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Simulation of electrically induced vortical flows

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Abstract
In this work, we study electrically induced flows numerically using open-source software and experimentally. Two systems are considered - single and multiphase (free surface) flows driven by axisymmetric DC and AC current injection. We investigate characteristic velocity and free surface deformation dependence on the injected current and validate it with experimental data. Results show that maximum axial velocity is a linear function of injected current, but free surface deformations are approximately proportional to current squared.

Keywords : magnetohydrodynamics, electrovortex, simulation

Introduction

Electrically induced flows are found in many applications – arc furnaces, welding, etc. [1]. The flow is driven by Lorentz force created by the interaction between injected current and its own magnetic field. Depending on specific electrode configuration different vortical structures can form.

Electrovortical phenomena have been extensively studied theoretically and experimentally [1]. Numerical work usually considers simplified systems, such as hemispherical arc furnaces [2][3] using commercial software. Free and open-source software is not widely used mostly due to lack of user interface and complicated coupling between, for example, electromagnetic and fluid dynamics simulations. The recent development of EOF-Library [4], which is a coupler between Elmer [5] and OpenFOAM [6] and is an open-source library itself, simplifies the task of simulating complex coupled systems. The coupling library has been validated against commercial solutions [7].

The goal of this work is to apply and validate open-source software for electromagnetically induced vortical flows, as well as to study two specific systems with industrial applications in mind. The first (*system A*) is a small cylindrical container with electric current flowing through the melt between a small electrode on top and conducting bottom of container. It is a model system of typical DC arc furnaces. The second system (*system B*) is more complex – it consists of cylindrical container with 50Hz alternating current flowing between a small bottom electrode and conducting side wall. In this case, the current flows through a layer of liquid metal causing free surface deformations near the small electrode at the center. Possible application of this system can be slag removal from the melt in special applications – surface deformation is pushing the slag towards the side wall where it can be easily collected – this is demonstrated experimentally. Another application could be surface wave generation and flow intensification for improved melt purification via evaporation from the surface.

Numerical model

Software used for electromagnetics is Elmer, which solves the Maxwell's equations in potential formulation using the finite element method, but for fluid dynamics – OpenFOAM, which solves the Navier-Stokes, k-ω SST turbulence model equations, and for system B also transport equation for volume fraction, using the finite volume method. The coupling is achieved with the EOF-Library. The schemes of system A and B are shown in Fig. 1 and 2, respectively. Relevant material properties are listed in Tab.1.

Since the 2D axisymmetric solver in Elmer is not designed to solve for azimuthal component of magnetic flux density (or current in meridional plane), quasi 2D approach is used modelling 2° sector of full cylinder. Electromagnetics mesh for system A consists of 133k hexahedral elements (three layers in azimuthal direction), but system B – 180k hexahedral elements (two layers in azimuthal direction).

Fluid flow is also solved in quasi 2D approximation as 2° sector of full cylinder, as OpenFOAM does not have pure 2D capabilities. Fluid dynamics mesh for system A is 22k hexahedral elements (one element thick wedge), but for system B – 250k hexahedral elements (one element thick wedge). The electromagnetic force is computed only once, and the flow simulation is performed with constant momentum source.

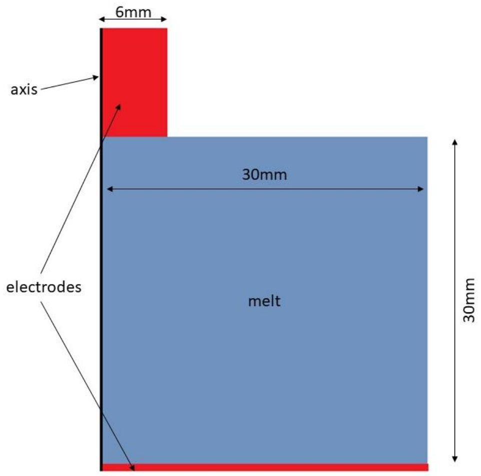

Fig. 1: System A

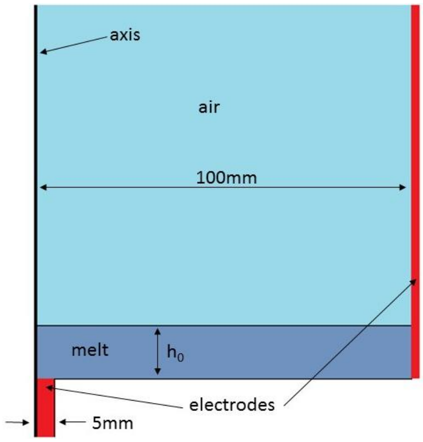

Fig. 2: System B

Table 1. Material properties

	System A	System B
Melt density, kg/m^3	13534	6440
Melt electric cond., S/m	$8.6 \cdot 10^5$	$3.46 \cdot 10^6$
Electrode electric cond., S/m	$5.8 \cdot 10^7$	$5.8 \cdot 10^7$
Melt viscosity, mPa·s	2.20	2.40
Surface tension, N/m	-	0.534

Experiments

Experimental results for system A are taken from [8], where liquid mercury flow velocity was measured using optical fiber sensor. Experiments for system B are performed at the Institute of Electrotechnology of the Leibniz University of Hannover. The picture of the setup is shown in Fig. 3. The two side electrodes are of the same polarity; the other pole is a small electrode at the bottom not seen here; dimensions as shown in Fig.2. Bottom wall of the container is plastic, so that the current is flowing from the bottom electrode to the side wall only through the melt. The current is provided by a 50Hz voltage source. At 50Hz, the skin depth in liquid galinstan is approximately 4cm.

Fig. 3: System B experimental setup

Results

System A

Example of current and velocity distributions are shown in Fig. 4 and 5, respectively. The highest current density is near the edge of the top electrode, and this is also where the Lorentz force concentrates, pushing the melt away from the electrode. Axial velocity distribution on axis for various injected current values is shown in Fig. 6. In Fig. 7, we plot maximum axial velocity (20mm from the top electrode) as a function of injected current. The theoretical analysis provided in [8] says that axial velocity in such system is proportional to the injected current and it is seen in simulation and experimental results.

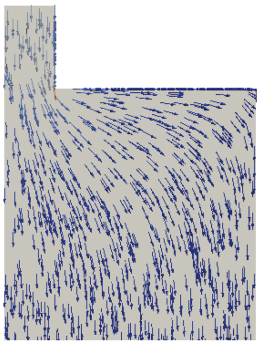

Fig. 4: Example current distribution

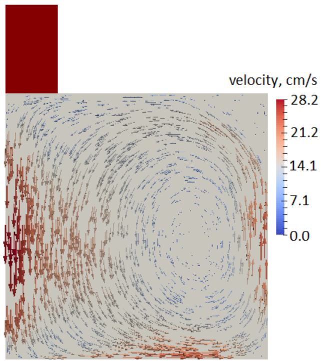

Fig. 5: Example velocity distribution, I=1kA

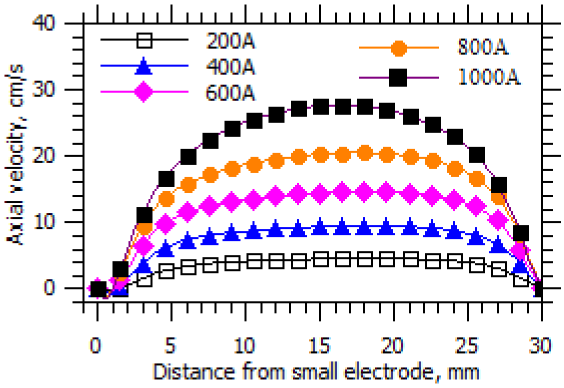

Fig. 6: Velocity on axis

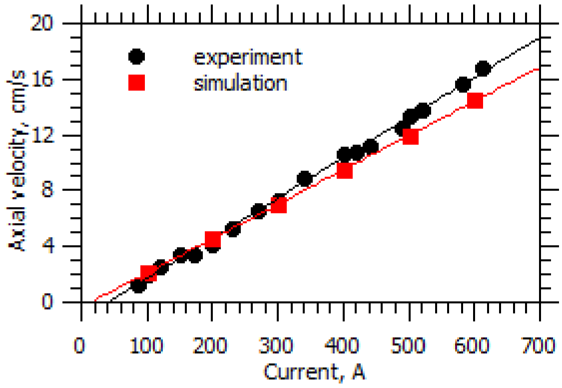

Fig. 7: Max. axial velocity vs current

System B

Example of current distribution (without surface deformation) is shown in Fig. 8 and velocity and surface deformation at I_{rms}=1000A is shown in Fig. 9. Free surface deformation height depending on current squared is shown in Fig. 10. In Fig. 11, we plot maximum axial velocity as a function of injected current.

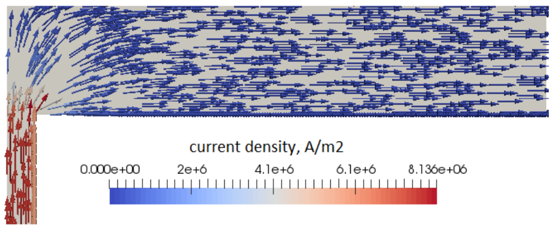

Fig. 8: Example current distribution, h_0=20mm

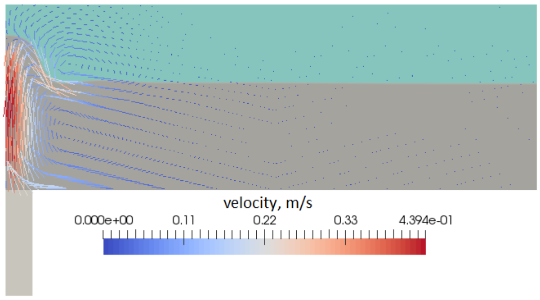

Fig. 9: Example velocity and surface deformation, h_0=20mm, I_{rms}=1kA

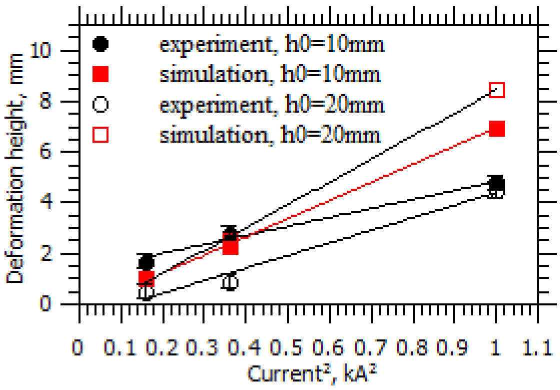

Fig. 10: Surface deformation vs current squared

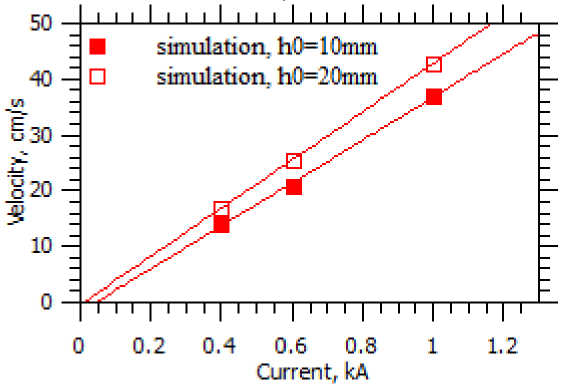

Fig. 11: Max. axial velocity vs current

In this system, no velocity measurements were performed at this stage, but are planned in the future. Deformation height disagreement between experiments and simulations can be due to many reasons. First, the surface height measurements were not done using precise equipment – they were manual measurements using simple tools. Second, the material properties (electric conductivity, viscosity etc) were not exactly known – values taken from literature may not be completely the same as in the experiments. Third, even the slightest imperfections (e.g., electrode centering) can cause different flow patterns and surface deformations. The numerical model, of course, is an idealization, especially being axisymmetric which does not allow the jet movement away from the axis. Nevertheless, the results of both simulation and experiment are the same order of magnitude and show the same tendency – in the considered range of currents surface deformation is approximately proportional to the square of injected current.
Finally, to study possible slag removal towards container walls by free surface deformation, we use small (d=2mm) plastic particles on the surface. Particle distribution without current and with I_{rms}=1000A is shown in Fig. 12 and 13, respectively. It is clearly seen that the surface deformation moves the “slag” away from the zone above the small bottom electrode. To move the particles even closer to the side wall, larger or several electrodes, or higher current could be used.

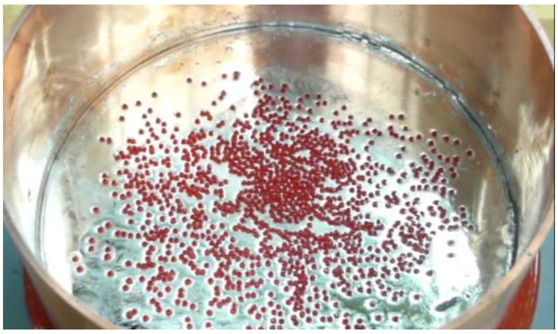

Fig. 12: Particle “slag” distribution; h_0=20mm, no current

Fig. 13: Particle “slag” distribution; h_0=20mm, I_{rms}=1000A

Conclusions

Firstly, numerical model of single-phase electrically induced flow in a cylindrical container was validated using experimental data – maximum axial velocity is in a good agreement to the measurements. The proportionality of axial velocity to the injected current is also a result agreeing to theoretical considerations [8].
An experimental device was created to study liquid metal free surface deformations induced by current flowing between small bottom electrode and conducting side wall. It was found that the deformation height is approximately proportional to square of the injected current in the considered range. Like in the first system, the maximum axial velocity is proportional to current.
The goal of applying open-source software for electrovortical flow simulations is achieved. The coupling solution EOF-Library is a very efficient interface between Elmer and OpenFOAM, which enables virtually any variable transfer and interpolation between different meshes of electromagnetic and fluid flow simulation.
Further experimental and numerical work will include different bottom electrode configurations to control the free surface deformations, as well as studying the process instabilities, as the deformation height was observed to be quite unstable, which can be of even more importance in industry-scale equipment.

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