High flux heat transfer in a target environment

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Radiation cooling

\[ Q \left[ \frac{W}{m^2} \right] = \sigma \varepsilon (T_H^4 - T_C^4) \]

High temperatures require refractory metals and also good vacuum quality to avoid target loss through oxidation and evaporation cycles.
Forced Convection

Consider turbulent heat transfer in a 1.5mm diameter pipe – Dittus Boelter correlation

$$\text{Nu}_D = 0.023 \text{Re}_D^{4/5} \text{Pr}^n$$

Valid for:

$$\text{Re}_D \gtrsim 10000 \quad 0.6 \leq \text{Pr} \leq 160$$

<table>
<thead>
<tr>
<th>velocity [m/s] (Mach=0.3 for gases)</th>
<th>Pr</th>
<th>Re</th>
<th>Nu</th>
<th>heat transfer coefficient [W/m²K]</th>
<th>allowable temp rise [K]</th>
<th>heat flux [MW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>air at 300K 1bar</td>
<td>100</td>
<td>0.72</td>
<td>11114</td>
<td>35</td>
<td>557</td>
<td>500</td>
</tr>
<tr>
<td>air at 300K at 10bar</td>
<td>100</td>
<td>0.73</td>
<td>111958</td>
<td>222</td>
<td>3558</td>
<td>500</td>
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<tr>
<td>helium at 300K at 1bar</td>
<td>300</td>
<td>0.67</td>
<td>4235</td>
<td>15</td>
<td>1516</td>
<td>500</td>
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<tr>
<td>helium at 300K at 10bar</td>
<td>300</td>
<td>0.67</td>
<td>42112</td>
<td>98</td>
<td>9520</td>
<td>500</td>
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<tr>
<td>helium at 1023K at 10bar</td>
<td>560</td>
<td>0.68</td>
<td>8400</td>
<td>27</td>
<td>6514</td>
<td>500</td>
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<td>water at 300K and 5bar</td>
<td>5</td>
<td>6.13</td>
<td>8823</td>
<td>68</td>
<td>26344</td>
<td>100</td>
</tr>
<tr>
<td>water at 300K and 5bar</td>
<td>10</td>
<td>6.13</td>
<td>17647</td>
<td>119</td>
<td>45868</td>
<td>100</td>
</tr>
<tr>
<td>water at 300K and 5bar</td>
<td>15 (erosion limited?)</td>
<td>6.13</td>
<td>26470</td>
<td>164</td>
<td>63444</td>
<td>100</td>
</tr>
</tbody>
</table>

Achenbach correlation for heat transfer in a packed bed of spheres

$$\text{Nu} = \frac{h_d}{k_g} = [(1.18 \text{Re}^{0.58})^4 + (0.23 \text{Re}^{0.75})^4]^{0.25}$$

Max power density for a sphere

$$\frac{Q}{V} = \frac{hA\Delta T}{V}$$

for a sphere $A = 4\pi r^2$ and $V = \frac{4}{3\pi r^3}$ so

$$\frac{Q}{r} = \frac{3h\Delta T}{0.003[m]} = \frac{3 \times 5000[W/m^2K] \times 500[K]}{0.003[m]} = 2.5[MW/m^3] = 2.5[\frac{MW}{l}]$$
Nucleate Boiling

Vapour bubbles forming at nucleation sites and separating from the heated surface thus enhances mixing and heat transfer.

Critical heat flux $>1\text{MW/m}^2$

Heat transfer driven by temperature difference alone, i.e. Plate above boiling temperature of water and no forced convection.
Critical heat flux
forced convection water flow (original graph Wimblett)

Burnout flux sensitive to channel thickness

Burn out curve

Nucleate boiling

Forced convection no boiling

Water temp = 40PSI
Temp = 30 to 50°C

10MW/m²

2MW/m²

ISIS TS1

ISIS TS2

5m/s

10m/s

15m/s

Burnout flux sensitive to channel thickness
Acoustic transducer used to detect burnout

Maximum heat flux could be achieved by monitoring for burnout
Heat flux may be limited by erosion due to high water velocities
Other ideas

Hypervapotrons

• Water cooled finned heat exchangers developed to cope with the high heat fluxes present in experimental fusion devices and ancillary systems.
• Water flow, heat load and channel width tuned to generate a repetitive cycle that moves steam out into the sub cooled bulk flow.
• Typically, these can sustain power densities of up to 20-30 megawatts/m² in steady-state, using water at flow velocities < 10 m/s and operating pressures < 10 bar.

Nanofluids

• Water-based nanofluids (suspensions of 0.001-10% nanoparticles, <100nm) have the potential to deliver much improved cooling while retaining the advantages of water.
• 10-14% increase in convective/conductive heat transfer and 100-200% increase in critical heat flux have been reported.
• Long-term stability of nanofluids, the deposition of particles, and their effect on erosion are not well understood.

The Calculation of Critical Heat Flux in Forced Convection Boiling

P. B. Whalley, G. F. Hewitt, P. Hutchinson

0 Reviews
Atomic Energy Research Establishment, 1973 - 17 pages

International Journal of Heat and Mass Transfer
Volume 30, Issue 11, November 1987, Pages 2261–2269

Critical heat flux of forced convective boiling in uniformly heated vertical tubes with special reference to very large length-to-diameter ratios