A STUDY OF LIQUID METAL FILM FLOW, UNDER FUSION RELEVANT MAGNETIC FIELDS

M. Narula, A. Ying and M.A. Abdou

Fusion Engineering Sciences, MAE Department, UCLA, Los Angeles CA 90095-1597. manmeet@fusion.ucla.edu

The use of flowing liquid metal streams or "liquid walls" as a plasma contact surface is a very attractive option and has received considerable attention over the past several years both in the plasma physics and fusion engineering programs. A key issue for the feasibility of flowing liquid metal plasma facing component (PFC) systems, lies in their magnetohydrodynamic (MHD) behavior. The spatially varying magnetic field environment, typical of a fusion device can lead to serious flow disrupting MHD forces that hinder the development of a smooth and controllable flow needed for PFC applications. The present study builds up on the ongoing research effort at UCLA, directed towards providing qualitative and quantitative data on liquid metal free surface flow behavior under fusion relevant magnetic fields, to aid in better understanding of flowing liquid metal PFC systems.

I. INTRODUCTION

Liquid metal free surface flows or "liquid walls" have the potential to be become ideal plasma contact surfaces inside a fusion device. This comes from the ability of some liquid metals, like lithium to pump hydrogen and getter impurities and hence act as an active particle control agent. In addition, liquid metal streams can handle the colossal heat fluxes, pounding on the plasma facing components and alleviate the very serious problem of melting and erosion, inevitably present in all the solid plasma facing components (PFC). However, flowing free surface liquid metal PFC systems have their own unique set of issues, the most prominent of these being the presence of strong flow disrupting magnetohydrodynamic (MHD) forces created due to liquid motion in a complex spatially and temporally varying magnetic field environment. Rapid deceleration of the flow accompanied by the thickening of the fluid film, unwanted flow deflection, creation of bare spots with no fluid protection, creation of regions of thick stagnant fluid leading to hot spots, stream wise and span wise variation of fluid film thickness are some of the MHD effects that need utmost attention and must be addressed to ensure a smooth, controllable and predictable flow of liquid metal streams for PFC applications.

The research effort at UCLA has been actively pursuing the behavior of free surface liquid metal flows under fusion relevant magnetic fields, to help answer some of the above mentioned issues. The Magnetic Torus (MTOR) facility at UCLA can closely simulate the three component '1/R' field, typical of toroidal fusion devices. Apart from this, assortments of strong permanent magnets are used to reproduce the required magnetic fields. The liquid metal used for the study is a eutectic of gallium indium and tin (Ga-67%, In-20.5%, Sn-12.5%) and is preferred over lithium because of safety issues and ease of handling and operation. The liquid metal is harbored inside a flow loop powered by an electromagnetic pump. Various test sections can be attached to the loop to conduct different studies. In the first set of experiments performed, a stainless steel channel with a wall thickness of 0.5mm was used. The channel was 34cm long and 5cm wide. The applied magnetic field was a scaled reproduction of the NSTX[1] divertor magnetic field conditions. The scaling was required to match the non dimensional Hartmann number, as gallium alloy was being used instead of liquid lithium, it being the actual design liquid. Inductive probes were used to measure the thickness of the fluid film over the substrate. Interesting insights were obtained from these experiments. It was observed that the film thickness varies considerably over the length of the channel. As much as six times increase in the film thickness was observed at the downstream measurement location. It was also ascertained by experiments that the wall normal component of the magnetic field had the most profound effect on the local film thickness. For additional details see [1]. The next step to these preliminary findings was to test more realistic divertor geometry in a better reproduction of the scaled NSTX wall normal field component and that is the subject of this paper.

The next section describes the new experimental test channel and the new optical diagnostic system developed to obtain the film thickness. Section III highlights the important observations and results from the experiments. To supplement the experiments and to get a better insight into the phenomenon, a conscious numerical modeling effort has been started. 'HIMAG', a unique code developed by HyPerComp Inc. is being modified to apply it to the problem at hand. HIMAG is a three dimensional, incompressible MHD free surface code. Section IV

1 NSTX: National Spherical Torus Experiment

describes the important features of the code and the preliminary results obtained from numerical simulation. Section V describes the important results and conclusions so far and also the future work planned both with regards to the experiments and numerical modeling.

II. EXPERIMENT SET UP

II.A Test Section

The test section consists of a stainless steel channel with a wall thickness of 0.5mm. The channel is 40cm long and 20cm in width, presenting more realistic divertor geometry compared to the earlier 5cm wide channels. 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 2mm. A 20cm long diffuser section connects the flow loop to the nozzle and helps in uniform spreading of the liquid metal in the span wise direction. A perforated plate before the nozzle also helps to condition the flow before it is introduced into the channel. 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. An assortment of permanent magnets has been arranged underneath the channel in order to closely reproduce the scaled NSTX divertor region wall normal magnetic field component. Figure 1 shows the essential components of the test section.

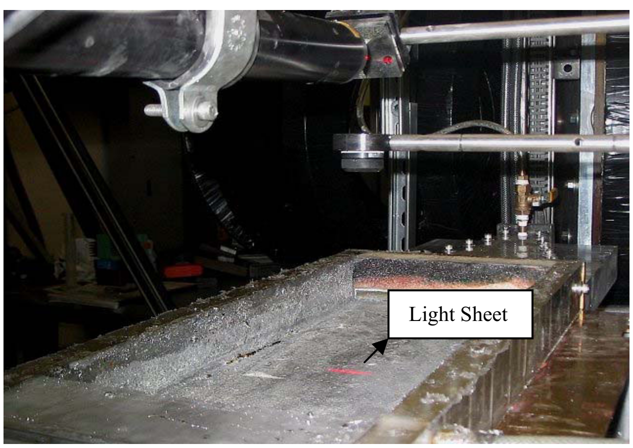

Fig.1. Test section with the laser diagnostic set up

II.B Film Thickness Diagnostic

A new optical technique has been developed to obtain the film thickness. In the earlier experiments, a set of inductive probes had been used but this approach was limited by the dearth of measurement points and was cumbersome and time consuming. The new technique 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. Figure 1 shows the laser light sheet created by the light sheet module, reflecting off the channel bottom. Spanning the laser light sheet through out the test section provides the stream wise and span wise variation of the film thickness. The technique has potential to yield additional information about the flow besides the film thickness, capturing the stream wise and span wise surface waves being one of them. The basic elements of the method have been established and refinements are underway. Figure 2 shows a schematic of the experimental set up with the laser light diagnostic.

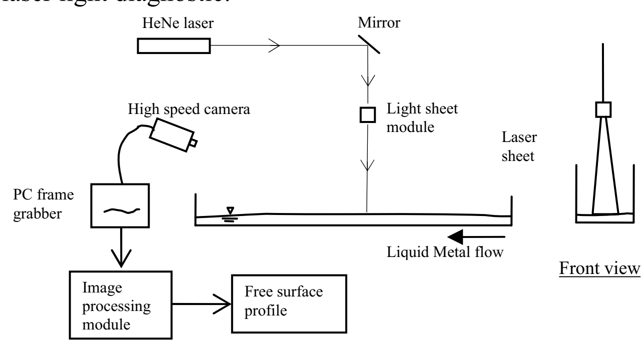

Fig.2. Schematic for the experiment

III RESULTS

III.A Observations

The liquid metal film flowing under the magnetic field set up exhibits some interesting features. The 2mm 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 is known as the hydraulic jump. The higher the initial velocity, the farther is the location of the jump from the inlet nozzle. Also the span wise behavior of the jump changes with the inlet flow velocity. 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. The span wise curvature of the discontinuity shows that the average fluid velocity close to the walls is higher than in the core indicating the presence of side wall jets. This can also be observed from the direction of rotation of the vortices that are shed close to the walls. The hydraulic jump dissipates a large amount of flow inertia and the flow downstream from the jump is slow and clearly unsuitable for divertor application due to overheating concerns. Furthermore at higher inlet velocities (2.5m/s-

3m/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 wall 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. Figure 3 shows this effect for an inlet velocity of 3.0m/s with and without the applied magnetic field. The magnetic field is applied perpendicular to the bottom wall. This pinching in effect leads to separation zones or bare spots where the liquid has completely pulled away from the wall. This effect is observed in the numerical simulation as well and will be discussed ahead. Attempts are being made to diagnose and extract quantitative information from the observed phenomenon. As a first step, the liquid metal film thickness has been obtained at a particular downstream location for different values of the inlet velocity.

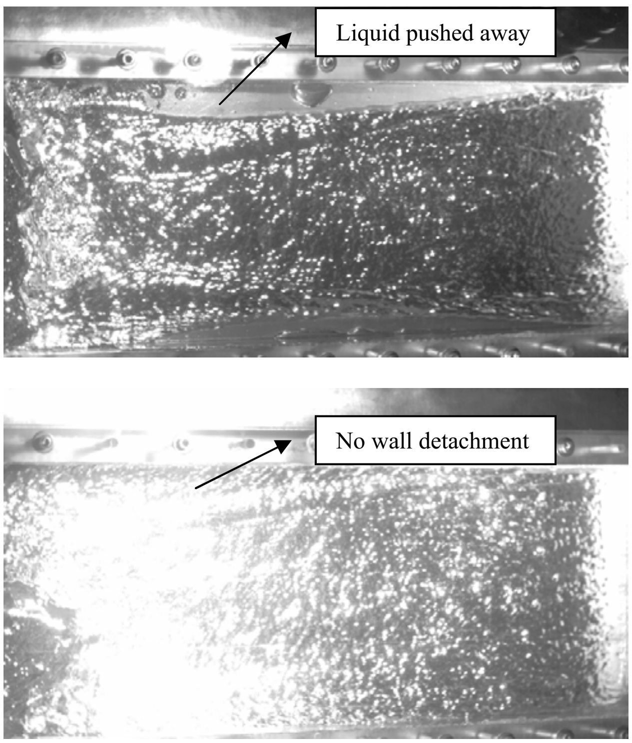

Fig.3. Top shows liquid behavior at 3.0m/s with the magnetic field, the dominant magnetic field component points out of the plane of the paper. Bottom shows the same inlet velocity but without an applied magnetic field.

III.B Results

For quantification of the film thickness, the laser light line was set up at 16cm downstream from the inlet nozzle and made to fall symmetrically about the channel center, covering a span wise length of 3cm. Inlet velocity was set at 1.0m/s, 1.5m/s, 2.0m/s and 2.5m/s. For the first two inlet velocity conditions, the measurement location lies downstream of the hydraulic jump, while for the higher inlet velocities, the measurement location is upstream of the jump. Comparing the film thickness for the different inlet velocity cases, give us an order of magnitude of the difference in the film thickness before and after the hydraulic jump. At higher inlet velocities, (2.5-3.0m/s) a large part of the flow domain lies upstream of the hydraulic jump and we can observe the flow thickening taking place purely on account of the opposing MHD body forces. The typical increase in the film thickness at 16cm downstream for the inlet velocity range 2.0m/s-3.0m/s is of the order of 1mm-2mm. For the velocity range 1.0m/s-2.0m/s, the hydraulic jump occurs close to the inlet nozzle and most of the flow domain lies downstream of the jump, the typical film thickness increase observed for this case is an order of magnitude higher and lies at 18mm-20mm. Figures 4 and 5 show the film height evaluation for the two scenarios with and without the hydraulic jump at the measurement location.

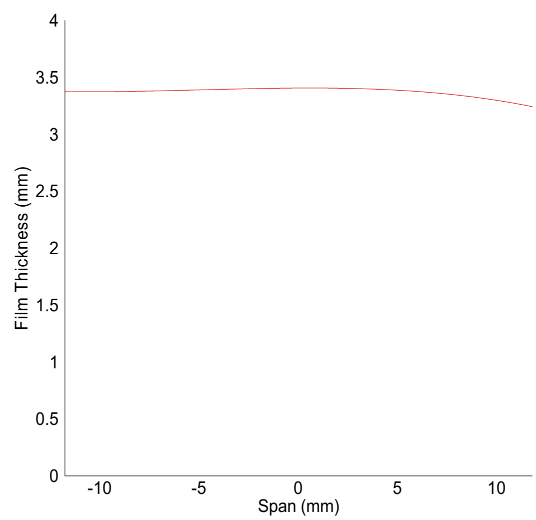

Fig.4. Film thickness at 16cm downstream, at the channel center and inlet velocity of 2.5m/s

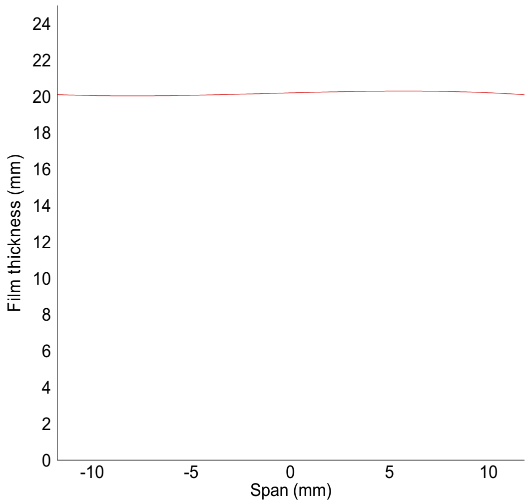

Fig.5. Film thickness at 16cm downstream, at the channel center and inlet velocity of 1.0m/s, the huge difference in film thickness is because of the hydraulic jump.

IV. NUMERICAL MODELING

IV.A HIMAG Features

HIMAG is a computer code originally developed by HyPerComp Inc. to perform a complete 3D numerical simulation of multi-phase flow of electrically conducting liquids in the presence of magnetic fields. It has been vigorously tested and used for closed channel MHD and is now being used to simulate the free surface flows of liquid metals under typical divertor magnetic field conditions and geometries. (see [4]) It is hoped that HIMAG results will help us understand the complex physics underlying these flows and hence aid in the design and control of liquid metal based divertor systems. The phenomenon underlying such flows presents a complex coupled interplay of magnetic body forces, inertial forces, viscous forces and surface tension forces. To make the matter worse, the electrical conductivity of the substrate harboring the flow influences the nature of the MHD body forces, making the conducting solid substrate an integral component in the study of the flow dynamics.

HIMAG uses a finite volume discretization of the governing equations on unstructured meshes, with a parallel architecture. It uses co-located arrangement of the unknowns, with all being located at the computational cell center. The hydrodynamic solver uses a four step projection method with semi implicit Crank Nicholson formulation for the convective and diffusion terms. Geometry weighted central differencing (Kim-Choi interpolation) is used to calculate the face based quantities from the cell centered values. The level set formulation is used to advance the free surface of the liquid. The level set formulation makes it easy to simulate surface effects like surface tension. Since the flow regime of interest is characterized by a low magnetic Reynolds number, HIMAG uses the electric potential formulation to calculate the current density induced due to fluid motion in the magnetic field. The current density calculated, along with the applied magnetic field, in turn gives the MHD body force acting on the fluid. The role of the conducting substrate (channel) is very important in calculation of the induced electric currents within the fluid as it allows paths for the currents to close through. HIMAG includes the conducting substrate in the computational domain. The ability to simulate multi material, multi phase free surface MHD flows on unstructured meshes with parallel architecture, makes HIMAG a truly unique code for the fusion community. The detailed description of the equations used in HIMAG and the resulting formulations are described in [3].

IV.B Numerical Simulation Details

HIMAG was used to simulate the gallium alloy flow, using the geometry and the magnetic field of the experimental set up. The first 20cm of the flow channel in the stream wise direction was simulated. Only the magnetic field component normal to the channel bottom was used for the simulation. The variation of this component in the stream wise and span wise direction was included by fitting a 3rd order polynomial surface to the experimentally measured data from the facility. The physical properties of gallium indium tin alloy were used for the heavier fluid and those of argon for the lighter fluid. The solid channel was gridded with cells having the electric conductivity of stainless steel. The Hartmann layer over the bottom wall was captured by mesh refinement. Mesh refinement was also carried out close to the solid -fluid and fluid -fluid interface. The average inlet velocity used for the simulation was 3.0m/s with an initial liquid film thickness of 2.0mm.

The results obtained from the simulation are encouraging. The simulation predicts that the MHD body force causes the liquid metal film to thicken by an order of 1mm, 18cm downstream into the flow at an initial velocity of 3.0m/s. This matches very well with the experimental value of an increase by 1.5mm at 16 cm downstream and at an initial velocity of 2.5m/s. The simulation of the induced current density within the fluid is enlightening. An important effect captured in the simulation is the tendency of the liquid metal to push away from the side walls. This tendency is observed experimentally as well and is attributed to the distribution of the axial induced currents near the side walls. This is shown in Figure 6.

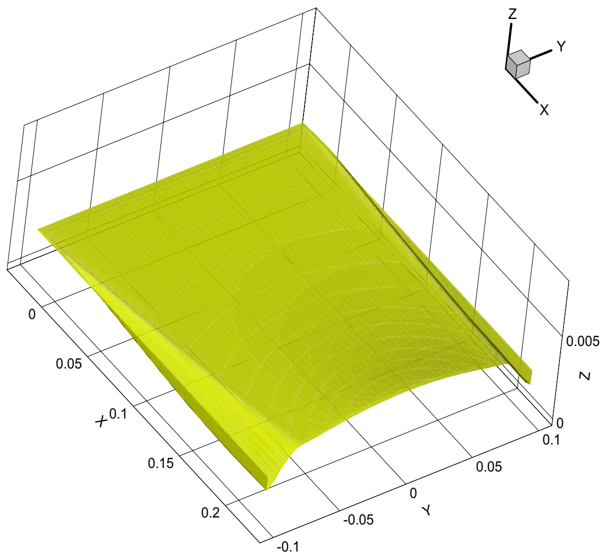

Fig.6. Free surface of liquid metal obtained from the simulation. The liquid is pushed away from the side walls, flow occurs in the 'X' direction. Stream wise flow thickening can also be seen.

Further improvement in the modeling effort will be valuable. The current numerical method cannot capture the hydraulic jump observed at low inlet velocities, which might become an important issue for designing the operational regime that avoids jumps. The current simulation used only a single component magnetic field, perpendicular to the bottom wall; the complete three component magnetic field will warrant a better simulation of the real flow. Improvements in the numerical methods for the hydrodynamic flow solver and addition of more cells in the computational domain for better resolution can help provide more accurate and stable solution. All these issues will be taken into consideration in the near future.

V. CLOSURE

Flowing liquid metal streams may form the ideal plasma contact surfaces for the high power density plasma facing components like the divertor, hence the study of fast flowing liquid metal streams in fusion relevant magnetic fields forms a very interesting and lucrative subject for the fusion community. The bane of the concept is the flow disrupting MHD body force acting on the fluid as it flows through the magnetic field. The flow of liquid gallium in a straight conducting channel with reproduced NSTX divertor region magnetic field conditions was studied. At low inlet velocities (1m/s-1.5m/s) a strong hydraulic jump close to the inlet nozzle causes a slow moving thick liquid film to fill up the channel. Though the bottom substrate is well protected in this scenario, the slow moving film might not be able to withstand the huge heat flux pounding on the surface. At high inlet velocities (2.5m/s-3.0m/s) the hydraulic jump location moves downstream the channel but a strong tendency of the fluid to move away from the side walls is observed. This pinching in of the fluid from the side walls causes bare spots on the channel bottom that beats the purpose of substrate protection. Further experiments with more realistic divertor geometries and configurations and a more representative magnetic field environment are planned to obtain additional insights into the flow behavior.

Future work in numerical simulations is aimed at improving the stability of the numerical technique being used, carrying out a complete channel, complete magnetic field simulation and establishing the effect of the different variables like the channel conductivity, channel width, magnetic field orientation, inclusion of gravity force etc on the flow behavior with a view to identify the design constraints for the development of real liquid metal PFC systems. Since HIMAG features an unstructured grid formulation, it is possible to use the code to simulate flow in complex toroidal geometries like the NSTX divertor and these simulations will be carried out once sufficient confidence and experience has been built with simple geometries.

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