WIDE FREE-SURFACE FLOWS OF GALLIUM IN A VARIABLE MAGNETIC FIELD: PRELIMINARY INVESTIGATIONS

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Introduction. Magnetohydrodynamic (MHD) channel flow is a field that has seen considerable activity over the past century. The state of the field is represented in the comprehensive review by Müller & Bühler [1]. Modern applications include wide free-surface flows of liquid metal (such as lithium), which are considered as possible boundaries for magnetic-confinement fusion devices, e.g., [2, 3]. Such flows may act as an efficient heat sink, via convective mixing, providing a wall surface that is renewable (instead of facing cumulative erosion) in the intense environment associated with thermonuclear fusion.

Fusion-relevant MHD flows of liquid metal typically possess two boundary characteristics that so far have received relatively little *experimental* attention: low aspect ratio (i.e., wide or shallow flows where channel width significantly exceeds flow depth), and a free surface. Here we briefly describe new experiments, both realized and forthcoming, designed to investigate these particular properties and provide a better experimental basis for these types of flows. These preliminary investigations also serve as a partial basis for a larger experimental program, here briefly described, that will ultimately serve as a full-scale model of a flow configuration proposed for fusion application.

1. MHD surface waves. We have recently finished an initial study of small amplitude surface waves in a pool of (non-flowing) liquid gallium [4]. Fig. 1 shows the experimental setup. It features a large square tank, with side length 37.8

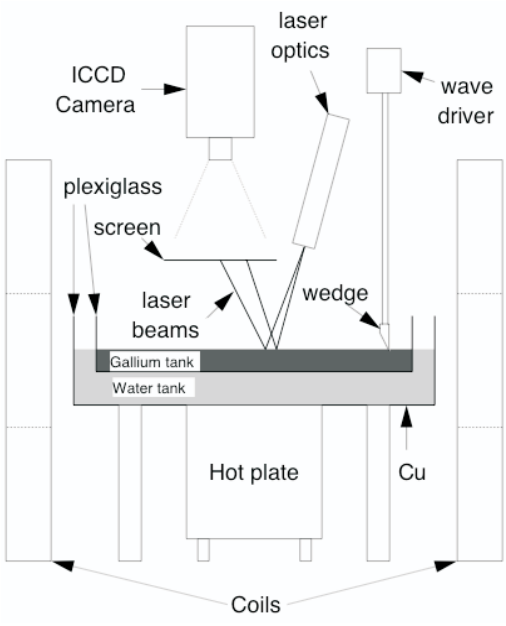


Fig. 1. Apparatus for surface wave experiments.

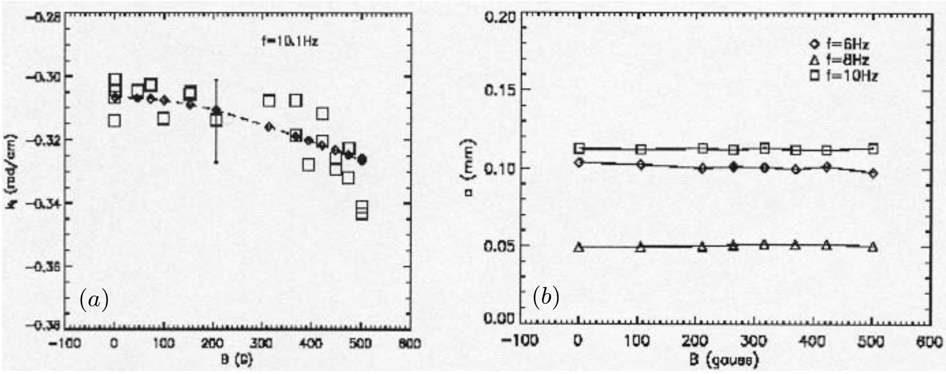


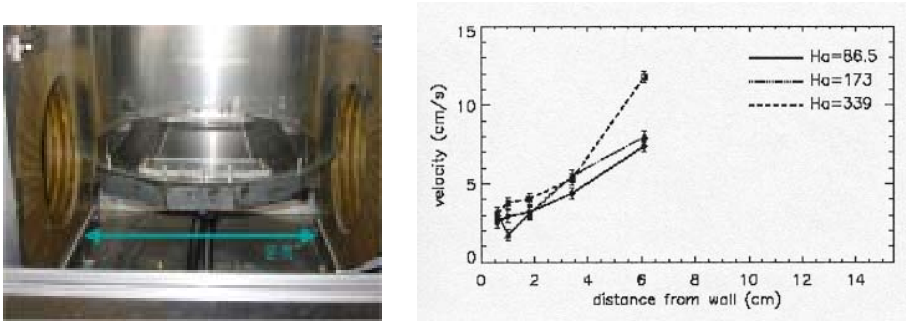
Fig. 2. (a) Wave damping due to parallel B, as reflected in a decreasing imaginary wavevector k_i; the dashed line is the linear prediction. (b) No damping is seen due to a transverse B for wave amplitudes at various frequencies.

cm, submerged in a water tank that is heated from below. A wedge shaped wave driver, controlled by a PC, drives surface waves at a given frequency and amplitude. Wave characteristics are measured as they propagate by laser reflections from the surface.

By using an approximation in the small magnetic Reynolds number ($\mathrm{Rm} \equiv UL/\eta \ll 1$) and deep-water ($kh \gg 1$) limits, a dispersion relation for small-amplitude MHD surface waves has been derived, $\rho\omega^2 = \left(\rho g + j_{0y}B_{0x} + k_r^2 T\right) k_r$. Here the waves propagate in the x-direction; T is the surface tension, $\mathbf{B}$ is the magnetic field, and other variables have their usual wave-based meanings. The imaginary component of the wavevector is given by $k_i = -(B_{0x}^2 \omega k_r)/2\eta(\rho\omega^2 + 2Tk_r^3)$, predicting that magnetic fields parallel to the wave propagation can damp the waves. Conversely, there are no (linear) effects from a transverse magnetic field (B_{0y}). These results can be understood physically in considering the energetics of bending field lines. The measured wave dispersions $\omega(k)$ are consistent with our theoretical predictions (see [4]), except for an apparent surface tension reduction from the published value, which is presumably due to the surface oxidation. Fig. 2 confirms the prediction regarding damping, which is significant when propagation is parallel to $\mathbf{B}$, and negligible when transverse to $\mathbf{B}$.

This result has implications for the liquid metal wall concept in fusion reactors. For instance, in order to completely cover the plasma in a fusion reactor, downward facing parts of the liquid metal layer need to be supported against gravity. One proposed method to provide this support is to use the Lorentz force by introducing an electric current into the liquid metal [5]. The expression for k_i, however, suggests that the supported liquid metal layer is still equally unstable to the Rayleigh–Taylor instability when a perturbing wave vector is perpendicular to the magnetic field (for sufficiently long wavelengths).

2. Wide channel flow. We have obtained preliminary internal flow profiles in an open channel that is pictured in Fig. 3a. The channel is 15.4 cm wide, 1.2 cm deep, and 35.6 cm long. The flow is of an eutectic of Gallium (67% Ga, 20.5% In, 12.5% Sn) that is liquid at room temperatures. Characteristic flow speeds are ~ 15 cm/s. The magnetic field is transverse and coplanar to the flow, and variable up to 1.2 kG. With these values we obtain fluid Reynolds numbers $\mathrm{Re} \equiv UL/\nu$ of $\sim$ 5e4 and Hartmann numbers $\mathrm{Ha} \equiv B_0 a/\sqrt{\eta\nu}$ of ~ 360. Internal velocity profiles were measured by two independent diagnostics: by measuring the drag force on a submerged paddle, which is proportional to the square of flow ve-



(*a*) (*b*)

Fig. 3. (*a*) Initial apparatus for wide Hartmann flow investigation. (*b*) Initial result indicating a more peaked profile with higher **B**. The channel center is at 7.7 cm.

locity, and by measuring the electric potential difference between two electrodes, i.e., by the induced Hall effect. The obtained results are qualitatively consistent with each other, and also with the (integrated) reading of a flow meter. Measured profiles by potential difference are shown in Fig. 3*b* for three Ha numbers. The data represent the average and standard deviations of 9 individual measurements. It is seen that the profiles becomes more peaked with increasing **B**. This is perhaps against one's usual intuition of the Hartmann flow, which would typically flatten the velocity profile with increasing **B**. It turns out that this result can be understood as an aspect ratio effect.

To illustrate this effect, Fig. 4 shows the calculated flow profile using a 2D incompressible MHD code for different combinations of **B** and aspect ratio. It is seen that when $h/a \geq 1$ (i.e., for square and narrow or deep channels), the peaked profile flattens with increasing **B**. However, when $h/a \ll 1$ (i.e., wide or shallow channels), the originally flattened profile (at $\mathbf{B} = 0$) at first becomes more peaked with increasing **B**. In this case the electric current paths generated by the flow are localized near each side of the channel, leaving an essentially current-free region in the center. As **B** increases further, these current paths (and attendant Lorentz forcings) eventually grow to fully penetrate the central flow region, so that the profile ultimately flattens. Thus the flattening behavior typical of 2D Hartmann flow and narrow (deep) channels is displayed also in wide channels, but only above a minimum **B** that is dependent upon the aspect ratio.

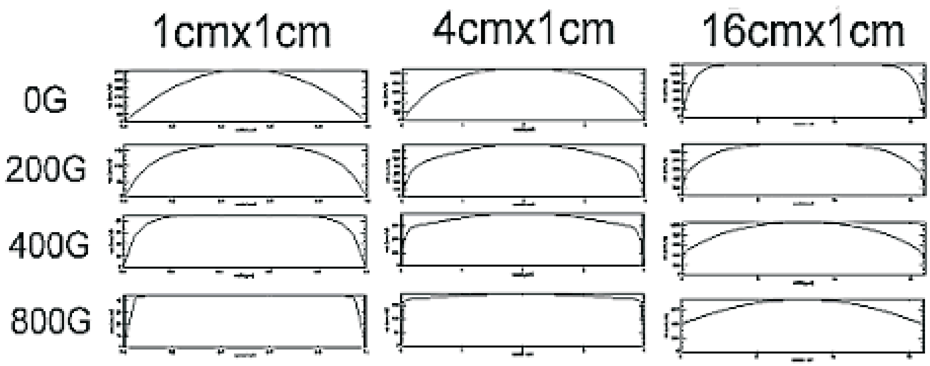


Fig. 4. Effect of channel aspect ratio and magnetic field strength upon the velocity flow profile. The width of each rectangle represents the full channel breadth. The ordinate is normalized velocity.

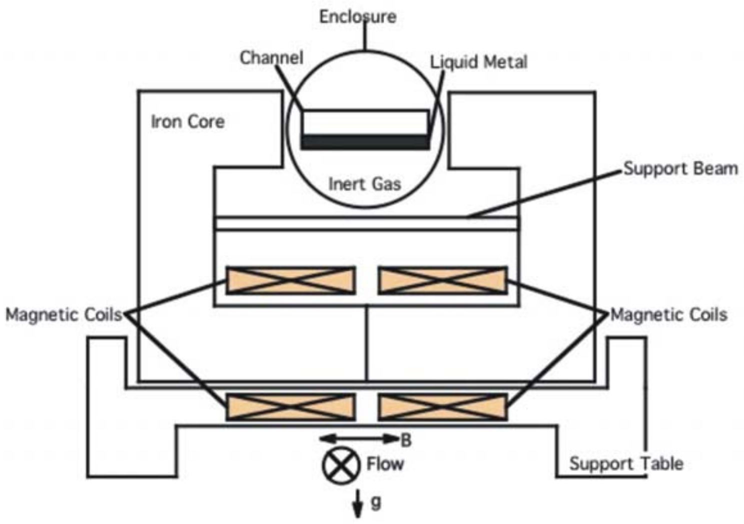


Fig. 5. Front view of the newly constructed apparatus.

3. New apparatus and future plans. The results outlined above form an experimental basis for a larger, more refined experiment that will investigate wide free-surface MHD flows of liquid Gallium. A schematic of the new experiment, about 70 cm long and possessing a cross-section of 10 cm$\times$1 cm, is shown in Fig 5. The apparatus will feature a higher flow rate in a stronger magnetic field, such that Ha $\sim$ 2000 and Re $\sim$ 4e5. These dynamical parameters are motivated by the proposed diverter module for the National Spherical Torus Experiment (NSTX, USA), and should allow for a MHD channel flow that is likely turbulent and amenable to various flow and transport studies. Studies of shear flow and surface instabilities, leading to mixing, will take advantage of the knowledge we have gained about wide channel flows and surface wave dynamics. Studies involving heat transport are also planned. Overall, the results of this experiment should help fill an important knowledge gap that should prove useful in the understanding of free-surface MHD channel flows, as well as in the design and control these flows in fusion applications.

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