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MHD problems in free liquid surfaces as plasma-facing materials in magnetically confined reactors☆

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Abstract

The development of solid plasma-facing components (PFCs) that can withstand high heat and particle fluxes during normal and abnormal events has proven to be a difficult task for future power-producing magnetically confined reactors. Solid PFC cannot be reliably used because of the large erosion losses during normal and off-normal events such as disruptions and their consequences. The use of liquid metal surfaces for protection of PFCs seems attractive but is not easily implemented. The ability to use liquids as PFC surfaces depends on their overall integrated interaction with the plasma as well as with the strong magnetic field in the reactor. The temperature of a flowing liquid surface governed by surface velocity should be low enough to avoid core plasma contamination by the metal vapor. A high liquid flow velocity, V, may also be necessary to overcome the force $F=[J\times B]$, where J is current and B is magnetic field. In this study, MHD flow patterns of the liquid metal across the magnetic field ($B=5$ T) are investigated. The retarding force $F=[J\times B]$ results in a rather high pressure drop required to move the liquid metal across the magnetic field. New two-dimensional calculations of MHD effects and resulting pressure drop have been completed with the upgraded HEIGHTS software package.

Keywords: MHD; Free liquid surfaces; Plasma-facing materials; Heights

1. Introduction

Application of liquid metal (LM) magnetohydrodynamic (MHD) streams for protection of PFCs in fusion devices has been considered since the very early stages of the tokamak reactor design concepts [1]. The LM divertor concept assumes that heat and particle fluxes (D, T, He, and impurities) arriving from the scrape-off-layer (SOL) are removed by the free flowing surface of the liquid metal above a solid structure or as free jets. The LM is assumed to have a velocity V_0 in several N_d toroidal sections with length $L_\theta=2\pi R/N_d$, sizes L_φ in poloidal direction, and thickness/depth $L_r=h_0$ in the radial (vertical) direction, where R is the major radius of the tokamak as schematically shown in Fig. 1.

The feasibility of LM concepts is determined by a number of issues. For example, the pressure drop

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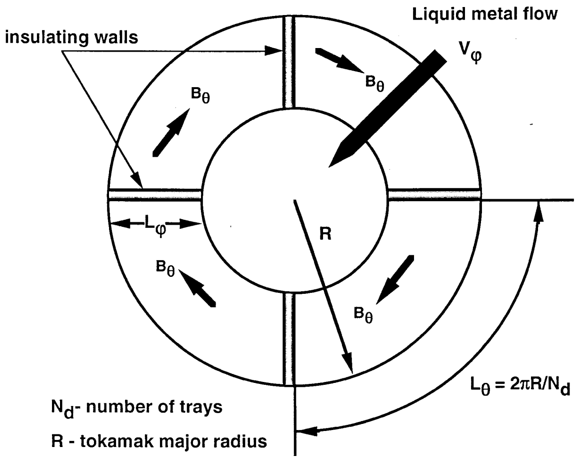

Fig. 1. Sectioned liquid metal divertor plate.

ΔP due to the MHD decelerating force is of critical importance since the ram pressure of the flow P_u is much less than the toroidal magnetic field pressure P_μ:

$$P_\mu \gg P_u, \quad P_\mu = \frac{B_0^2}{8\pi} = 100B_0^2 \text{ atm}, \quad P_u = \frac{1}{2}\rho V_0^2 = 0.25V_0^2 \text{ atm}. \tag{1}$$

Hereafter, the unit of velocity is in 10 m/s, the magnetic field is in 5 T, the density ρ is g/cm^3, and the liquid metal is lithium. The velocity V_0 and thickness/depth h_0 are those at the exit orifice or nozzle.

The electromagnetic force $\bar{F}_j = 1/c[\bar{j} \times \bar{B}]$ will result in braking or decelerating the flow, and this force is very high for ducts with conducting walls. The pressure drop ΔP is determined by the ratio of the electromagnetic force and the inertial force (i.e., by a flow resistance coefficient, λ, or by the Stuard number, N_{stuard}):

$$\lambda = N_{\text{stuard}} = \Delta p/(\rho V_0^2/2) = 2(P_\mu/P_u)(V_0 L_\varphi/v_m) = 240\ L_\varphi \gg 1,$$

$$v_m = \frac{c^2}{4\pi\sigma}, \tag{2}$$

where σ is the LM electrical conductivity. Thus, the flow in this condition cannot overcome the braking force. Therefore, the LM tokamak concept assumes that the walls of the trays (in the toroidal direction) are electrically insulated; the conductivity of the bottom is of little significance. The free surface can then be regarded as an insulated wall. The dynamics of such flows thus qualitatively resembles that of the flow in ducts with insulating walls.

The main feature of the flow in ducts with insulating walls is that the current path should close inside the flow as schematically shown in Fig. 2. This is possible since the liquid has friction with the walls (in the toroidal direction); thus the velocity at these walls is equal to zero (no-slip condition). Therefore, at a short distance δ (Hartman layer) from the wall, the flow velocity decreases from V_0 to zero with a corresponding decrease in the electromagnetic force that makes possible the closing of the current path through this layer, i.e., the current in the Hartman layer should have an opposite sign. As $\delta \ll L_\theta$ the electrical resistance of the current circuit, R_c, increases by the factor $(1+L_\theta/\delta)$, which decreases the magnitude of the full current to a level that make the flow possible without a large drop in kinetic energy:

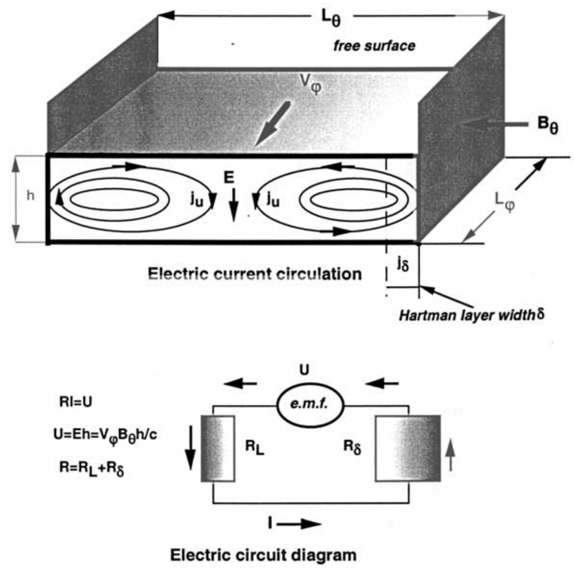

Fig. 2. Electric current flow patterns inside liquid metal flow.

$$I = \frac{U}{R_c}, \text{ where } R_c = R_u + R_\delta, \ U = E_0 h, \text{ and } E_0 = \frac{1}{c} V_0 B_0. \quad (3)$$

The characteristic values of the current density I and the electric field E_0 are $I = 10V_0B_0$ kA/cm^2 and $E_0 = 0.5V_0B_0$ eV.

The flow resistance coefficient, λ, in each toroidal section depends on the ratio L_φ/L_θ, i.e., on the number of trays N_d:

$$\lambda = 2\sqrt{\frac{P_\mu}{P_u} \nu v_m} \frac{L_\varphi}{L_0} = 2\frac{\text{Ha}}{\text{Re}}, \quad (4)$$

where ν is the viscosity. The maximum N_d obtained from the condition $\lambda = 1$ is $N_{d\text{-max}} = 40$, i.e., the minimum tray width is $L_{\theta\text{-min}} = 94$ cm (for typical $L_\varphi \approx 50$ cm, $R \approx 600$ cm). For the LM concept using free jet streams without walls, N_d is equal to unity, and $\lambda = 0$. This indicates that for LM concepts at certain conditions, the resulting pressure drop can be negligible, and flow streams can penetrate/cross the magnetic field without serious difficulties.

However, note that most previous theoretical studies assumed ideal conditions of flows with infinite length in the poloidal direction. Also, most experimental studies have not investigated the possible influence of both ends of flow (i.e., inlet and outlet) channels in a strong magnetic field. Only limited data are available for such a situation [2]. Recent studies have concluded that the feasibility of LM divertors depends on the MHD effects in the supply and feed systems requiring absolute electrical insulation of the LM loop from the environment [3]. This paper investigates the MHD effects and resulting pressure drop using the upgraded HEIGHTS, an Argonne-developed software package for simulating material behavior under intense energy exposure.

2. Edge current

The LM concepts that use free jet streams exiting the orifice/nozzle and incoming into a collector tube/container are analyzed below as the most representative or desired case. The obtained results are also valid for free surface flow with an insulating bottom. Total electrical insulation of the LM loops from the surrounding environments is impossible due to, for example, the potential for current closing through the SOL plasma or, at least, through regions of flow outside the magnetic field.

To study the consequences of this current closing, the following simplified flow stream is used. The planar system of coordinates ($x \to r$, $y \to \varphi$, $z \to \theta$) is used. Then, the flow stream is considered as a planar slab with infinite size in the toroidal direction, length L in the poloidal direction, and thickness/depth h in the radial direction, as schematically shown in Fig. 3. The stream has a velocity $V_y = V_0$ and thickness h_0 at the orifice/nozzle $y = L$. The top surface is at $x = b$, and the bottom surface is at $x = -b$ (i.e., $2b = h$). These surfaces have electrical connection through resistance R_s (see Fig. 3); thus in the $x-y$ plane, the current I_0 (amperes per unit length in the toroidal direction) emerges from the point (0, 0) and then enters into the point (h, 0).

The current density distribution can be described by the potential function Ω_Σ(I) as

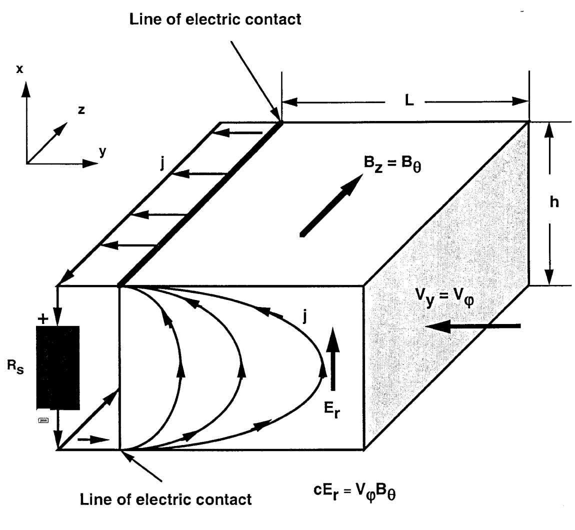

Fig. 3. Current closing patterns inside liquid metal flow.

$$\Omega_\Sigma = \Phi_\Sigma + i\Psi_\Sigma = I_0 \sum_0^{+\infty} \Omega_k,$$
$$\Omega_k = (-1)^k \ln \left\{ \frac{(x - b_k) + iy}{(x + b_k) + iy} \right\}, \tag{5}$$

where ϕ and Ψ are the real and imaginary part of the function Ω.

The current j, its magnetic field B, electric potential U, and the electric field E are then given by:

$$j_x = \frac{\partial \Phi_\Sigma}{\partial x} = \frac{\partial \Psi_\Sigma}{\partial y}, \quad j_y = \frac{\partial \Phi_\Sigma}{\partial y} = -\frac{\partial \Psi_\Sigma}{\partial x}, \tag{6}$$

$B_Z = \frac{4\pi}{c}\Psi_\Sigma, \quad U = \frac{1}{\sigma}\Phi_\Sigma, \quad \vec{E} = -\vec{\nabla} U$.As shown in Fig. 4, equipotential lines of Ψ are lines of equal j, and the equipotential lines of Φ are lines of equal electric potential U.

The total current I_0 is determined from the total potential between the walls at $x = \pm b$ and the internal resistance R_u of the LM and the external resistance R_s:

$$I_0 = \frac{U}{R_u + R_s} = \frac{U/R_u}{(1 + R_s/R_u)},$$

$$U = \int_{-b}^{+b} E\mathrm{d}x = 2bE_0, \quad E_0 = \frac{1}{c} V_0 B_0, \; j_0 = \sigma E_0. \tag{7}$$

The main part of R_u is grouped in a small region near the point of current contact. Assuming that the point of contact has a size r_c, the resistance R_u is

$$R_u = 2\frac{2}{\pi}\frac{1}{\sigma}\int_{r_c}^{r_m} \frac{\mathrm{d}r}{r} = \frac{2}{\pi}\frac{1}{\sigma} \ln\frac{r_m}{r_c}, \tag{8}$$

and has a maximum effective radius $r_m \approx b$ Therefore,

$$I_0 = \frac{U}{R_u + R_s} = \frac{2}{\pi} j_0 \frac{2b}{\lambda_R},$$
$$\lambda_R = \ln\frac{r_m}{r_c}(1 + R_s/R_u). \tag{9}$$

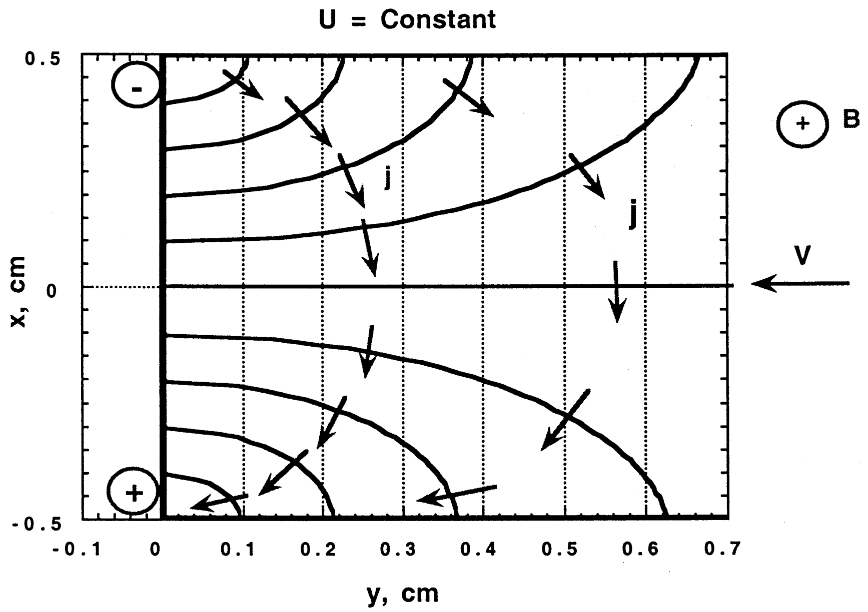

Fig. 4. HEIGHTS calculations of the current and electric field.

3. Flow dynamics and pressure drop

The acting electromagnetic forces are given as:

$$F_y = \frac{1}{c} j_x B_0 = -\frac{1}{c}\frac{\partial \Psi}{\partial y} B_0, \qquad F_x = +\frac{1}{c} j_y B_0 = -\frac{1}{c}\frac{\partial \Psi}{\partial x} B_0. \tag{10}$$

The flow retardation force; F_y, results in a decreased stream velocity, i.e., a pressure drop. The force F_x is a flow shifting force that changes sign at $x=0$, resulting in the compression of the liquid toward the stream axis at $x=0$, i.e., a pinching effect takes place. The rising pressure, P_{pinch}, further decreases the stream velocity due to the force

$$F_{y,pinch} = -\nabla_y P_{pinch}. \tag{11}$$

The total acting force F and the current $I(x, y)$ are determined from the new function P:

$$\frac{\partial P}{\partial y} = -F_y, \quad \frac{\partial P}{\partial x} = -F_x, \quad \vec{F} = -\vec{\nabla} P, \quad P = \frac{1}{c} B_0 \Psi, \qquad I(x, y) = \frac{\pi}{2}\Psi(x, y). \tag{12}$$

The part of the function P from force F_x is the real pressure due to compression, and the part from the force F_y is the potential of this volumetric force due to the pinching effect. The loss of kinetic energy is determined by the 'pressure' P proportional to the imaginary part, Ψ, of potential Ω: shown in Fig. 5,

$$P = \frac{8}{\pi} P_\mu \mathrm{Re_m}(V_0, h_0)\frac{1}{\lambda_R}\frac{\Psi(x, y)}{\Psi_0}, \qquad \Psi_0 = \Psi(0, 0). \tag{13}$$

Fig. 5 plots the potential function P calculated with HEIGHTS. The liquid flow can be regarded as incompressible in equations of mass and momentum discontinuity; thus, stationary flow is described by the equations for the motion of an incompressible liquid in the given potential field P ('pressure'):

$$\nabla\cdot\vec{V} = 0, \quad \rho(\vec{V}\vec{\nabla})\vec{V} = -\vec{\nabla} P. \tag{14}$$

4. Qualitative consideration

The above equations describe the stationary flow of a free-surface liquid metal stream in a homogeneous transverse magnetic field $B_Z = B_0$. The potential P must be defined in a self-consistent way with the solution of the Maxwell equations. For a stationary flow the mass flux conservation law coincides with the momentum M_y conservation law:

$$M_y = \int_{-b(t)}^{+b(t)} \rho V_y \mathrm{d}x = \mathrm{const}(y). \tag{15}$$

Since the magnetic field cannot change the flow momentum, the decrease in velocity V_y means increasing the size of the flow in the x-direction, i.e., $\Delta L_x = 2b(t)$. The flow kinetic energy decreases due to the transformation into thermal energy by Joule heating processes.

Liquid metal flow that only crosses the magnetic field means a small pressure drop and a correspondingly little change in velocity. Thus, for the following estimates the potential $P = P$ ($V \approx$ const, $b \approx$ const). From the Bernoulli equation:

$$\frac{\rho V^2}{2} + P = \frac{\rho V_0^2}{2}, \quad V = V_0\sqrt{1 - 2P/\rho V_0^2}. \tag{16}$$

Therefore, the conditions for the LM flow to cross the magnetic field are

$$\eta = \frac{2P(0, 0)}{\rho V_0^2} < 1, \quad V_0 > V_{crit}, \qquad V_{crit} = C_A \mathrm{Re_m}\frac{16}{\pi}\frac{1}{\lambda_R},$$

$$C_A = \sqrt{B_0^2/8\pi\rho} = 140 B_0 \; m/s, \; \mathrm{Re_m} = 0.325 h V_0 \approx 1, \tag{17}$$

$$V_{crit} = V_{crit,0}\frac{1}{\lambda_R}, \quad V_{crit,0} = 3.24\times10^3 B_0^2 \; m/s.$$

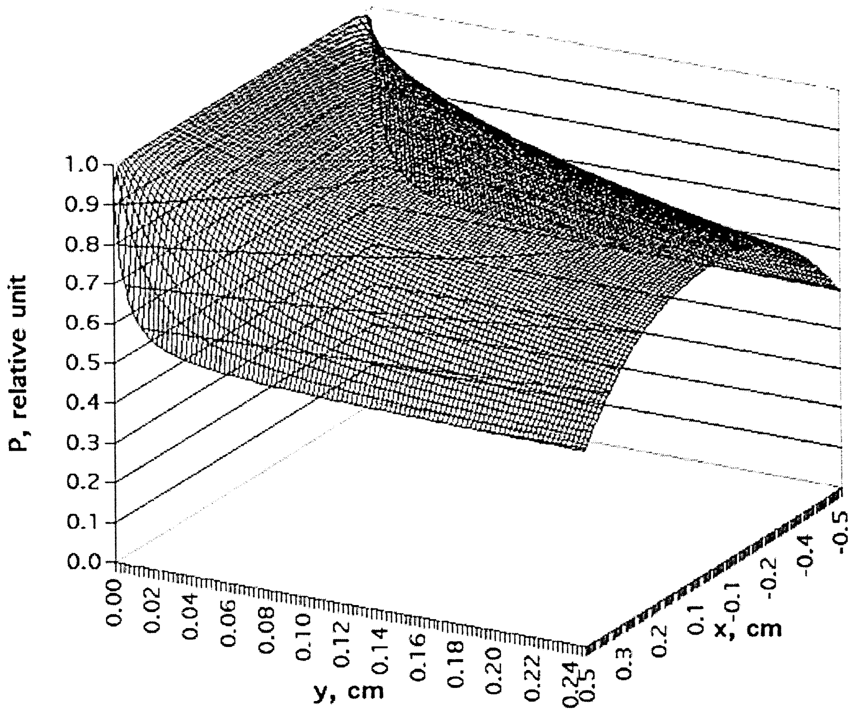

Fig. 5. HEIGHTS calculations of the potential function.

These conditions mean that the outer resistance of the electric circuit, R_s, must be very high:

$$\lambda_R > \frac{V_{\mathrm{crit},0}}{V_0} = 160B_0^2/V_0, \quad R_s/R_u \approx \lambda_R/10 \approx 15B_0^2/V_0, \tag{18}$$

at the reasonable $\ln(r_m/r_c) = 10$.

For a small crossing parameter $\eta < 1$, flow can easily cross the magnetic field. Distribution of the velocity $V_y\ (x, y)$ is defined from the Bernoulli equation, i.e.,

$$V_y(x,\ y) = \sqrt{1 - \eta\frac{\Psi(x,\ y)}{\Psi(0,\ 0)}}. \tag{19}$$

The velocity $V_x\ (x, y)$ can be obtained from the equation of discontinuity. The calculated shape of the flow streams is shown in Fig. 6.

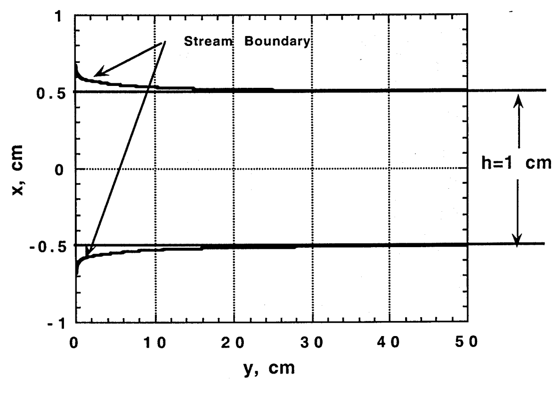

Fig. 6. HEIGHTS simulations of the liquid metal jet shape.

5. Summary

Application of liquid metal flow streams in fusion devices has been considered since the very early stages of the tokamak reactor design concepts. The LM divertor/first-wall concept assumes that heat and particle fluxes (D, T, He, and impurities) arriving from the scrape-off-layer (SOL) are removed by the free flowing surface of the liquid metal above the solid structure or as free jets. The electromagnetic forces can be too high for conducting walls and will result in braking or slowing down the flow. It is possible, however, to decrease the resulting pressure drop to acceptable values, i.e., $\Delta P \ll \rho V^2/2$, by insulating the walls of the structure or by using free jets. The free jet surface behavior was shown to be similar to that of a perfectly insulated wall.

The feasibility of the LM concepts depends on the MHD effects in the supply and feed systems requiring total electrical insulation of the LM loop from the surrounding environment. Most previous considerations assumed that the induced current closes its path only inside the liquid metal flow. This is valid at ideal conditions of flow, including infinitive length in the poloidal directions, perfect insulation of inlet and outlet nozzles, no current between the flow streams and SOL plasma, and liquid metal loops that only exist in regions with magnetic field. In the case where any one of the above assumptions does not apply, current can close its path across the flow stream, and the corresponding electromagnetic force can result in a significant pressure drop that causes the stopping of flow near inlet or outlet nozzles.

The effect of current path closure across the flow stream was considered. It was shown that the resistance of the current circuit (along the surface of nozzles, through the SOL plasma, in the region free of the magnetic field) should be much higher than the resistance of the liquid metal in order to decrease the pressure drop to acceptable values. To obtain such resistance values, the design of the LM loops should be studied in detail to pay more attention to the problems of current path closure.

Acknowledgements

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