LIQUID METAL FREE SURFACE FLOW THROUGH A NON-UNIFORM MAGNETIC FIELD: AN EXPERIMENTAL STUDY

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The idea of using fast flowing liquid metal streams or "liquid walls", as plasma facing components (PFC) in magnetic fusion energy (MFE) devices has received considerable attention from the fusion engineering community. MFE devices are associated with a strong and highly non-uniform magnetic field environment. Under these conditions, the liquid metal free surface flow behavior is predominantly characterized by strong MHD effects. A critical plasma facing component, under the present design of the MFE devices, is the divertor. This study is aimed at investigating the flow of liquid metal streams inside a typical divertor geometry under a non-uniform magnetic field environment.

Introduction. Liquid metal free surface flows or "liquid walls" have the potential to be become ideal plasma contact surfaces inside a magnetic fusion device. However, the presence of strong MHD effects, arising due to liquid motion in a complex spatially varying magnetic field environment, tend to disrupt the flow. Rapid deceleration of the flow accompanied by sudden thickening of the fluid film, unwanted flow deflection, creation of regions of thick stagnant fluid, stream wise and span wise variation of fluid film thickness are some of the MHD effects that must be addressed to ensure a smooth, controllable and predictable flow.

A number of experiments have been carried out to study the liquid metal free surface flow behavior under different magnetic field configurations. The liquid metal used for the experiments is a eutectic of gallium indium and tin (Ga-67%, In-20.5%, Sn-12.5%). The liquid metal is harbored inside a flow loop powered by an electromagnetic pump. The 'Magnetic Torus' facility at UCLA can closely simulate the '$1/R$' magnetic field, typical of toroidal magnetic fusion devices. In the first set of experiments performed, a rectangular stainless steel channel, with a wall thickness of 0.5 mm was used. The channel was 34 cm long and 5 cm wide. A set of inductive probes was used to measure the thickness of the fluid film over the flow length of the channel. As much as six times increase in the film thickness was observed at the downstream measurement location. It was also observed that the free surface fluctuations get damped and manifest as columnar disturbances, elongated in the direction of the applied toroidal magnetic field, very much in light of phenomenon described in [1]. Further details can be found in [2]. In the next set of experiments a longer and wider stainless steel rectangular channel was used. The dominant magnetic field component was aligned perpendicular to the bottom wall of the channel, with the field strength increasing in the flow direction from 0.06 T at the inlet to 0.2 T at the outlet. This configuration will be referred to as a surface normal configuration in the paper.

1. The experiment. The test section consists of a stainless steel channel with a wall thickness of 0.5 mm. The channel is 40 cm long and 20 cm wide. At the inlet, a nozzle introduces the liquid metal into the channel in the form of a thin stream with a uniform span wise thickness of 2 mm. A 20 cm long diffuser section connects the flow loop to the nozzle and helps in uniform spreading of the liquid metal in the span wise direction. The entire channel is enclosed in a vacuum box and a constant flow of argon is maintained over the channel to prevent the liquid surface from oxidation. The inlet velocity of the liquid metal film at the nozzle is varied over a range from 1.0 m/s to 3.0 m/s. A new optical technique has been developed to obtain the liquid metal film thickness. It involves creating a thin laser light line on the surface of the liquid metal. The idea is to reflect a laser light line from the bottom surface of the flow channel without the liquid film and then doing the same, off the liquid metal free surface. By recording the two digital images by high speed video and using image processing tools, the vertical movement of the laser light line and hence the location of the liquid metal free surface can be accurately predicted. This has been discussed in much detail in [3].

2. Observations. The liquid metal film flow exhibits some interesting features. The 2 mm thick film emerging from the nozzle tends to have a rapid increase in thickness at a particular downstream location depending on the initial inlet velocity. This sudden increase in the fluid film thickness will be referred to as the jump. The higher the initial velocity, the farther is the location of the jump from the inlet nozzle. This is an important observation because the jump can be flushed out of the channel, as the inlet velocity is increased. For an inlet velocity of 1 m/s, the jump is located 7 cm downstream from the inlet nozzle, for an inlet velocity of 2 m/s the jump location is approximately 15 cm downstream. The principal cause of the jump is the Lorentz body force acting on the fluid, against the flow direction. At low inlet velocities the hydraulic jump is straight along the span but it gets progressively bowed in the span wise direction as the inlet velocity is increased. This is suggestive of the presence of fast jet like structures close to the side walls, where the local fluid velocity is higher than in the central part of the channel. At an inlet velocity around 3 m/s, an increasing cross sectional force is observed manifesting in the tendency of the fluid to being pushed away from the side walls of the conducting channel. The surface normal magnetic field component progressively increases downstream and causes the liquid metal stream to pinch inward, trying to change shape to keep the linked magnetic flux constant. This pinching in effect leads to separation zones or bare spots where the liquid has completely pulled away from the wall. Fig. 1 and Fig. 2 show the behavior of liquid metal flow with and without the applied surface normal field component. The jump is discernable in both the cases with an inlet flow velocity of 1 m/s and 2 m/s. Fig. 3 shows the pinching in effect as discussed above, for the case with an inlet flow velocity of 3 m/s. Despite the pinching in effect, the hydraulic jump is not present in this case. The liquid metal film thickness measurement diagnostic was set to obtain the film thickness at a distance of 16 cm downstream from the

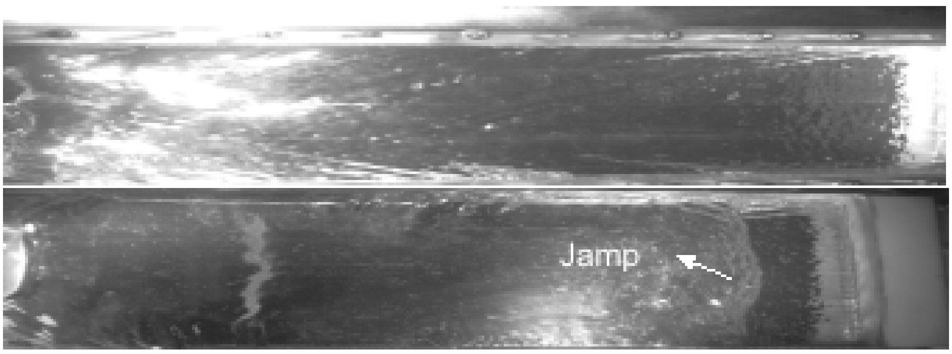

Fig. 1. Bottom shows liquid behavior at 1.0 m/s with the surface normal magnetic field component pointing out of the plane of the paper. Top shows the same inlet velocity but without an applied magnetic field. The hydraulic jump is almost straight in the span wise direction. The flow direction is from the right to the left.

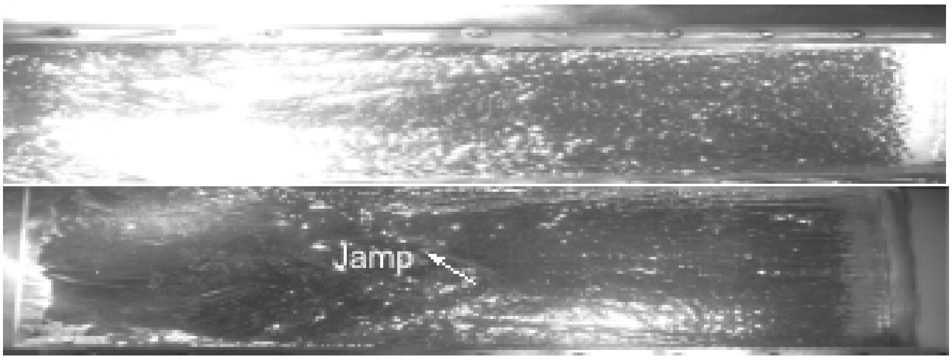

Fig. 2. Bottom shows liquid behavior at 2.0 m/s with the surface normal magnetic field component pointing out of the plane of the paper. Top shows the same inlet velocity but without an applied magnetic field. The hydraulic jump is bowed in the span wise direction and is located further downstream compared to Fig. 1. The flow direction is from the right to the left.

inlet nozzle and was placed symmetrically about the channel center, covering a span wise length of 3 cm. It was observed that the film thickness downstream of the jump, is of the order of 20 mm. For a more detailed description of the film thickness measurement, please refer [3]. These observations are interesting from the PFC design point of view as they leave us with a compromising situation. If the inlet velocity of the liquid metal stream is low, a jump is present which causes about a 10 times increase in the liquid metal film thickness and hence a 10 times reduction in the flow velocity, clearly an unwanted situation. The hydraulic jump can be flushed out by increasing the inlet velocity but as the inlet velocity is increased, other unwanted effects like increasing side wall separation and bare zones begin to show up. The design strategy is to find an optimal set of conditions that minimizes both of these effects.

3. A simple analytical model for the jump. Simple analytical models are being developed to help understand the phenomenon of the jump. The first model assumes a constant surface normal field, applied perpendicular to the bottom wall. This will be extended to include the variation in field strength in the next study. The model assumes the Hartmann velocity profile in the z-direction, which is the direction of the applied field and the direction in which the thickness of the fluid film is measured. The conservation of electric charge is used to obtain

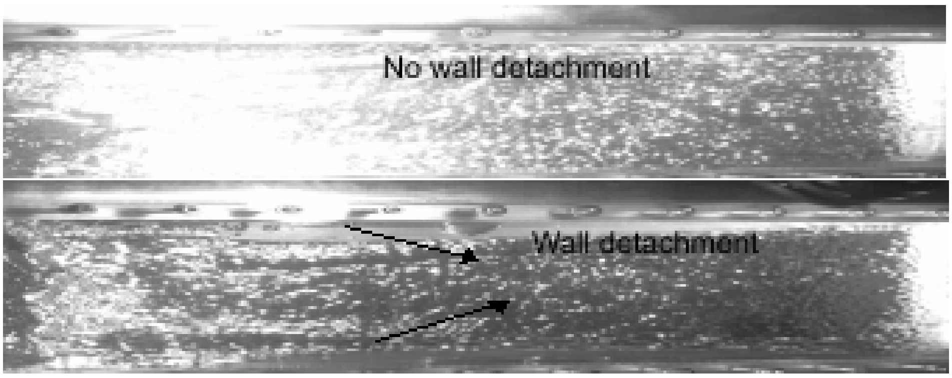

Fig. 3. Bottom shows liquid behavior at 3.0 m/s with the surface normal magnetic field component pointing out of the plane of the paper. Top shows the same inlet velocity but without an applied magnetic field. The hydraulic jump has been flushed out and is not observed. The flow direction is from the right to the left.

an equation for calculating the electric potential in the domain. The presence of conducting side walls leads to a coupling of the cross sectional currents flowing in the y-z planes in the fluid and bottom wall, through the axial currents flowing in the side walls. Axial currents flow in the fluid part as well because of the variation of the film thickness and velocity as the flow progresses downstream. The electric potential is used to calculate the Lorentz force on the fluid. The mass conservation equation and the momentum equation for the fluid is written in the shallow water approximation along with the Lorentz force term. The equations developed can be solved for the unknowns, $U\,(x, y)$, $V\,(x, y)$, $H\,(x, y)$ and $\Phi\,(x, y)$ which are the non-dimensional velocity components, the non-dimensional film thickness and the non- dimensional electric potential. The model equations developed form a system of hyperbolic equations with a strong source term due to the Lorentz force. Efforts are underway to develop procedures for a numerical solution for the model.

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