Influence of the Earth Magnetic Field on Electrically Induced Flows

Abdellah Kharicha, Menghuai Wu, Andreas Ludwig, Ebrahim Karimi Sibaki
(Christian Doppler Laboratory for Advanced Process Simulation of Solidification and Melting,
University of Leoben, 8700 Leoben, Austria)

Abstract: The present paper aims at numerical simulation of the intriguing experimental observations made by Bojarevics on the appearance of swirl in flows in an electrically induced flow. Although controlled by poloidal force, the flow rotates due to the presence of the earth magnetic field. The bulk flow rotates almost as a whole which indicates that the swirl is generated through a mechanism of "poloidal suppression".

Key words: fundamental MHD; instability; electric; swirl; metallurgy; earth; dynamo; turbulence

1 Introduction

Electrically induced flows are present in many industrial processes such as electroslag remelting, vacuum arc remelting, DC arc furnaces, smelting, aluminium reduction cells...etc[1-2]. Such currents induce a magnetic field in the tangential direction, which after interaction with the imposed current, generate a strong poloidal flow. However the presence of a surrounding magnetic field even of small magnitude can considerably modify the flow dynamic. For instance, the presence of a small axial magnetic field in aluminium reduction cells can destabilize the metal/bath interface. It is then necessary to include the entire current path as well as all other possible sources of magnetic field in the calculation model. Recently a numerical model was built to simulate 2D and 3D electrically induced flows as those observed in the industrial scale processes [3]. This model is used here to explore numerically phenomenon observed by Bojarevics in 1983 [1]. The experiment consisted in supplying an electric current to a small water-cooled electrode of 0.8 cm diameters, in the centre of free surface mercury filling a hemispherical copper container, 36 cm in diameter, which represents the other electrode (Fig.1). The electrode is electrically insulated in most of its length except over a short distance below the free surface. The electric current can be applied from the top; it flows then at the level of the air, and penetrates the mercury as soon as the level of free surface is passed. It can also be applied from the bottom; in this case the current flows along the insulated part of the electrode under the level of free surface, and enters finally the liquid metal at vicinity of the free surface. When the electric current is applied from above the free surface, a converging flow is set up. The flow is coupled with a rotation. No rotation is observed when the current is supplied from below the free surface. The fact that the earth magnetic field can be at the origin of the swirling has clearly been stated by Bojarevics [1-3]. To explore the origin of this interesting phenomenon, 2D calculations of the MHD flow are performed. The numerical model is based on a potential formulation for the electro-magnetic field. The evolution of the free surface flow is tracked with a VOF model.

2 Numerical Method

We assume the system being laminar and 2D axisymmetric. The equations for electric potential, magnetic potential vectors, as well as the velocity field are solved in a fully coupled and transient way. The coupling between the flow and the electromagnetic field is done through the possible movement of the metal/air interface which can modify the electric

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Biography: Abdellah Kharicha (1973-), Male, Doctor; **E-mail:** abdellah.kharicha@unileoben.ac.at

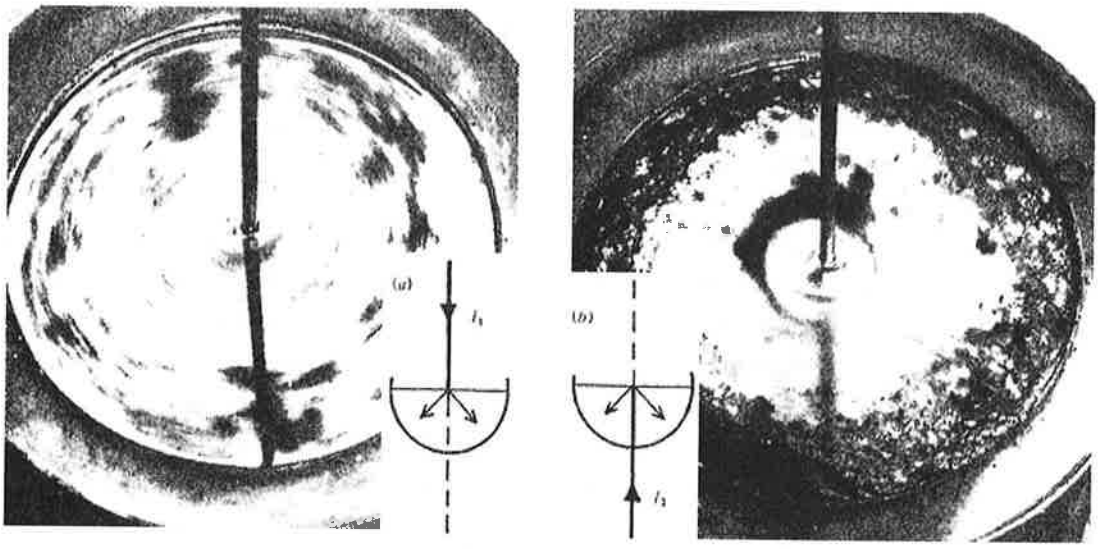
current path. Depending on which force is acting on the tangential direction, four configurations are explored (a) The case of current from the top of the electrode (TC) with only earth Coriolis force (b) TC with earth coriolis and magnetic field, (c) the case of current supplied from the bottom of the electrode (BC) with only coriolis force, and (d) BC with earth coriolis and magnetic field. All the cases include the conventional poloidal forcing due to the interaction of the current with the self tangential magnetic field (induced by the current). Numerical schemes used here are second order in time and third order in space accuracy.

The coriolis force and the Lorentz force resulting from the interaction with the earth magnetic field are: $\vec{F}_c = -2\vec{\Omega}\times\vec{u}$, and $\vec{F}_{\mathrm{LE}} = \vec{j}\times\vec{B}_{\mathrm{Earth}}$

These forces are added to the Navier stokes equation. The values for Ω (earth angular speed) and BEarth are the values for the town in Riga(Latvia) in 1982. It must be recalled that in the northern hemisphere $\vec{B}_{\mathrm{Earth}}$ and $\vec{\Omega}$ are pointing in opposite direction, the vertical component of $\vec{B}_{\mathrm{Earth}}$ is negative, while $\vec{\Omega}$ it is positive.

Table 1 Physical and numerical parameters for the present study

Current	1200 A	Density Mercury	13529 kg/m^3	Magnetic permeability	4 πe-7
Ω	6.03e-5 1/rad	Viscosity Mercury	1.53e-3 kg m/s	Max. Grid size	3e-3 m
B_{Earth}	-0.4754 G	Electric conductivity Mercury	1e6 1/S	Min. Grid size	1e-5 m
Air/Mercury surface tension	0.49 N/m	Electric conductivity Cooper	5.96e7 1/S	Time steps	1e-4 s



(a) TC; (b) BC.

Fig. 1 Flow at the surface of mercury in a hem ispherical container. (a) If 1200 A is supplied from above, converging flow is coupled with rotation. (b) If 1200 A is supplied from below, diverging flow does not rotate. The surface is deformed in the centre, where fluid ascends (Picture and caption from Bojarevics [11])

3 Results

The results with earth magnetic field are presented in Fig.2 and 3. The results are also summarised and compared with the case without magnetic field in Table 2. The predicted deformation of the liquid/air interface in Fig.2 reproduces clearly the pattern observed in Fig.1. If neglecting the difference due to this interface, within the liquid flow the calculated electric current distribution is almost the same in both configurations. However since the electric current within the electrode is in different direction, the configurations differs by having induced magnetic field in opposite direction. The result is Lorentz force acting radially inward in the top current direction, and radially outward in the configuration with electric current coming from the bottom. The force direction explains why the flow is converging in (TC) and diverging in (BC). When comparing cases with and without earth magnetic field, the TC seems to be much more affected than the BC case. When the earth magnetic field is taken into account in TC the swirl kinetic energy (SKE) is increased by a factor of almost 106, and represents 7% of the poloidal KE. By comparison in the BC case, the SKE represents only 0.17% of the PKE. It is interesting to notice that the maximum poloidal velocity is the same for all the cases. In the case of TC the radialy converging flow flows is attenuated by the generation of swirl velocity through the action of the centrifugal force ($-u_\theta^2/r$) acting radially outward. In the BC the centrifugal force acts in the same direction than the radial flow at the surface. The consequence is that the swirling lowers the poloidal flow KE by about 13 % in TC and increases it by only 1.6% in BC. The maximum swirl velocity is always located along the electrode (Fig.3). The angular speed is almost invariant with the height, with however some small unsteady variation in BC. In fact the poloidal flow was found to be unsteady in all configurations, however the case of TC with earth magnetic field have shown the highest level of turbulences characterised by the generation of small eddies. These eddies are emitted near the rotating core. In all cases the swirl velocity is much steadier than the poloidal one.

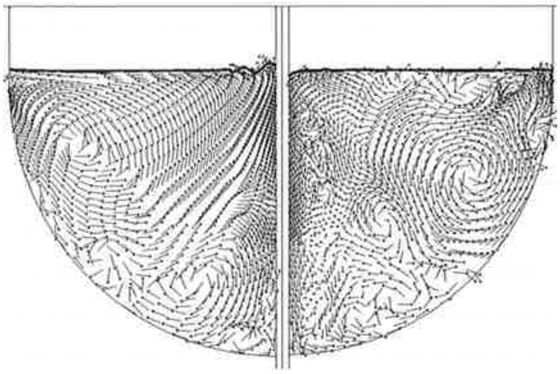
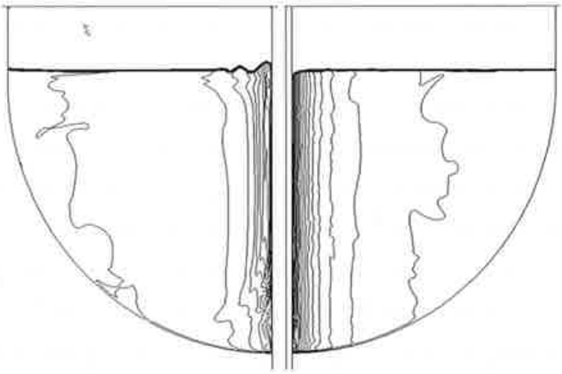


Fig. 2 Flow direction distribution with earth magnetic field (a) Current from bottom, (b) Current from above. Regions where swirl dominates are characterised by small apparent vectors



(a) Current from bottom; (b) Current from above.

Fig. 3 Isoline of swirl velocity with earth magnetic field The maximum swirl magnitude is located near the electrode in the centre

Table 2 Summary of the results for the four cases studied

	Current from bottom (BC)		Current from above (TC)	
	Coriolis only	Coriolis and earth magnetic field	Coriolis only	Coriolis and earth magnetic field
Poloidal Kinetic Energy (m^2/s^2)	1.91e-3	1.94e-3	1.962e-3	1.71e-3
Swirl kinetic Energy (m^2/s^2)	6.92e-10	3.26-6	1.96e-10	1.26e-4
Maximum swirl velocity (m/s)	5.34 e-4	0.03	2.7e-4	0.2
Maximum poloidal velocity (m/s)	0.35	0.36	0.34	0.34
Maximum angular speed velocity (rad/s)	0.12	6. 73	0.06	45.09
Average angular speed (rad/s)	6.4e-4	4.34e-2	3.3e-4	0.28

4 Discussion and Conclusions

The numerical model has successfully simulated the flow supplied to a liquid metal bath by a small electrode. The prediction of the main features such as the deformation of the free interface as well as the swirl generation was in agreement with the experimental observation. Depending on the electric current direction, the system can be very sensitive to magnetic field as small as the one from the earth. Although the ratio of tangential over the poloidal forcing was very small (~1/100 order near the electrode) the flow was clearly rotating. Davidson et al [4]. have shown that a flow may be dominated by the azimuthal body force even when the poloidal one is much larger. However by comparing the swirl with the poloidal kinetic energy, we could not state that the flow is dominated by the azimuthal body force. Grants et al. [5] suggested that the present flow is the result of a "concentrated vortex", which has two main features (i) enhancement of the swirl velocity towards the centre of the pool; (ii) large axial gradient of the bulk swirl velocity. It was stated that the second property could influence the appearance of the surface depending on the direction of the electric current. The present both results (TC and BC) do not show the existence of a large axial gradient, instead of that the core rotates as a whole (Fig.3). The later is a clear indication of the so called 'poloidal suppression' regime (also known as forced uniform vortex). In addition, we could argue that this regime is not fully developed since the surface radial velocity is not fully suppressed. With higher current we could expect a continuous decrease of the poloidal motion, until a full establishment of the "poloidal suppression" regime. Further calculations are necessary to confirm this hypothesis. The pattern formed at the free surface (Fig.1 a) form circles and not spirals. Circles indicate the presence of the "poloidal suppression" regime, while spirals (in a plughole sink) are related to the "concentrated vortex". In the case of current supplied from bellow, it was argued that although the surface of mercury was not rotating, the liquid was rotating in the bottom of the cavity where the poloidal flow converges. The present simulation shows the existence of a very small rotation (Fig.3 a) all along the height, with some variations where the poloidal flow impact the electrode (Fig.2 a). The fact that the experiment clearly shows that the current direction considerably influences the surface appearance [1,5] cannot be taken as sign for the existence of a concentrated vortex nor an uniform one. A uniform vortex can simply be strong or weak.

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