

Estimates of the effect of a plasma momentum flux on the free surface of a thin film of liquid metal

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Abstract

The use of a thin film of liquid metal (LM) to protect a divertor surface requires that the LM film be able to withstand the flux of momentum carried by the energetic plasma exhaust flow. This momentum flux was estimated from edge modeling results of an ITER conceptual design activity (CDA) type divertor, and was found to be comparable with the hydrostatic pressure of a typical LM film of the order of millimeters in height. A two-dimensional, free boundary fluid code, RIPPLE, was modified to account for this flux and used to give an initial estimate of the seriousness of this effect. Lithium films are dramatically affected, to such a degree that their use in an LM divertor is seriously questioned. Gallium films withstand the momentum flux much better, with speeds of around 1 m s^{-1} giving adequate performance in a realistic CDA divertor momentum flux profile. The inclusion of magneto-hydrodynamic forces, not present in this initial estimation, is required to describe fully the LM film response.

1. Introduction

The use of a fast flowing, thin film of liquid metal (LM) as a possible plasma contact surface is envisioned to eliminate the erosion, radiation and thermal stress damage typical of solid divertor designs. Of the several problems anticipated with the use of flowing LM films in this capacity, the response of the LM film to the plasma momentum, the so-called *plasma wind*, has yet to be adequately modeled. Some existing flowing film models [1,2] assume the film height to be constant across the channel width, including a momentum flux of normal incidence only. However, the direction of the motion of particles along field lines results in an obliquely incident momentum flux on the free surface

of poloidally flowing LM divertor design concepts. One other past model includes the oblique flux in a geometry with infinitely removed sidewalls [3]. The oblique direction of the momentum flux in a channel of finite size, however, tends to bunch the LM on one side of the channel, possibly leaving the underlying substrate unprotected and negating the assumption of a flat surface profile.

In this study we made a scoping investigation into the plasma wind effect to determine whether it is a serious concern in the pursuit of the LM contact surface application. Section 2 derives a simple formula for the momentum flux in terms of the plasma edge parameters. Section 3 describes the use of the fluid code RIPPLE to predict the effect of the momentum flux on an LM film, and details the computational results. Conclusions are summarized in Section 4.

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2. Plasma momentum flux

The momentum flux of a particle stream composed of different species is defined as (Appendix A)

$$\Gamma_m = \sum_j (M_j v_j) \Gamma_{p,j} \quad (1)$$

where M_j , v_j and $\Gamma_{p,j}$ are the mass, velocity and particle flux of species j . Substituting the particle energy $E_j = \frac{1}{2} M_j v_j^2$ for the velocity gives

$$\Gamma_m = \sum_j (2M_j E_j)^{1/2} \Gamma_{p,j} \quad (2)$$

for the momentum flux. With electrons and ions of roughly the same energy, the momentum contribution of the electrons is reduced by $(M_e/M_i)^{1/2}$ (nearly $68\times$) compared with that of the ions, and thus is neglected here. If we assume further that the ions consist of deuterium (D) and tritium (T) of equal concentration and energy, Eq. (2) simplifies to

$$\Gamma_m = (\sqrt{M_D} + \sqrt{M_T}) \sqrt{E_i/2} \Gamma_{p,i} \quad (3)$$

where $\Gamma_{p,i}$ is the total ion flux and E_i is the ion energy at the divertor sheath. Similar equations are seen in Ref. [4] with verification by pressure measurement given in Ref. [5].

This energy can be written in terms of the ion temperature kT_i using the fact that $E_{ave} \sim kT_i$. In general, the motion will be three dimensional, translational along the field line with an accompanying gyro motion around the field line, with both components contributing to the energy. The momentum due to the gyro motion will tend to increase the normal component of the momentum flux. This is taken into account in the cases run later.

The increase in momentum flux on the LM surface due to the tendency of the plasma sheath on the divertor plate to accelerate ions is assumed to be canceled out by the electrostatic pulling action on the negatively charged LM surface by the relatively positive plasma [6]. Therefore, the momentum flux boundary conditions on the LM surface can be determined with the presheath data from [7] and Eq. (3) for different ITER conceptual design activity (CDA) divertor reference cases. CDA results are used because the LM film flowing on large plates is closer to the CDA divertor design than to the EDA radiative divertor. In Table 1, DN stands for double null configuration, SN for single null, A for ignited and B for quasi-steady-state operation. Also given is the hydrostatic pressure for 1 mm depth of gallium and lithium for comparison. From the magnitude of momentum flux, which has the same dimensions as pressure, it seems quite likely that the plasma flow has enough momentum to disturb the film.

Table 1

Plasma parameters and momentum flux at the divertor for different CDA operating points

Configuration	$\Gamma_{p,i}$ ($10^{23} \text{ m}^2 \text{ s}^{-1}$)	kT_i (eV)	Γ_m (Pa)
DN A.1 (o)	4	10	50
SN A.1 (i)	2	210	105
SN B.1 (i)	2.5	137	106
1 mm Ga	—	—	57.9
1 mm Li	—	—	4.9

3. RIPPLE modeling

In order to explore the plasma wind effect on an LM surface, the free surface computer code RIPPLE [8] was modified to take this force into account. RIPPLE is a two-dimensional, incompressible flow code that tracks the free surface using the volume of fluid (VOF) technique. RIPPLE's authors employ a continuum surface force technique that applies the pressure-like surface tension force as a volume force distributed over a thin depth near the free boundary. We take advantage of this transformation to incorporate the effect of a surface momentum flux in a similar manner. The new variables PFMAG and PFANG are added to supply RIPPLE with the magnitude and angle of incidence of Γ_m with respect to the orientation of the computational grid. Additional programming is added to insure that portions of the surface in the "shadow" of LM film peaks or channel sidewalls do not feel the effect of the plasma momentum. A full description of code modifications is given in Ref. [9].

The RIPPLE program is limited in its application to true fusion conditions by its lack of magnetohydrodynamic (MHD) forces and three spatial dimensions. The two-dimensional code must be set up to model the yz -plane in order to view the effect of an obliquely incident flux, eliminating the possibility of including the dominant \hat{x} (poloidal) velocity. What we are left with is a model of a stagnant pool of LM (see Fig. 1) undergoing recirculation owing to the force of the particle flux on the surface. However, it is adequate to develop a qualitative idea of whether this effect is truly significant enough to warrant further investigation.

3.1. Constant momentum flux

As seen in Fig. 1, the momentum flux is directed downward and to the right. The walls are set low so overflow due to perturbation of the film by Γ_m is lost.

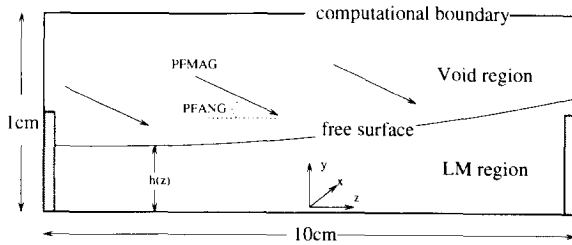


Fig. 1. RIPPLE model geometry.

No-slip boundary conditions are enforced on all walls, with the space above the walls employing a continuous outflow condition available as a RIPPLE supported boundary condition. At all walls the LM contact angle is set to 90° so that wall adhesion due to wetting (or the lack thereof) does not play a role.

The channel investigated is 10 cm wide containing a liquid metal adjustable in height. Owing to the submillimeter resolution required to compute accurately the height of the LM, computational cells of 0.5 mm are used in the \hat{y} direction. RIPPLE requires that the computational cell aspect ratio be less than or equal to 2, so 1 mm cells are used in the longer \hat{z} direction. Channels wider than 10 cm with thin initial heights of LM require a greater amount of computer time and memory than is warranted in this preliminary study.

The initial film height is set to 4.8 mm and a wall height of 5 mm is used in most cases, with deviations noted when encountered. These heights are fairly typical of those that may be required in fusion reactors. It is necessary to keep at least a 2 mm film covering all parts of the channel substrate in order to protect sufficiently the substrate from damage during major disruptions. Runs are performed with $|\Gamma_m|$ varying from 1 to 100 Pa and the angle of incidence of Γ_m varying from 15° to 45° . Even smaller angles than 15° may be expected for the field lines, but the gyro particle motion is expected to increase the normal component of the flux. The flux is turned on the initially flat surface at time $t = 0$ and continues until the end of computation.

Calculations were run with both Li and Ga films and, as expected, the Ga owing to its greater mass density is affected much less dramatically by a given Γ_m . At a constant flux of 10 Pa in magnitude at an angle of 15° (see Fig. 2(a)), the Ga film is pushed to the right and loses LM over the right wall for about 3.5 s. As the surface is disturbed by the flux, the free surface never drops below 2.5 mm. By about 4.5 s, the film settles into a fairly static free surface profile with the top 1.5 mm of the LM lost over over the wall. The film stays fairly

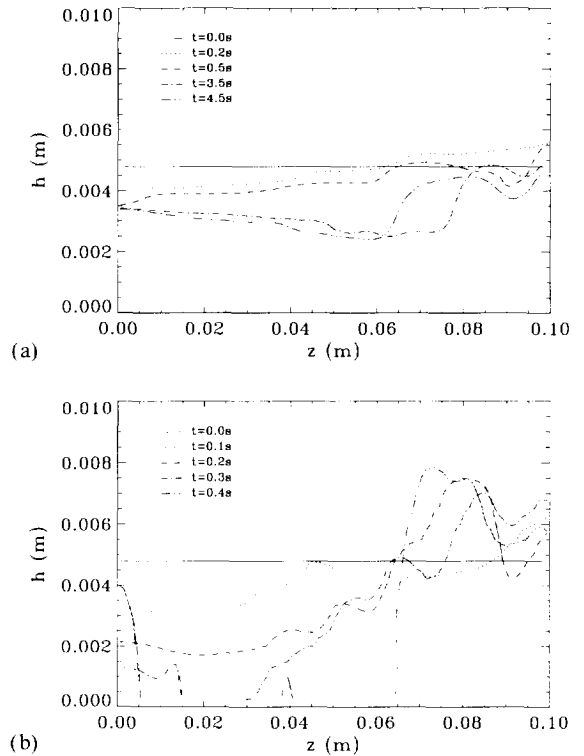


Fig. 2. Free surface profiles of (a) Ga and (b) Li films with Γ_m of 10 Pa in magnitude and angle of incidence of 15° .

constant until computation is terminated at 5 s. An Li film exposed to the same flux (see Fig. 2(b)) drops below the critical 2 mm mark in the first 0.2 s and bare spots on the substrate are seen by 0.4 s. The majority of the LM is lost during the first 1 s, with only small pockets remaining at the walls.

Variation of the angle from 15° to 45° for the channel size used here has little effect. For the Ga case of Fig. 2(a), a change to 45° results in slightly less loss of LM (top about 1 mm) and less penetration of the disturbance (surface never drops below 3 mm). An increase in angle does not save the Li surface from destruction. In other cases no dramatic difference is noticed for this angle variation.

Many runs showed the fact that the surface wave speed, estimated by \sqrt{gh} , limits the response time of the LM film. Shifting of the LM from one side to the other, for this size of channel, takes about 0.5 s. Thus if several oscillations are required for the LM to find equilibrium, the expected relaxation time is of the order of several seconds. Indeed this is seen in practice.

Runs were performed at $|\Gamma_m| = \rho gh_{1mm}$, the hydrostatic pressure of 1 mm of a given LM, to see whether the weight of the metal alone determines the severity of a given film response. The Ga film is affected much more seriously than the Li film, indicating that the weight of the LM is not the only determinant of the fluid response to a given magnitude of momentum flux.

3.2. Time varying flux

In this section the channel geometry of the constant momentum flux cases is retained, but the applied particle flux is varied in magnitude with exposure time. By assuming the film is moving with a given velocity down a divertor plate of length 2.5 m, we pseudo-model the effect of particle flux varying with position along the divertor plate. This flux as a function of position along the plate is simply transformed into a flux varying with RIPPLE problem time t

$$x_p = tv_p \tag{4}$$

Here x_p is the position down the divertor plate and v_p is the constant film velocity down the plate. Thus as the velocity of the film is increased, the time of exposure to the plasma momentum flux is decreased.

Data for the particle flux and ion temperature profiles, required by Eq. (3) to determine the momentum flux profile, are obtained as before from Ref. [7]. Fig. 3 shows the normalized product of $\Gamma_{p,i}\sqrt{kT_i}$ which, when multiplied by the peak $|\Gamma_m|$ for a specific configuration (see Table 1) gives the momentum flux profile supplied to RIPPLE in discrete form. As seen in the figure, the initial value of the momentum flux falls two orders of magnitude in the first 1.2 m, and almost four orders by the end of the divertor plate. Thus if a film can survive the first 1 m it is likely that it will smooth out and last the entire length of the plate.

Using the peak momentum flux $|\Gamma_m| = 100$ Pa of the single null cases given in Table 1, RIPPLE was run with a variety of different film velocities v_p and flux angles. As was seen in the constant flux cases the variation in the angle of incidence of Γ_m between 15° and 45° does not affect dramatically the response of the film, but it does have more of an effect on the surface roughness than in the constant flux results. The velocity range ($0.5\text{--}5\text{ m s}^{-1}$) is estimated as that typical of self-cooled LM divertor designs.

Again the Ga film is affected much less drastically than the Li films exposed to the same momentum flux. Fig. 4 shows the free surface profiles of both Ga and Li films flowing at 5 m s^{-1} (total exposure time 0.5 s). The initial impulse of momentum pushes the Ga film to the

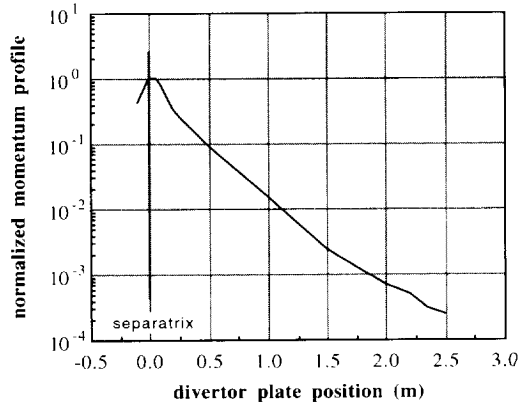


Fig. 3. Normalized momentum flux profile along the divertor plate.

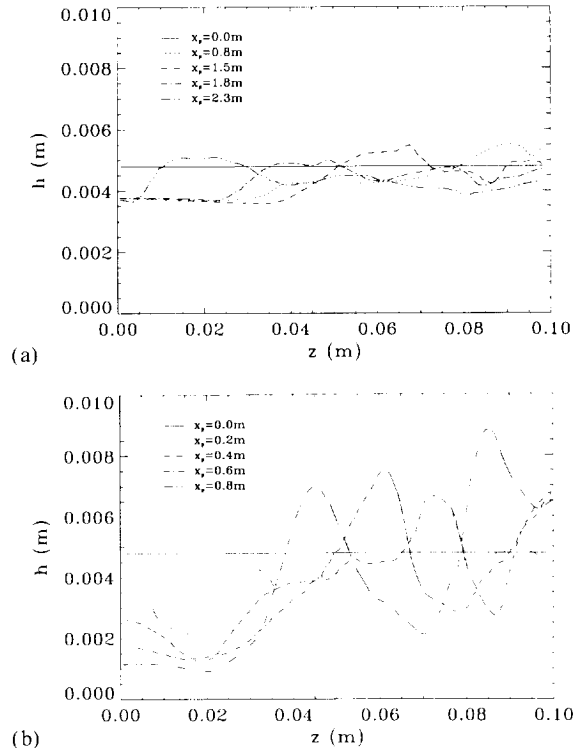


Fig. 4. Variable flux free surface profiles of (a) Ga and (b) Li films with $v_p = 5\text{ m s}^{-1}$ and angle of incidence of Γ_m of 15° .

right side of the duct but does not penetrate more than about 1.3 mm. The film recoils back to the left-hand side close to the end of the plate. This response time corresponds to the nearly 0.5 s transit time of surface waves noted earlier for a 4.8 mm deep film. Indeed the

propagating wavefront can be seen in Fig. 4(a) to traverse the channel with a speed of about 0.25 m s^{-1} . Ga survives adequately even at velocities as low as 1 m s^{-1} . Lower velocities can be used if the film thickness is increased.

The Li film (see Fig. 4(b)) forms bare spots and large surface waves by the time the LM has traveled the first 1 m of the divertor plate. As the magnitude of the momentum flux drops, presumably the LM begins to fill in the bare spots (although the computational run dies before this point), but part of the substrate near the left sidewall is inadequately protected for a large portion of the flow.

4. Summary of results

We see in the preceding sections that the magnitude of the plasma wind expected from a CDA edge plasma at the divertor plate is sufficient to alter the surface, sometimes drastically, of a stagnant thin film of LM. Li is seriously affected and it is likely that its use in this role will be precluded by the plasma wind effect for CDA edge plasmas. Lower edge temperatures and particle fluxes will result in a weaker Γ_m which may allow Li use. Ga is much more robust, owing to its greater density, and its use is acceptable at relatively modest velocities (greater than or equal to 1 m s^{-1}) on the divertor plate.

Since the analysis does not take into account the magnetic field, known to suppress strongly surface disturbances with motion perpendicular to the direction of induction, these results must be viewed as a first approximation used to estimate the seriousness of the plasma wind effect, and as a gauge as to the necessity of more elaborate modeling or experimental verification. This need is indeed demonstrated before the use of LM film for divertor surface protection can be seriously considered as a viable alternative concept for fusion reactor high heat flux components. The sensitivity of the film to the magnitude of the momentum flux requires the quantification of this value from the order of magnitude approximation presented here.

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Appendix A: Nomenclature

h	film height
Γ_m, Γ_p	momentum, particle fluxes
v_p, x_p	velocity, position on divertor
E, T, v	particle energy, temperature, velocity
ρ	LM density
k, g	Boltzmann constant, acceleration of gravity

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