THERMOMECHANICAL ASPECTS OF THE LIQUID METAL COOLED LIMITER

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ABSTRACT

Analysis has been performed to evaluate the possibility of using liquid lithium as a coolant for the limiter. A global analysis was carried out to determine limiter's shape and configuration, and then detailed MHD, heat transfer, and structural analysis, were performed to determine limiting coolant velocities, operating pressures, Nusselt number, and allowable heat fluxes. For one of the most suitable choices of materials i.e. vanadium structure, lithium coolant, and Be coating (10 mm), the limiting heat flux has been found to be 2.5 MW/m^2. For High-Z coating of tungsten the limiting heat flux has been found to be 5.7 MW/m^2. In both cases the operating pressure was maintained at 10 MPa.

INTRODUCTION

Liquid metals have been proposed as breeders and coolants for fusion reactor blankets[1-2]. Their breeding and cooling capabilities are satisfactory. However, they react very strongly with water, and this makes it necessary to identify a non-water coolant for the invessel components[3]. The purpose of this work is to study the use of liquid lithium as the coolant for the limiter. This was achieved by first performing a global analysis of the problem, secondly, by performing MHD and heat transfer analysis, thirdly by carrying out a structural analysis of the limiter, and finally by predicting the optimum limiter configuration, as regards geometrical configuration, choice of materials etc., and the maximum permissible heat flux which the limiter can bear.

ANALYSIS AND RESULTS

A limiter can be designed in a variety of ways, however in our case the operating conditions are so harsh (high heat fluxes, high operating pressures and temperatures, high particle fluxes and erosion rates etc.) that we considered it necessary to perform global analysis of the problem. Global analysis was intended to choose the best possible combination of geometry, substrate materials, coating materials etc., which would function satisfactorily under the imposed constraints[4]. The imposed constraints were:

1) The interface temperature between lithium and structure must remain below the limiting value (~650°C if vanadium is used as the structural material).

2) The structural temperature must remain below the limiting value set by radiation effects, creep and other considerations (~700°C for vanadium structure).

3) The coating temperature should remain below the value necessary to avoid plasma contamination (physical vaporization in the case of beryllium).

4) The primary stress (hoop stress) should remain below the value described by the ASME code:

$$\sigma_{hoop} < S_m$$

$$S_m = 233 \text{ MPa at } 500°\text{C for V15 Cr 5Ti}^{2,5}$$

5) The primary plus secondary stress (thermal stress) must remain below the limiting value described by the ASME code:

$$\sigma_{primary} + \sigma_{secondary} < 3S_m$$

6) Sufficient space should be provided in the high plasma density region of the scrape off for the particles to be pumped out.

The various combinations considered are shown in Table 1. The global analysis led to the choice of a curved double edged limiter with insulated feed pipes and manifolds, uninsulated coolant channels on the face of limiter, flow in cooling channel parallel to the toroidal magnetic field and in feed pipes and manifold perpendicular to the toroidal magnetic field, vanadium substrate, and beryllium or tungsten as coating depending on the edge temperature of plasma. The process of elimination is shown in Table 2. The limiter is shown in Fig. 1.

Table 1: Different Options considered for Global Analysis

Limiter Geometries	Single Edge Limiter Double Edge Limiter Curved Double Edge Limiter
Substrate Materials	Copper (Cu) Vanadium (V)
Coating Materials	Beryllium (Be) Silicon Carbide (Sic) Tungsten (W)
Type of Piping	Insulated Pipes Uninsulated Pipes
Orientation of the flow	Parallel to Toroidal Magnetic Field Perpendicular to Toroidal Magnetic Field

Flow of liquid lithium in a heat flux and magnetic field environment gives rise to high pressure drops and suppression of turbulence. High pressure drops require high operating pressures and suppression of turbulence gives rise to difficulty in heat transfer. Thus, to ensure satisfactory operation of the limiter, MHD fluid flow and heat transfer analysis of the limiter must be carried out. MHD analysis was performed by simplification of the flow path of the coolant into individual sections of known geometries, then calculation of MHD pressure drop in each section using known relationships. The application of hoop stress limit provides the limiting coolant velocity in each section. Heat transfer analysis included calculation of temperature profiles in the structure. The calculation of Nusselt number is a key part of the heat transfer analysis.

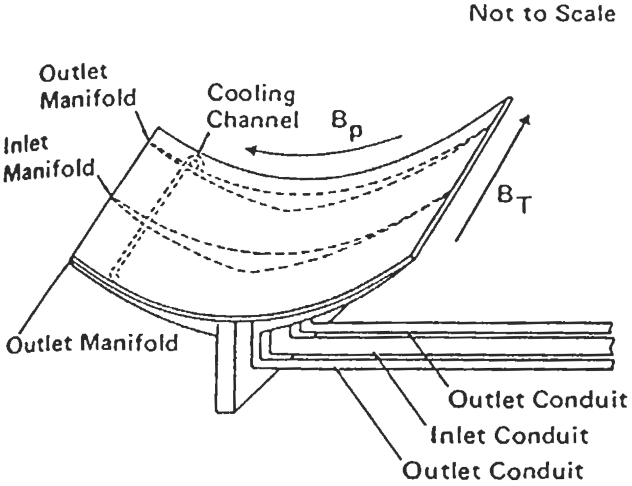

Fig. 1 Geometrical configuration of the limiter

The MHD analysis of the flow path of the limiter, shown in Fig. 1, was carried out subject to engineering constraints and the MHD pressure drop at different coolant velocities was calculated. The pressure at the inlet to the cooling channels versus the coolant velocity in the cooling channel is shown in Fig. 2. It can be seen that the use of insulation allows the limiter to operate at high cooling velocities with low pressure drop. Keeping into consideration the pumping cost and low material stress requirement, it was decided to choose 6 m/s as coolant velocity.

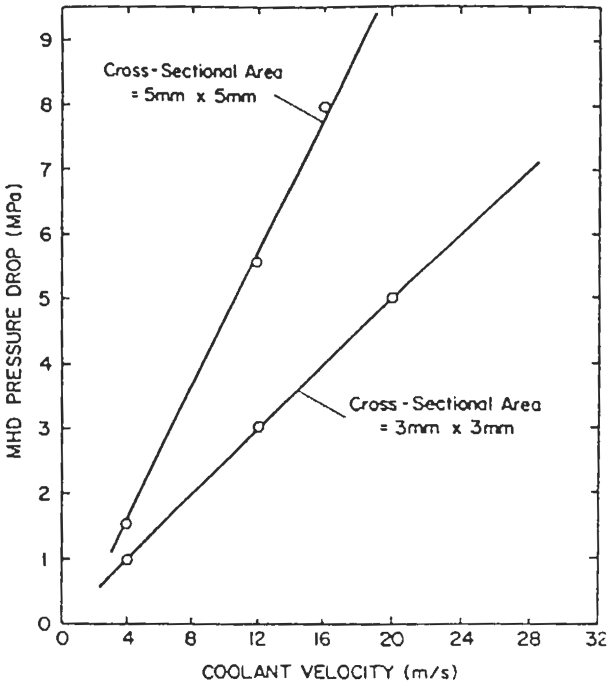

Fig. 2 Variation of MHD pressure drop with coolant velocity in cooling channels, when insulation is used everywhere, except cooling channels on the face of the limiter. Wall thickness of cooling channels is 1 mm

The heat transfer analysis were performed to choose a value of Nusselt number, for the coolant channel shown in Fig. 1. An accurate value of Nusselt number for the type of flow, i.e. the three-dimensional flow of liquid lithium in a square cross-section channel under constant wall heat flux, does not exist. The velocity profiles that exist are approximations to some degree. To predict a reasonable value of Nusselt number, a computer code was developed which solved the three dimensional energy equation, in the geometry mentioned above, and predicted curves of Nusselt number along the cooling channel for different fully developed velocity profiles. This made it possible to describe an upper and a lower bound on the Nusselt number in both the thermal entry length and the developed regime. However this was based on the known velocity profiles, so only a closer value to the actual value could be obtained. It has to be noted that the flow in the cooling channel remains within the thermal entry length. The use of a value of Nusselt number for the thermal entry region led to the definition of higher values of the allowable heat flux for the limiter. The profiles of Nusselt number for different fluid velocity profiles are shown in Fig.

Table 2: Elimination Chart after Global Analysis

OPTION	ACCEPTED	REASON FOR ELIMINATION
Beryllium or Tungsten Coating	Both considered	
Copper or Vanadium Substrate	Vanadium	Compatability of lithium and Cu is very poor. It has been shown[7] that there is substantial solubility of lithium in copper, approaching 20 a/o at the melting point of Li (180° C). The inlet temperature of lithium has to be about 225° C or more to avoid solidification at cold spots in the coolant loop. Thus expected temperatures at copper and lithium interface would be about 300°C, at which the solubility of lithium in copper would be ~17 a/o. The creep strength of copper also goes down at higher temperatures.
Insulated or Uninsulated Pipes	Insulated Pipes	Uninsulated pipes give rise to very high pressure drop in the system. MHD pressure drop in a curved double edge limiter with uninsulated pipes and flow velocity of coolant, in the cooling channels, of about 1 m/s is ~40 MPa.
Flow in coolant channel Parallel or Perpendicular to toroidal magnetic field	Parallel to toroidal magnetic field	Perpendicular flow to toroidal magnetic field gives rise to higher pressure drops (additional ~2 MPa in a curved double edge limiter).
Single Edge, double Edge or curved double Edge limiter	Curved double Edge limiter	Incident heat flux on a curved double edge limiter is 25% of the maximum heat flux on a flat limiter. Incident heat flux on a flat double edge limiter is 35% of the maximum heat flux on a flat single edge limiter.

3. The curves correspond to a bulk velocity of the fluid of 5 m/s and the results also include internal heat generation. For our analysis we choose a value of Nusselt number equal to 8.

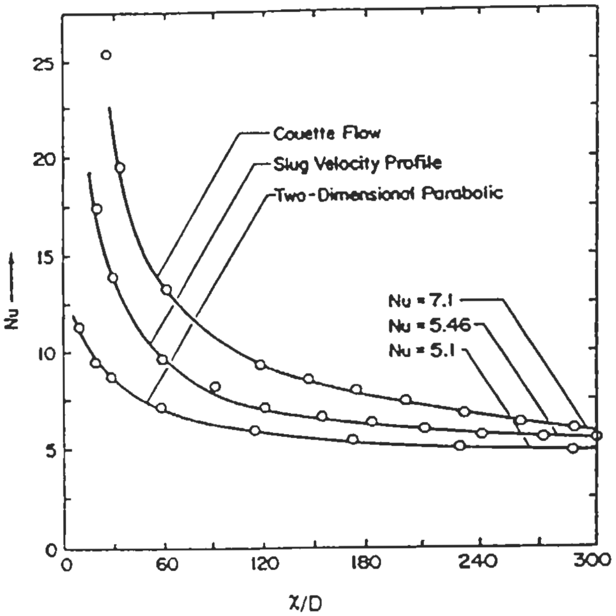

Fig. 3 Variation of Nusselt number along the heated length of the coolant channel

The purpose of this work had been to determine whether it is possible to cool the limiter in a fusion reactor by using liquid lithium. This could be established by comparing the maximum permissible heat flux (for our purposes here, the maximum permissible heat flux is defined as that value of heat flux for which the primary plus secondary stress limit is violated) for the limiter which evolves through the optimization process with the heat flux which is expected in a commercial tokamak fusion reactor. If the maximum permissible heat flux exceeds the value expected in a commercial fusion reactor the limiter shall function otherwise not (nominal heat flux in a fusion reactor, based upon previous conceptual design studies is about 5 MW/m^2 or greater). Structural analysis is a key part in this evaluation.

The structural analysis of the limiter was carried out by defining the remaining variables which would affect the heat bearing capacity of the limiter, then optimizing them and then predicting the maximum permissible heat flux for the optimum choice. Structural analysis code ANSYS[6] was used for this purpose. The remaining variables which were considered to affect the maximum allowable heat flux were :

1. width and breadth of the cooling channel
2. front and back wall thickness of the cooling channel
3. side wall thickness or spacing between the cooling channels.

As it was not possible to analyze each channel, so critical channels were analyzed and identified. They were the ones on the leading edge and at the center of the limiter.

It was found out that an increase in the channel width when the breadth was fixed led to an increase in the total stress in the material for both the critical channels, whereas an increase in the channel breadth, when the width was fixed, decreased the total stress. Apparently the total stress was minimum when channel width and breadth were equal, thus square cross-section channels appeared to be the best. It was observed that a decrease in front and side wall thicknesses decreased the total stress in the material. It was seen that the thickness of the back wall played an important role in controlling the total stress in the material for a beryllium coated limiter. It was observed that the back wall thickness should observe the following empirical relationship to keep the total stress low in the limiter with Be coating.[2] This relationship for value of front wall and coating thicknesses expected in a fusion reactor is:

$$t_{bw} = m\,(t_{fw}+t_c)$$

where m is calculated from:

$m = 8.5 - \frac{1}{2}(t_{fw} + t_c)$
t_{bw} = back wall thickness
t_{fw} = front wall thickness
t_c = coating thickness

The inverse in back wall thickness when Be coating is used can be attributed to the high coefficient of thermal expansion of Be. The beryllium coating because of its higher coefficient of thermal expansion exerts additional stresses on the back wall and thus the thickness of the back wall have to be increased. In case of limiters with high z coating, an increase in the back wall thickness increased the total stress. Thus it was decided to choose square cross-section channels and minimize front and side wall thickness. For high z coatings the back wall thickness is minimized. For Be coating the back wall thickness is calculated from the empirical relationship. Keeping into consideration the primary stress requirement and manufacturing considerations, the channel chosen was a 5 mm x 5 mm channel, with 1 mm front and side wall thickness, 1 mm thick back plate for high z coating and back wall thickness determined by above empirical relationship for Be coating. It has to be mentioned that the size of the channel plays a significant role in determining the velocity of the coolant in cooling channels for a given mass flow valve in channel, the exit temperature of the coolant, and stresses in the material. For a given flow rate, smaller size channels would cause larger coolant velocities and if heat flux is kept constant then would reduce the exit temperature of the coolant. The effect of channel size on material stress can be observed in Figs. 4-6.

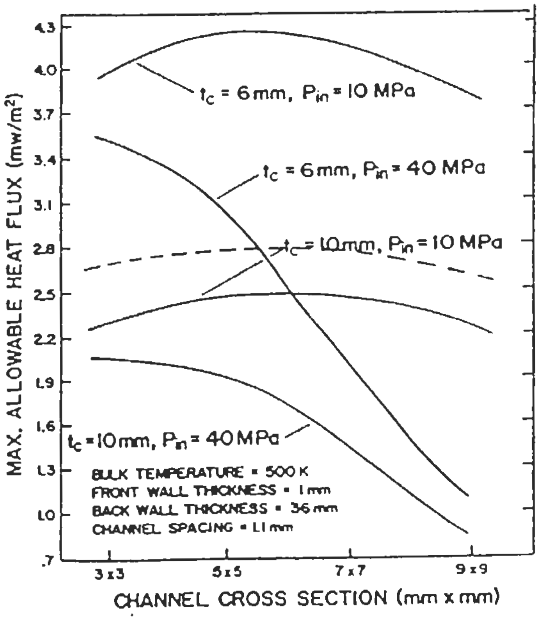

Fig. 4 Maximum permissible heat flux for beryllium coated liner

Once an optimum cooling channel configuration was found, it was easier to calculate the maximum permissible heat flux. For the center channel the curves representing maximum permissible heat flux, based upon total stress, are shown in Figs. 4 and 5, for beryllium and tungsten coatings respectively. It can be seen that the maximum permissible heat flux for a limiter with beryllium coating (~2.5 MW/m^2 at 10 MPa) is much lower than maximum permissible heat flux for a limiter with tungsten coating (~5.7 MW/m^2 at 10 MPa). This can be attributed towards much thinner coatings when high z coating materials are used. For the leading channel the maximum permissible heat flux curves with tungsten coating are shown in Fig. 6.

The leading channel can withstand up to 3.5 MW/m^2 heat flux, with tungsten coating. It has to be noted that these figures are based upon total stress limit. Application of the primary stress limit would rule out the possibility of channel cross-section more than 5 mm x 5 mm in most cases. In Fig. 6, for the leading edge channel, this cut off point can be seen explicitly for 40 MPa curves.

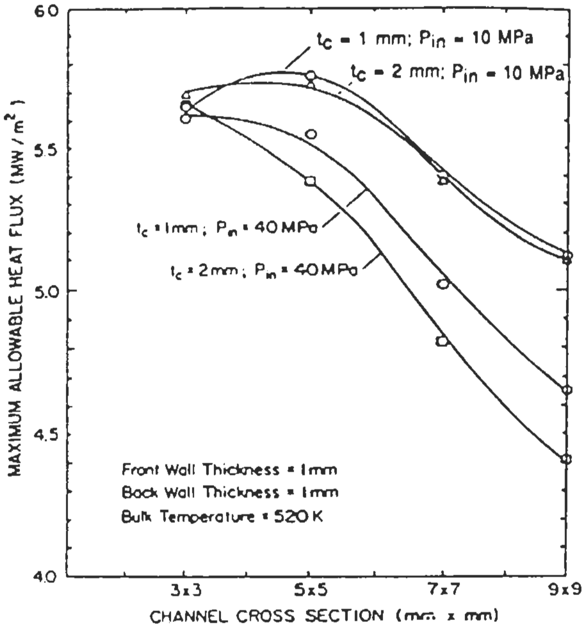

Fig. 5 Maximum permissible heat flux for tungsten coated limiter

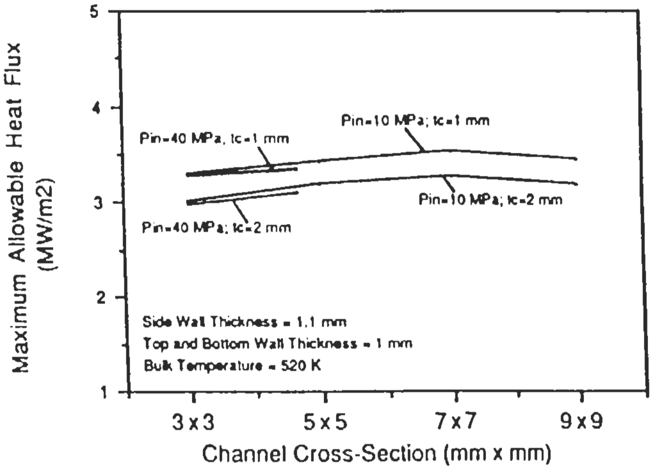

Fig. 6 Maximum permissible heat flux for tungsten coated leading edge channel

CONCLUSION

The above results indicate that based on erosion rates predicted in previous conceptual design studies (10 mm for Be, 1 mm for tungsten with the appropriate plasma edge conditions), the maximum permissible heat flux exceeds the nominal heat flux in a fusion reactor only in the case of tungsten coating. Lowering the operating pressures would raise the value of maximum permissible heat flux, but in no case do we expect the maximum permissible heat flux for beryllium coated limiter to reach the nominal heat flux of a fusion reactor (for 10 mm Be coating). In Fig. 6 the dotted curve represents the maximum permissible heat flux which would result if the coolant pressure in the coolant channel is reduced to 1 MPa. It can be seen that the curve does not exceed 3 MW/m^2. Plasma contamination problems may not allow the use of high z coatings in close proximity to the plasma. The only possibilities which remain are either to redesign the commercial fusion reactors (regarding heat flux on the limiters) and lower the erosion rates of the limiter (for example, Be coating thickness should remain below 5 mm) or lower the plasma edge temperature, using special techniques, so that high z coatings can be used. It is also recommended that other types of coolants like organic coolants be examined as potential coolants for the limiter. Another problem which occurs is that the Insulations which are used to achieve low pressures in the cooling channels cannot withstand the radiation environment. (It is concluded, therefore, that the state of the art technology and available information from conceptual design studies make it a difficult task to design a liquid metal cooled limiter for a commercial fusion reactor.) It has also to be added that the limiter design studied incorporates square cross-section channels. Circular cross-section channels have not been studied.

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