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Exploring liquid metal plasma facing component (PFC) concepts—Liquid metal film flow behavior under fusion relevant magnetic fields

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Abstract

The use of fast moving liquid metal streams or "liquid walls" as a plasma contact surface is a very attractive option and has been looked upon with considerable interest over the past several years, both by the plasma physics and fusion engineering programs. Flowing liquid walls provide an ever replenishing contact surface to the plasma, leading to very effective particle pumping and surface heat flux removal. A key feasibility issue for flowing liquid metal plasma facing component (PFC) systems, pertains to their magnetohydrodynamic (MHD) behavior under the spatially varying magnetic field environment, typical of a fusion device. MHD forces hinder the development of a smooth and controllable liquid metal 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.

Keywords: Liquid metal; Free surface; Plasma facing components; Magnetohydrodynamics; Numerical modeling; NSTX divertor

1. Introduction

Liquid metal free surface flows or "flowing 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. However, flowing free surface liquid metal plasma facing component (PFC) systems have their own unique set of issues, the most prominent of these being the presence of strong flow disrupting magnetohydrodynamic

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forces created due to liquid motion in a complex spatially and temporally varying magnetic field environment.

The research effort at UCLA has been actively pursuing the behavior of free surface liquid metal flows under fusion relevant magnetic fields. There is a particular interest in studying the behavior of liquid lithium streams, flowing at a velocity of 10 m/s inside the divertor region of The National Spherical Torus Experiment (NSTX at Princeton, NJ, USA). The liquid metal used for the experiments at UCLA, is a eutectic of gallium indium and tin (Ga-67%, In-20.5% and Sn-12.5%). 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. As much as six times increase in the film thickness was observed at the downstream measurement location. It was also ascertained that the wall normal component of the magnetic field had the most profound effect on the local liquid metal film thickness. Further details can be found in [1]. Next, a 40 cm long and 20 cm wide stainless steel rectangular channel was used, and is the subject of this paper. An assortment of permanent magnets was used to reproduce a scaled version of the NSTX wall normal field component (in this paper, the term wall normal component will be used for the magnetic field component perpendicular to the bottom wall of the channel). A scaling factor of 2.0 was multiplied to the NSTX magnetic fields to ensure that the dimensionless Hartmann number remains the same while working with the gallium alloy so that the results obtained could be applied to lithium flows inside the NSTX divertor environment. For a description of the NSTX divertor magnetic field environment, please refer Ref. [2].

2. 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. The entire channel is enclosed in a vacuum box and a constant flow of argon is maintained over the channel. The inlet velocity of the liquid metal film at the nozzle is varied over a range from 1 to 3 m/s. A new optical technique has been developed to obtain the liquid metal film thickness. 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. Fig. 1 shows a schematic of the experimental set-up with the laser light diagnostic.

The wall normal magnetic field component reproduced by the permanent magnet assembly, matches the scaled NSTX wall normal component in the first half of the channel. Fig. 2 shows the variation of the reproduced wall normal component with the stream wise coordinate, at the channel center.

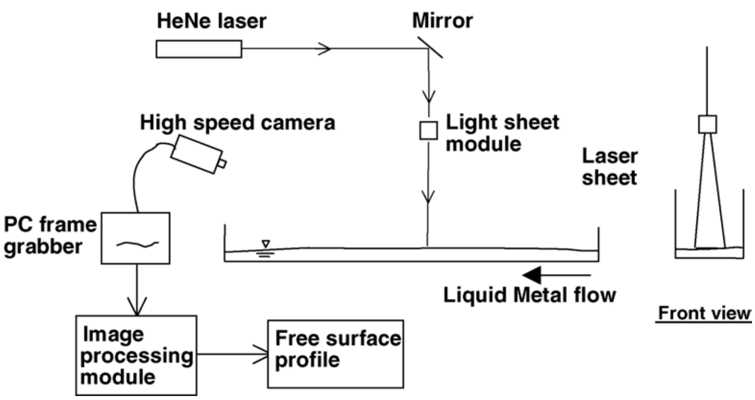

Fig. 1. Schematic for the experiment.

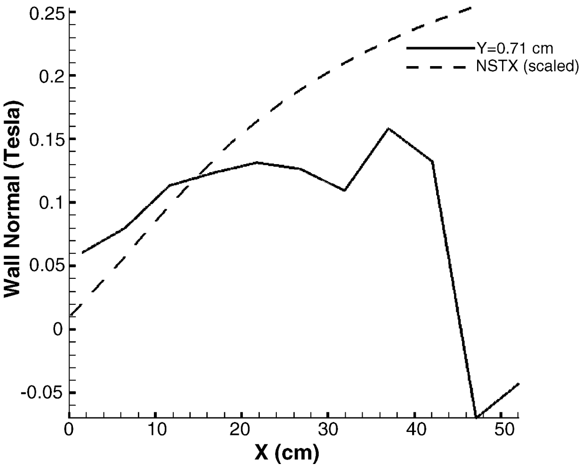

Fig. 2. Wall normal magnetic field component variation in the stream wise direction.

3. Observations and results

The liquid metal film flowing under the magnetic field set-up exhibits some interesting features. The 2 mm thick film emerging from the nozzle tends to have a rapid increase in thickness (a jump) at a particular downstream location depending on the initial inlet velocity. The higher the initial velocity, the farther is the location of the jump from the inlet nozzle. At low inlet velocities the jump is straight along the span but it gets progressively bowed in the span wise direction as the inlet velocity is increased. The jump dissipates a large amount of flow inertia and the flow downstream from the jump is slow and clearly unsuitable for divertor applications. This makes the inlet flow velocity, an important design parameter to ensure a jump free regime. However, at higher inlet velocities (2.5–3 m/s) an increasing cross-sectional force is observed manifesting in the tendency of the fluid to being pushed away from the sidewalls 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. Figs. 3–5 show the behavior of liquid metal flow with and without the applied wall normal field component at different inlet velocity conditions.

The liquid metal film thickness measurement diagnostic was set to obtain the film thickness at a distance of 16 cm downstream from the inlet nozzle and was placed symmetrically about the channel center, covering a span wise length of 3 cm. For the case with an inlet velocity of 1 m/s, this location is downstream of the jump and the observed film thickness is 20 mm. For an inlet velocity of 3 m/s, the film thickness at the measurement location is 3.3 mm. For a more detailed description of the film thickness measurement, please refer Ref. [3].

These observations are interesting from the design point of view as they leave us with a compromising

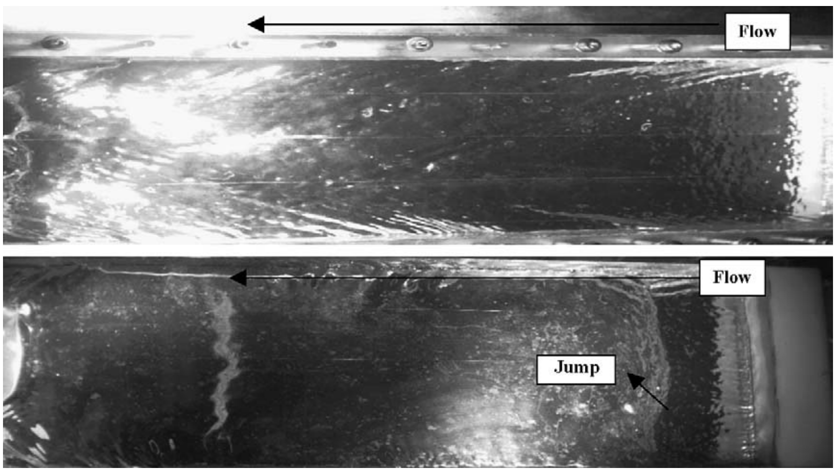

Fig. 3. Bottom figure shows liquid behavior at 1 m/s with the wall normal magnetic field component pointing out of the plane of the paper. Top shows the same inlet velocity but without an applied magnetic field. The jump is almost straight in the span wise direction.

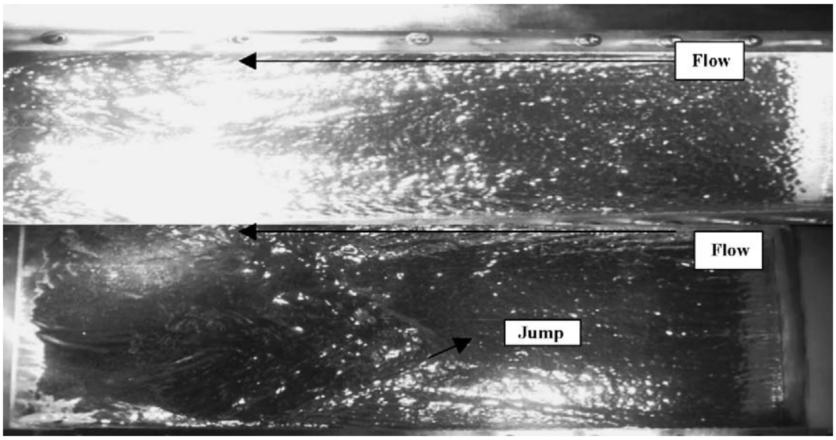

Fig. 4. Bottom figure shows liquid behavior at 2 m/s with the wall normal magnetic field component pointing out of the plane of the paper. Top shows the same inlet velocity but without an applied magnetic field. The jump is bowed in the span wise direction and is located further downstream compared to Fig. 3.

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 for divertor applications. The jump can be flushed out by increasing the inlet velocity but as the inlet velocity is increased, other unwanted effects like increasing sidewall detachment and appearance of bare zones begin to show up. The design strategy is to find an optimal set of conditions that minimizes all of these unwanted effects.

4. Numerical modeling

The design of flowing liquid metal PFC systems is very challenging because of numerous flow disrupting effects occupying the center stage. HIMAG is a unique

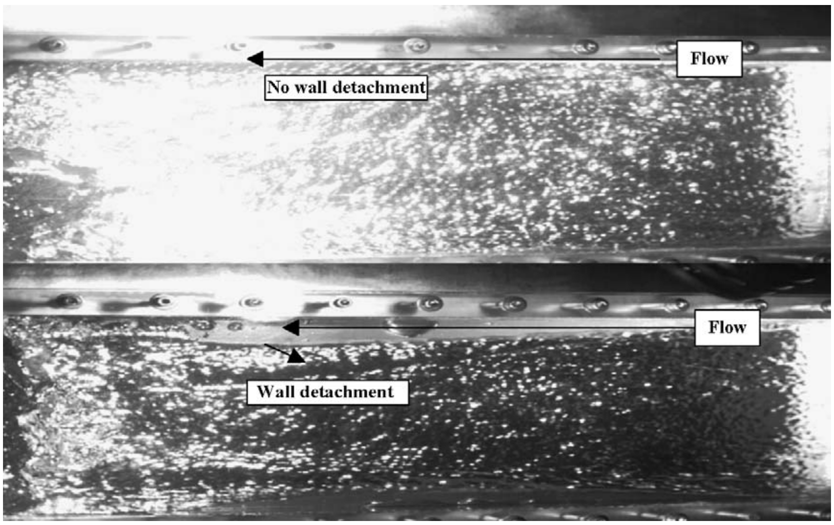

Fig. 5. Bottom figure shows liquid metal behavior at 3 m/s with the wall normal magnetic field component pointing out of the plane of the paper. Top shows the same inlet velocity but without an applied magnetic field. The jump has been flushed out and is not observed. Bare zones are created near the sidewalls.

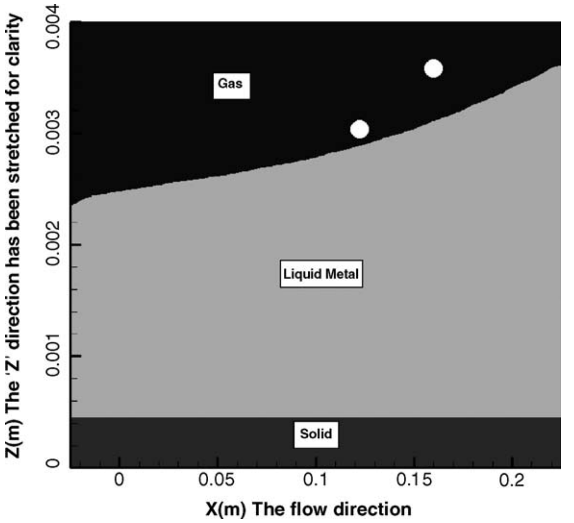

Fig. 6. Comparison with the experiment. Scaled NSTX wall normal field is applied. The gallium alloy inlet velocity is 3 m/s, the inlet film thickness is 2 mm. The section is cut from the channel center, the dots represent the experimental data.

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. HIMAG uses a finite volume discretization of the governing equations on unstructured meshes, with a parallel architecture. The detailed description of the equations used in HIMAG and the resulting formulations are described in Ref. [4].

HIMAG was used to simulate the gallium alloy flow, using the geometry and the magnetic field distribution of the experimental set-up. The case with an inlet flow

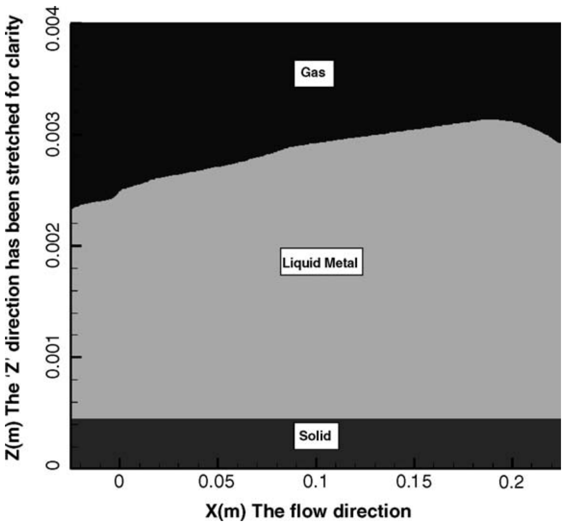

Fig. 7. Stream wise variation of liquid metal film thickness at the channel center. Scaled NSTX toroidal and wall normal field are applied. Inlet fluid velocity is 3 m/s, inlet flow thickness is 2 mm. The fluid is gallium alloy.

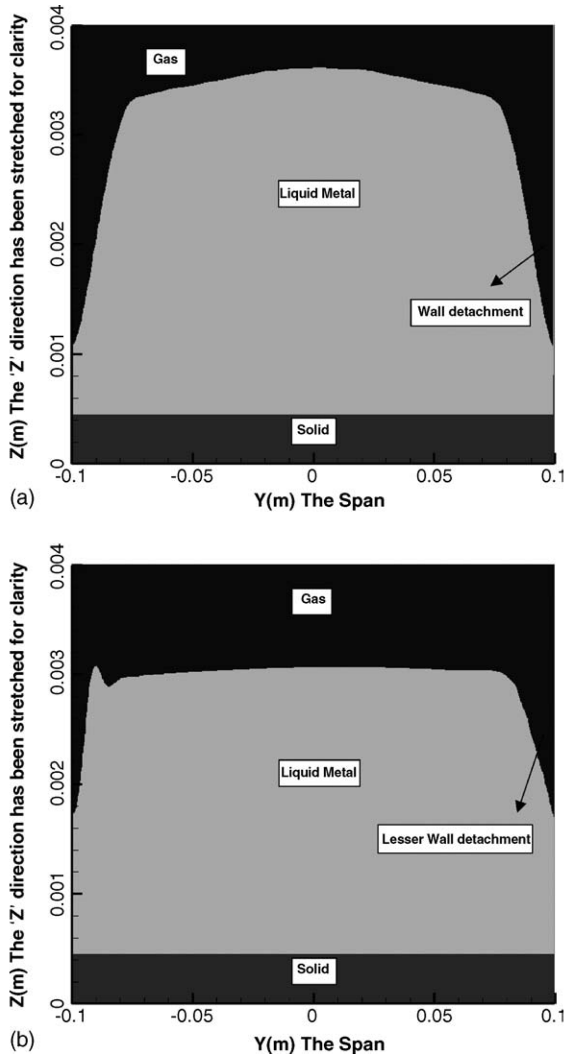

Fig. 8. (a) Span wise variation of liquid metal film thickness at 16 cm downstream the channel length. Scaled NSTX wall normal field is applied alone. Inlet fluid velocity is 3 m/s, inlet flow thickness is 2 mm. The fluid is gallium alloy. (b) Span wise variation of liquid metal film thickness at 16 cm downstream the channel length. Scaled NSTX toroidal and wall normal field are applied. Inlet fluid velocity is 3 m/s, inlet flow thickness is 2 mm. The fluid is gallium alloy.

velocity of 3 m/s was selected for comparing the experimental and numerical results. Only the first 20 cm of the channel flow length was simulated. The solid channel was gridded with cells having the electric conductivity of stainless steel. The simulation predicts that the MHD body forces cause the liquid metal film to thicken by an order of 1 mm at 16 cm downstream into the flow, at an initial velocity of 3 m/s. This matches well with the experimental value of an increase by 1.3 mm at the same location. Fig. 6 highlights this comparison in more detail. Encouraged by a successful match of the numerical results with the experiment, HIMAG was used to simulate some other interesting cases.

In one of the cases, in addition to the scaled NSTX wall normal component, the scaled toroidal component was added so see the effect of the combined field on the flow of liquid gallium alloy in the same geometry as before. The inlet flow velocity was fixed at 3 m/s and the inlet liquid metal film thickness at 2 mm. The stream wise variation of the height of the liquid metal for this case is shown in Fig. 7.

As can be observed from Fig. 7, the addition of the toroidal field component does not significantly change the stream wise film thickness variation along the centerline of the channel. Fig. 8 shows a comparison of the film thickness distribution in a span wise cross-section, cut at 16 cm downstream from the inlet nozzle. Addition of the toroidal component along with the wall normal component leads to creation of axial currents that cancel in one part of the channel span and reinforce in the other, hence leading to an asymmetric film thickness distribution in the span wise direction.

The HIMAG simulations lead to some important insights into the behavior of liquid metal streams in the typical magnetic field environment of the divertor region of NSTX. It is observed that the wall normal component of the magnetic field plays the most important role in determining the local film thickness. The liquid metal has a tendency to get detached from the sidewalls as it progresses downstream. Future work in numerical simulations is aimed at improving the stability of the numerical technique being used, carrying out a full channel flow length simulation and establishing the effect of the different variables like the channel conductivity, channel width, magnetic field orientation, 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 expertise has been established with simple geometries.

Acknowledgement

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