Correlational Model for Heat Transfer Coefficient of Solid Particle-to-CO2 Moving Bed Heat Exchangers with Finned Tubes

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ECHOGEN
power systems

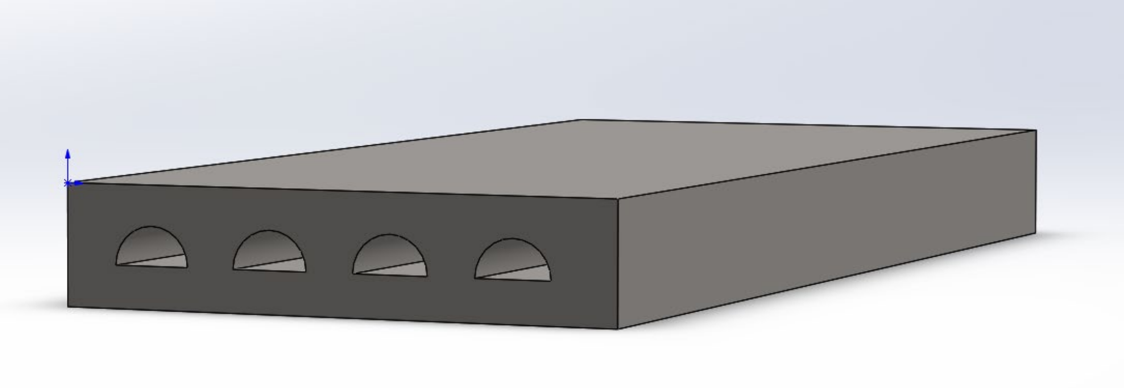
Supercritical CO_2
Power Cycles
Symposium

Project Background

- Solid particle-to-CO_2 heat exchangers are desired for many power cycle applications
  - Concentrated Solar Power (CSP)
  - Pumped Thermal Energy Storage (PTES)
- Two major classes of exchangers:
  - Fluidized Bed
    - High heat transfer coefficient (HTC), but high parasitic loads
    - Bi-directional flow is possible
  - Moving Bed (MBHE)
    - Low HTC, and low parasitic loads
    - Unidirectional flow

Existing Technology

- Solid particle MBHEs are traditionally constructed as:
  - “Pillow Plate” welded designs
    - Currently unsuitable for high pressure CO_2 power cycle applications
  - Diffusion bonded Printed Circuit Heat Exchangers (PCHE)
    - High pressure applications are possible using costly INCONEL® 617
    - Tight passages have inherent susceptibility to particle clogging and passage-to-passage flow variations



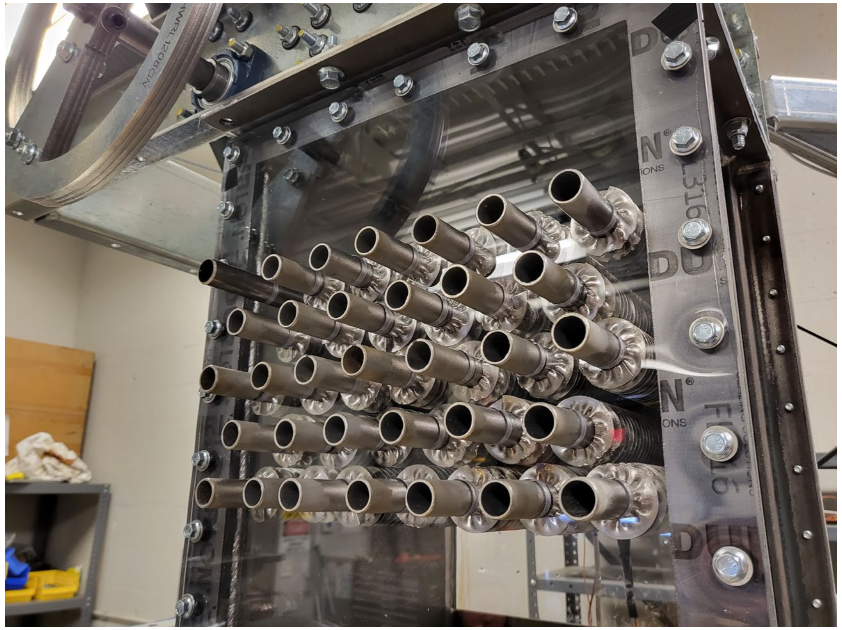
Tubular Moving Bed Heat Exchangers

- Tubular constructions for MBHEs have been suggested as an alternative to PCHE designs by Baumann & Zunft[1]
  - Bare tube prototype was found to have effective HTC of a comparable magnitude to PCHE constructions (ca. 200 – 250 $W/m^2/K$)
- Tubular construction permits the use of INCONEL® 740H which is of higher strength than 617
  - Thinner walls than required for PCHEs, yielding material cost savings in addition to simpler construction
  - Use of bare tubes has inherent flaw of decreasing the amount of external heat transfer surface area in a given heat exchanger volume

1: T. Baumann and S. Zunft. "Development and performance assessment of a moving bed heat exchanger for solar central receiver power plants". In: Energy Procedia 69 (May 2015), pp. 748–757.

Finned Tube MBHEs

- Echogen has considered the feasibility of adding fins to tubular MBHEs
  - Allows the use of lower cost 316L stainless steel as fin material
  - Increases the density of heat transfer surface area in the heat exchanger volume
  - Finned tubes have a risk of clogging with particles or inducing large stagnation zones with low particle flow

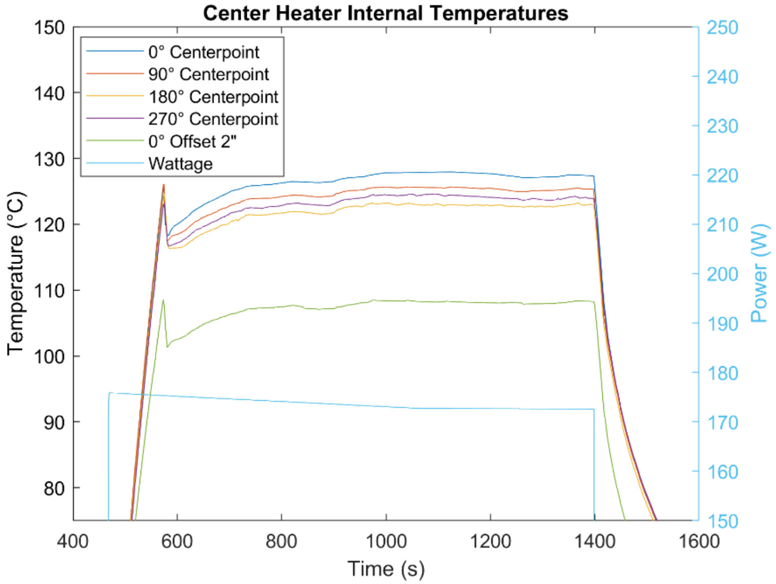


Test Facilities

- Echogen fabricated a MBHE test facility allowing quick reconfiguration of tube bundles
  - 1.0 metric tons total capacity
  - Particle discharge is designed to prevent funnel flow conditions
  - Particle flowrate is controlled by variable area slot on the discharge and metered by loss-in-weight via load cells

Test Facilities, cont.

- Convective HTC is evaluated by a single instrumented tube in the center of the test section
  - Electric cartridge heater and several thermocouples are soldered into the tube
  - Tubes to left and right were also heated to reduce impact of thermal conduction
  - Power is controlled by variac



HTC Calculation

- The particle HTC is calculated by:

$$h_{part} = \frac{1}{A}\left(\frac{\Delta T}{Q} - R_{cond}\right)^{-1}$$

  - Q is measured power, A is the heat transfer area, and ΔT is the measured difference between the tube surface temperature and the bulk particle temperature
  - R_{cond} is the measured thermal resistance between the surface of the tube and the internal thermocouple location
    - R_{cond} was experimentally determined and is a function of Q

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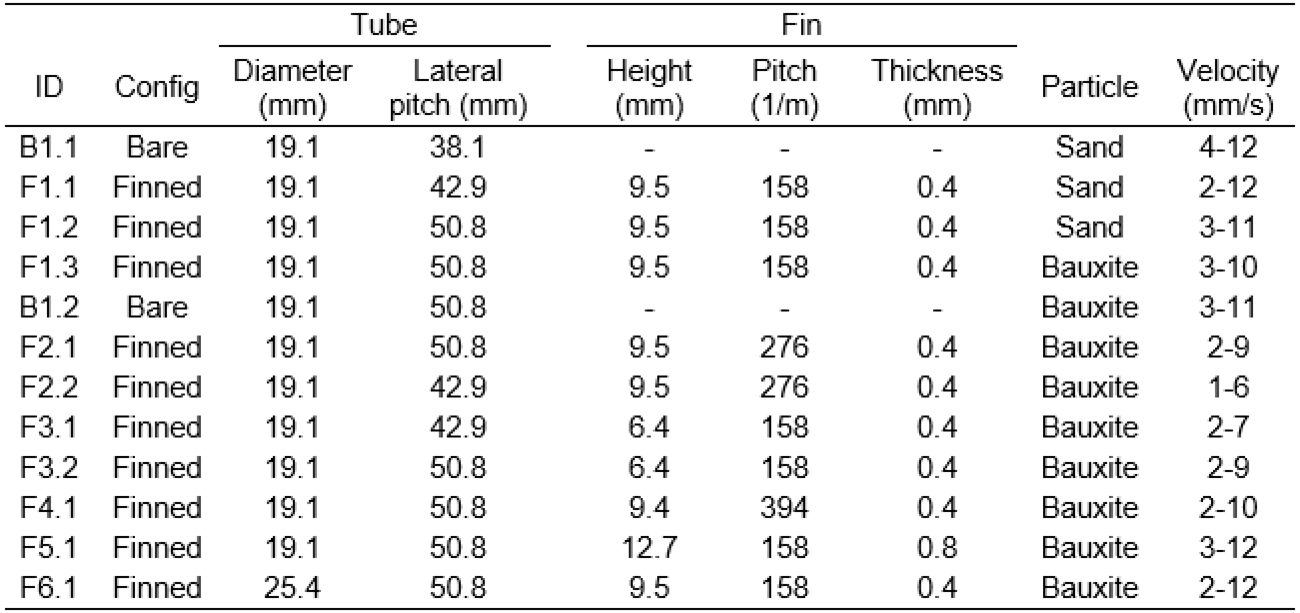
Tested Configurations

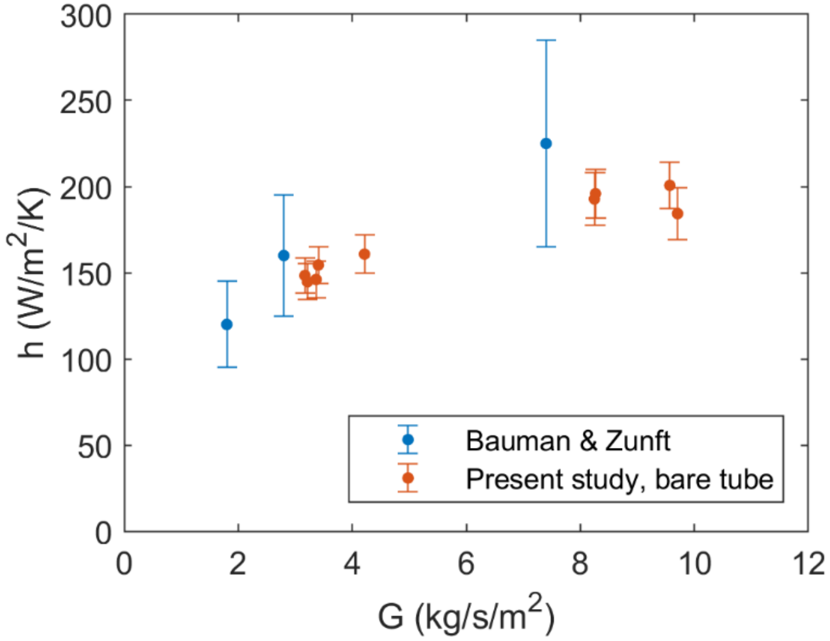
- Tube configurations were selected to be representative of typical tubular heat exchanger designs
- Finned tubes are spiral type brazed fins
- All tubes are carbon steel



		Tube		Fin				
ID	Config	Diameter (mm)	Lateral pitch (mm)	Height (mm)	Pitch (1/m)	Thickness (mm)	Particle	Velocity (mm/s)
B1.1	Bare	19.1	38.1	-	-	-	Sand	4-12
F1.1	Finned	19.1	42.9	9.5	158	0.4	Sand	2-12
F1.2	Finned	19.1	50.8	9.5	158	0.4	Sand	3-11
F1.3	Finned	19.1	50.8	9.5	158	0.4	Bauxite	3-10
B1.2	Bare	19.1	50.8	-	-	-	Bauxite	3-11
F2.1	Finned	19.1	50.8	9.5	276	0.4	Bauxite	2-9
F2.2	Finned	19.1	42.9	9.5	276	0.4	Bauxite	1-6
F3.1	Finned	19.1	42.9	6.4	158	0.4	Bauxite	2-7
F3.2	Finned	19.1	50.8	6.4	158	0.4	Bauxite	2-9
F4.1	Finned	19.1	50.8	9.4	394	0.4	Bauxite	2-10
F5.1	Finned	19.1	50.8	12.7	158	0.8	Bauxite	3-12
F6.1	Finned	25.4	50.8	9.5	158	0.4	Bauxite	2-12

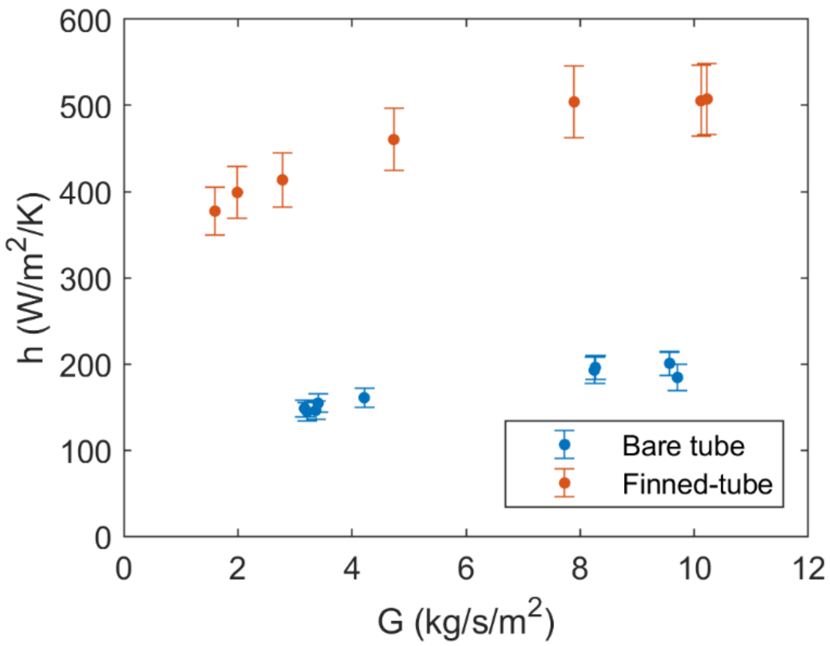
Results - Comparison to Literature

- Initial bare tube testing to replicate data from Baumann & Zunft
- Good agreement between data sets validates test methodology



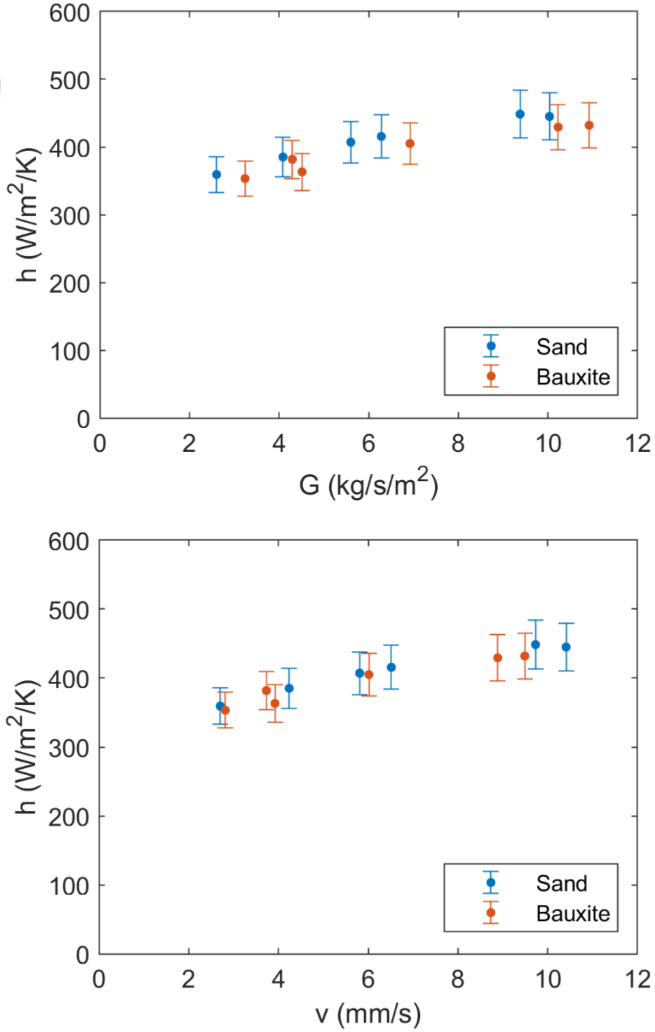
Results - Finned vs Bare Tubes

- Finned tubes compared with bare tubes all other variables the same
- HTC reported for finned tubes is evaluated based on the bare tube area of the tube to allow direct comparison
    - Actual-area HTC of finned tubes is 40% less than bare tubes – but the area is 460% larger



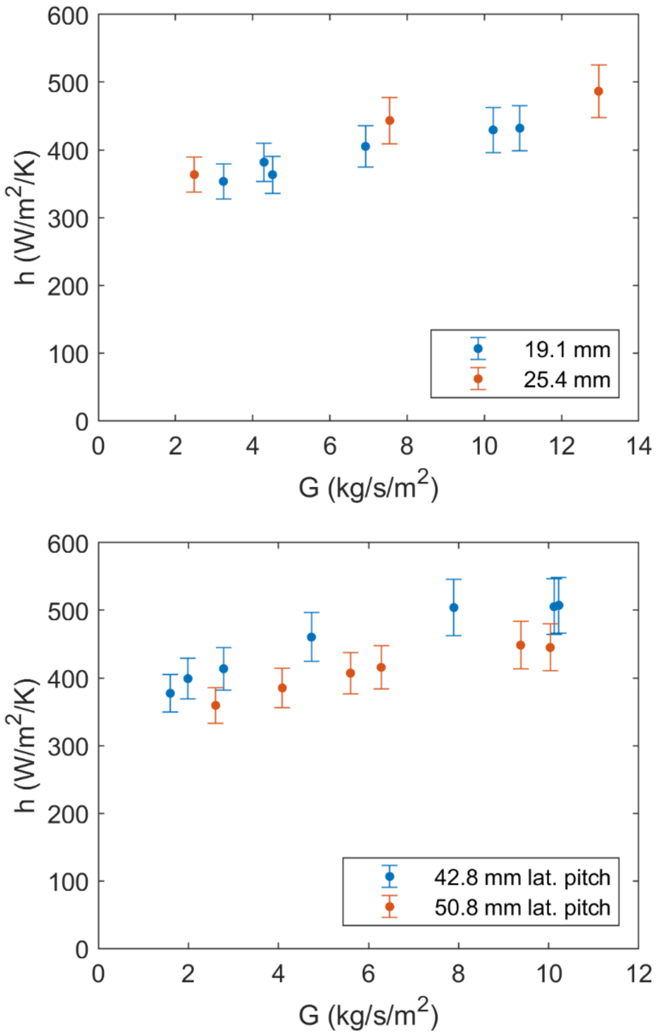
Results - Sand vs Sintered Bauxite

- Measured HTC of identical tube bundles with sand and sintered bauxite
- Top is by mass flux, bottom is by velocity
- Comparison by velocity is required when particles are of different bulk density
- Differing particle size is not seen to be a significant factor for HTC
    - Sand is 170 µm
    - Bauxite is 350 µm



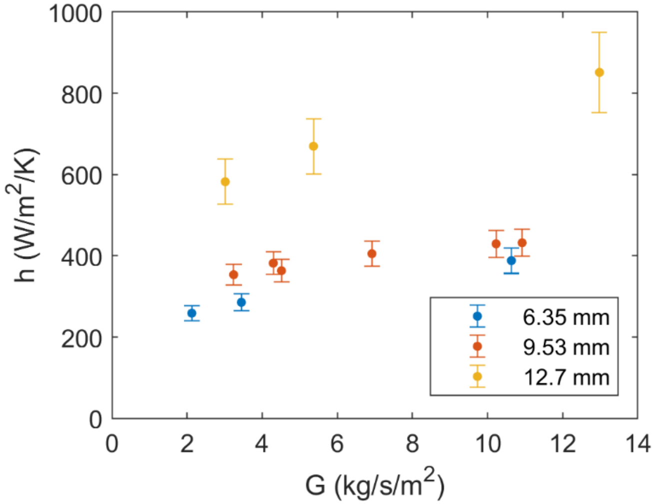
Results - Diameter and Tube Pitch

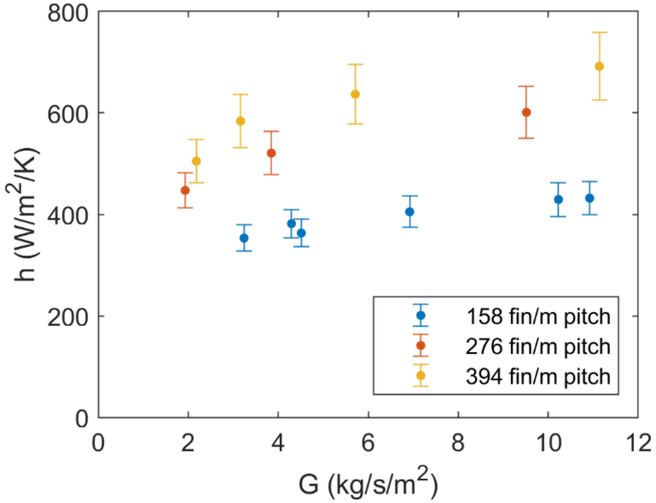
- Measured HTC, changing tube diameter (top) and lateral tube pitch (bottom)



Results - Fin Height and Fin Spacing

- Measured HTC changing fin height (top) and fin spacing (bottom)
- Note that the expected upper limit to fin spacing performance was not found in this study
    - 394 fins/m was maximum available from supplier
    - Fin spacing is only 6x the maximum particle diameter





Correlation via Nusselt Number

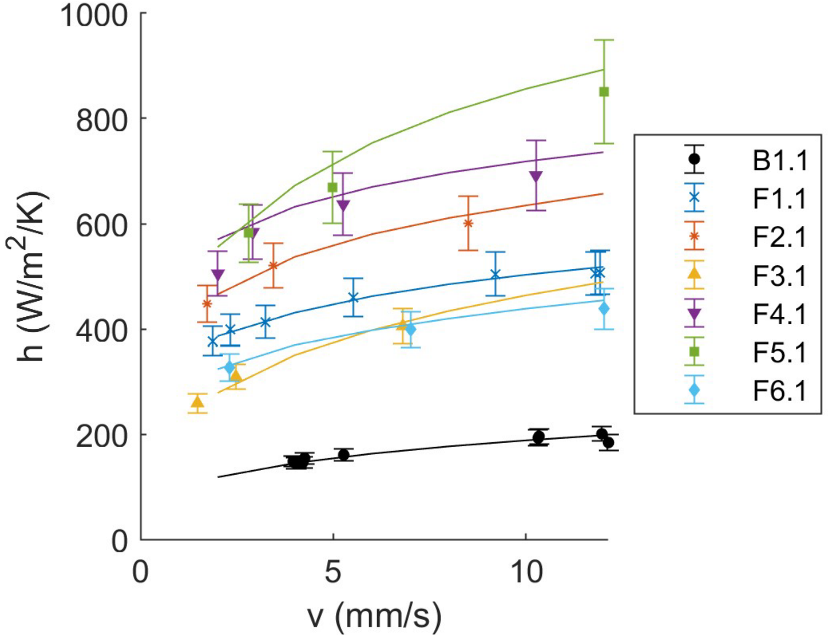
- Measured HTC were correlated to Nusselt Number using a power-law trend with maximum particle velocity

$$h_p = \frac{Nu * k_{eff}(T)}{D_h} \qquad Nu = \alpha \left(\frac{v_{p,max}}{10mm/s}\right)^{\beta}$$

  - D_h is the hydraulic diameter of the finned tube, $k_{eff}(T)$ is the particle thermal conductivity as a function of temperature
  - α and β are correlation parameters found by reducing the root mean squared difference between the measured and calculated HTCs
  - $v_{p,max}$ is the maximum particle velocity (i.e. the velocity at the point between tubes where the flow area is the least)

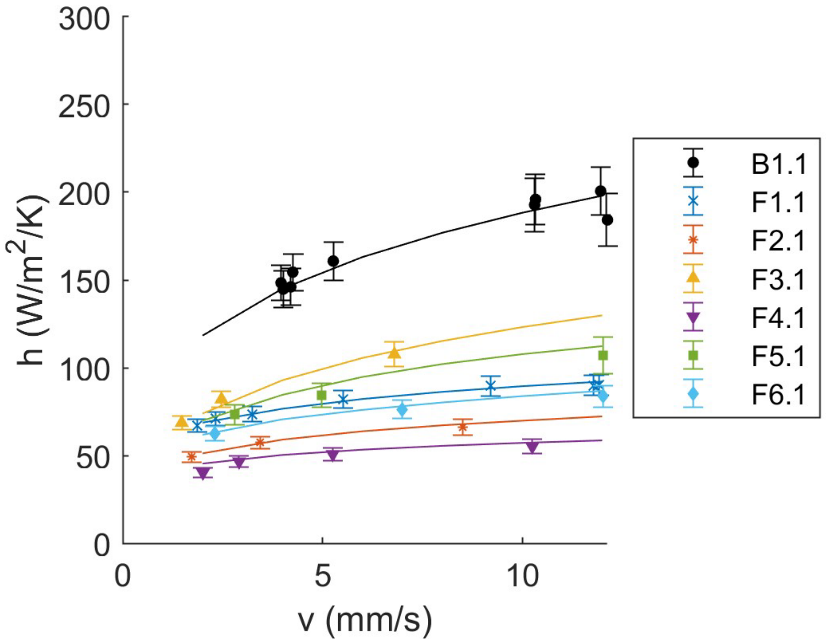
Correlation Output

- HTC vs Velocity on a basis of bare tube heat transfer area
  - Lines are Nusselt number correlations, points are measured data
  - Only select configurations are shown for clarity
- HTC increases monotonically by area density except for F5.1 which had taller and thicker fins
  - Larger fin area increases fin efficiency



Correlation Output, cont.

- HTC vs Velocity on a basis of true geometric heat transfer area
- Lowest HTCs of F4.1 and F2.1 correspond to decreasing fin spacing
    - Economic modeling is required to identify presence of diminishing returns due to increased manufacturing costs



Conclusions

- Measured equivalent area HTC was found to increase with increasing surface area
  - Increasing area did not result in any penalties to HTC
  - Economic analysis is required to identify diminishing returns
- The equivalent area HTC values measured are of comparable magnitude to existing PCHE designs, suggesting a material cost advantage for FT/MBHE
- No flow disruptions due to presence of fins was detected

Disclaimer

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