Verification of the Thermal Performance of the HEMJ Divertor

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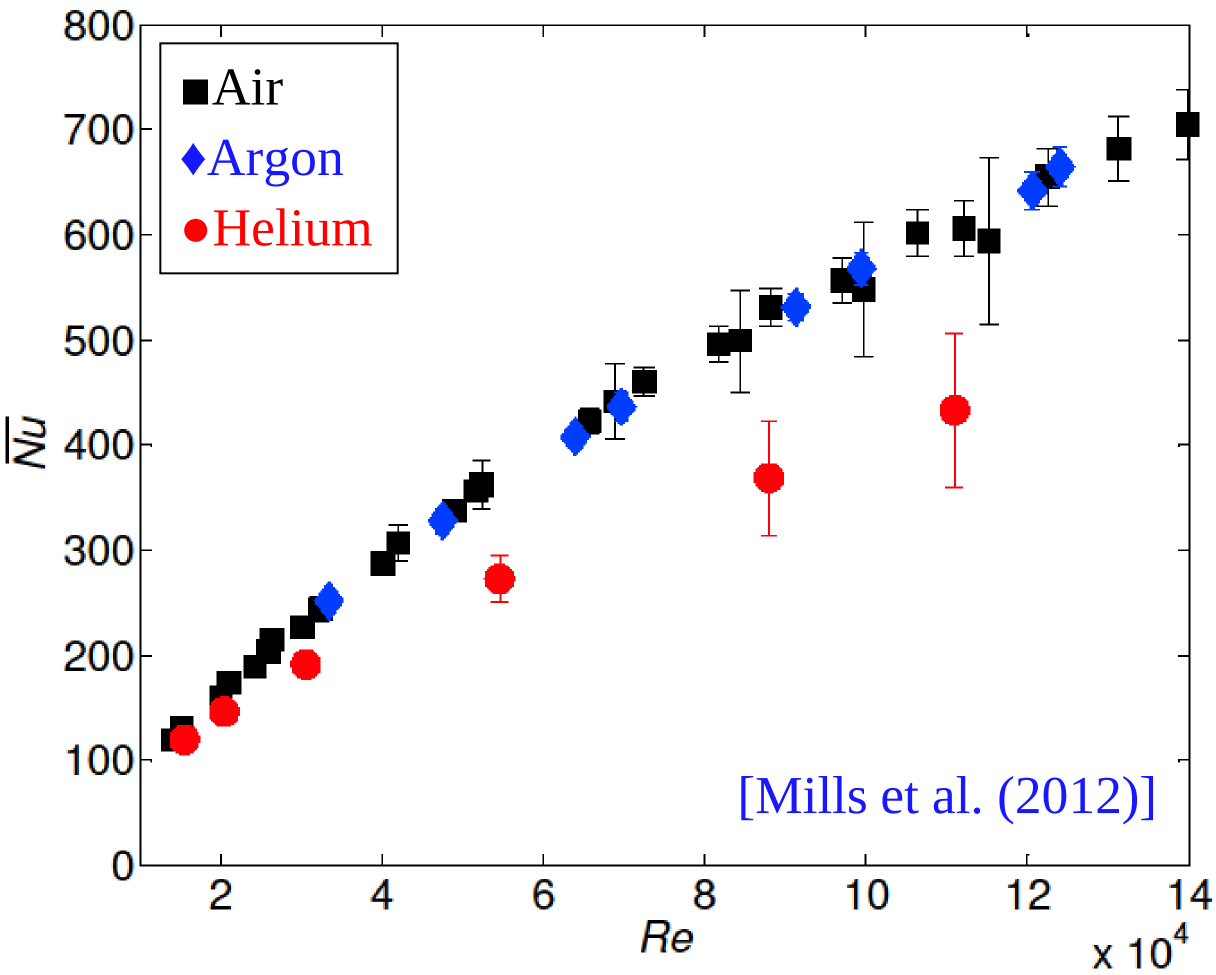
Objectives

- Update previous predictions of the thermal performance of the helium-cooled multi-jet (HEMJ) modular divertor design
  - Recent results on finger-type divertor ⇒ dynamic similarity requires matching non-dimensional coolant flow rate *Re* <u>and</u> ratio of divertor to coolant thermal conductivities
- Perform experiments on steel and brass HEMJ-like test sections cooled by helium, air, or argon
  - Incident heat fluxes $q'' \leq 3$ MW/m2
- Following previous approach, extrapolate results to prototypical conditions to obtain parametric design curves for HEMJ
  - Max. heat flux q''_{max} at given max. pressure boundary temperature
  - Pressure drop (loss coefficient K_L) at prototypical *Re*

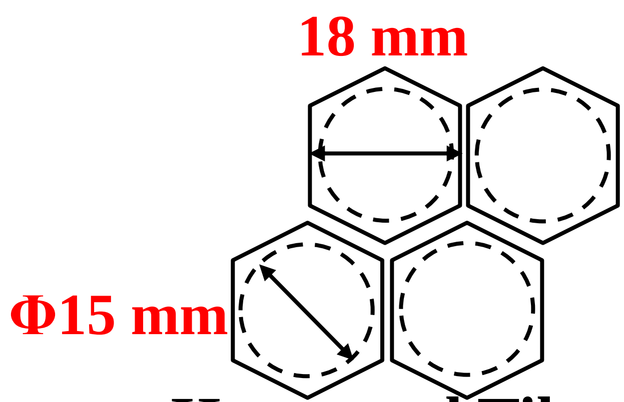
Previous Experiments



- Experiments with He and Ar to validate procedure
- He *Nu* did not match air, Ar *Nu*
- Similarity not achieved matching only *Re*
- Account for changes in conduction vs. convection
- Thermal conductivity ratio, κ

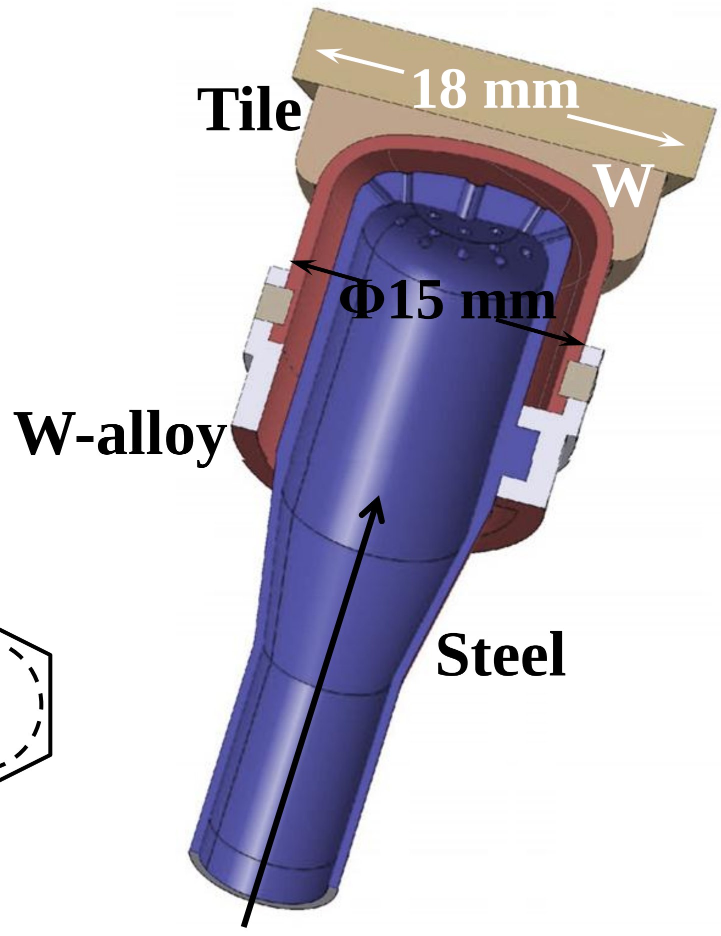
HEMJ Divertor

- Accommodate $q'' > 10$ MW/m^2
  [Ihli *et al.* 05; Weathers 07; Crosatti 08]
  - Hot He enters at 10 MPa, cools W tile as an array of impinging jets
  - Require many modules (~5×10^5 for HEMJ) to cover $O(100\ \text{m}^2)$ divertor



Hexagonal Tiles

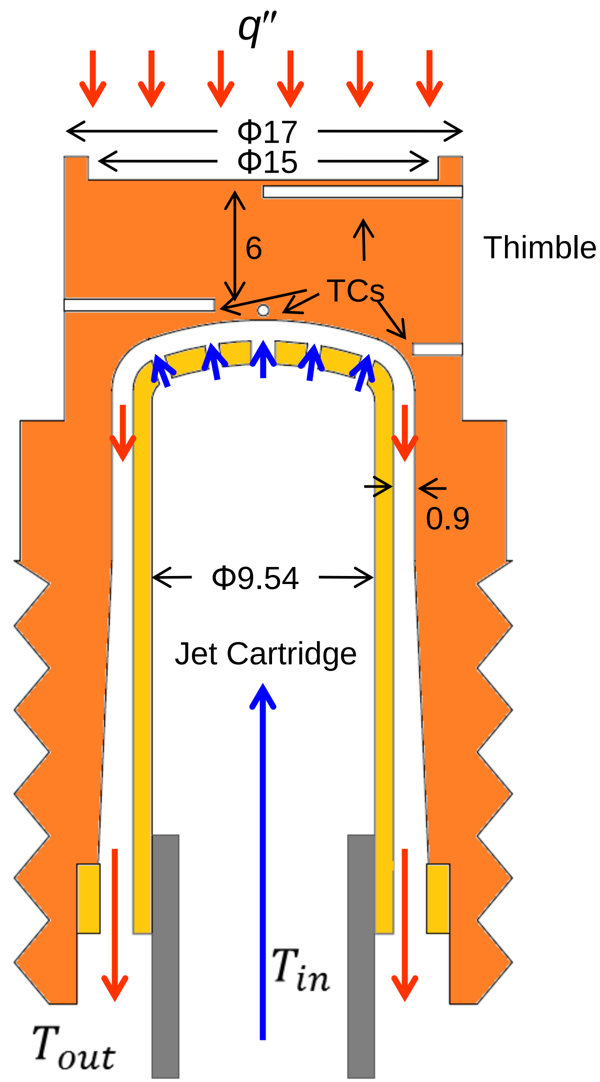
HEMJ



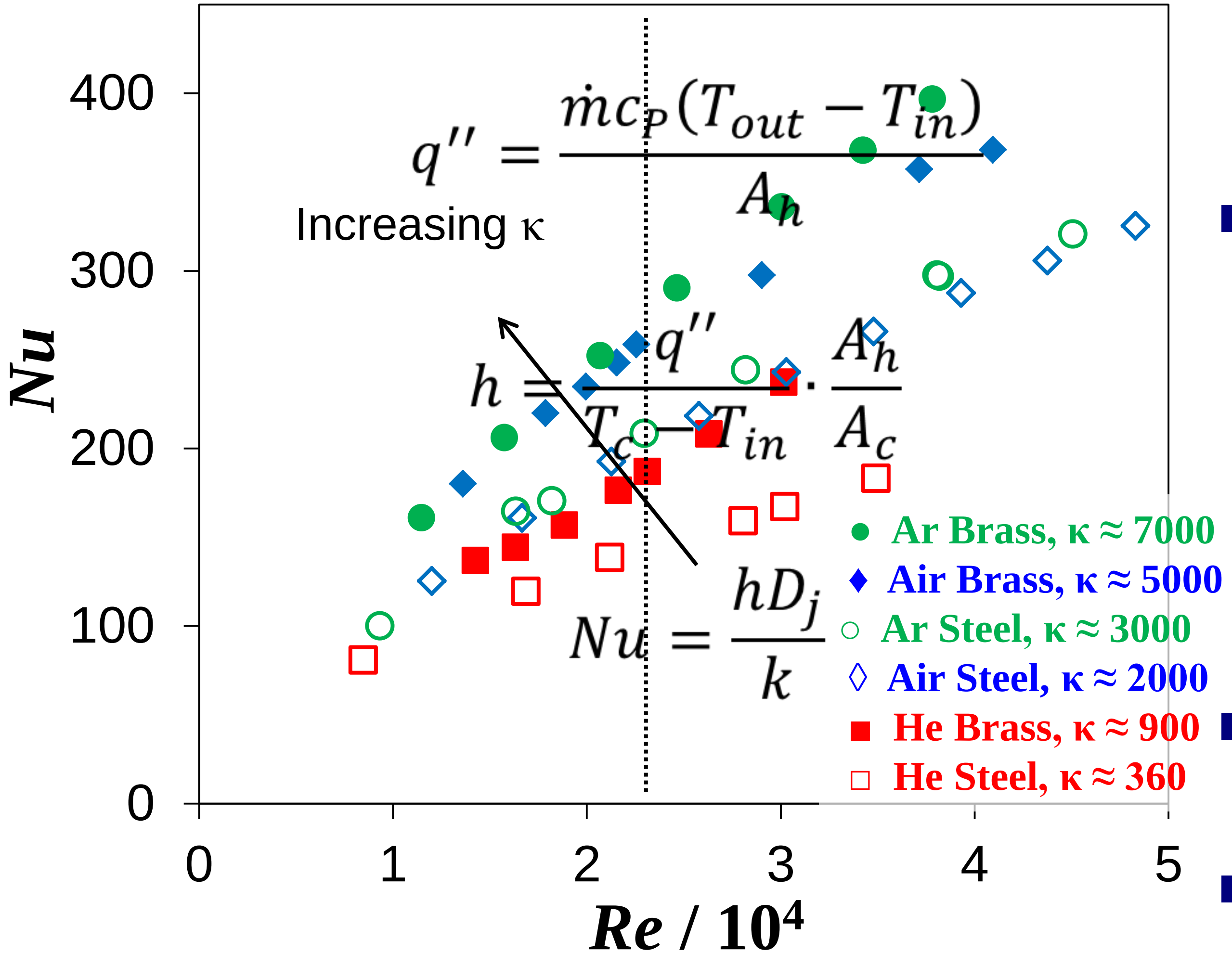
GT Test Module

- Brass and steel thimbles (pressure boundary) cooled by helium (He), air, argon (Ar) at near-ambient temperatures
  - Prototypical conditions: $Re = 2.16 \times 10^4$ (mass flow rate $\dot{m} = 6.8$ g/s), κ = 340
  - Experiments: $Re = 8\times10^3 - 6\times10^4$
    $\kappa \equiv k_s / k = 360 - 7000$
  - Incident heat flux $q'' \leq 3.0$ MW/m^2 (torch), $q'' \leq 0.9$ MW/m^2 (electrical)
  - Measure temperatures near cooled surface with embedded thermocouples (TC) ⇒ T_C, pressure drop across module Δp

$$Re = \frac{\dot{m} D_j}{A_j \mu_i}$$

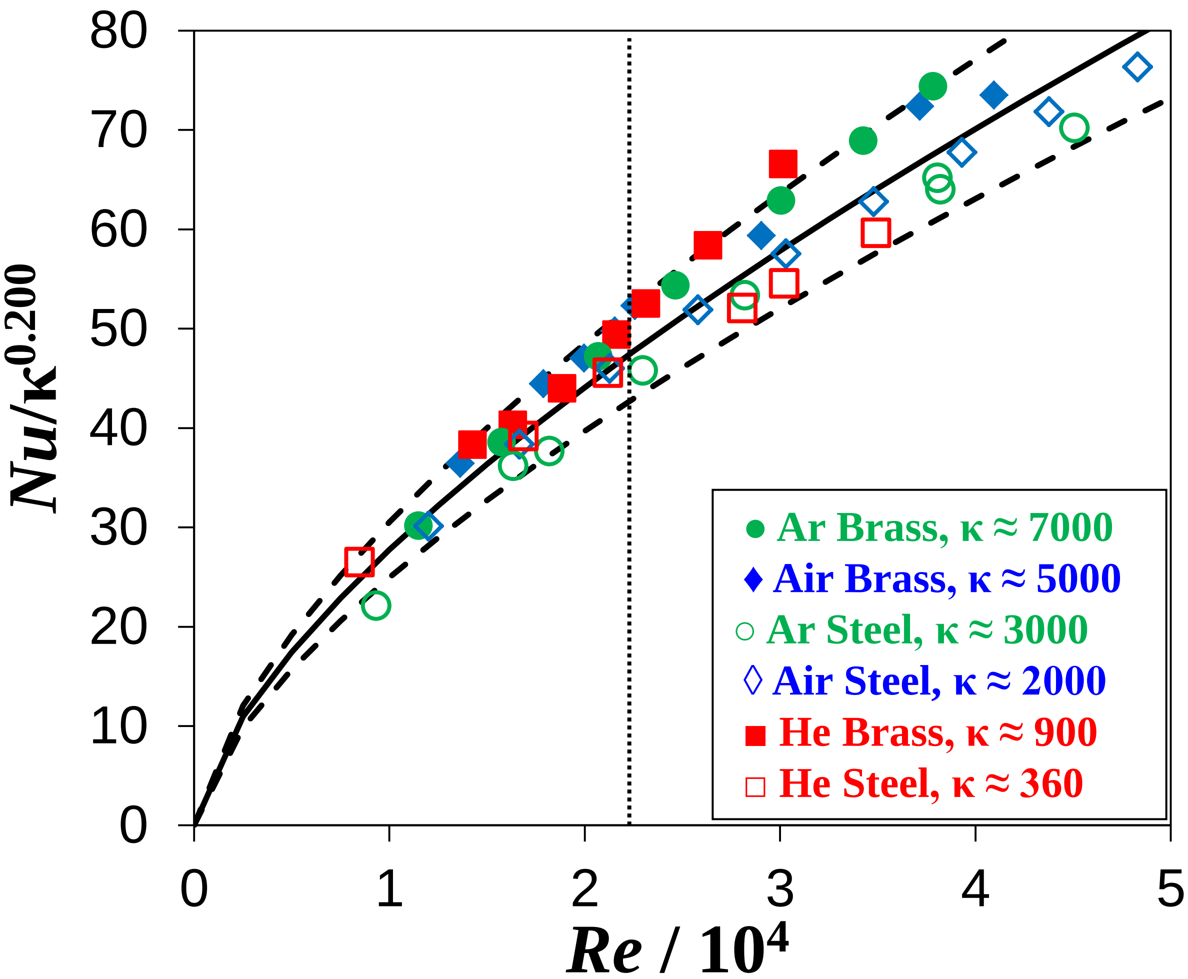


Nu v Re



- Heat flux based on energy balance of coolant
- HTC assumes all heat absorbed through cooled surface
  - Doesn't take conduction into account
- Each scenario shows its own trend
- Cases arranged by κ

Accounting for κ

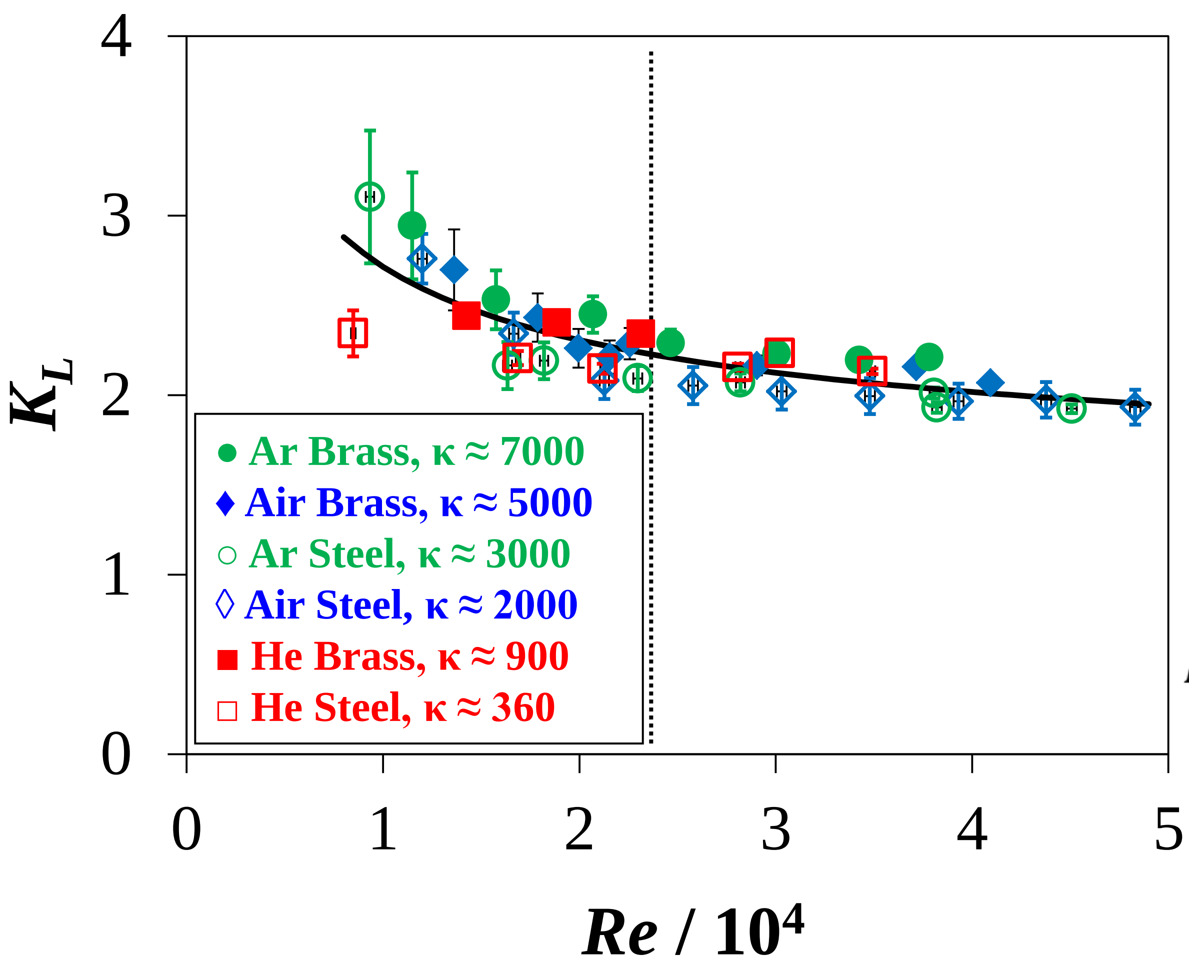


- Multilinear curve fitting assuming power law
- Nearly all data fits within ±10%
- Prototypical values:
  - Re = 21,600
  - κ = 340

$$Nu = 0.056 \cdot Re^{0.666} \kappa^{0.200}$$

R^2=0.96

Pressure Loss Coefficient



- Pressure loss coefficient K_L

$$K_L = \frac{\Delta p}{\frac{1}{2}\rho V^2}$$

- Hydraulic parameter independent of κ
- Correlate to Re

$$K_L = 1.39 \cdot \left({Re}/{10^4} \right)^{-0.50} + 1.32$$

Prototypical Conditions

- Use $Nu = f(Re, \kappa)$ and $K_L = f(Re)$ to calculate performance for a range of high pressure/temperature operating conditions
- Lines of constant pressure boundary temperature, T_s,
  - Use Nu correlation to calculate q''_{max}
    - T_{in} = 600 °C
    - T_s = 1200 °C

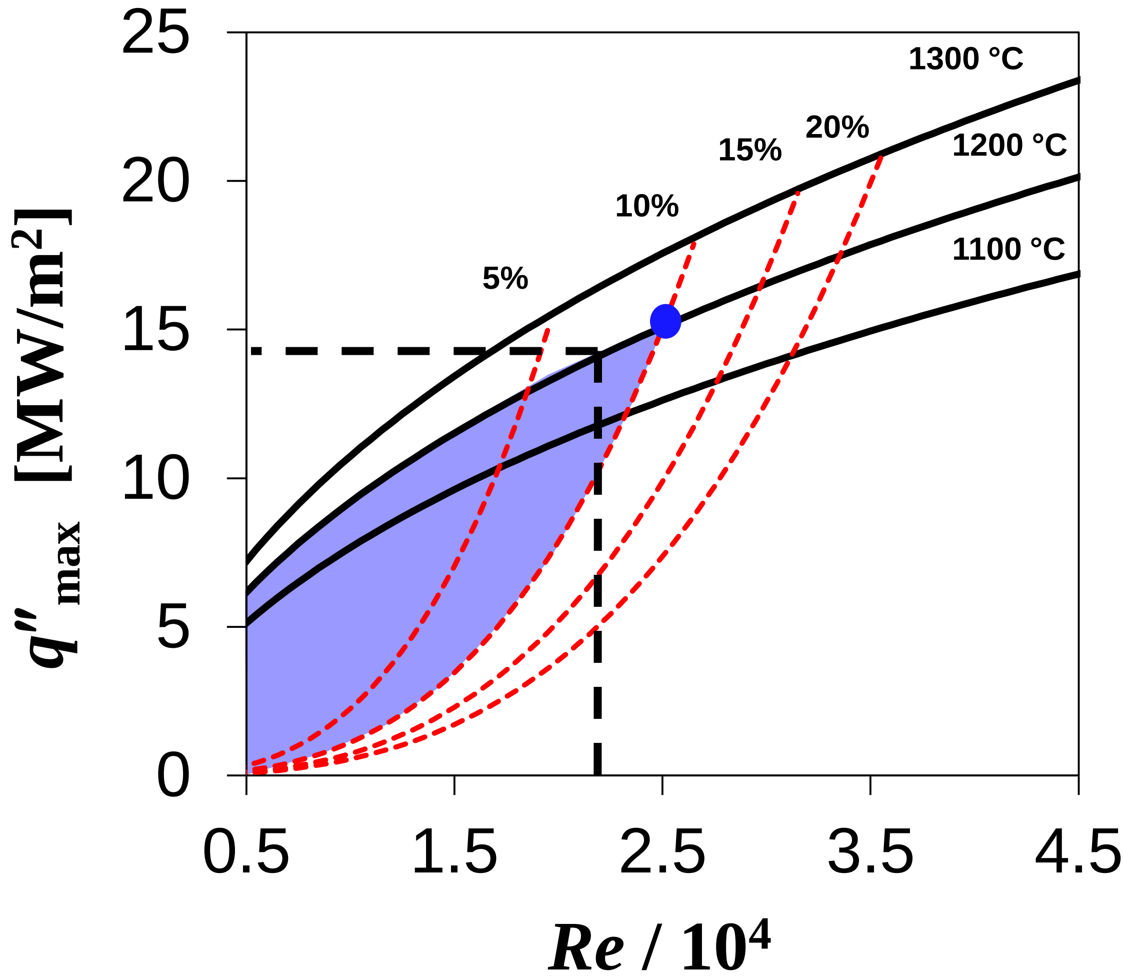
$$q''_{max} = \frac{T_s - T_{in}}{R_T}$$

$$1.25\, q''_t = q''$$

  - Area changes result in q'' focusing from tile to pressure boundary
- Loss coefficient K_L gives pressure drop for prototype Δp_p
- Lines of constant pumping power as fraction of incident thermal power, β
  - Desire to have $\beta < 10\%$

$$\beta = \frac{\dot{m}\Delta p_p}{\bar{\rho} q'' A_h}$$

Performance Curves



- For $\dot{m}_{He} = 6.8$ g/s $Re = 2.16\times10^4$
  - $\beta \approx 8\%$
  - $q'' \approx 14.1$ MW/m^2
  - $q_t'' \approx 11.4$ MW/m^2
- For $\beta < 10\%$ and $T_s < 1200$ °C
  - $Re < 2.5\times10^4$
  - $q'' < 15.5$ MW/m^2
  - $q_t'' < 13$ MW/m^2

Summary

- Seven experimental configurations
  - HEMJ shows similar conduction/convection characteristics as the previous finger-type design
- Parametric design curves were created to aid in further design iterations and to account for changes in operating conditions
  - For $\beta < 10\%$ and $T_s < 1200$ °C → $Re < 2.5\times10^4$, $q'' < 15.5$ MW/m^2 and $q_t'' < 13$ MW/m^2
- These studies show that thermal conductivity ratio methodology can be applied to other divertor designs with similar geometries/heat transfer paths
  - Performance verification with dynamically similar experiments over a wide range of conditions