Abstract:

This memorandum describes the thermodynamic behavior of helium flowing in the GEM detector magnet's CICC. The purpose of the calculations described herein is to find optimal cooling for a range of parameters including heat input, mass flow rate, and pressure. The method of analysis is based on work at NET done by H. Katheder. Our results suggest that by specifying an inlet pressure of approximately $5.4$ bar, and a helium mass flow rate of approximately $1.3$ g/s, an external heat load of more than $23$ watts could be extracted from the $1140$ m length of CICC, and the maximum temperature of the helium along the length of conductor would not exceed $6$ K. On the other hand, if the outlet temperature were limited to only $5$ K for stability reasons, a maximum of only $1.8$ watts could be extracted with the corresponding optimal flow rate of approximately $1$ g/s, and inlet pressure of $3.9$ bar. Because of uncertainty in the value of the Reynold number for this conductor, these results are preliminary. If full-scale flow measurements are ever done in order to measure flow rates and pressure drops, the calculations described in this memo should be repeated.
Cooling Capacity of Flowing Supercritical Helium

29 June 1992

J.R. Hale

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Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139
MIT GEM Detector Memoranda
Approval Sheet

B.A. Smith
Project Engineer

A.M. Dawson
Technical Editor

12/26/92
Date

29 Feb 92
Date
1 Introduction

Early in 1991, a memorandum by H. Katheder, of the NET team at Garching\textsuperscript{1} dealt with the thermodynamic behavior of helium flowing in NET/ITER CICC. One purpose of the memo was to find optimal cooling for a range of parameters including heat input, mass flow rate, and pressure.

The present memorandum is an application of the approach utilized by Katheder to the proposed GEM CICC.

\textsuperscript{1}Katheder, H., Thermodynamic considerations of helium flow in cable in conduit superconductors, February 20,1991, N/R/3511/1/A
2 Discussion of Methods and Parameters

The following table lists GEM conductor characteristics that were used for calculations of cooling parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of cooling channel, $\ell$ (m)</td>
<td>1140</td>
</tr>
<tr>
<td>Friction factor, $\lambda$</td>
<td>0.15</td>
</tr>
<tr>
<td>Helium area, $A$ (m$^2$)</td>
<td>$1.16 \times 10^{-4}$</td>
</tr>
<tr>
<td>Hydraulic diameter, $d$ (m)</td>
<td>$5.40 \times 10^{-4}$</td>
</tr>
<tr>
<td>Helium inlet temperature, $T_{in}$ (K)</td>
<td>4.5</td>
</tr>
<tr>
<td>Maximum allowed temperature rise, $\Delta T$ (K)</td>
<td>1.5</td>
</tr>
<tr>
<td>Helium outlet pressure, $P_{out}$ (bar)</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 1: GEM CICC physical parameters

As was done by Katheder, the calculations described in this memorandum are carried out with these additional approximations:

- Averages are used for helium density; I have made use of the values that appear in Katheder's appendix B to generate a 5th order polynomial representation of the average density, $\bar{\rho}(P_{in})$. \(^2\)

- Again making use of values listed in appendix B, an average viscosity of $3 \mu\text{ps}$ was used to estimate a Reynolds number of $\approx 2200$ for the GEM CICC, and hence, to adopt the same constant friction factor (European definition), $\lambda = 0.15$, as he did.

- A constant heat load per unit length of conductor is assumed.

The plots presented in the referenced memorandum extend on the horizontal axis from 5 to 15 bar; for this memorandum, the range selected was 3 to 10 bar. Rather than attempt to scale values of enthalpy from a helium properties graph, I again chose to make use of Katheder's results by scaling values from one of his figures ($\Delta h$ vs. $P_{in}$), and from those values generating $P_{out} = 3 \text{ bar}$

\(^2\)with $P_{out} = 3 \text{ bar}$
coefficients for a 5th order polynomial which could be plotted over the range 3 to 10 bar.

Finally, I carried out calculations for just three values of inlet temperature, 5.0 K, 5.5 K, and 6.0 K. It is evident from the shape of curves on the P-h diagram that the largest values of \( \Delta h \) are available within the temperature range 5.5 \( \leq T_{\text{max}} \leq 6.0 \). Calculations for 5.0 K inlet temperature were included because of potential interest in additional stability.

3 Results

Figure 1 is a plot of data generated by the helium properties code HE-SS\textsuperscript{3}. One of its chief values to magnet designers is to show that as a result of the variation of internal pressure along the length of CICC, the helium temperature can in some circumstances be higher along a significant fraction of the conductor length than it is at the outlet, even when there is no external heat input.

The first step in calculating the maximum heat removal capacity is to plot \( \Delta h \) as a function of inlet pressure, for constant outlet pressure, \( P_{\text{out}} = 3.0 \) bar. This plot is shown in Figure 2, over a range of input pressure from 3 to 10 bar. As described above, the three curves are for maximum temperatures of 5.0 K, 5.5 K, and 6.0 K. All further plots, too, will show curves for just these three temperatures, and are labeled accordingly.

Next, the helium mass flow rate as a function of inlet pressure was calculated, utilizing the following equation from Katheder:

\[
\dot{m} = \sqrt{\frac{2 \bar{\rho} A^2 d \Delta P}{\lambda e}}
\]

where \( \bar{\rho} \) is the average density over the appropriate pressure range. These plots are shown in Figure 3.

Then, with the functions \( \dot{m}(P_{\text{out}}) \) and \( \Delta h(P_{\text{out}}) \), the maximum tolerable heat load can be calculated:

\[
\dot{Q} = \dot{m}\Delta h
\]

\textsuperscript{3}Written by L. Bottura

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These results are shown in Figure 4. This figure also shows curves of isentropic fluid work, the pumping work that must be expended to overcome internal friction. The equation used here is

\[ W = 0.72\Delta P \dot{m} \]

Finally, the net extractable heat load can be obtained by subtracting the pumping loss curves from the corresponding curves of maximum heat load: these plots are shown in Figure 5.

4 Conclusion

From Figure 5, one can see that by specifying an inlet pressure, \( P_{in} \approx 5.4 \text{ bar} \), and a helium mass flow rate of \( \approx 1.3 \text{ g/s} \), an external heat load of more than 23 watts could be extracted from the 1140 m length of CICC, and the maximum temperature of the helium along the length of conductor would not exceed 6 K. On the other hand, if the outlet temperature were limited to only 5 K for stability reasons, a maximum of only 1.8 watts could be extracted with the corresponding optimum flow rate of \( \approx 1 \text{ g/s} \), and inlet pressure of 3.9 bar.

4.1 Caveat

Although the actual value of Reynolds number is not known for this conductor, rough calculations by others suggest that it may lie within the range 650 – 700 rather than \( \approx 2200 \), the value used in this memorandum. If this were to be the case, the friction factor would be larger than the value used herein. If a ‘smooth tube with correction factor’ relation between Reynolds number and friction factor is assumed, then the mass flow rate could be \( \approx 15\% \) lower than that calculated earlier. If, on the other hand, the correlation measured in the POLO experiment were to hold for the GEM conductor, the mass flow rate could be \( \approx 46\% \) lower than that calculated earlier. At lower mass flow rates, the maximum heat load that could be cooled would be less, but the pumping losses would also be lower, inasmuch as both of

\(^4\text{e.g., B. Smith}\)
these quantities are proportional to \( \dot{m} \) in the formulation adopted for this (and Katheder’s) memorandum.

If full scale flow measurements are ever done in order to measure flow rates and pressure drops, the calculations described herein should be repeated, incorporating actual GEM conductor data into the equations.
Temperature Increase Due to Pressure Drop

Figure 1 Helium Pressure Inside CICC (atm.)
Maximum Available Enthalpy

Figure 2  Outlet Pressure Is 3 bar
Figure 3
Outlet Pressure Is 3 bar
Maximum Total Heat Load

Figure 4  Outlet Pressure Is 3 bar
Figure 5  Outlet Pressure Is 3 bar