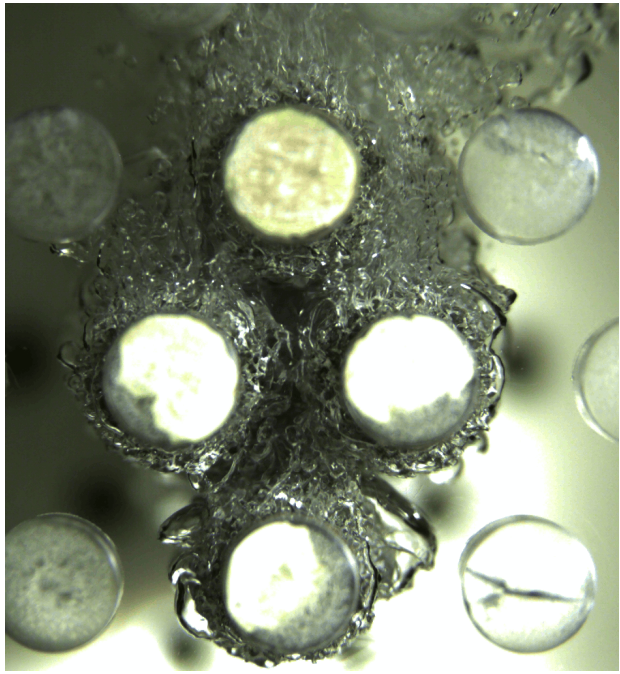


Front view

Metal foam enhanced tube bundle



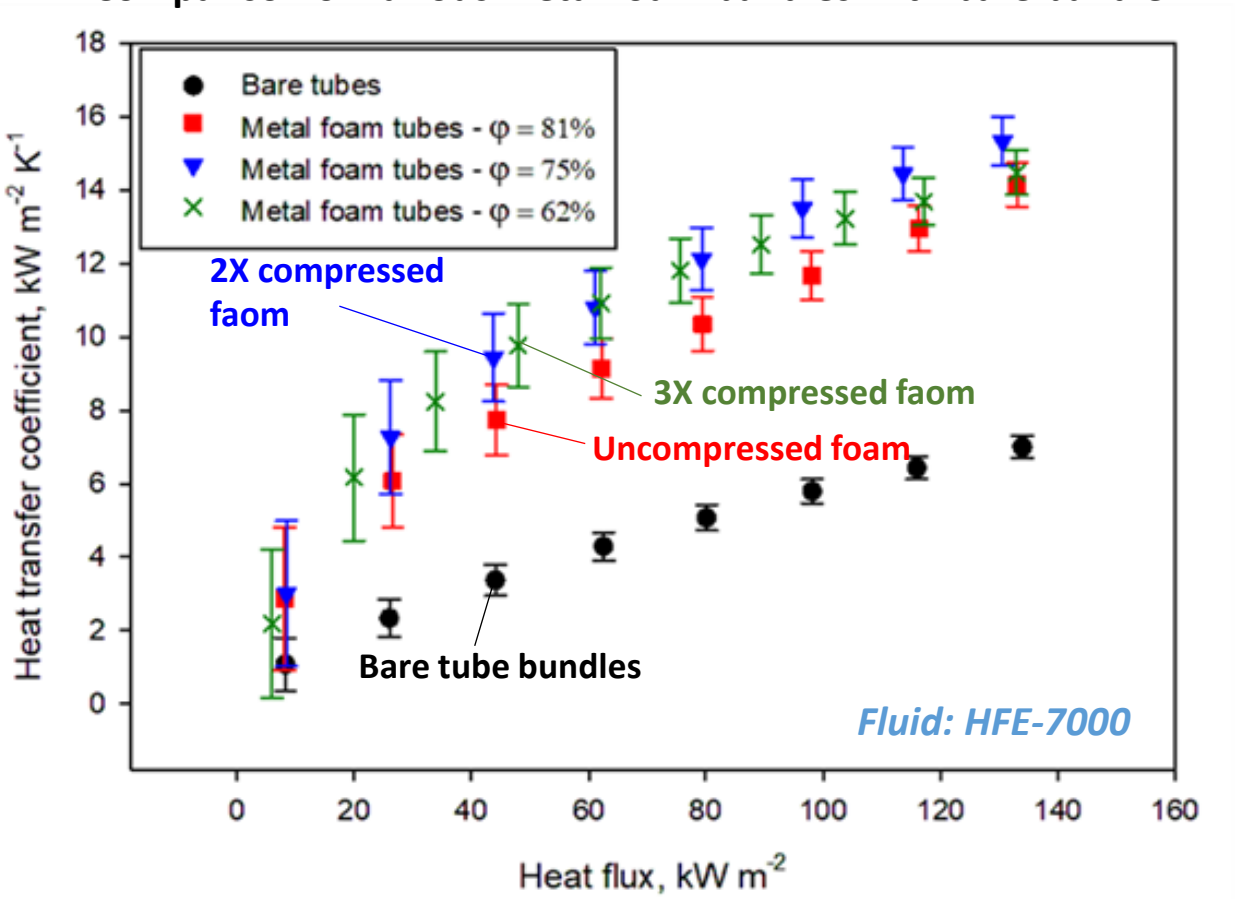
Side view



Front view

Effect of metal foam porosity

Comparison of various metal foam bundles with bare bundle



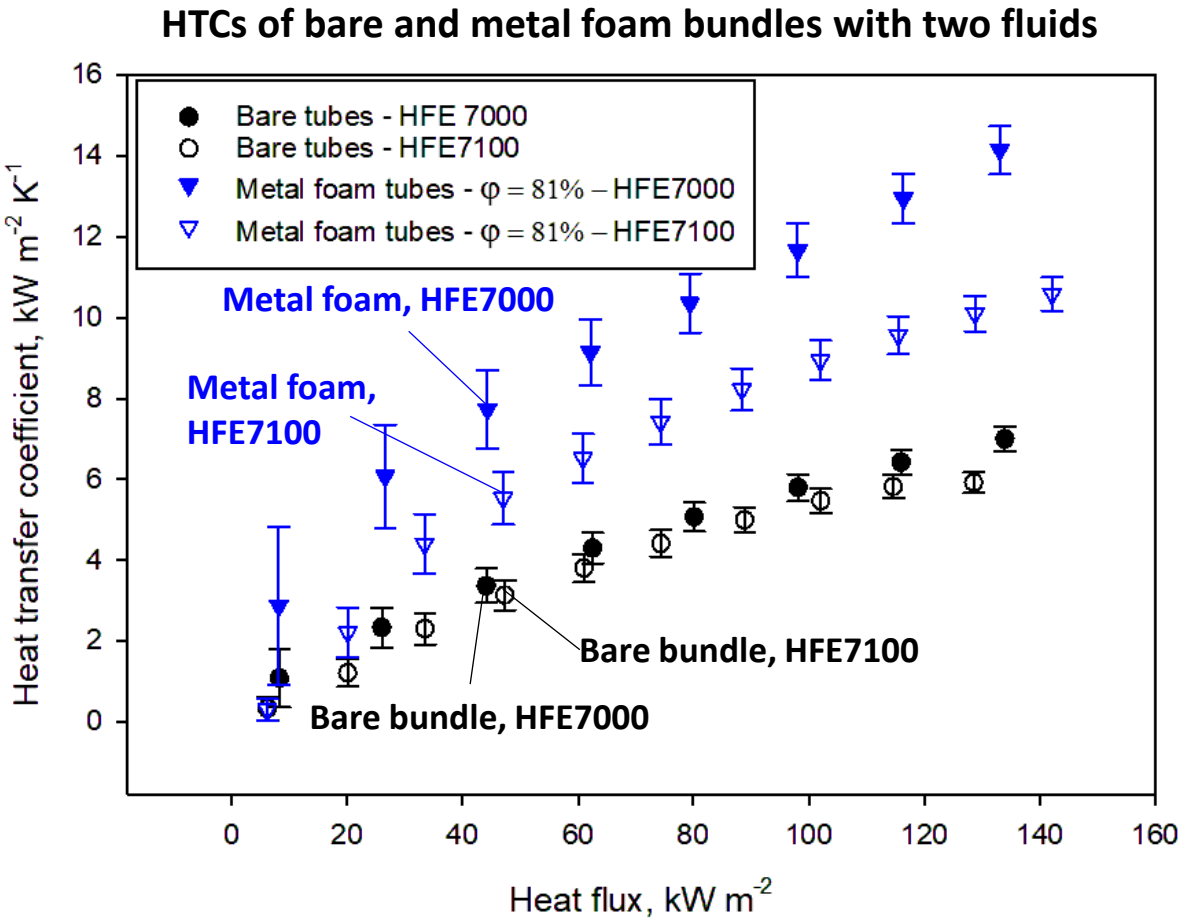
- Enhanced tube bundle experiments:
  - Fluid: HFE-7000
  - Tube pitch: 19 mm
- 2X compressed≈3X compressed >uncompressed foam>bare bundle
- HTC increases with decreasing porosity.

Tube bundle	Enhancement ratio
Uncompressed foam	100-160%
2X compressed foam	120-180%
3X compressed foam	115-154%

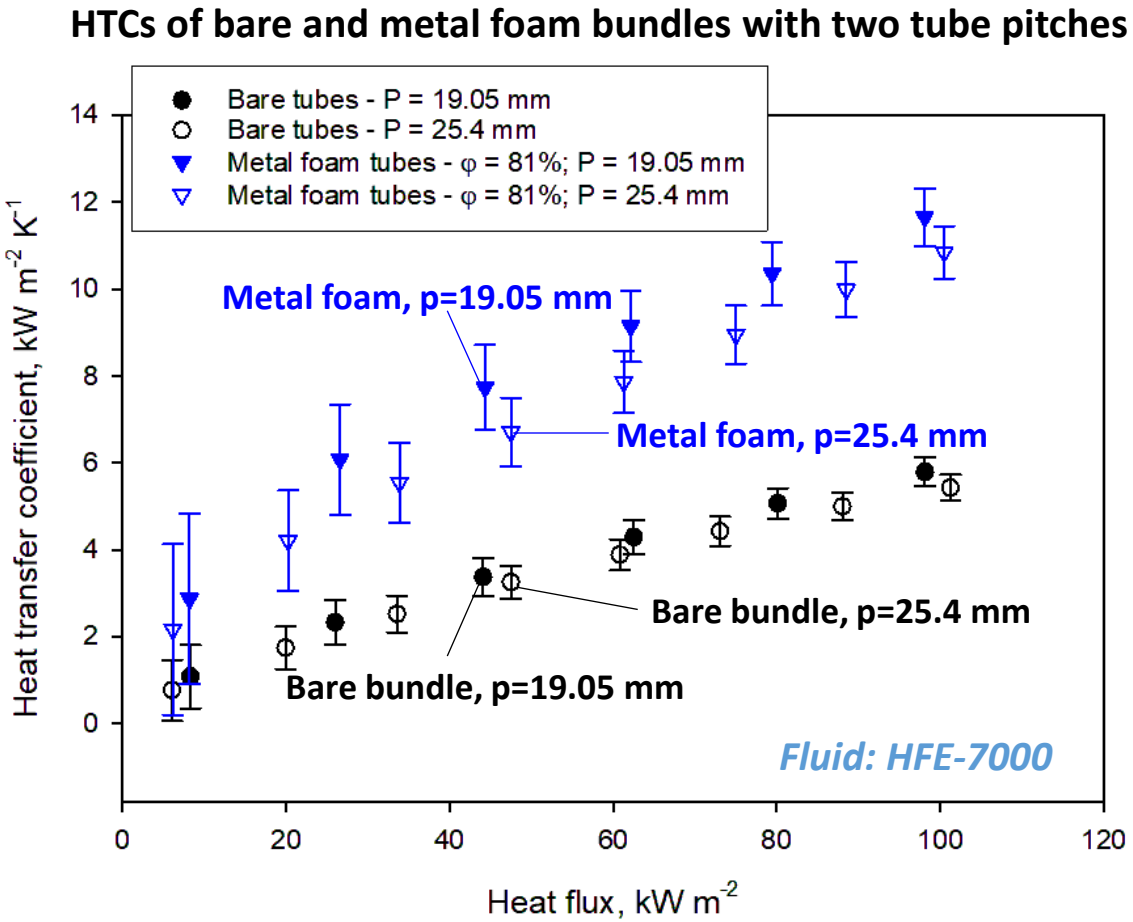
Effect of fluid on bundle performance

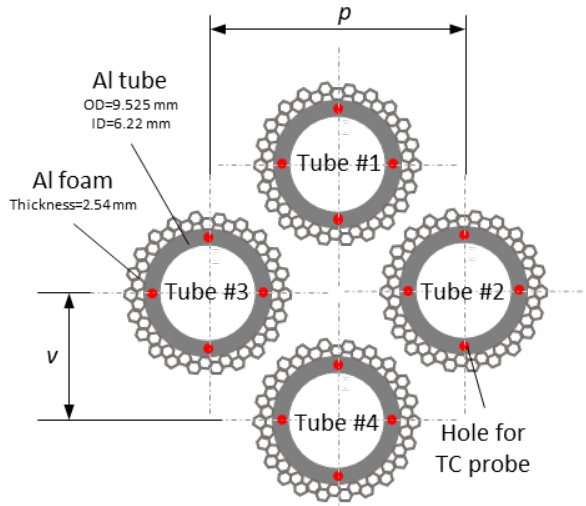
Properties	HFE-7000	HFE-7100
Boiling point, ^{o}C	34	61
Liquid density, kg m^{-3}	1400	1510
Kinematic viscosity, m^2 s^{-1}	3.20E-07	3.80E-07
Dynamic viscosity, Pa s	4.50E-04	5.80E-04
Latent heat of vaporization, KJ kg^{-1}	142	125
Specific heat, J Kg^{-1} K^{-1}	1300	1183
Thermal conductivity, W m^{-1} K^{-1}	0.075	0.069
Surface tension, N m^{-1}	0.0124	0.0136

- For bare tube bundles, HTC of HFE-7000 is 10% higher than that of the HFE-7100.
- For the metal foam bundle, the HTC enhanciement of HFE-7000 is 100–166%, whereas it is 70–90% for HFE-7100.



Effect of tube pitch





- HTC of the bare bundle with 19.05 mm pitch is 3–9% higher than that of 25.4 mm.
- For the metal foam tube bundle, the enhancement for 19.05 mm pitch is 7–14% than that of 25.4 mm.
- When the tube spacing is small, the chance of bubble impingement and sweeping is higher.

Summary

- The heat transfer coefficient of the bare tube bundle is 3-5% higher than that of the single tube.
- As compared to the bare tube bundle, the metal foam tube bundle provides a 100-180% enhancement in heat transfer coefficient under the current test conditions.
- Metal foam structure provides more surface area and nucleation sites.
- For the tested tube bundles: 2X compressed≈3X compressed >uncompressed foam>bare bundle
- The metal foam tube bundle has a higher enhancement ratio in HFE-7000 than HFE-7100.
- When the tube pitch is increased from 19 mm to 25.4 mm, the heat transfer coefficient values decrease by a maximum of 9% and 14% for the bare and metal foam tube bundles, respectively.
- In the future, the tube bundle experiments using refrigerants will be studied in a pressure vessel.

Thank You!

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