ANALYSIS OF THIN FILM LIQUID METAL PROTECTION OF FUSION REACTOR LIMITER/DIVERTOR SURFACES

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ABSTRACT

In an effort to prolong the lifetime of impurity control components, the idea of protecting the contact surface from erosion and radiation damage with a thin film of liquid metal has been advanced. This flowing, liquid metal film could also be used to remove the high heat fluxes incident on limiter or divertor surfaces, thus eliminating problems with thermal stresses in the components as well. In order to determine the attractiveness and feasibility of such a concept, the heat transfer characteristics of a thin film of liquid metal are examined when the film is exposed to a large, one-sided heat flux incident on the free surface. The method developed yields the temperature at any location in the film and is used to determine, for a given design and space-dependant heat flux, the film velocity required to keep the maximum film temperature below whatever T_{max} limit is imposed.

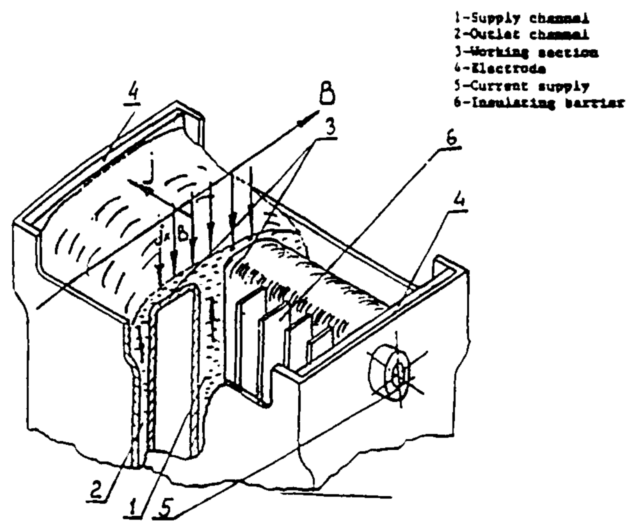
In addition, the behavior of the film flow at the required velocity is examined in order to determine if such a flow is possible. This analysis is accomplished by using a one-dimensional model of the film height, developed from the basic set of MHD equations, to show the design conditions that allow for a stable film. The analytical method is applied to ITER-type limiter and divertor configurations, resulting in required film velocities ($v < 5$ m/s for the cases examined) and allowable values of the design parameters (channel size, wall conductivity, and substrate angle) that yield a stable film, capable of removing all incident heat.

I. INTRODUCTION

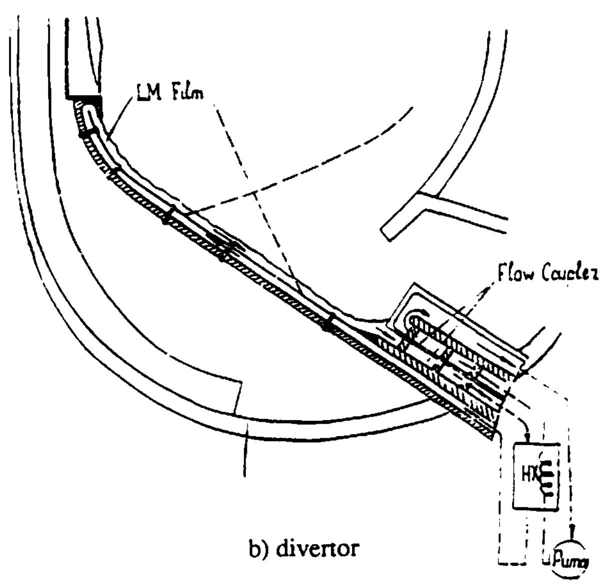
The concept of using a thin film of liquid metal (LM) to protect limiters and divertors was originally advanced in an effort to eliminate the erosion and radiation damage problems associated with the use of solid materials as plasma contact surfaces. In these devices, flowing liquid metal films form a continually renewed surface that suffers no ill effects due to sputtering erosion caused by incident energetic particles. Preliminary designs of such devices were presented in the INTOR study[1], and since then several variations have been proposed, some of which are tailored for use in ITER.[2,3]

Thin film LM protection schemes are generally divided into the two main categories of slow and fast films; where fast films have a flow rate sufficient to remove all incident energy, while slow films serve only to protect the contact surface from the energetic particle flux exiting the plasma. Fig. 1 shows examples of a fast film limiter and divertor.

In the context of these classifications, fast films then have the additional advantage that the need for a separate coolant is eliminated and thus thermal stresses in the limiter/divertor structure are significantly reduced. Due to the higher velocities required, however, MHD effects and substrate corrosion by the LM may limit their effectiveness in a fusion reactor situation.



a) limiter



b) divertor

Fig. 1. Examples of a Fast Film Limiter and Divertor[2]

To address these concerns, it is helpful to build a model from the basic governing equations of heat transfer and MHD that can describe the behavior of the film. It will then be possible to determine under what conditions fast films can be employed for plasma contact surface protection in the fusion environment.

II. HEAT TRANSFER

The choice of LM's as the working fluid is motivated by their ability to carry large amounts of heat and operate in a wide temperature range. Useful comparisons of different LM properties have been carried out[3–6] on the basis of many different criteria including: melting and boiling point, evaporative losses relative to sputtering losses, heat removal capability, corrosion properties, and tritium solubility. Based on this past work, gallium is chosen as the working metal in subsequent calculations. Other candidates include: lithium, excluded here due to its limited temperature window; tin, disregarded because of its high melting point relative to gallium; and a gallium-indium-tin eutectic, not used here due to a lack of thermal information but having the advantages of lower melting point and improved corrosion properties as compared to pure gallium.

A. Energy Equation

In order to describe the heat transfer characteristics of a thin film of LM flowing transverse to a space-varying heat flux incident of the free surface (Fig. 2), we begin with the two-dimensional, steady state energy equation:

$$\rho c_p u\frac{\partial T}{\partial x} - k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) = 0 \qquad (1)$$

where ρ is the density, u is the axial velocity, c_p is the specific heat, and k is the thermal conductivity. Notice here that volumetric heating due to neutrons and induced electric currents is neglected (both are small), and the velocity is assumed to have no y-component. Further, it can be shown that for a velocity of the order 1 m/s that axial conduction is small relative to axial convection,[6] and is therefore disregarded. Both this omission and that of a y-velocity component, make this a worst case analysis.

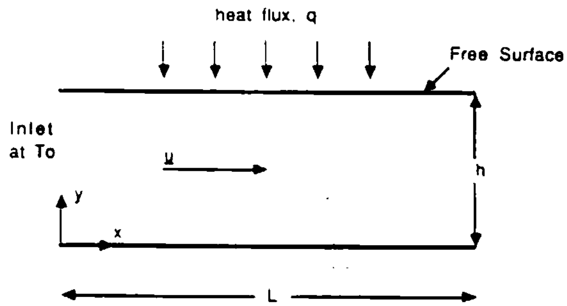


Fig. 2. Geometry of a Thin Film Exposed to a One-Sided Heat Flux.

Assuming a constant axial velocity, it is possible to make the transformation t=x/u, where t is the time that the film is exposed to the heat flux. Thus, Eq. 1 can now be written as:

$$\frac{\partial T}{\partial t} = \alpha\frac{\partial^2 T}{\partial y^2} \qquad (2)$$

with α defined as the thermal diffusivity, $k/\rho c_p$. The solution to this equation with an insulating boundary at the substrate and an arbitrary space-varying heat flux at the free surface is developed in Ref. 6 and gives the analytic expression:

$$T(y,t) = T_{in} + q(t)\left(\frac{y^2 - h^2/3}{2hk}\right) + \frac{\alpha}{hk}\int_0^t q(\tau)d\tau + \sum_{n=1}^{\infty}\frac{2\,(-1)^{n+1}}{\lambda^2 hk}\cos\left(\frac{y}{\lambda}\right)\exp\left(\frac{-\alpha t}{\lambda^2}\right) \times \left(q(0) + \int_0^t q'(\tau)\exp\left(\frac{\alpha\tau}{\lambda^2}\right)d\tau\right) \qquad (3)$$

with $\lambda = \frac{h}{n\pi}$, and h as the film height.

B. Limiter/Divertor Temperature Analysis

Given a specific heat flux distribution, Eq. 3 can be solved for the temperature at any point in the fluid. Figure 3 shows the distributions used in the following examples, including a standard constant heat flux and an approximate ITER-like tokamak distribution along the length of a one-piece divertor.[2]

For these examples, an inlet temperature of 50°C is chosen for the gallium. The temperature of interest is the maximum temperature reached in the film, since it is this temperature that must be kept below whatever limit is imposed for reasons of corrosion or evaporation. Figure 4 plots the maximum film temperature against the exposure time for the different heat flux conditions.

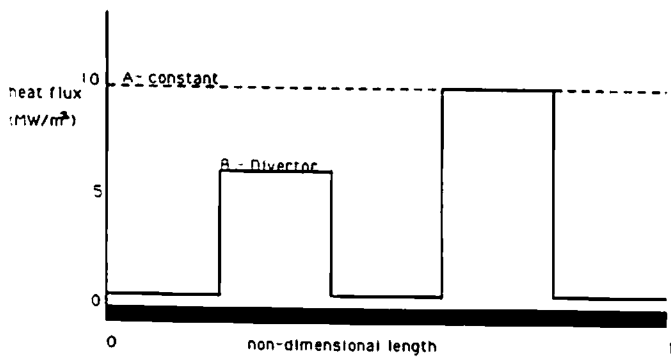


Fig. 3. Heat Distribution for a Constant and Divertor Heat Flux

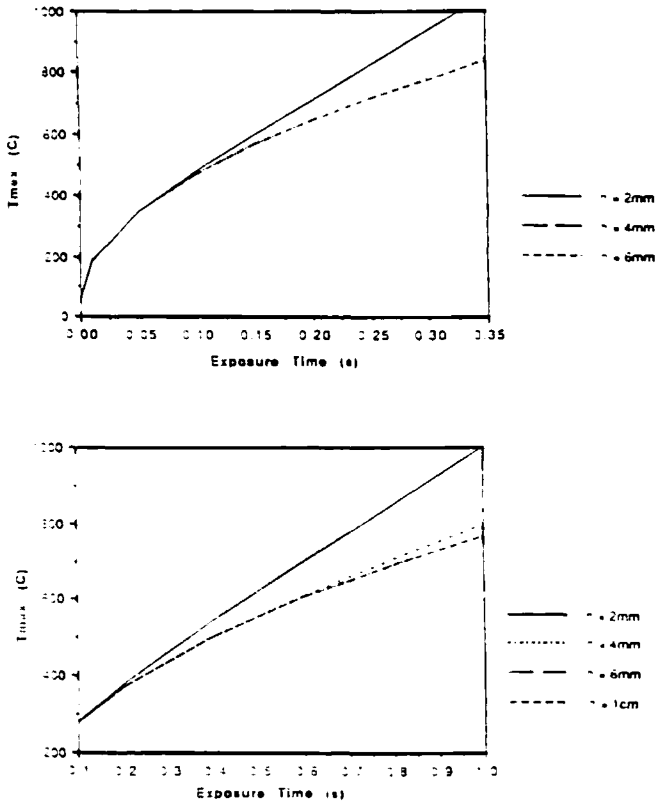


Fig. 4. Maximum Film Temperature vs. Exposure Time for (a) Constant Heat Flux, and (b) Divertor Heat Flux.

If T_{max} for gallium is fixed at 750°C (boiling point at 10^{-5} $Torr^{4}$), then from Figs. 4a and 4b we can evaluate the minimum velocities (and maximum exposure times) required to remove all incident energy from a given heat flux distribution while keeping the temperature below a required limit (T_{max}). Table 1 summarizes the results.

Also seen from Fig. 4 is the fact that an increase in the film thickness past 4 mm (with this T_{max} = 750°C) for the constant heat flux, or past 6 mm for the varying flux, has no effect on the minimum required velocity. This is due to the fact that once a sufficient thickness is reached such that the heat cannot penetrate all the way through the film to the substrate, any additional thickness has no effect.

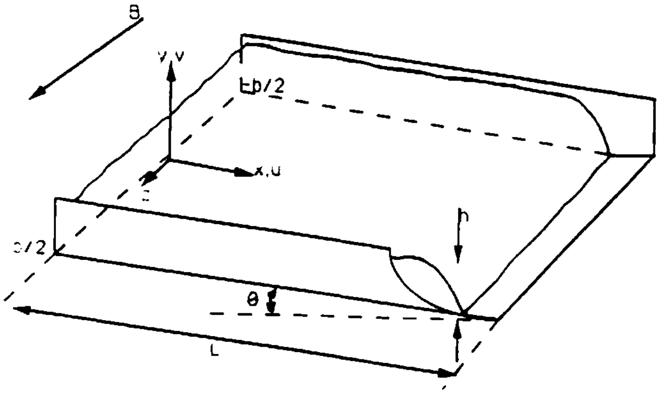
Table 1 Minimum velocity and maximum allowable exposure times calculated for the fast film contact surface

heat flux type	film depth	flow length	exposure time (t)	min. axial velocity (u)
constant	4 mm	1 m	0.27 s	3.7 m/s
	2 mm	1 m	0.22 s	4.54 m/s
	4 mm	0.5 m	0.54 s	1.85 m/s
	2 mm	0.5 m	0.44 s	2.77 m/s
varying	4 mm	1 m	0.95 s	1.05 m/s
	2 mm	1 m	0.65 s	1.54 m/s

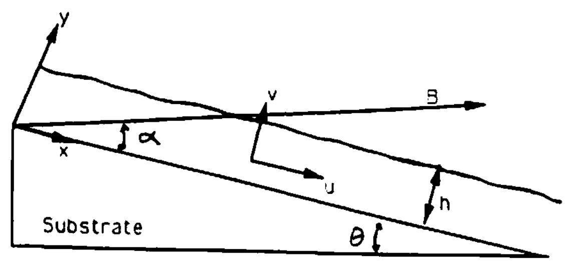
Although the required velocity is reduced for thicker films, the volumetric flow rate is increased. This means that more pumping power will be needed for the slower, but thicker, films.

III. THIN FILM MAGNETOHYDRODYNAMICS

Two different geometries will be treated in the following analysis: the coplanar case, and the quasi-longitudinal (QL) case. These names correspond to the orientation of the main component of the magnetic field to that of the fluid velocity. Figure 5 shows the variables in each geometry.



a) coplanar case



b) quasi-longitudinal case

Fig. 5. Geometries of Fluid Flow in the (a) Coplanar and (b) Quasi-longitudinal Orientations.

The fluid model uses the basic MHD equations, 4a-e, to obtain a non-linear differential equation for film height that depends only on x, the distance down the channel:

Navier-Stokes Equation:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\,\nabla^2 u + g\sin\theta + \frac{1}{\rho}(\underline{j}\times\underline{B})_x$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\,\nabla^2 v - g\cos\theta + \frac{1}{\rho}(\underline{j}\times\underline{B})_y \quad (4a,b)$$

Current conservation and continuity equations:

$$\nabla\cdot\underline{J} = 0, \quad \nabla\cdot\underline{v} = 0 \qquad (4c,d)$$

Ohm's law:

$$\underline{J} = \sigma(\underline{E} + \underline{v}\times\underline{B}) \qquad (4e)$$

Notice that this is a steady state system of equations, and that the velocity $\underline{v} = (u,v,0)$. Other definitions include:

$p \equiv$ pressure

$\underline{J} \equiv$ current density

$\underline{E} \equiv$ electric field

$\nu \equiv$ kinematic viscosity

$\sigma \equiv$ electrical conductivity

The development and application of one-dimensional models for film flow[6–9] require assumed velocity profiles in order to integrate out the dependence of the fundamental equations on the y- and z-variables. In this article, the velocity profiles are assumed to be Hartmann profiles with various values of the Hartmann number ($Ha = aB\sqrt{\sigma/\rho\nu}$, a≡length scale). The equations are then simplified by solving the y-component of the Navier-Stokes equation for the pressure and substituting it back into the x-component equation. The velocity and current are then eliminated with the help of Ohm's Law and the continuity and current conservation equations.

The final equation for the coplanar geometry case is:

$$\frac{dh}{dx} = h' = \frac{gh^3\sin\theta - \left(\frac{2\nu Ha}{b^2} + \frac{2\Phi B^2\sigma_f}{(1+2\Phi)\rho c}\right) f h^2 - f\nu M}{gh^3\cos\theta - f^2 W/c^2} \quad (5a)$$

while different approximations and a slightly different approach yield:

$$\frac{dh}{dx} = h' = \frac{\left(\frac{\sigma_f E_z B\sin\alpha}{\rho} + g\sin\theta\right)h^3 + \left(\frac{\sigma_f B^2\sin^2\alpha}{\rho} + \Lambda_c\right) f h^2 - f\nu M}{\left(\frac{\sigma_f E_z B\cos\alpha}{\rho} + g\cos\theta\right)h^3 - \left(\frac{\sigma_f B^2 T\sin(2\alpha)}{\rho c}\right) f h^2 - f^2 W/c^2} \quad (5b)$$

for the QL geometry. In the above expression, $f = F/b$, where F is the volumetric flowrate; h is the film height; and T, c, M, and W are artifacts of the velocity profile assumptions,[6] and have the approximate value $M = 26$, $T/c = 0.5$, and $W/c^2 = 1.02$ for the fusion situations we will be examining. $\Lambda_c \equiv 2\nu Ha_c/b^2$ is used to account for the effect of any coplanar magnetic field component present in a mainly QL case. The presence of E_z in the QL equation replaces Φ (wall conductance ratio) seen in the coplanar equation so that the effect of an externally applied electric field across the width of the film can be seen. This field, we will see, may be needed to avoid a phenomenon known as detachment.

From the form of Eq. 5a,b it is possible to define two important film heights. The equilibrium thickness h_{eq}, is a zero of the numerator polynomial, while the critical thickness, h_c, is defined as a root of the denominator. Thus at the equilibrium height $h' = 0$ and the film height is no longer changing. By contrast, at the critical height h' goes to infinity. Assumptions made in the development of the model equations result in the film behavior around h_c not being accurately described, but it is still apparent that this depth is to be avoided. In the parameter ranges we examine in the following examples, two roots of each third order polynomial are either complex or negative and are never encountered as the fluid changes height. Using the one positive real root of each polynomial, it is possible to define two regimes of flow which we name the unstable and stable regime. Figure 6 plots typical values of h' vs. h. Here we see that for $h_{eq} > h_c$, h_{eq} is not a stable equilibrium point. All choices of the initial film height, h_o, result in the film either moving toward the critical point or growing large. This is the unstable regime. Conversely, when $h_{eq} < h_c$, h_{eq} is now a locally stable equilibrium and provided that $h_o < h_c$, the film will tend towards the equilibrium height. For this reason this flow situation is named the stable regime.

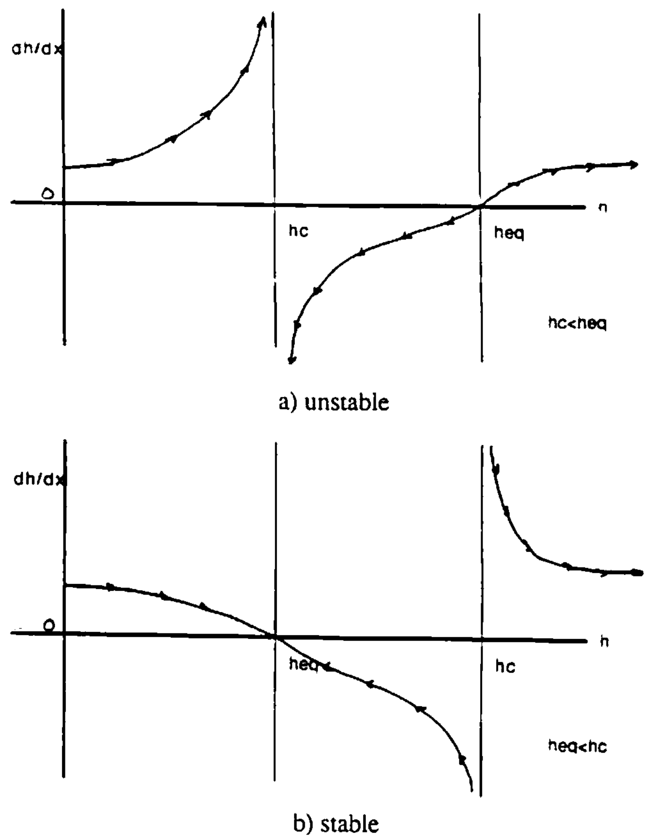


Fig. 6. Plot of h' vs. h Showing (a) the Unstable and (b) the Stable Flow Regimes.

The importance of determining h_c, h_{eq}, and thus the flow regime is demonstrated by the practical requirements setting a limit on the minimum and maximum film heights allowed in a specific design. The minimum thickness can be fixed at the amount of fluid vaporized in a plasma disruption. For gallium this is calculated at around 1 mm.[5] If the film height increases as it flows down the channel, then for a constant flowrate its velocity must decrease. Channel flooding is defined as the point at which the velocity has decreased enough such that the maximum film temperature now exceeds T_{max}. This maximum, or flooding, height is not a constant, but a function of other flow parameters. From these limits we see that changes in film height must be strictly controlled in order to stay within operating ranges. Ideally we would like to have a stable regime flow with the value of h_{eq} close to h_o so that the film will be of uniform height throughout the length of the flow. As we will see, this is not always possible.

Another interesting consequence of the MHD forces is the possibility of film detachment from the substrate.[6,9] Due to the fact that induced currents in the film can interact with the magnetic field to produce forces that are oriented normal to and outward from the substrate, it is possible that if these forces are sufficiently large, the film will detach from its base and fly out into the vacuum chamber. Defining film detachment as the point when pressure equals zero at y = 0, the following two relations can be derived.

Coplanar:

$$f_d < \frac{-2\rho g h h' \cos\theta}{B^2 \sigma_f}\left(\frac{\Phi+1}{\Phi+Ha^{-1}}\right)$$

$$h' < 0 \qquad (6a)$$

QL:

$$f_d < \frac{h(\rho g \cos\theta - \sigma_f B E_z \cos\alpha)}{\sigma_f B^2 \cos\alpha(\sin\alpha - h'T/c \cdot \cos\alpha)}$$

$$\cos\alpha(\sin\alpha - h'T/c \cdot \cos\alpha) < 0 \qquad (6b)$$

Flow rates larger than f_d have such a significant interaction with the magnetic field that detachment always occurs. If the qualifying conditions are not true then the original inequality sign is flipped. In this case the coplanar flow is always attached.

IV. APPLICATION TO FUSION LIMITER/DIVERTORS

Due to the large number of parameters involved in solving the previously derived equations in a general way, it is helpful to gain insight into film behavior by applying the equations to specific fusion problems. We proceed using the ITER relevant parameters in Table 2, and an assumed size of the contact surface.

Table 2 ITER Reference Parameters [10]

Plasma Major Radius	6 m
Plasma Half-Width (midplane)	2.15 m
Elongation (95% flux surface)	1.98
Toroidal Magnetic Field (axis)	4.85 T
Plasma Current (nominal)	22 MA

A. Coplanar Divertor

Most, if not all, LM divertor designs fall into the coplanar geometry case (see Fig. 1). Again, using gallium as the working metal, the toroidal field given above, values of M and W/c^2 given previously, and a length of 1 m, we begin by looking back to Section II for the required velocity. Since the governing equations for film height were averaged over the channel width (z), double the minimum film thickness estimated at 1 mm will be used to insure that no point in the width of the film drops below 1 mm. From Section II then we use the divertor heat flux distribution and see that a velocity of 1.54 m/s will be required. It seems prudent to use a larger velocity, however, to allow for a safety margin in the temperature, to compensate for the presence of a distribution of axial velocity in the y-direction (instead of the constant assumed in Section II), and to account for the fact that the film may grow as it flows down the channel. For these reasons, double the required velocity will be used initially. Therefore, for a 2 mm × 1m film flowing at 3.08 m/s, the flowrate f = 0.0062 m^2/s.

It is now possible to calculate h_{eq}, h_c, f_d, h', and h for a variety of different substrate angles, θ, and wall conductance ratios, Φ. The first thing apparent from the mass of data obtained is that both f_d and h_c are out of the ranges of values that may be encountered. Thus detachment is not a problem for steady state conditions. Also, stable regime flow should be possible since h_c is on the order of centimeters.

Figure 7 shows the value of h_{eq} vs. substrate angle for several values of Φ. From this graph we can see that as θ is increased, h_{eq} is reduced. The trend for lower h_{eq} is also noticed in the reduction of Φ. Thus for large angle and low Φ, stable regime flow is encountered and h_{eq} comes very close to 2mm (h_o).

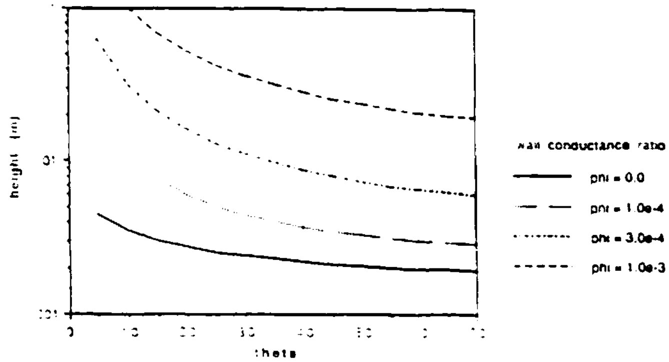


Fig. 7. Equilibrium Height, h_{eq}, vs. θ for a Coplanar Divertor with f= 0.0062.

Since Φ=0 is generally not possible, then h_{eq} will be greater than h_o and the film will tend to grow. Because double the required flowrate is used initially, this growth is allowed until the flooding condition is reached. It can be seen in the data that flooding occurs for all values of $\Phi > 3 \times 10^{-4}$ for $\theta < 70°$ (inclinations greater than 70° do not help significantly and are not considered). If a Φ less than 3×10^{-4} can be achieved, then the minimum angle at which the flow will not flood becomes shallower and the operating range is increased. For a ratio σ_f/σ_w of 1 and a wall thickness of 0.5 mm, a width (b) of 1.67 m is sufficient to set $\Phi = 3 \times 10^{-4}$. The term in which b appears explicitly in Eq. 3.2a is small compared to its neighbor whenever Φ has a value greater than 0; therefore, adjustment of the achievable wall conductance ratio by changing the width is acceptable. Further increases in b, up to whatever practical design limitations may exist, will further increase the band of angles at which flow without flooding is possible.

Another way to combat the flooding problem is to lower the equilibrium height at shallower angles by reducing the needed flowrate. Since the minimum flowrate value is fixed by the maximum temperature conditions, any attempt to lower the flowrate, and thus h_{eq}, significantly would require the use of multiple films in series so that a portion of the total energy is removed by each film. The viability of this sort of coplanar design has not yet been explored.

B. Quasi-Longitudinal Limiter

Implementation of a limiter in an ITER-like reactor requires estimating the magnetic field values of a non-diverted plasma using the parameters given in Table 2. B_{vert} is determined as 0.46T and B_p as 1.1T. B_p is then used as the coplanar field value in Λ_c and B_{vert} and B_T are transformed into a vector in the xy-plane with a magnitude of 4.87 T at an angle ± 5.42° to the horizontal (the ± depends on the direction of the vertical field).

In this example, use of the constant heat flux information from Section II is more appropriate since a cross-sectional element that originally sees 10 MW/m^2 will continue to see this heat flux as it flows down the channel. Again using a 2-mm film, but this time taking the working length equal to 0.5 m (this corresponding to a device of total length 1 m that has flow is both directions, see Fig.1), we see that double the required velocity is 4.34 m/s. The flowrate for a 1m wide film is then f = 0.0086 m^2/s.

Once again the quantities h_{eq}, h_c, f_d, h', and h are evaluated, but this time for different values of the substrate angle (notice that the angles α and θ are not independent parameters in this example, but are related by $\alpha = \theta \pm 5.42°$) and the applied electric field. As feared earlier, the data shows that detachment is now a major concern that limits α so that the film is close to parallel with the magnetic field (α small or negative). From Figure 8, a plot of the detachment flowrate as a function of θ, we can see the need for an applied electric field. This field increases the flowrate limit so that a greater range of angles is allowed before detachment occurs. The electric field also reduces h_{eq} (not pictured) so that flow without flooding is possible as well. Analysis reveals that one acceptable value of the applied electric field seems to coincide with the MHD emf (v x B ≡ 1V/m in this example). Thus an applied field that reflects this value is similar to a perfectly insulating duct with no applied field.

Due to reasons of flooding, negative values of α are not allowed. Thus non-flooded, attached flow is only possible for small (≤ 6.5° for E_z = 1V/m) but positive values of α. Once again shorter working lengths, and consequently more units running in series, would allow a greater range of angles and greatly ease restrictions on the flow.

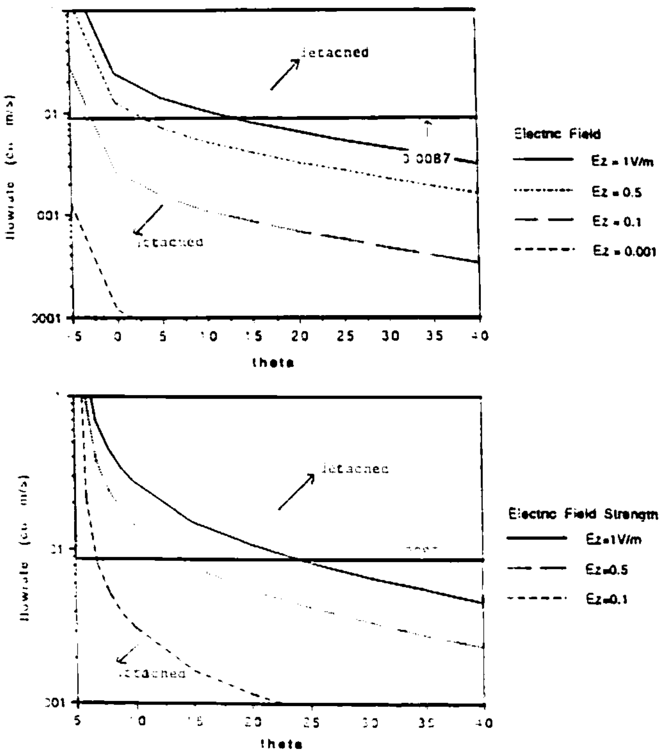


Fig. 8. Detachment Flow Rate Limit, f_d, vs. θ for QL Limiter with the Magnetic Field 5.42° a) Above and b) Below Horizontal.

V. CONCLUSIONS

Motivated by a desire to explore the possibility of creating a fast flow LM limiter/divertor protection scheme, a model has been devised that describes the film behavior. The heat transfer is approximated with a solution to the 2-D energy equation that can be used to determine the film velocity required to remove all incident energy. In all the examples presented, this velocity is ≤ 5 m/s. Analysis with the MHD equations then determines the free parameter ranges for flow at this velocity. In general, flow is possible at low values of Φ, or with applied electric fields oriented to cancel induced electric currents. Angular restrictions are also determined for for the different geometries.

Due to the uncertainties introduced by the simplifying assumptions employed to reduce the fundamental equations, the accuracy of the results may be greatly affected, especially in regions where $|h'|$ is large. This problem is further exacerbated by the lack of experimental data with which results could be compared. For this reason a more accurate numerical treatment of the original equations is required if exact limits on parameter ranges for a highly specific design is needed. This model, however, is sufficient to show the trends resulting from design parameter changes as well as giving an initial parameter range estimate with which evaluation of existing designs can be accomplished.

A more detailed treatment of the topics discussed in this work is available in Ref. 6. The authors would like to thank Oak Ridge Associated Universities/DOE for their support of this research through a Magnetic Fusion Energy Technology Fellowship.

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