Verification of the Thermal Performance of the HEMJ Divertor

J. D. Rader
B. H. Mills
D. L. Sadowski
S. I. Abdel-Khalik
M. Yoda
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 $Re$ and 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 $q'' \leq 3 \text{ MW/m}^2$
- 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 $Re$
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, $\kappa$

[Mills et al. (2012)]
HEMJ Divertor

- Accommodate $q'' > 10 \text{ MW/m}^2$
  
  \[ \text{[Ihli et al. 05; Weathers 07; Crosatti 08]} \]

- Hot He enters at 10 MPa, cools W tile as an array of impinging jets

- Require many modules ($\sim 5 \times 10^5$ for HEMJ) to cover $O(100 \text{ m}^2)$ divertor
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 \( \dot{m} = 6.8 \text{ g/s} \), \( \kappa = 340 \))
  - Experiments: \( Re = 8 \times 10^3 - 6 \times 10^4 \)
    \( \kappa \equiv k_s / k = 360 - 7000 \)
  - Incident heat flux \( q'' \leq 3.0 \text{ MW/m}^2 \) (torch), \( q'' \leq 0.9 \text{ MW/m}^2 \) (electrical)
  - Measure temperatures near cooled surface with embedded thermocouples (TC) \( \Rightarrow T_C \)
    pressure drop across module \( \Delta p \)

\[
Re = \frac{\dot{m}D_j}{A_j\mu_i}
\]
**Nu vs Re**

\[
q'' = \frac{\dot{m}c_p(T_{out} - T_{in})}{A_h}
\]

Increasing \( \kappa \)

\[
\begin{align*}
q'' & = h \left( T_{out} - T_{in} \right) \\
N_u & = \frac{hD_j}{k}
\end{align*}
\]

- **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 \( \kappa \)

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[Notes and references related to heat transfer and fluid dynamics, potentially with graphs and data points for different materials and conditions, illustrating the relationship between Nusselt number (Nu) and Reynolds number (Re) for various scenarios such as Ar Brass, Air Brass, Ar Steel, Air Steel, He Brass, and He Steel, with associated thermal conductivities (\( \kappa \)).]
Accounting for $\kappa$

- Multilinear curve fitting assuming power law
- Nearly all data fits within $\pm 10\%$
- Prototypical values:
  - $Re = 21,600$
  - $\kappa = 340$

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

$R^2 = 0.96$
Pressure Loss Coefficient

- Pressure loss coefficient $K_L$
  \[ K_L = \frac{\Delta p}{\frac{1}{2} \rho v^2} \]

- Hydraulic parameter independent of $\kappa$

- Correlate to $Re$
  \[ K_L = 1.39 \cdot \left( \frac{Re}{10^4} \right)^{-0.50} + 1.32 \]
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 $q''_{\text{max}}$
    - $T_{\text{in}} = 600 ^\circ C$
    - $T_s = 1200 ^\circ C$
  
  $q''_{\text{max}} = \frac{T_s - T_{\text{in}}}{R_T}$
  
  $1.25 q''_{\text{t}} = q''$
  
  - Area changes result in $q''$ focusing from tile to pressure boundary

- Loss coefficient $K_L$ gives pressure drop for prototype $\Delta p_p$

- Lines of constant pumping power as fraction of incident thermal power, $\beta$
  - Desire to have $\beta < 10\%$
  
  $\beta = \frac{\dot{m} \Delta p_p}{\rho q'' A_h}$
Performance Curves

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