Effects of Thermal Conductivity Ratio in Helium-Cooled Divertors

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Objectives and Background

Objectives

- Experimentally verify dynamic similarity of experiments of a finger-type divertor module performed with different coolants and different test section materials
  - Match nondimensional coolant flow rate and solid-to-coolant thermal conductivity ratio
- Verify previous predictions of thermal performance at prototypical conditions and general parametric design curves

Background

- Part of the ARIES study and GT effort on evaluating the thermal-hydraulics and improving the thermal performance of various helium-cooled divertor designs

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Original Experimental Approach

- Fabricate and instrument test sections that closely simulate geometry of proposed divertor module
  - Heat test sections with oxyacetylene torch or electrical heaters
- Perform dynamically similar experiments spanning prototypical operating conditions with air instead of helium (He)
  - Match nondimensional coolant flow rate $\leftrightarrow$ Reynolds number $Re$
  - Prandtl and Mach number effects negligible
- Calculate nondimensional heat transfer coefficient $Nu$ and loss coefficient $K_L$ from experimental data
  - Measure surface temperature, pressure drop
- Extrapolate results to prototypical conditions: Tungsten-alloy module cooled by high-temperature He
GT Test Module

- Single jet-impingement design
  - Dimensions similar to HEMP
  - Constructed of C36000 brass alloy
  - Heated by oxy-acetylene torch at heat fluxes $q'' < 2.0 \text{ MW/m}^2$
- Operating conditions determined from energy balance on HEMP design at 10 MW/m² ⇒
  - $Re = 7.6 \times 10^4$ at central port
  - Experiments: $1 \times 10^4 < Re < 1.4 \times 10^5$
  - Coolants: air, Ar, and He
- Embedded thermocouples (TC) measure temperature near cooled surface
Calculating $\bar{Nu}$ and $Re$

- Determine Reynolds number from mass flow rate $\dot{m}$

$$Re = \frac{4\dot{m}}{\pi \mu D_o}$$

- Calculate average HTC

$$\bar{h} = \frac{\bar{q}''}{(\bar{T}_c - T_{in}) \frac{A_H}{A_c}}$$

- Average heat flux $\bar{q}''$ determined from energy balance for coolant
- Avg. cooled surface temperature $\bar{T}_c$ extrapolated from embedded TC

- Determine nondimensional HTC, or average Nusselt number

$$\bar{Nu} = \frac{\bar{h}D_o}{k}$$

- Determine a correlation for $\bar{Nu}$ from these experimental data

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Experiments performed with He and argon (Ar) to verify similarity. For He, the Nusselt number (Nu) is lower than those for air and Ar.

But He has higher thermal conductivity ($k$).

Matching $Re$ is not sufficient for similarity.

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Multi-Coolant Experiments

[Mills et al. (2012)]

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**Thermal Conductivity Ratio**

- Numerical simulations (courtesy J. Rader) show that fraction of the incident heat flux removed by convection at cooled surface varies between different coolants.

<table>
<thead>
<tr>
<th>Coolant</th>
<th>Re</th>
<th>$\bar{T}_c$ (Expts.)</th>
<th>$\bar{T}_c$ (Simulations)</th>
<th>Removed heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>$4.94 \times 10^4$</td>
<td>291 °C</td>
<td>293 °C</td>
<td>37.7 %</td>
</tr>
<tr>
<td>Helium</td>
<td>$5.09 \times 10^4$</td>
<td>121 °C</td>
<td>121 °C</td>
<td>55.9 %</td>
</tr>
</tbody>
</table>

- Dimensional analysis: fraction of heat removed by convection (vs. conduction through divertor wall) characterized by solid-to-coolant thermal conductivity ratio $k_s / k$

- Assume power-law correlation for $\overline{Nu}$

$$\overline{Nu} = A Re^B (k_s / k)^C$$

(still neglecting $Pr, Ma$ effects)
Based on experimental results for He, air and Ar, $Nu$ well-described by power-law correlation for $Re$ and $k_s/k$

$$Nu = 0.0348 Re^{0.753} \left( \frac{k_s}{k} \right)^{0.118}$$

- $10^4 < Re < 1.4 \times 10^5$
- $Pr \approx 0.7$
- $900 < k_s/k < 7000$, but only one value of $k_s$ considered
Thermal Conductivity Ratio

- $\bar{Nu}$ correlation experimentally validated for $900 < k_s/k < 7000$, all at one value of $k_s$

<table>
<thead>
<tr>
<th>Test Section Material</th>
<th>$k_s$ [W/(m-K)]</th>
<th>Coolant</th>
<th>$k$ [W/(m-K)]</th>
<th>$k_s/k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brass</td>
<td>148 (at 300 °C)</td>
<td>Air</td>
<td>0.028 (at 50 °C)</td>
<td>5290</td>
</tr>
<tr>
<td>Brass</td>
<td>148 (at 300 °C)</td>
<td>He</td>
<td>0.16 (at 35 °C)</td>
<td>925</td>
</tr>
<tr>
<td>W-1%La$_2$O$_3$</td>
<td>116 (at 1000 °C)</td>
<td>He</td>
<td>0.34 (at 650 °C)</td>
<td>~340</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>55 (at 200 °C)</td>
<td>He</td>
<td>0.16 (at 35 °C)</td>
<td>~340</td>
</tr>
</tbody>
</table>

- Prototypical conditions (W-1%La$_2$O$_3$ cooled by He), $k_s/k \approx 340$
- Test section of AISI 1010 carbon steel cooled by He at near-ambient temperatures will also give $k_s/k \approx 340$
  - Twenty additional experiments performed with air, He, and Ar
Experimental data from steel test section in excellent agreement with those for brass test section.

$Nu$ correlation now experimentally confirmed for

- $10^4 < Re < 1.2 \times 10^5$
- $Pr \approx 0.7$
- $350 < k_s/k < 7000$
Loss Coefficient

\[ K_L = (8.495 \times 10^4) Re^{-1.337} + 1.056 \]

- Loss coefficient
  \[ K_L = \frac{\Delta p}{\rho \bar{V}^2 / 2} \]
  - \( \Delta p \) coolant density
  - \( \bar{V} \) average speed at central port
- As expected, results for steel and brass test sections in excellent agreement since \( K_L \) hydraulic parameter

Open Symbols [Mills et al. (2012)]
Maximum Heat Flux Charts

- Experimentally validated for prototypical conditions
  - He/W-1%La$_2$O$_3$
  - $T_i = 600 \, ^\circ C$
  - $T_s = 1100 \, ^\circ C, 1200 \, ^\circ C, 1300 \, ^\circ C$
  - $\beta = 5\%, 10\%, 15\%, 20\%$

- At $Re = 7.6 \times 10^4$, $T_s = 1200 \, ^\circ C$
  - $q''_{\text{max}} = 17.3 \, \text{MW/m}^2$
  - On tile: $q''_T = 12.4 \, \text{MW/m}^2$ for $A_T = 1.4 \, A_h$

[Mills et al. (2012)]
Summary

■ Experimentally verified correlation for $\bar{Nu}(Re, k_s/k)$ at prototypical values of $Re$ and $k_s/k$
  □ Steel test section cooled by He at near-ambient temperatures gives $k_s/k \approx 350$: value for W-1%La$_2$O$_3$ divertor cooled by He at 600 °C
  □ Experiments for steel test section cooled by air and Ar also in good agreement with previous results for brass test section

■ Extrapolating these correlations to prototypical conditions gives:
  □ At $Re = 7.6 \times 10^4$ and $T_s = 1200$ °C: $q''_{\text{max}} = 17.3$ MW/m$^2$
  □ Including a tile with $A_T = 1.4 A_h$: $q'_T = 12.4$ MW/m$^2$