ABSTRACT

Fairly recently, a new experimental free surface liquid metal MHD facility, the so-called MTOR facility, has come on-line, and new data has been taken concerning flows of gallium alloy across a moderately strong toroidal field with characteristic $1/R$ field gradient. The purpose of these experiments has been two-fold: to gather data for benchmarking currently existing one and two dimensional free surface computational flow models (as well as 3D models currently under development), and to investigate phenomena not predicted by models, especially effects of nozzles, drains, waves and turbulence. Data is presented concerning MHD effects on the mean flow height and wave structure, both with and without the so-called Zakharov magnetic propulsion current added to help control and stabilize the flow. The test section is wide enough so that the characteristic factor (Hartmann Number $\times$ Aspect Ratio) is less than unity. In this case the Hartmann layer drag effects are small, allowing comparison of experimental data to two-dimensional axisymmetric models. Preliminary conclusions suggest that the field gradient in these experiments does not adversely affect the stability of the surface, and that magnetic propulsion current is effective in flattening and accelerating the liquid metal flow.

1. INTRODUCTION

The APEX and ALPS studies, underway in the U.S. fusion program over the past several years, have considered the use of flowing liquid metals (LM) as plasma facing surface [1]. Many of the concepts for first wall and divertors propose some sort of thin layer flow in the poloidal direction. Magnetohydrodynamic effects stemming from flow across magnetic field and field gradients, and externally applied magnetic propulsion [2] currents, have been identified as key issues for these plasma facing liquid flow concepts.

Development of a test facility enabling study of free surface liquid metal flows in characteristic tokamak magnetic fields was called for in the APEX Interim Report [3] as necessary for furthering the liquid wall idea. Such a facility has been constructed and continuously modified over the past two years, but the detailed capabilities of this facility have not yet been published. This situation is rectified in Section 2 of this paper, followed in Section 3 and 4 by a presentation of the design of, and initial data from, a series of experiments studying the effect of the $1/R$ toroidal field gradient on the dynamics of a thin film of liquid metal flowing down an inclined plane. A summary of conclusions and description of on-going work is provided in Section 5.

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<th>Toroidal Configuration</th>
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<td>Maximum Dev. Pressure</td>
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* MTOR wired in 2 parallel strings of 12 coils in series
* Max. flowrate and pressure not achieved simultaneously
The co ils are driven by a Rapid Technologies DC power supply loaned to UCLA by PPPL. The power supply matches well the ~600 kW 480V service in the UCLA laboratory, but can only deliver half the rated current each coil is designed to handle. This means that peak magnetic field on the toroidal inboard is 0.6 T, falling off inversely with the major radius (1/R) to ~0.2 T on the outboard. In order to boost the field for experiments that do not need large magnetic volume, ferromagnetic flux concentrators have been installed inside the MTOR at certain toroidal locations that give amplified magnetic fields with controlled field direction and gradients. Field strengths in excess of 1.3 T have been demonstrated for some experiments [4].

The flowloop utilizes a Ga-In-Sn alloy that is liquid at room temperature and is relatively benign in terms of toxicity and chemical reactivity, unlike many liquid metal alloys, and is compatible with a wide variety of metals, plastics, rubbers and glasses at low temperatures. While
the main flowloop components are stainless steel and
copper to allow for the possibility of higher temperature
operation of the loop, test sections have been made from
acrylic and lexan. The metal slowly oxidizes in air
creating Ga2O3 contaminants, so it is normally handled
under argon cover case. However the loop is routinely
opened for modifications and repairs. The alloy can be
periodically cleaned with solutions of alcohol and
hydrochloric acid [5] to remove the oxide buildup.

The high electrical conductivity of the alloy makes it
good for MHD experiments, but its high density compared
to alkali metals results in lower MHD parameters than can
be achieved with NaK, Na, Li, for example. However, Ga
and its alloys are good when compared to Hg, Pb-Bi alloys,
which are common alternatives. The drawback to Ga is the
price - it is this cost that has limited us to our current 15
liter volume.

The LM is pumped using an annular geometry
electromagnetic (EM) induction pump. The flowrate is
continuously adjustable using a 3-phase variable
transformer and is measured with a custom EM flowmeter.

3. INCLINED PLANE TEST SECTION

The film flow test section shown in figure 2 is 20 cm
wide by 60 cm long and constructed from transparent
acrylic. The width w of this test section is large in order to
minimize the flow aspect ratio, defined as \( \beta = h/w \), where
\( h \) refers to the height of the liquid layer. Previous
modeling [6] has indicated that drag from the Hartmann
layers that form on channel walls will not alter the velocity
profile in the channel center if the parameter \( \text{Ha} \beta < 1 \),
where \( \text{Ha} = Bh \sqrt{\sigma/\rho \nu} \) refers to the Hartmann number
based on the film height. For flows where \( h \) is a few
millimeters then the \( \text{Ha} \beta < 0.5 \) for our alloy and geometry,
even at the strongest magnetic field. By meeting this
criteria, we attempt to insure that the flow behaves largely
two-dimensionally, i.e. infinitely wide flow in order to
compare directly with model equations that also make this
assumption of two-dimensionality [7].

The depth and wave behavior of the gallium alloy flow
is measured quantitatively by high resolution ultrasonic
depth probes mounted at various locations along the flow
direction. The ultrasonic system has been used successfully
with water flow experiments to determine the instantaneous height of the liquid layer by measuring the
time-of-flight of a high frequency (10MHz) compression
wave through the liquid layer and dividing by the known
speed of sound (see [8, 9] for system details). Preliminary
tests indicated that this technique could be successfully
applied to LM flows as well [9].

The acrylic channel is not electrically conducting, but
a metallic coating is used on some tests to provide good
wetting of the liquid to the flow plane. This coating is
\~100 nm of Inconnel and can be made to wet the gallium
alloy after cleaning with a chemical flux. Some tests
utilize an acrylic nozzle fixed at a 2 mm outlet height,
while other tests use no nozzle, and the liquid turns by
gravity from the near vertical supply channel, to run down
the flow plane.

The angle of the channel inclination to the horizon is
measured with a digital protractor with 0.01° resolution.
The 1 inch thick acrylic flow plane has some slight
warpage, though it was machined flat, so that angle is
steeper by about 0.25° at the inlet compared to the outlet.
This is important to note for the shallow angle experiments
reported here, where our desire was to minimize
gravitational acceleration compared to drag /acceleration
forces coming from the magnetic field gradient / magnetic
propulsion currents.
4. EXPERIMENTAL RESULTS

Complete channel filling was a problem for the non-wetted channel, especially at larger inclination angle. As gravity accelerates the liquid, it tends to form rivulets, leaving a large portion of the back wall uncovered. This tendency was not observed when the channel flow plane with the Inconnel coating was pre-wetted to the gallium alloy.

The series of experiments reported here were all at very shallow angle and very low flowrate in order to maximize the relative effect of the magnetic field gradient drag. Initial conditions with Froude Number $Fr = U^2/gh$ both greater than (supercritical) and less than (subcritical) unity were explored, but in all initially supercritical cases up to flowrate $Q = 0.15 \text{ l/s}$, the flow experience a hydraulic jump condition near the nozzle exit and became subcritical for the remainder of the flow.

The presence of the magnetic field did not alter this situation, even though the data indicates that the flow is at least partially laminarized by the magnetic field. Figure 3 shows the average (over ~60 samples taken in a 5 sec interval) flow height as a function of probe number (streamwise location) with and without the magnetic field. In this example case the presence of the field is seen to reduce the film height. This tendency is also seen in a separate set of data shown in figure 4 A and B, where the temporal height data stream from one single probe is plotted. The reason for this tendency is most likely due to the suppression of turbulence (and frictional drag) and the reduction in the strength of the hydraulic jump.

A decrease in small wavelength surface waves is also apparent when the magnetic field is on. Since the channel is so elongated in the field direction, this surface wave reduction is likely due to both a reduction of turbulence as the source for such waves, as well as direct dissipation of the wave energy from joule heating. The relative influence of these two factors has yet to be determined conclusively.

Both the data sets shown in Figures 3 and 4 also show the effectiveness of the externally applied streamwise magnetic propulsion current in accelerating the liquid in an average sense. The film height is significantly reduced, the reduction increasing with increasing applied current, and the liquid velocity correspondingly increased. However, the temporal data shows a fairly distinct instability wave with period about 1 sec, resulting in a large increase in the standard deviation (which we have been using as a measure of surface waviness) of the height data as compared to flow with no field at all. It is as yet unknown if this instability is a result of some unique experimental condition in our apparatus, or a general property of the magnetic propulsion scheme. Over the length of this relatively short channel, the wave does not grow larger than 1 mm peak-to-peak.

![Graph showing average flow height data for test section without nozzle and Q = 0.1 l/s and $\theta = -0.3^\circ$ at inlet. Error bars show standard deviation.](image)

The magnetic propulsion current was also effective in forcing uniform channel filling, even in the case where the flow plane is not wetted to the gallium alloy. The rivulets are pushed against the back wall and spread out, and no portion of the backwall is left uncovered.

5. CONCLUSIONS AND FUTURE WORK

Both turbulence suppression and wave reduction was observed in these experiments in a toroidal field gradient. This is not an unexpected result. However, the degree of suppression was not enough to inhibit the formation of a hydraulic jump near the nozzle exit. The magnetic propulsion current was sufficient to both accelerate the flow as well as ensure complete channel filling, even in cases where the flows natural tendency was to form rivulets.

The ultrasound technique proved effective with gallium alloy flows described above, and good data with a high degree of resolution temporal an spatial was obtainable. But the signal behavior was erratic, sometimes disappearing and reappearing with no good explanation. Care was required to keep the flow surface clean of oxides that tend to build up during operation [5], and keep the probes seated well against the acrylic back wall. More work is needed to improve the technique data acquisition and processing procedures for our future LM experiments.

A detailed comparison of the quantitative data acquired form this experiment to the 2D and 3D numerical models still needs to be performed, but conditions like hydraulic jumps are not well modeled by most codes. Higher velocity and steeper inclinations will have to be explored experimentally to gather data for purely
supercritical flows, even if this means less magnetic field interaction.

A new film flow experiment in the MTOR facility, in a higher field flux concentrator, is also underway to explore higher velocity regimes. These experiments can look at stronger field and field gradient effects, but have narrow channels ~5-7 cm as compared to the 20 cm channel described above. The result will be flows where Hartmann wall effects are also strong, and will not necessarily be easy to decouple in data analysis. While this data will still be useful for benchmarking 3D modeling tools, 2D infinite film models cannot use this data directly.

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REFERENCES


