INSTABILITY OF ELECTROLYTIC FLOW DRIVEN BY AN AZIMUTHAL LORENTZ FORCE IN A CYLINDRICAL CONTAINER

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Abstract: We study experimentally and theoretically the free surface flow produced by an azimuthal Lorentz force in a layer of either a liquid metal or an electrolyte contained in an open electromagnetic stirrer with cylindrical geometry. The force is created by the interaction of an electric current applied in radial direction and an approximately constant magnetic field (0.04 T) parallel to the cylinder's axis. For the liquid metal flow, we found a pure azimuthal motion at the free surface with applied currents from 1 to 2 A. However, for the electrolytic flow we observed the appearance of an instability that leads to the formation of anticyclonic vortices in the horizontal plane normal to the magnetic field with applied currents in the range 25-400 mA. We found 4 to 11 traveling vortices that form a polygon and remain for long times once they appear.

1. Introduction

Magnetohydrodynamic flows in annular ducts have been widely explored both experimentally and theoretically. From the experimental point of view, annular ducts avoid the difficulty of considering the entrance region that is present in rectilinear ducts under a strong uniform magnetic field. In the most common configuration, the annular duct is formed in the gap between two coaxial electrically conducting cylinders, limited by insulating top and bottom walls. By placing the duct in the center of a magnetic solenoid, we get an approximately uniform magnetic field parallel to the cylinder's axis. If an electric potential difference is applied between the lateral walls of the cylinders, a radial electric current density will arise in the conducting fluid. The interaction of the radial current with the axial magnetic field produces an azimuthal Lorentz force that drives the flow. Since the pioneering work of Baylis [1] and Baylis and Hunt [2], attention has been mainly focused on liquid metal flows at high Hartmann numbers, motivated by important applications related with metallurgical and fusion blanket technologies. Moresco and Alboussière [3] used the annular duct configuration to investigate experimentally the stability properties of the Hartmann layer and the transition to turbulence in a liquid metal flow. More recently, disregarding the Hartmann walls with the aim at understanding better the role of the sidewall layers, Zhao et al. [4] explored numerically the centrifugal instability between coaxial infinite conducting cylinders at large Hartmann numbers. They found a system of several axially elongated counter-rotating vortices arranged in the radial direction. In a subsequent numerical study, Zhao and Zikanov [5] considered the existence of insulating top and bottom Hartmann walls in an annular (toroidal) duct of square cross-section with the same geometry and parameter range used in the experiment by Moresco and Alboussière. The purpose was to analyze the flow features at Reynolds numbers below the threshold of transition to turbulence in Hartmann layers. Among many interesting things, they found that the first instability leads to an axisymmetric unsteady flow characterized by quasi-periodic transformations of meridional circulation vortices.

In contrast with the substantial number of studies of MHD flows in annular ducts using liquid metals, it appears that just a few works have been published for the case of electrolytes. Unlike liquid metal MHD flows, the Hartmann number in electrolytic flows is usually very small. Digilov [6] analyzed the flow of an electrolyte driven by an azimuthal Lorentz force in an annular channel. The author obtained an analytic solution for the case of infinite cylinders although he assumed that the electric field established between the cylinders (electrodes) is decoupled from the fluid flow, which in general is not the case. He performed very simple demonstrative experiments finding a pure azimuthal stable flow that showed reasonable agreement with the theory. Digilov, however, called the attention about the existence of flow regions where, according to the theory of Marcus [7], anticyclonic vortices could appear. In a recent paper, Qin and Bau [8] performed a theoretical analysis of the electromagnetically driven flow of a binary electrolyte in a concentric annulus under a uniform, axial magnetic field. They studied the linear stability of the azimuthal flow when the cylinders are infinitely long and found that when the current is directed outwardly, electrochemical effects destabilize the flow, originating convective flows in the transverse plane. In turn, when the current is directed inwardly, electrochemical reactions have a stabilizing effect and the azimuthal flow is linearly stable for all Dean numbers. When the annular duct is finite, pure azimuthal flows are not possible and the flow is always three-dimensional independently of the direction of the current. To the best of our knowledge, this is the only stability analysis performed in electrolytic MHD flows in annular channels.

In the present study, we investigate experimentally the free surface flow driven by an azimuthal Lorentz force in a layer of either a liquid metal or an electrolyte contained in two different open cylindrical configurations. When the fluid is an electrolyte, experiments have shown the appearance of a flow instability consisting of a varying number of anticyclonic traveling vortices for given flow conditions, that is, electric potential difference between the electrodes and height of the fluid layer. In spite of the rather simple experimental configurations, the studied flow offers a rich dynamic behavior.

2. Experimental setup

The experimental setup consists of a cylindrical open cavity of 76 mm diameter and 12 mm depth with one electrode made of a thin sheet of copper wrapped around the inner wall of the cavity. A second electrode is introduced in two different configurations (see Fig. 1). In the first one, an inner concentric copper cylinder of 25.4 mm diameter is inserted so that the fluid is contained in the gap between the cylinders. In the second configuration a circular coin-shaped copper electrode (of the same diameter as the inner cylinder of configuration I) is placed concentrically and embedded in the bottom of the container so that the fluid occupies the whole extension of the cylindrical container. In both configurations the container is filled with either a liquid metal layer of 5 mm thick (eutectic alloy GaInSn) or a weak electrolytic solution of sodium bicarbonate (NaHCO3) at 8.6% by weight that forms a layer whose thickness was varied from 2.5 to 10 mm. The container is placed on top of a rectangular permanent magnet (150 mm X 100 mm X 25.4 mm) so that an approximately uniform magnetic field in the axial direction exists within the layer thickness. The magnetic field strength on the bottom of the container is 0.04 T. When an electric potential difference is set between the electrodes, a DC radial electric current passes (either outwardly or inwardly, depending on the polarity of the electrodes) through the conducting fluid whose intensity varied from 1 to 2 A for liquid metal and form 25 to 400 mA for the electrolyte. The interaction of the radial current and the axial magnetic field produces a Lorentz force that generates fluid motion mainly in the azimuthal direction. Note that electric current in configuration II is not strictly radial in the electrode region but presents an axial component that decreases the strength of the driving Lorentz force in that region.

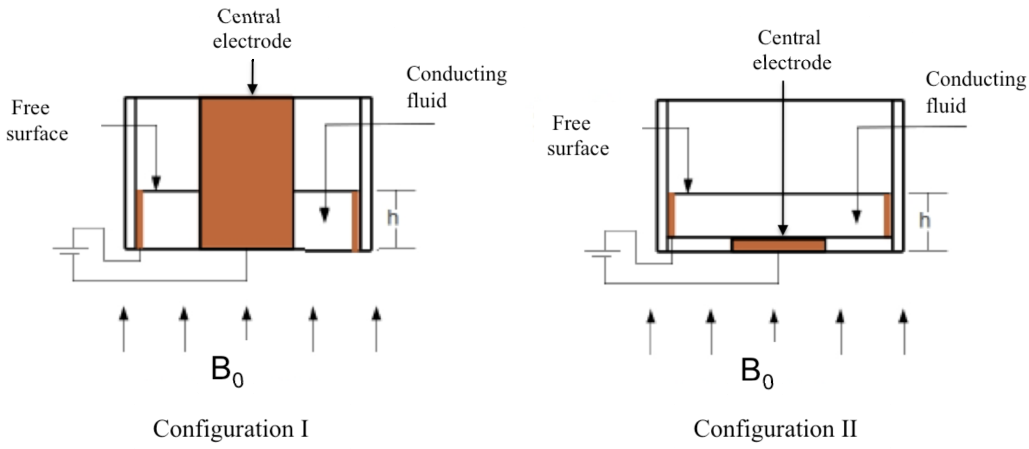

Figure 1: Sketch (lateral view) of the experimental setup in the two explored configurations.

3. Results

Let us first present some experimental results for the liquid metal flow. By taking the 5 mm thickness of the liquid metal layer as the characteristic length, the Hartmann number in this case is approximately 8. In order to avoid oxidation, a thin layer of hydrochloric acid of 1 mm thick was poured on top of the liquid metal, producing small bubbles. Using these bubbles as flow tracers, Particle Image Velocimetry (PIV) was implemented to discern approximately the free surface flow of the liquid metal. Within the range of explored electric current intensities (1 to 2 A), the PIV analysis revealed a pure azimuthal flow on the free surface, as shown in Fig 2. Due to the restricted experimental conditions results are not conclusive and a more complete characterization of the flow is necessary.

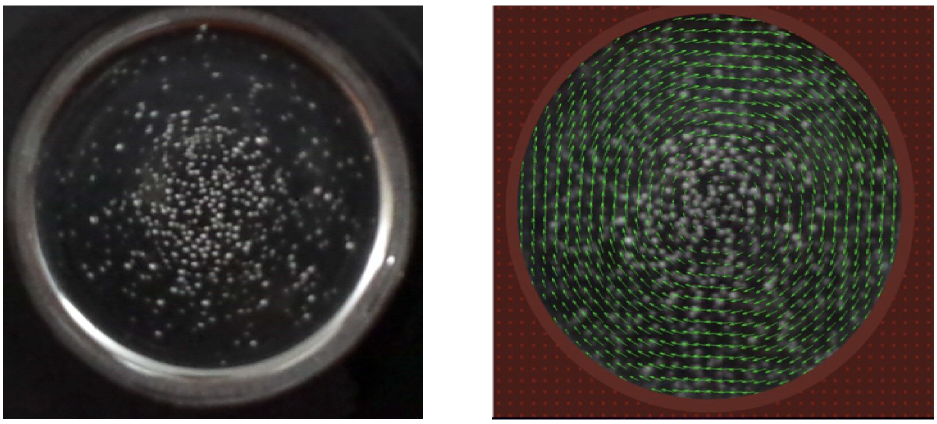

Figure 2: Top view of the liquid metal driven flow with configuration II for an electric current of 2 A. The left panel shows the bubbles created once the acid is poured on top of the liquid metal. The right panel shows the purely azimuthal velocity field obtained from the PIV analysis using the bubbles as tracers. Notice the almost stagnant region where the central embedded electrode is located.

For the electrolytic flow, experiments in both configurations showed the appearance of an instability that leads to the formation of anticyclonic vortices (i.e vortices that rotate in opposite sense to the global azimuthatl flow) independently of the direction of the current. Due to the small electrical conductivity of the electrolyte ($\sigma \approx 6.36$ S m^{-1}) and the weak magnetic field, the Hartmann number is very low ($Ha \approx 0.03$). Traveling anticyclonic vortices, visualized using dye, are observed to appear close to the wall of the exterior cylinder, their number varying from 4 to 11 according to the flow conditions. Vortices form a polygon and once they appear, they remain for long times. Figure 3 shows a sample of the vortex visualization in both configurations. By changing the layer depth and potential difference, it is possible to find the critical layer thickness and electric current for the appearance of the instability. All the experiments correspond to small aspect ratios, $0.01 < h/L < 0.4$, where h is the layer thickness and L is the space between the outer and inner electrodes. For the smallest aspect ratio bottom friction inhibits the appearance of anticyclonic vortices. As the aspect ratio increases, the current intensity necessary for the emergence of vortices diminishes. The flow very close to the surface was explored using PIV. This analysis revealed that in some cases vortices also appear close to the inner electrode although these structures were not detected with dye visualization.

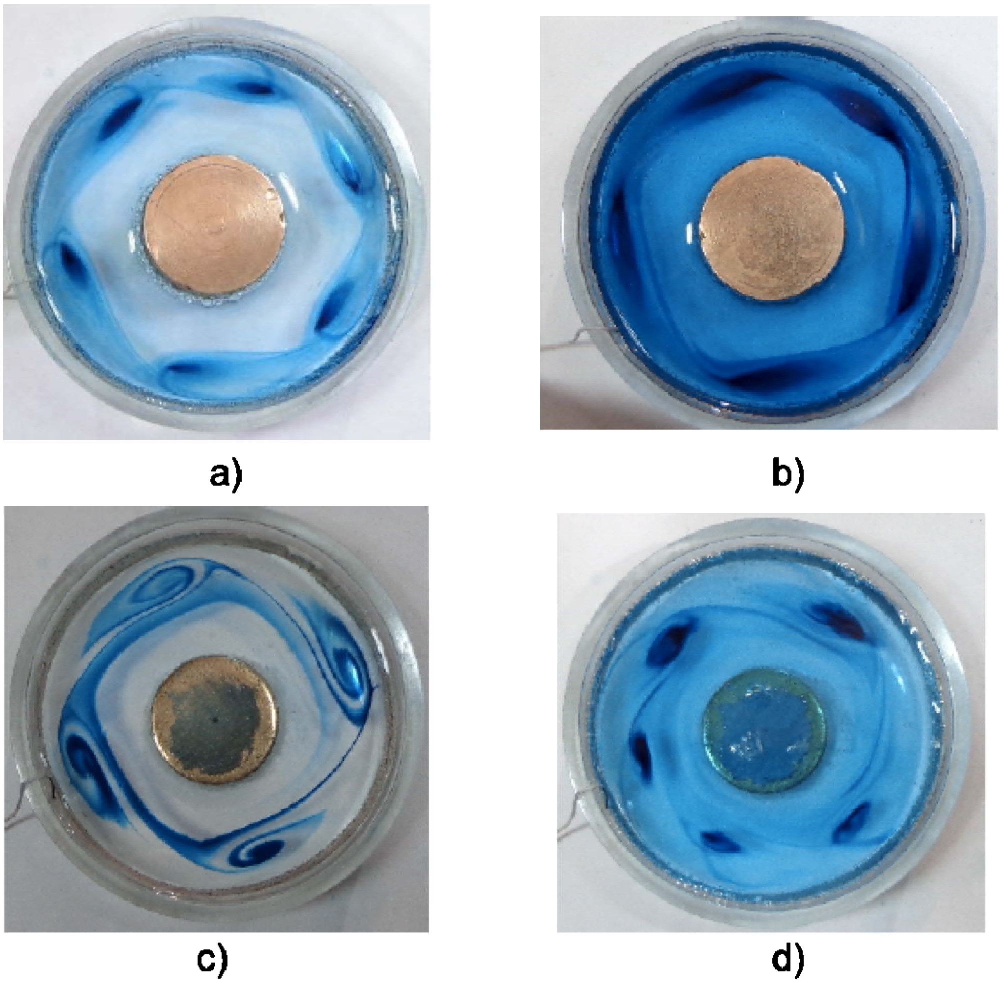

Figure 3: Dye visualization of the instability observed for a layer thickness of 10 mm. a) and b) correspond to configuration I. c) and d) correspond to configuration II. Current intensity for a) and c) is 100 mA. while for b) and d) is 300 mA.

According to Marcus [7] vortices embedded in a shearing zonal flow where shear stress and vorticity have opposite sign, tend to be fragmented and destroyed in a turn-around time. In those regions where the signs are the same, vortices redistribute their vorticity so that its maximum value is at the center. This appears to be consistent with the shear stress and vorticity calculated from the analytical solution [9] corresponding to the flow between infinite cylinders. This solution (see Fig. 4) shows that shear stress and vorticity have the same sign close to the inner and outer cylinders and, according to Marcus, these are the zones where vortices could exist. These zones can be modified by varying the gap between the cylinders.

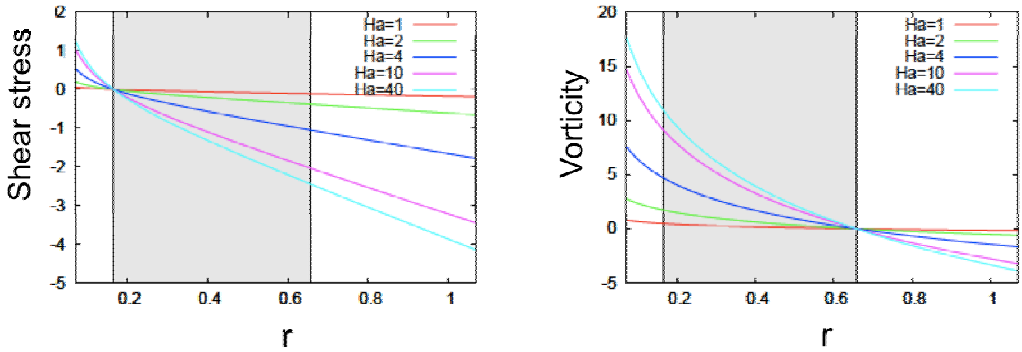

Figure 4: Shear stress and vorticity as function of the radial coordinate at different Ha, calculated from the exact analytical solution for infinite coaxial conducting cylinders [9]. Shaded region denotes the zone where, according to Marcus [7], vortices cannot persist.

4. Conclusion

We reported the existence of an instability in the electrolytic flow driven by an azimutal Lorentz force in a cylindrical electromagnetic stirrer. The instability is characterized by the emergence of stable anticyclonic traveling vortices that form a polygon in the plane normal to the axial magnetic field. We observed a varying number of vortices mainly located near the outer cylinder although PIV analysis revealed the existence of vortices close to the inner electrode. This behavior seems to be supported by the theoretical analysis of Marcus [7] for a shearing zonal flow.

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