Modeling Geometric Effects on Heat Transfer with Graphite Foam

Dr. James Klett, April McMillan, Dave Stinton
Metals and Ceramics Division
P.O. Box 2008, Oak Ridge National Laboratory
Oak Ridge, Tennessee, 37831-6087
(865) 574-5220
klettjw@ornl.gov

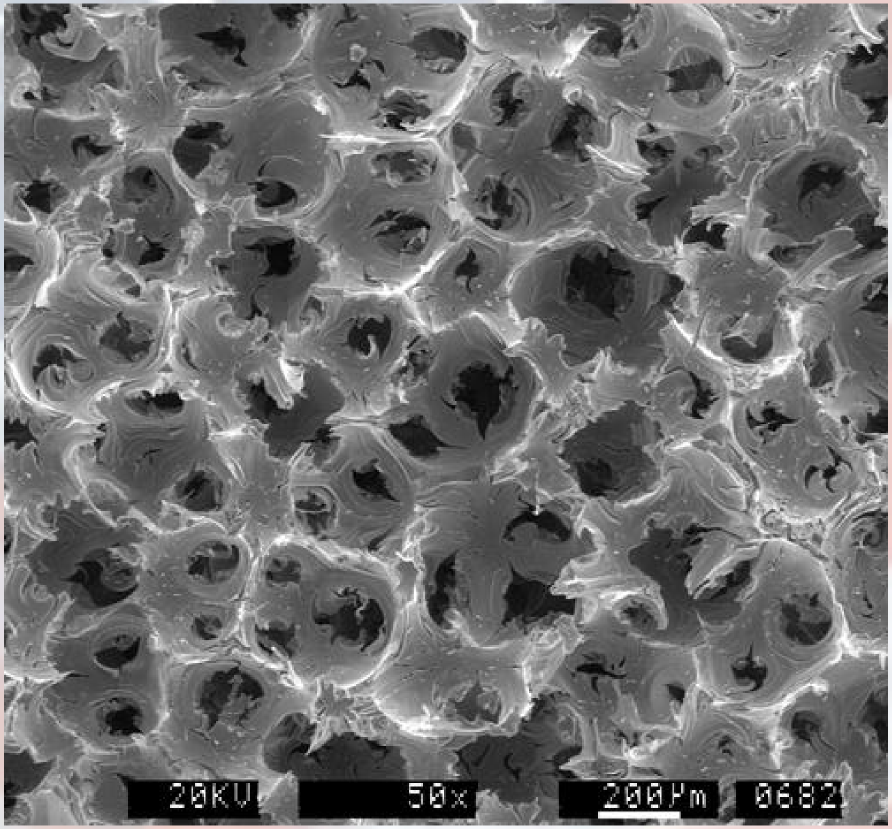
www.ms.ornl.gov/sections/mpst/Cimtech/default.htm

Keywords: Graphite Foam, Thermal Conductivity, Thermal Management

July 27, 2002

ORNL Mesophase-Derived Graphitic Foam

- **5 patents, 11 pending, 2000 R&D 100 Award Winner**
- **Novel Process and Novel Material**

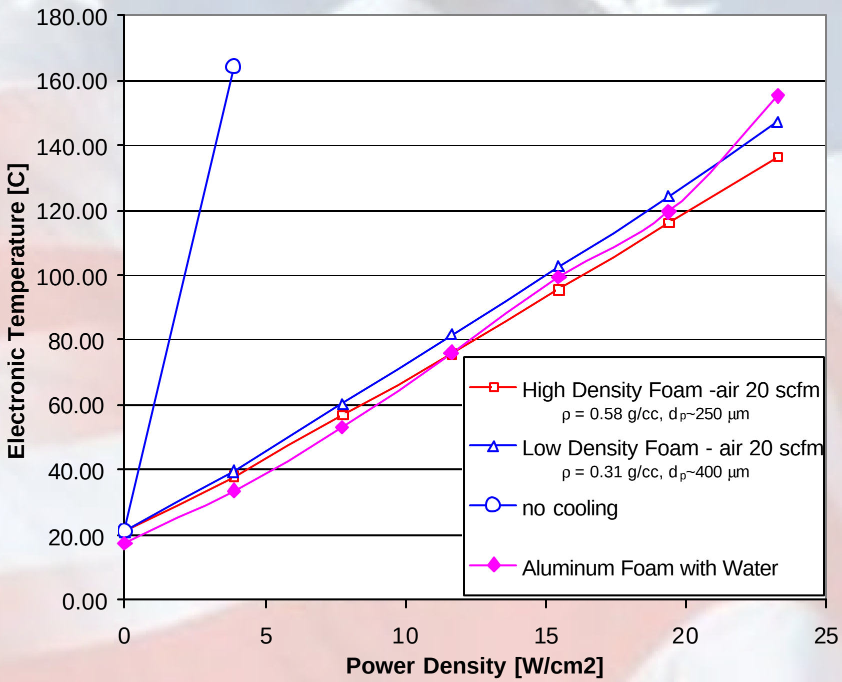


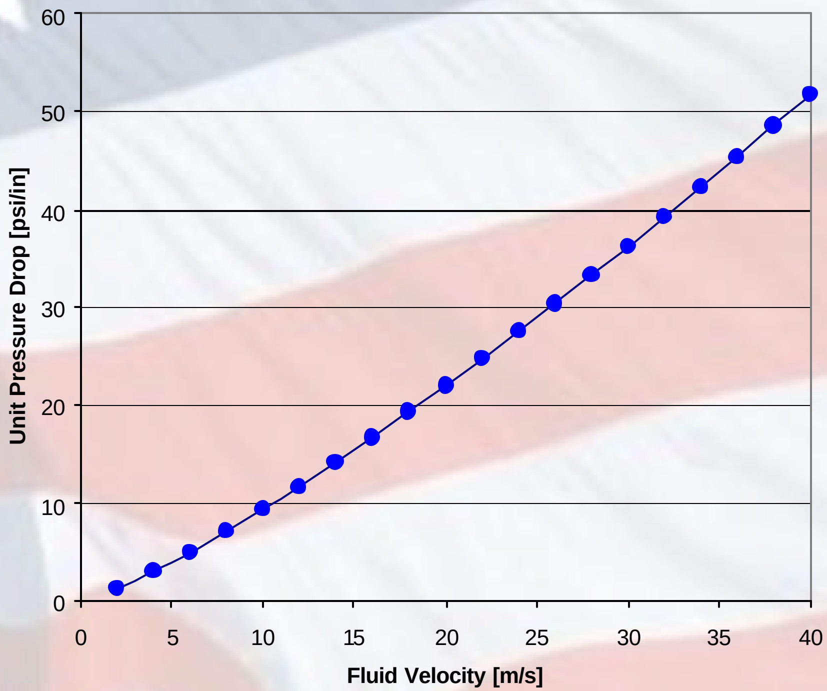
- **Highly ordered graphitic ligaments**
  - **Graphitic-like properties**
- **Dimensionally stable**
  - **low CTE - ~2 - 4 µin/in/°C**
- **Open Porosity**
  - **Permeable to fluids**
- **Excellent thermal management material**

2000 R&D 100 Award Winner

Graphite Foam Heat Sinks

- **Graphite foams have been demonstrated to be excellent heat sinks**
- **However, pressure drop is significant**





Material and Geometry Changes to Reduce Pressure Drop

- Lower the density (open the porosity)
  - May reduce heat transfer?
  - May also reduce pressure drop?
- Machine finned structure
  - Dramatically reduces heat transfer
- Corrugate structure like a HEPA filter
  - Should reduce heat transfer
  - Should also reduce pressure drop?

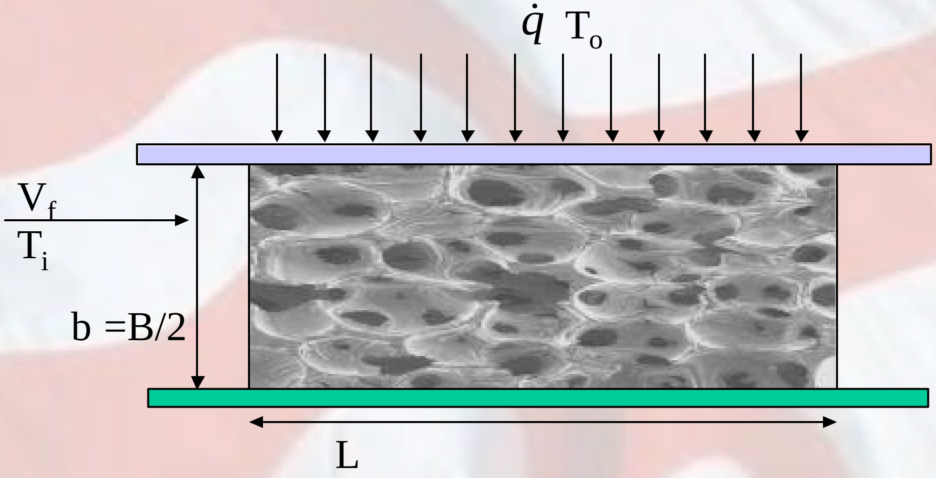
- Many variables can affect performance
- Need to model heat transfer to change structure virtually and save time and lower design costs

Heat Transfer in Foam

- **Model steady state heat transfer**
- **Assume heat transfer is similar to flow through packed bed**

$$N_{Nu} = \frac{h_{loc} \cdot d_p}{k_f}$$

h_{loc} = local heat transfer coefficient
d_p = pore diameter
κ_f = fluid conductivity



Nusselt Numbers

- **Nusselt number is empirically related to Reynolds number, foam properties, and fluid parameters**

$$N_{Nu} = m\,N_{\mathrm{Pr}}^{0.36}\,N_{\mathrm{Re}}^{\;y}$$

$$N_{\mathrm{Re}} = \frac{V_f\,d_p}{n_f}$$

$N_{\mathrm{Pr,air}}$ = 0.72
h_{loc} = local heat transfer coefficient
d_p = pore diameter
V_f = fluid velocity [m/s]
ν_f = air kinematic viscosity [15.05×10^{-6} $\mathrm{m^2/s}$]

- **For the graphitic foam, the constants were experimentally determined to be:**

m = 0.0158
y = 0.7225

Heat Fluxes

- **Unit heat transfer is related to temperature differences and the local heat transfer coefficient**

$$Q = L \cdot W \cdot h_{loc} \cdot A \cdot \Delta T$$

- **However, since total surface area is unknown, we relate this to an effective heat transfer coefficient.**

$$Q = L \cdot W \cdot h_{eff} \cdot \Delta T$$

$$h_{eff} = \frac{2}{d_p} \tilde{k} \sqrt{N_{Nu} \left(\frac{k_f}{k_s} \right)} \tanh \left[\frac{4b}{d_p} \sqrt{N_{Nu} \left(\frac{k_f}{k_s} \right)} \right]$$

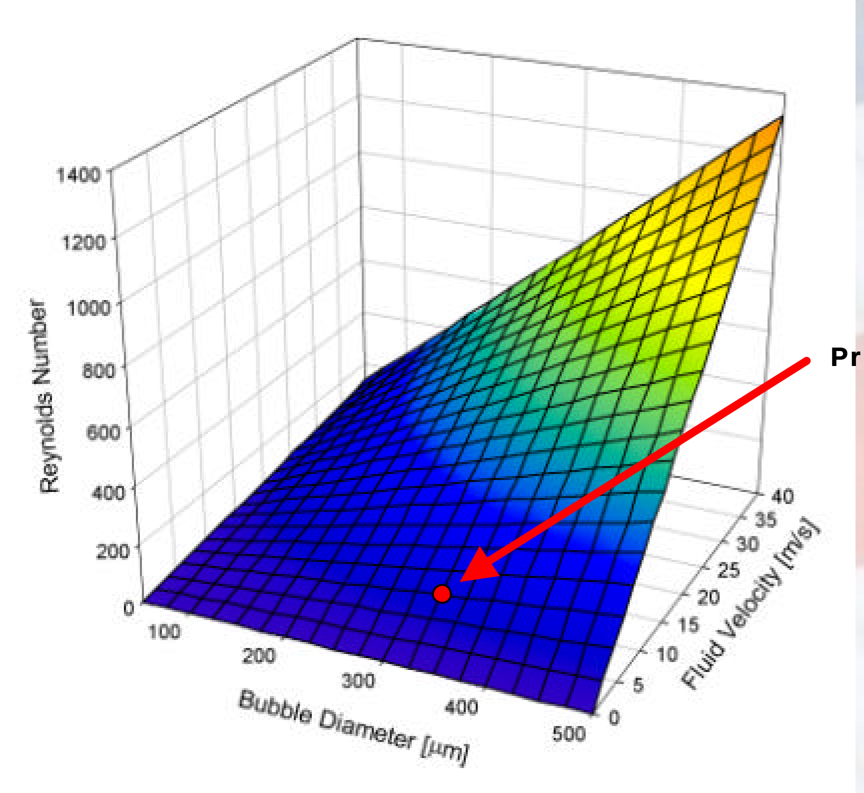
$$\Delta T_{LM} = \frac{T_e - T_i}{\ln \left(\frac{T_h - T_i}{T_h - T_e} \right)}$$

k_f = thermal conductivity of fluid (0.02624 W/m·K for air)

k_s = thermal conductivity of solid (1800 W/m·K for foam ligament)

Reynolds Number

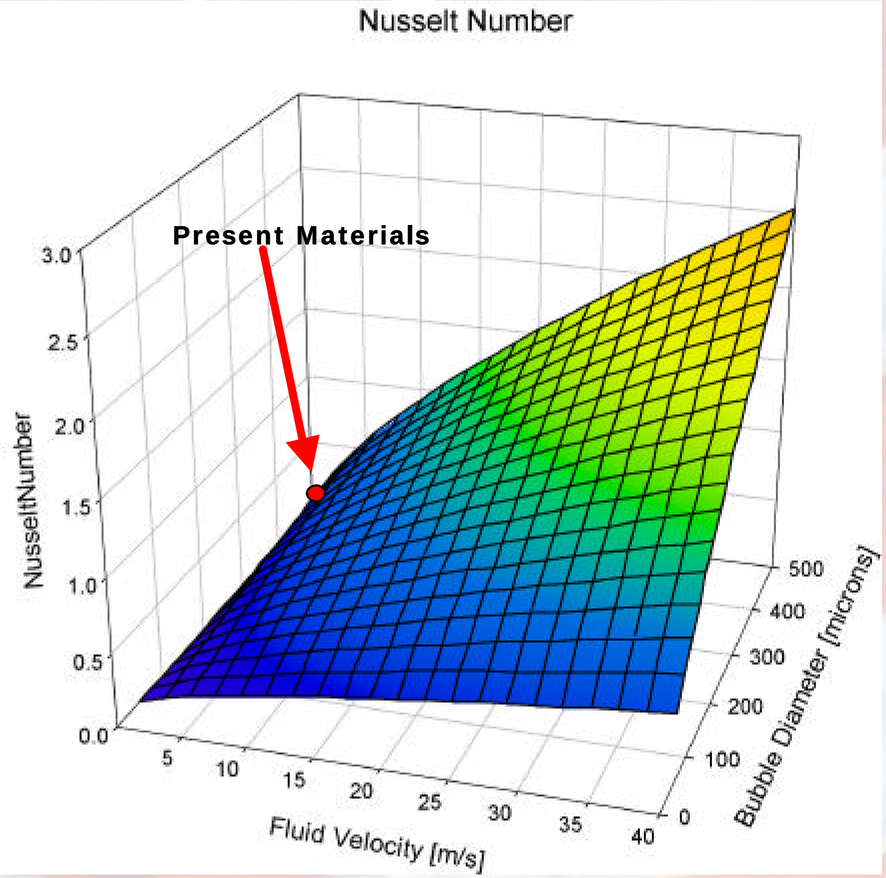
- Reynolds number is in the laminar regime
- Indicates that there is little turbulence developed in bubbles



Present Materials

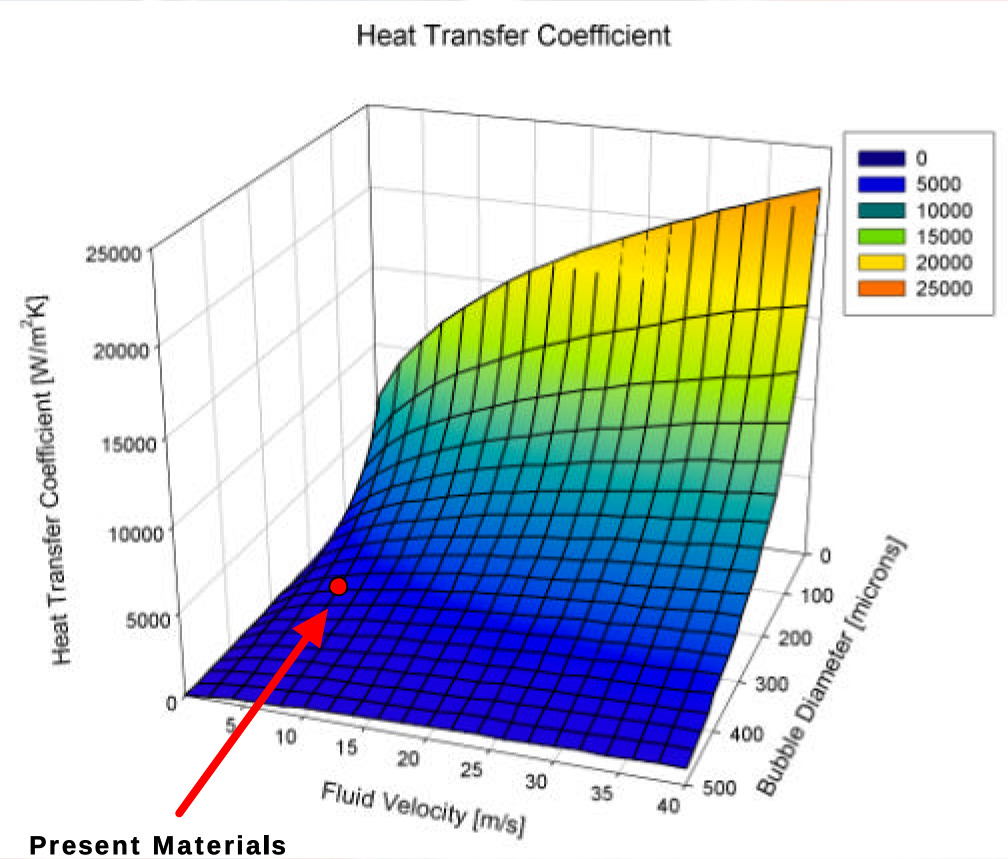
Model Results – Nusselt Number

- **Increasing fluid velocity increases heat transfer**
- **Higher velocities results in larger dependence of N_{Nu} on pore diameter**



Model Results – Heat Transfer Coefficient

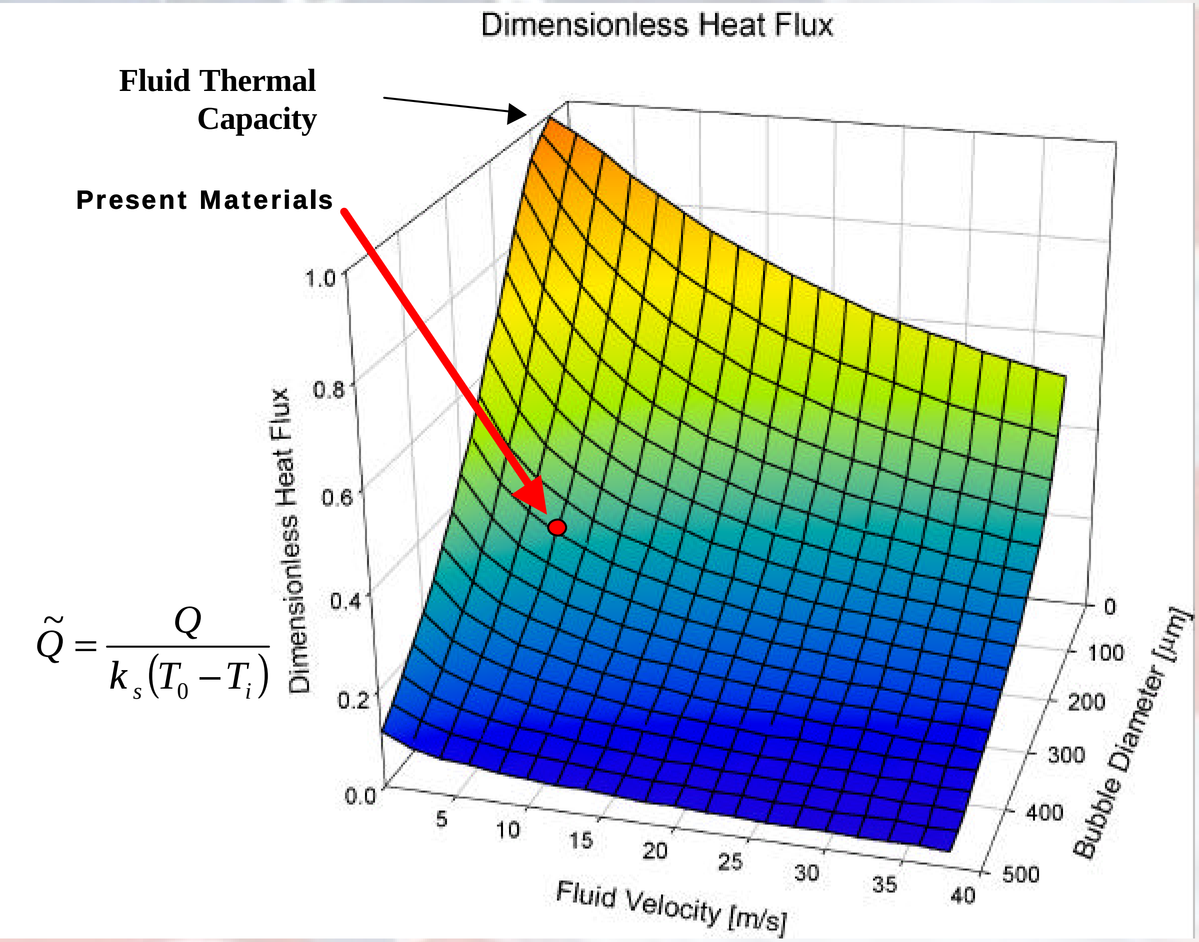
- Decrease in pore diameter increases heat transfer coefficient
- Increasing the velocity has diminishing returns on heat transfer



Present Materials

Dimensionless Heat Flux

- **Decreasing bubble diameter increases heat flux**
- **Increasing fluid velocity increases heat flux, but with diminishing returns**
- **Both result in higher pressure drops**



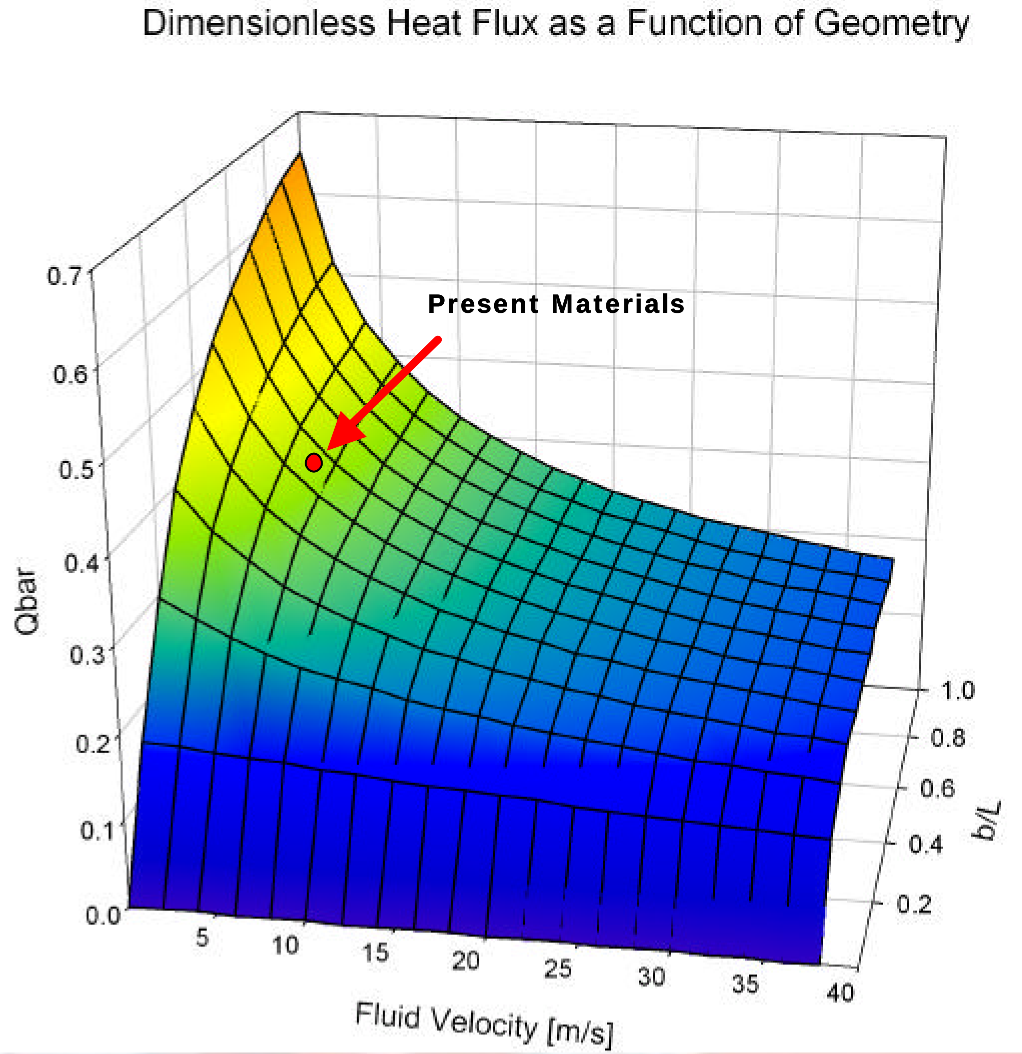
Fluid Thermal Capacity

Present Materials

$$\tilde{Q} = \frac{Q}{k_s(T_0 - T_i)}$$

Geometric Effects

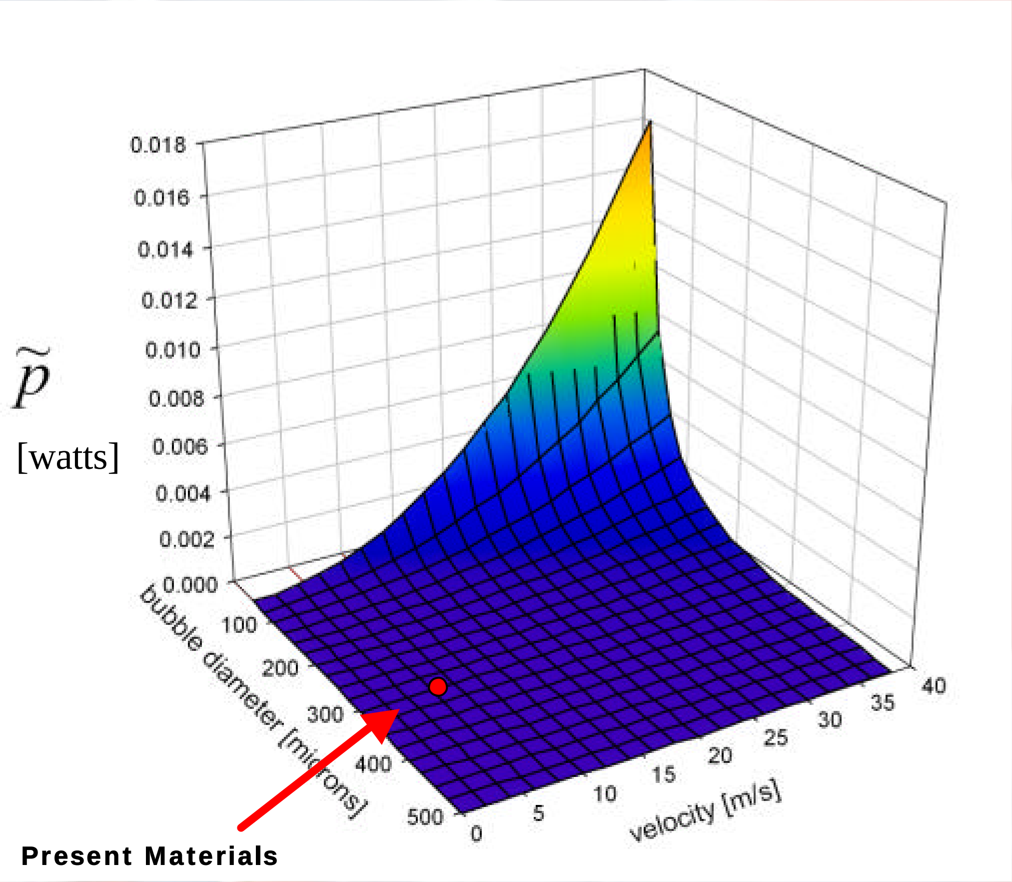
- **Increasing ratio of thickness to flow length results in improved heat transfer**
- **There is a delicate balance between thickness and system volume**


Dimensionless Heat Flux as a Function of Geometry

Pumping Power

- Dramatic increases in pumping power as bubble diameter decreases
- Dramatic decrease in pumping power as fluid velocity decreases

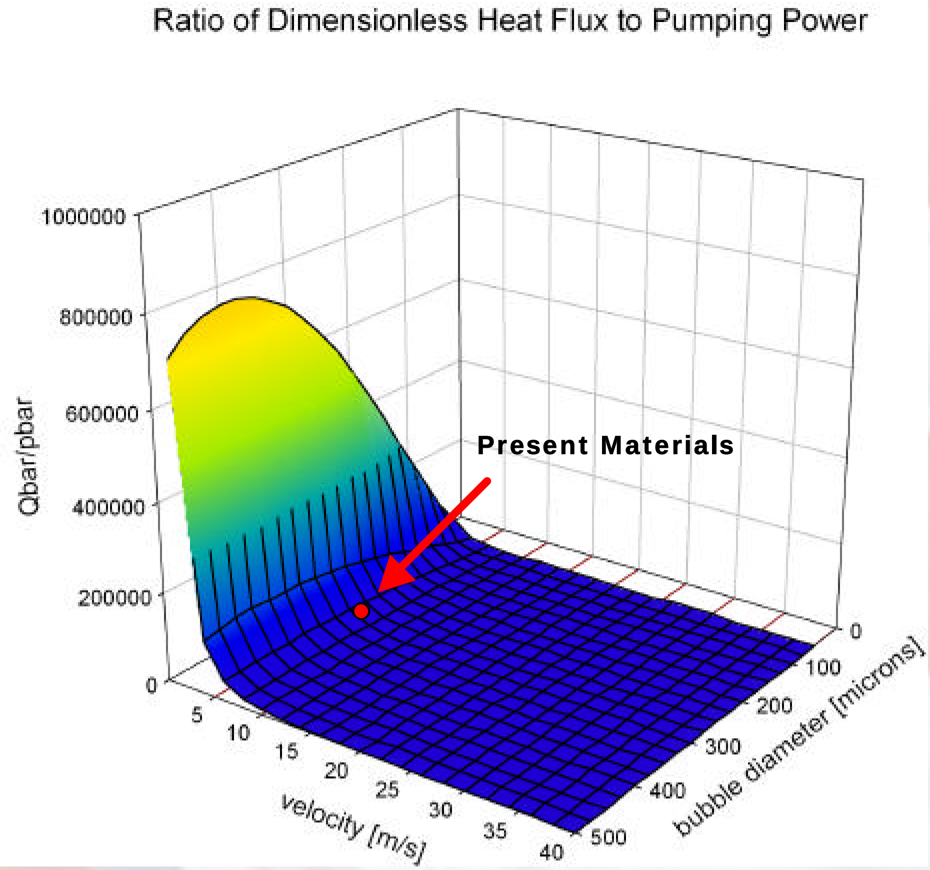
- Decreasing pumping power typically correlates with decreased heat transfer
- Balance much be reached between pumping power and heat transfer



Present Materials

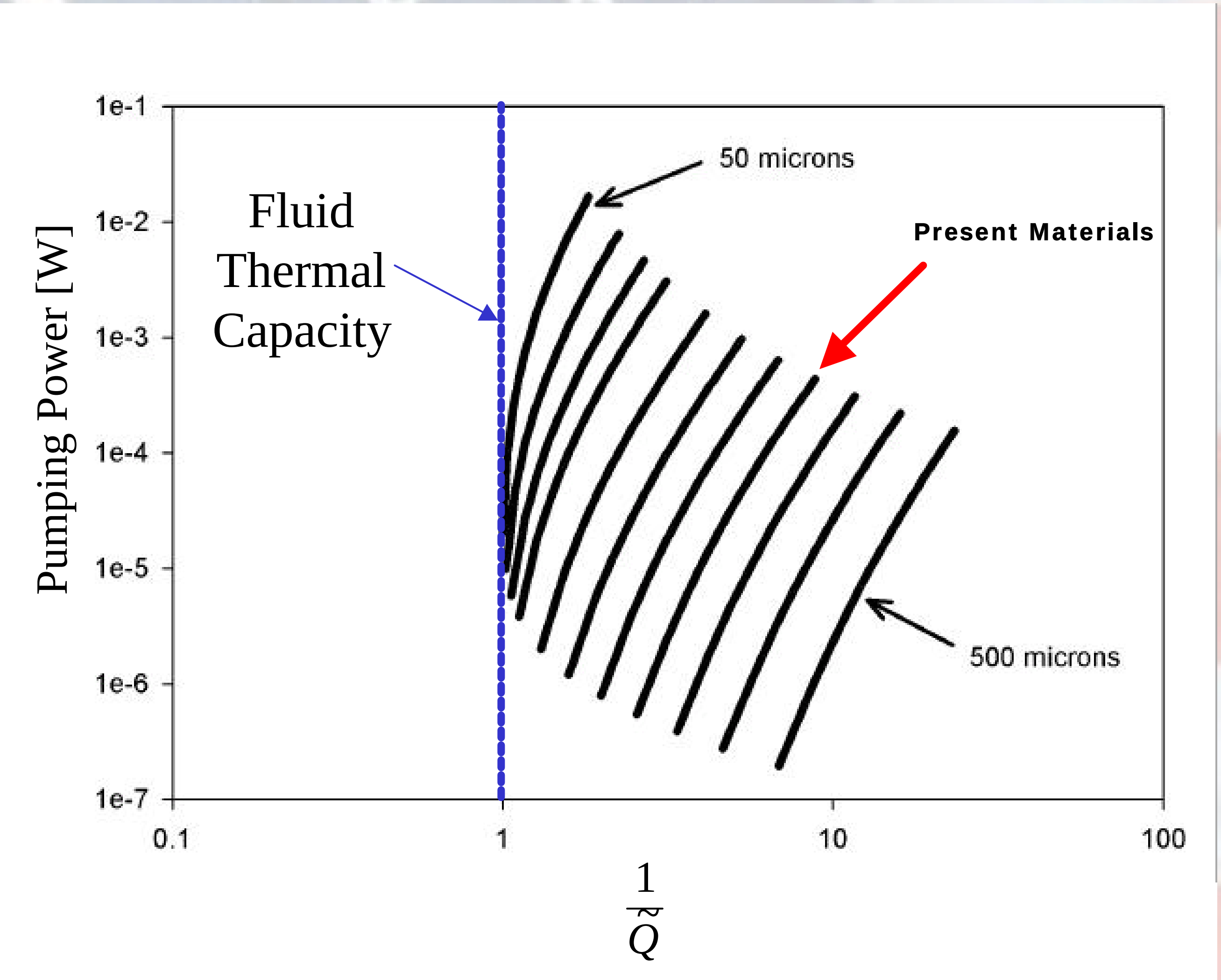
Ratio of Heat Flux to Pumping Power

- Ratio of heat flux to pumping power increases at lower flow velocities.
- However, there is a maximum in this ratio, indicating that reducing pressure drop too far by adjusting foam structure will eventually decrease heat transfer



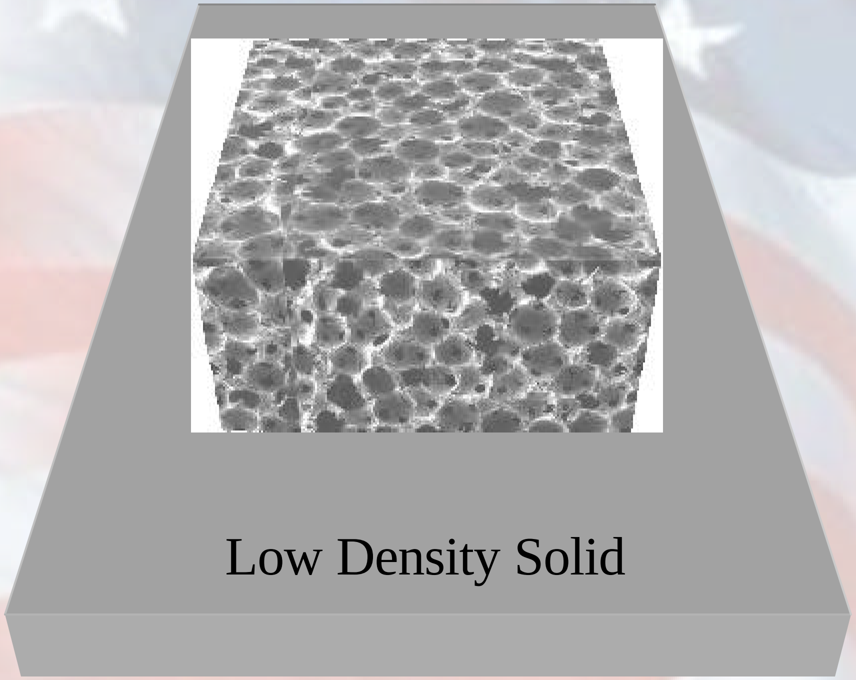
Pumping Power versus Heat flux

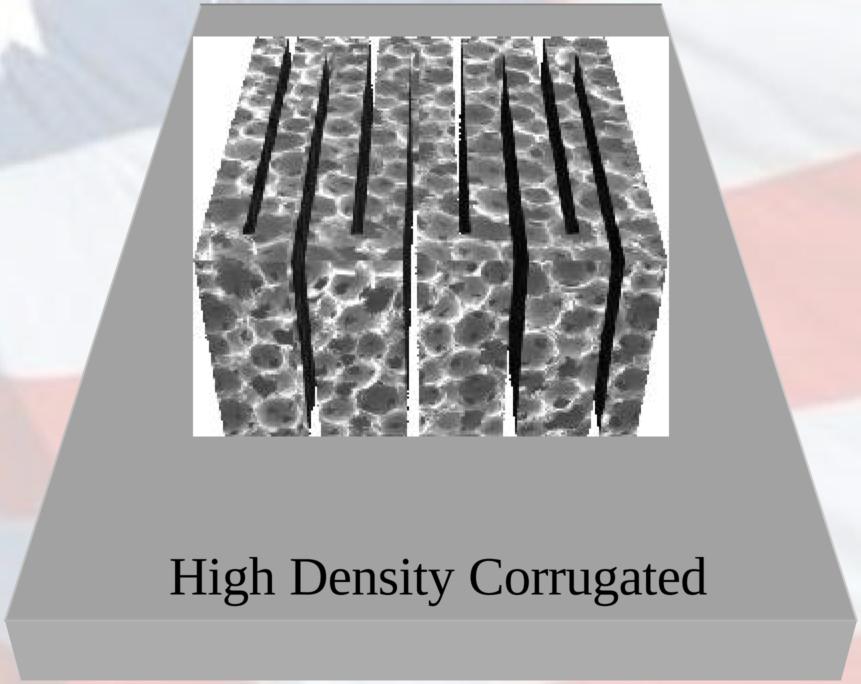
- **Heat transfer is limited by the fluid thermal capacity**
- **This balance needs to be met at the lowest pressure drop.**



Corrugate vs. lower density

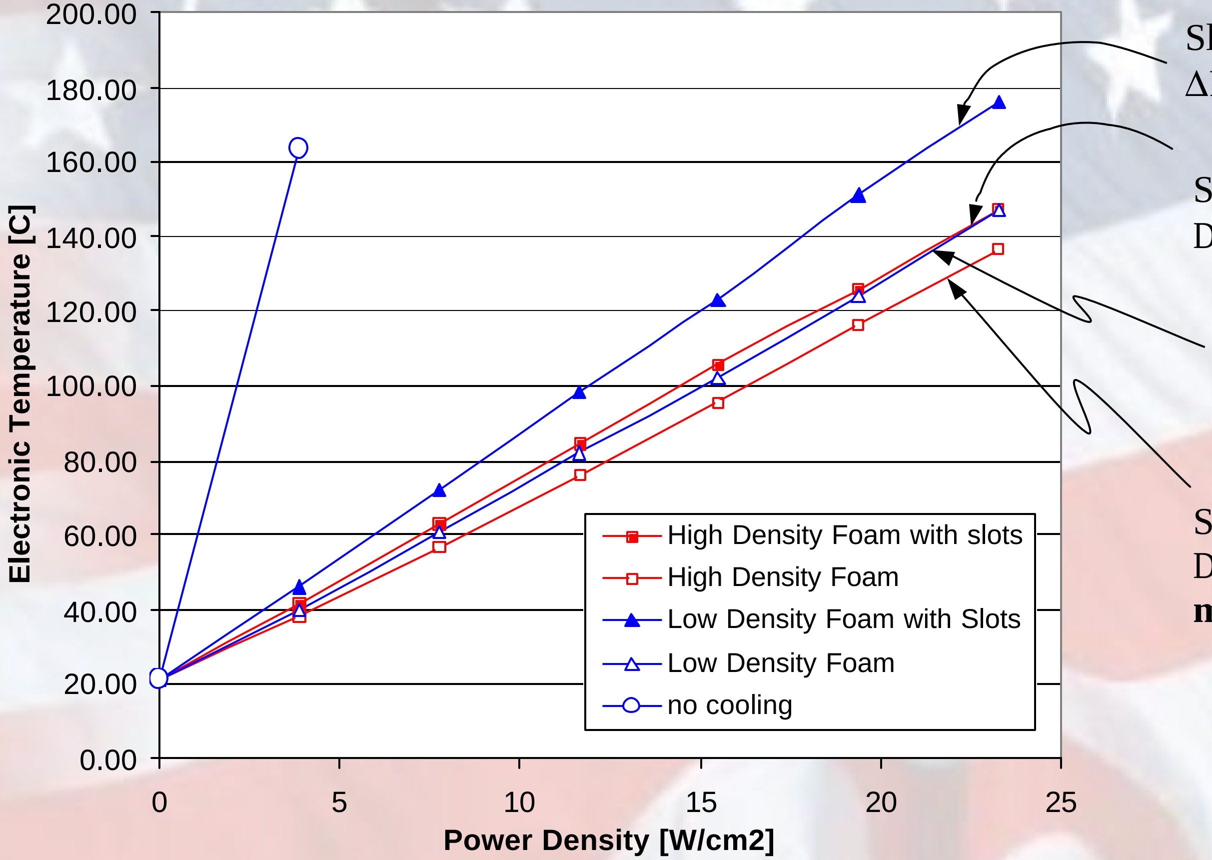
- **Both lowering density (increasing bubble size) or corrugation can be utilized to reduce pressure drop.**
  - **Higher density yields higher heat transfer**
  - **Larger thickness to flow length increases heat transfer**
  - **Slower velocities increases ratio of heat transfer to pumping power**


Low Density Solid


High Density Corrugated

Experimental Results

- **Corrugation works well to reduce pressure drop without sacrificing heat transfer**



Slotted LD Foam
ΔP ~ not measurable on current system

Solid LD Foam
D**P = 1 psi/in at 6 m/s**

Slotted HD Foam (solid squares)
ΔP ~ not measurable on current system

Solid HD Foam
D**P = 4 psi/in at 6 m/s**

Conclusions

- A preliminary model for the heat transfer with graphite foams was developed and presented
- This model assumes heat transfer is dominated by the turbulence developed in the pores of the foam.
- Proper use of models can help optimize foam based heat exchangers through parametric studies.
  - For example, the model predicts the effects of a geometric change in the system to reduce pressure and maintain high heat transfer.
- This type of model should be very useful in developing revolutionary new and exciting heat transfer devices.