Vortices generated by fixed and free-moving magnets in shallow electrolyte layers

Eduardo Ramos, Aldo Figueroa, Alberto Beltrán and Sergio Cuevas
Centro de Investigación en Energía, Universidad Nacional Autónoma de México
A. P. 34, Temixco, Mor. 62590 MEXICO

Abstract

Electromagnetic forcing is a common experimental method to produce vorticity in shallow layers of electrically conducting fluids. The idea is to create a rotational Lorentz force in a thin fluid layer by the interaction of electric currents (induced or injected) with a steady external magnetic field. This method has been widely used with the purpose of exploring fundamental topics such as quasi-two-dimensional turbulence [1], chaotic mixing [2] and fully controlable multi-scale flows in laboratory [3]. Several applications involve the use of permanent magnets with dimensions much smaller than the fluid container. In such a case, both the non-uniform field produced by the magnet and the Lorentz force resulting from the interaction with the electric currents can be visualized as localized. In the case of an externally imposed flow passing through a localized magnetic field, electric currents induced by the fluid motion interact with the applied field and produce an opposing Lorentz force that acts as a *magnetic obstacle* [4]. Internal shear layers created by the Lorentz force may become unstable and led to a vortex shedding process in a similar manner as it occurs in the flow past a rigid obstacle. In turn, if a uniform current is injected, a typical flow structure, namely, a dipolar vortex, occurs when a permanent magnet is placed externally but close to the fluid layer [5]. In this case, the localized Lorentz force acts as a *source of momentum* creating a jet in the zone of highest magnetic field that eventually is spread to form a pair of counter-rotating vortices.

An entirely new situation arises when the localized magnetic field is generated by a magnet that can move freely on the surface of the electrolyte, interacting with an electrical current that is externally imposed. Under these conditions, the pair of counter-rotating vortices are still generated, but the Lorentz force sets both the fluid and the magnet in motion, in such a way that the travelling magnet acts like a self-propelled body, grabbing the fluid with a volumetric force that overcomes the drag force on the solid magnet. This propulsion mechanism is different from the conventional magnetohydrodynamic (MHD) thrust that involves the ejection of fluid in the opposite direction to the displacement of the object. This situation can be accomplished experimentally by suspending a small magnet on the surface of the electrolyte by buoyancy or surface tension. Preliminary observations made using a saturated sodium bicarbonate ($NaHCO_3$) solution in water as the electrolyte, a neodynium-iron-boron cilyndrical magnet, 3 mm in diameter and maximum magnetic field of 0.27 Teslas, indicate that the magnet moves with a velocity of 0.4 cm/s, which corresponds

to a Reynolds number of 12, when the injected current reaches 175 mA. If an alternate current is injected, the magnet is set in an oscillatory motion with constant frequency, producing a periodic wake. In this presentation, we will describe our experimental observations of the flow around the free-moving magnet based on the physical principles of vorticity generation by Lorentz forces. The trajectory of the magnet itself as functions of the magnetic field strength and electric current will be presented along with numerical simulations based on the solution of a fully MHD model.

Acknowledgment. Authors thankfully acknowledge valuable suggestions of Dr. Andrew Belmonte from PennState University.

Outline of the Presentation

1. Background: Generation of vorticity by localized Lorentz forces
2. Vortices generated by fixed magnets
   - Steady state
   - Unsteady state
3. Vortices generated by free-moving magnets and physical principles of self-propulsion mechanism
   - Experimental results
   - Numerical simulations

References

[1] P. Tabeling 2002 Two-dimensional turbulence: a physicist approach *Rev. Mod. Phys.* **362**, 1-62

[2] N. T. Ouellette and J. P. Gollub 2007 Curvature Fields, Topology,and the Dynamics of Spatiotemporal Chaos *Phys. Rev. Lett.* **99**, 194502

[3] Rossi, L., Vassilicos, J. C. & Hardalupas, Y. 2006 Multiscale laminar flows with turbulentlike properties *Phys. Rev. Lett.* **97**, 144501.

[4] Cuevas S, Smolentsev S and Abdou M 2006 On the flow past a magnetic obstacle *J. Fluid Mech* **553** 227–252

[5] Figueroa, A., Demiaux, F., Cuevas S and Ramos, E. 2008 Electromagnetically driven dipolar vortices in shallow fluid layers. To be submitted to *J. Fluid Mech.*