ABSTRACT

A design window for a liquid metal cooled limiter is being sought to establish the viability of the use of liquid metals as coolants for the limiter. The problem is approached by first establishing the constraints, then defining the geometrical configuration and design parameters, and finally, by analyzing a limiter without coating. The maximal allowable heat flux is found to be \(-4\) MW/m\(^2\). It can be increased to \(-3\) MW/m\(^2\) if tapered or insulated feed pipes are used. The presence of coatings required to withstand particle erosion will further reduce the allowable heat flux.

INTRODUCTION

Liquid metals are strong candidates as breeders and coolants for fusion blankets. A key feasibility condition defined recently for such blankets is identifying a viable non-water coolant for the in-vessel components such as limiters and divertor plates. The presence of water in close proximity to lithium or lithium-lead is considered an unacceptable safety risk. The purpose of this work is to investigate the feasibility and attractiveness of liquid metals as coolants for the in-vessel components. In detailed calculations, a pumped limiter in a commercial tokamak reactor was used as an example. A technique used extensively in this work is that of defining the possibility of a design using a design window. A design window can be exemplified as a permissible region of operation defined by various limits.

A key problem with the design of the pumped limiter, or other in-vessel components, is the simultaneous presence of high particle and heat fluxes. High particle fluxes dictate thick walls in order to withstand erosion. High heat fluxes require thinner walls to minimize temperature and stresses. Present designs, e.g., INTOR, use water coolant at low temperature (<100 °C), and hence, low pressure. Low temperature operation permits the use of high conductivity materials such as copper and the low pressure reduces stresses.

Liquid metal cooling of the limiter introduces new and difficult problems. The combination of high melting point and considerable film temperature drop in laminarized fluid flow under the effect of magnetic field results in operating temperatures of the structural material much greater than those acceptable for copper alloys. The much higher thermal stress induced in other structural materials sharply reduces the maximum allowable heat flux. Another problem is the N2D pressure drop in the liquid metal coolant. The resulting pressure stresses further reduce the allowable heat flux.

DESIGN APPROACH

As the problem of cooling of a limiter with liquid metal was quite complicated, it was approached first by introducing various constraints which the design must observe; second, by choosing geometrical configuration and design parameters in accordance with the constraints; and last, by analyzing a limiter without coating. The introduction of coating on the limiter reduces the maximum allowable surface temperature if low-Z coatings are used. It also introduces a new constraint on the structural material, thus aggravating the thermal stress problem. As the possibility of a design window for a limiter without coating is better than that for a limiter with coating, it was decided to treat the simpler problem of a design window for a limiter without coating first. Future work will address the coating problem.

The constraints imposed on the limiter design were:
1) The limiter surface area should be large enough to provide lower particle and heat fluxes.
2) The space provided for particles to be pumped must be sufficient enough to provide efficient impurity removal.
3) The materials used for surface coating must not excessively contaminate the plasma.
4) The structural material must have good compatibility with the coolant.
5) As the corrosion due to liquid metals is temperature dependent, an upper limit on the interface temperature between the coolant and structure must be defined and observed.
6) The structural materials have a tendency to creep at higher temperatures. Thus, structural temperature during operation must...
remain below a limiting value.
7) The inlet temperature of the coolant must be -40°C above the melting point.
8) The primary and secondary stresses arising in the material must remain below the 3 S_p value, as determined by the ASME code.
9) The primary stress in the material must remain below the S_p value, again or set by the ASME code.

In light of the above constraints, the geometrical configuration of the limiter was chosen and is shown in Fig. 1. It is a curved double-edged limiter with one inlet and two outlet feed pipes which we shall call conduits, one inlet and two outlet horn-shaped pipes which are called manifolds, and minute cooling channels running on the face of the limiter. The cooling channels rise from the inlet manifold, each separating into two parts and then terminates at the outlet manifold. The coolant flows on the face of the limiter is cooling channels parallel to the toroidal magnetic field and flows perpendicular to the toroidal magnetic field in the conduits and in the manifolds. This flow pattern was primarily chosen because:
1) it provides shorter path lengths which are highly desirable to keep the rise in bulk temperature low because of the above mentioned limits, and 2) the flow is parallel to the toroidal magnetic field where the flow speed is highest in order to reduce the MHD pressure drop. However, large MHD pressure drops are still expected to occur in the conduits and manifolds if conducting wall pipes are used.

Fig. 1 Geometrical configuration of the limiter

For further analysis the structure material was chosen to be vanadium because of its high corrosion resistant properties and relatively acceptable characteristics as a heat sink material. Based upon previous studies, a maximum value of 650°C was selected for the interface temperature and a value of 670°C for the structure temperature. The design was expected to endure up to 5 MW/m² heat flux. (The heat flux limits discussed in this paper refer to peak values). A Nesbit number of 8 was taken for heat transfer calculations accounting for the fact that flow in the coolant channels on the face of the limiter is not fully developed. However, reliable data for the type of heat transfer problem encountered in the limiter was not found, and it is hoped that this topic will be investigated in detail later.

DESIGN CALCULATIONS AND RESULTS

The first step towards obtaining a design window was to determine the dimensions of the coolant channels. The dimensions of the coolant channels were chosen after a thermal and stress analysis. The channels picked for analysis were the one near the center of the "flat" face and the one at the leading edge. The coolant channel at the center is subjected to the maximum heat flux because it is nearest the plasma. The coolant channel at the leading edge has a different construction with particular constraints that require detailed stress analysis. Thus, these two channels were analyzed.

Figure 2 shows the construction and nomenclature of the two channels. For both thermal and stress analysis the finite element code.

Fig. 2 Details of the leading and center channel

ANSYS, was used. To study the effect of changing wall heat flux, inside pressure, wall thickness, width and breadth of channel, and spacing between channels a sensitivity study was performed. The results of the sensitivity study are presented in Table 1. It was observed that,
for both cases, total stress is highly sensitive
to wall heat flux, wall thickness and spacing
between channels. It was noted that total
stress in the most critical element increases
with an increase of any of the above variables.
Another important observation was that total
stress is least sensitive to variations in
inside pressure for that below 30 MPa, however,
increases sharply at pressure above 60 MPa.

Table 1. Results of the Sensitivity Study

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SENSITIVITY</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Flux</td>
<td>High</td>
<td>Stress increases with increasing heat flux</td>
</tr>
<tr>
<td>Inside Pressure</td>
<td>Medium</td>
<td>Stress increases; increase rapid at high pressures</td>
</tr>
<tr>
<td>Channel Width</td>
<td>Low</td>
<td>Stress increases with increasing width</td>
</tr>
<tr>
<td>Channel Breadth</td>
<td>Low</td>
<td>Stress rises and falls — peaks at 9 mm</td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>High</td>
<td>Stress increases as wall thickness grows</td>
</tr>
<tr>
<td>Channel Spacing</td>
<td>High</td>
<td>Stress increases as channel spacing grows</td>
</tr>
</tbody>
</table>

Choosing of dimensions of the cooling chan-
nels essentially means that once coolant velo-
city is chosen in the cooling channels, the
total mass flow rate to the limiter can be
determined. The determination of the mass flow
rate would lead to a decision about wall thick-
ness, cross section area, and coolant velocity
in the manifolds and conduits once the hoop
stress limit is applied. Here, because of the
constraint of not excessively blocking the
limiter slot (the space behind the limiter for
pumping), an additional criterion was introduced
to establish the viability of a particular
design. This criterion is stated as:
The total length blocked by the feed pipes
to the toroidal direction must be less than half
the total toroidal length of the limiter.

With this additional criterion in place
there were three possibilities for the overall
design, namely:
1) liquid metal cooled limiter using untapered,
insulated conduits;
2) liquid metal cooled limiter using tapered
conduits;
3) liquid metal cooled limiter using insulated
conduits.

The effect of the above criterion on an
untapered, untailed walled conduit design can
be observed in Fig. 3. It is a plot of path

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Table 2. Dimensions of the Channels

<table>
<thead>
<tr>
<th>CENTER CHANNEL</th>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Width</td>
<td>12 mm</td>
<td></td>
</tr>
<tr>
<td>Channel Breadth</td>
<td>3 mm</td>
<td></td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>1.2 mm</td>
<td></td>
</tr>
<tr>
<td>Channel Spacing</td>
<td>1.7 mm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LEADING CHANNEL</th>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Width</td>
<td>12 mm</td>
<td></td>
</tr>
<tr>
<td>Channel Breadth</td>
<td>3 mm</td>
<td></td>
</tr>
<tr>
<td>Wall Thickness</td>
<td>1.2 mm</td>
<td></td>
</tr>
<tr>
<td>Channel Spacing</td>
<td>1 mm</td>
<td></td>
</tr>
</tbody>
</table>
length versus coolant velocity in the cooling channels. As is obvious for a wall heat flux of 1 MW/m², it will be impossible to satisfy the above criterion, although not for a wall heat flux of 5 MW/m². This can be seen from the plot, since for coolant velocities up to 7-8 m/s the maximum permissible path length does not exceed the minimum required path length. Above 7-8 m/s coolant velocity the pipes get so thick that a design can be practically ruled out. This, however, does not occur for a design employing tapered conduits. For a coolant velocity between 5 to 6 m/s the above mentioned criterion can be met for a wall heat flux of 5 MW/m². This can be observed in Fig. 4.

![Graph showing relationship between path length and coolant velocity](image)

Legend
- A - Maximum permissible path length at 4 MW/m² heat flux
- B - Maximum permissible path length at 5 MW/m² heat flux
- C - Half of minimum required path length

Fig. 3 Design margin with tapered conduits at 4 and 5 MW/m² heat flux

The overall design with all limits in place was considered for the cases with tapered and insulated conduits. The design window obtained for these cases is shown in Figs. 5-6. It exists for both the cases, however, decreases considerably for an increase in wall heat flux from 4 to 5 MW/m². It is also observed that the design window for a design employing tapered conduits at 5 MW/m² is very narrow. Which essentially means that it will be possible to have a design, but without much flexibility in operation. Also noted is that a design employing insulated conduits appears to be the most attractive if insulators can be developed for the harsh radiation and corrosive environment.

![Graph showing design window](image)

Legend
- A - Minimum inlet temperature limit
- B - Maximum structure temperature limit
- C - Maximum interface temperature limit
- D - Maximum primary stress limit

Fig. 5 Design window with tapered conduit at 4 MW/m² heat flux
CONCLUSIONS

Design of limiters with liquid metal cooling appears very difficult but feasible under certain conditions. In light of the above analysis it can be concluded that (for an uncoated limiter):

1) Coolant should be constrained to flow parallel to toroidal magnetic field in the coolant channels.

2) Design of limiter coolant channels appears difficult at 5 MW/m² peak heat flux due to large thermal stresses arising in the structure.

3) For conducting walls with no tapering in the feed pipes the maximum permissible peak heat flux is 4 MW/m².

4) Insulating or tapering the thickness of the feed pipes increases the allowable peak heat flux to 5 MW/m².

5) A limiter design employing insulated feed pipes appears to be the most promising, if suitable insulators can successfully be developed. All the results are based on thin structural material facing the plasma with no coating. This is valid only if no surface erosion occurs. Coating will further reduce the allowable heat flux.
REFERENCES


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