The influence of electric current application configuration on the electro-vortex flow structure of conductive medium in cylindrical cell

S Mandrykin, I Kolesnichenko
Institute of Continuous Media Mechanics, Perm, Russia
E-mail: msd@icmm.ru

Abstract. A numerical study of the liquid metal electro-vortex flows (EVF) in a closed cylindrical cell, the radius of which is equal to its height, is performed. A direct current of 1000 A is applied through the electrodes at the bottom cylinder face, and is collected at the entire surface of the cylinder top end face. Various configurations of electrode location are considered. Namely, from one to five electrodes are placed on the cylinder bottom end face. The three-dimensional fields of the conducting medium flow velocity in the cell are obtained as a result of numerical simulations. The EVF is non-stationary in all considered regimes. In the one-electrode case, the flow is poloidal and is represented by one large-scale vortex. In the multielectrode case, the flow consists of multiple small-scale vortices, the size and quantity of which depend on the configuration of the electric current application. At the same electric current value of 1000 A, the mean flow velocity and characteristic frequency of the process are higher for the localized current application — 6.4 and 2.5 times respectively.

1. Introduction

Electro-vortex flows (EVF) are at the root of many modern technological applications for liquid metals, such, for example, as arc furnaces [1, 2], aluminum reduction cells [3], as well as actively developing liquid metal batteries [4–6]. EVF arise as a result of the interaction between an electric current in a conducting medium and its own magnetic field, provided that the current distribution is nonuniform [7].

The structure and characteristics of EVF significantly depend on the configuration of the problem. There are well-studied canonical EVF configurations, such as hemispheres [8] and flat layers [9–11] (including the multielectrode electric current application [9]). Albeit it is shown that in some cases the formation of stationary EVF is feasible, in the real-world industrial applications they are usually non-stationary. The non-stationary nature of EVF can have a positive effect on the product of the technological process, for example, it can enhance the mixing of the molten metal, which inevitably improves the quality of the ingots produced.

However, in liquid metal batteries the EVF have both positive and negative effect. On the one hand, they introduce a positive effect of mixing the melt, thereby decreasing formation of the intermetallic compounds, which can affect corrosion rate and reduce the device lifespan. Moreover, this mixing can help equalizing temperature fluctuations of the melt [12]. At the same time, the expected current values during operation of such devices are thousands of amperes, which corresponds to EVF with high intensity. Thus, EVF can lead to deformation of the
electrolyte layer [13], previously observed in aluminum reduction cells [14], and its excessive thinning, causing a subsequent short-circuiting and failure of the device [15–17].

The simplest way to decrease the EVF intensity, while maintaining the electric current value, is to increase the electrode cross section, that is, to reduce the non-uniformity of the electric current distribution. Another approach is to increase the number of electrodes used. Obviously, the latter option is more preferable from both the economic and a technical points of view.

In this work, the EVF of a conducting medium in a closed cylindrical cell is studied numerically for various electric current application configurations. A direct current of 1000 A is applied through electrodes at the cell bottom end face and is collected over the entire surface of the cell top end face. Problem configurations with electrodes amount from 1 to 5 are considered.

2. Methods

The problem is solved numerically using the Ansys software. Namely, the Ansys Emag is used for simulating the electromagnetic part of the problem, and the Ansys Fluent — for the hydrodynamic part. The computational domain is a cylinder with a height of \( H = 0.100 \) m and a diameter of \( D = 0.200 \) m, as shown in Fig. 1. The electrodes with a radius of 0.020 m are located at the lower end of the cylinder. The electric current is collected at the entire top surface of the cell. The Cartesian coordinate system is used in the simulations and in the presentation of results. Its origin is located in the center of the cylinder bottom end face, and the \( Oz \) axis is collinear to the central symmetry axis of the cell. An unstructured mesh with tetrahedral elements is used. The linear size of its elements does not exceed 3 mm. For the velocity, the no-slip conditions are applied at all boundaries. The problem is considered isothermal. All computations begin from a state of equilibrium.

![Figure 1. Computational domain scheme](image)

The following configurations of the distributed current application are considered, as shown in Fig. 2: 5 electrodes, one of which is located in the center, and the other four are equidistant from it with the inter-space 0.070 m; 4 electrodes, also equidistant from the center; 3 electrodes are lined up, so that two electrodes are equidistant from the third one, located in the center; 2 electrodes are equidistant from the center. The results are also presented for the case of localized
current application (the case when a single electrode is located at the center) to compare it with that of the distributed electric current application. For the sake of simplicity, in the following, each of the above configurations will be designated by the number of electrodes it includes.

Figure 2. The scheme of distributed current application configurations

Gallium alloy GaSnZn is selected as a conducting medium, which has the following material parameters: kinematic viscosity $\nu = 3.1 \cdot 10^{-7}$ m$^2$/s, density $\rho = 6265$ kg/m$^3$, electric conductivity $\sigma = 3.56 \cdot 10^6$ S m$^{-1}$. The electric current has a fixed value of 1000 A.

The wavelet analysis was used in processing results [18, 19], since the numerical simulations showed the presence of non-harmonic oscillations in the process. The wavelet transform translates a one-dimensional time series $f(t)$ into the two-dimensional frequency-time plane $(\nu, t)$ is performed as:

$$W(\nu, t) = \sqrt{\nu} \int f(\tau) \psi(\nu, (\tau - t)) d\tau.$$  

The Morlet wavelet

$$\psi(t) = \exp\left[-t^2/2\sigma^2\right] \exp[i2\pi t],$$

where $\sigma$ is an adjustable parameter, is one of the most popular wavelets. It was selected in this study as an analyzing wavelet, since it better suits for signals of complex nature. By changing the value of $\sigma$ one can obtain optimal resolutions of time $t$ and frequency $\nu$. Low values of $\sigma$ are used to achieve better time resolution, whereas large ones can provide better frequency resolution of the wavelet. However, an excessive increase of $\sigma$ is undesirable, since it leads to attenuation of the analyzing function. The commonly adopted value of $\sigma$ is 1 [20], while the limit $\sigma \to \infty$ corresponds to the Fourier transform. In this paper we assume $\sigma = 3$.

The map $W(\nu, t)$ has an easily interpreted structure only in case of the simple data analysis. However, in case of the real data, wavelet map interpretation can be a lot more difficult. The wavelet transform integral spectrum

$$M(\nu) = \int |W(\nu, t)|^2 dt,$$

which is one of its simplest characteristics, is calculated as a convolution of $W(\nu, t)$ along the time axis. It is a smoothed Fourier transform. The smoothing degree decreases with increase in $\sigma$.

3. Results

Several flow regimes that are realized with a localized and distributed electric current application, including up to 5 electrodes (see Fig. 2), are studied. The three-dimensional velocity fields of gallium alloy in the cell are obtained. To evaluate the flow characteristics, the time
dependencies of the velocity \( z \)-component in the cell center are used, since it is precisely the component, which is measured by a Doppler anemometer in such laboratory installations [21,22]. The mean flow velocity in the cylinder center does not exceed 0.10 m/s, which corresponds to the Reynolds number determined through the cylinder diameter (\( \text{Re} = \langle V_z \rangle D/\nu \) \( \text{Re} = 64516 \) for the examined configurations of localized and distributed current application (5 electrodes). The mean flow velocity in case of the localized current application is up to 6.4 times higher, than that in the multielectrode case.

The mean flow velocity in case of the localized current application is up to 6.4 times higher, than that in the multielectrode case.

A qualitative flow structure can be obtained using the visualizations of the velocity fields in the \( zOy \) section, shown in Fig. 3. Here, the color indicates the velocity magnitude, and the lines indicate the interpretation of the velocity vector field. As is evident from the figure, in the multielectrode case there is no pronounced large-scale single-vortex structure. In contrast, in the case of localized current application (Fig. 3a), one large-scale toroidal vortex is clearly distinguishable. In all the studied multielectrode configurations, the flow is represented by many small-scale vortices (Fig. 3b, c, d, e), the amount and size of which vary with the variation of the current application.

Fig. 4 shows the time dependencies of the velocity \( z \)-component in the center of the cell, for the multielectrode configurations only. It follows from the figure, that the observed EVFs are non-stationary, and differ both in the mean velocity and in statistical characteristics. Such a flow pattern is preserved over the entire time interval studied, which is significantly higher than the typical characteristic time scales in such problems [21].

The statistical characteristics of the process are studied using the wavelet analysis. In particular, the wavelet diagrams of the velocity \( z \)-component of the gallium alloy in the center of the cell were plotted (see Fig. 5), using using signal data presented in the Fig. 4. The wavelet diagrams show that the observed EVF in the cylinder are of non-stationary character, and the oscillations are non-harmonic.

The wavelet analysis of the data also makes it possible to calculate the wavelet integral spectrum, which is more convenient for quantifying the characteristic frequencies of the process. The values of these frequencies for each of the considered configurations are presented in Fig. 6. The figure shows the presence of two frequencies, one of which is higher than the other one. In the multielectrode case, the first frequency increases with increasing number of electrodes, reaching a maximum value of 0.10 Hz, which is 2.5 times lower than that with a localized current supply. With a further increase in the number of electrodes, this frequency decreases. The second (lower) frequency decreases monotonically with increasing number of electrodes.

Thus, the distributed electric current application reduces both the intensity and the characteristic frequencies of a non-stationary EVF.

4. Conclusions

The electro-vortex flow (EVF) of liquid metal in a closed cylindrical cell, with the height equal to its radius, is studied numerically. The direct electric current is applied at the cell bottom end face and is collected at the cell top end face. The the numerical simulations are carried out for configurations that include from 1 to 5 electrodes, placed on the bottom end face. The electric current value was fixed at 1000 A. The three-dimensional velocity fields of gallium alloy in the cell are obtained, as well as the statistical characteristics of the process.

It is shown that in all considered configurations the flow is non-stationary. In the case of localized current application, the flow is represented by one large-scale vortex. In the case of distributed electric current application the flow is represented by multiple small-scale vortices. The size and number of these vortices depend on the number of electrodes used. In the case of localized current application the mean flow velocity is 6.4 times higher and the process characteristic frequency is 2.5 times higher than in the multielectrode case.

Thus, for the same electric current value of 1000 A, the use of multielectrode electric current
Figure 3. Visualizations of instantaneous velocity field in the $zOy$ section. The color represents the velocity magnitude. The number of electrodes is: a — 1, b — 5, c — 4, d — 3, e — 2

application reduces both the intensity and the characteristic frequency of the EVF, compared to the case of the localized current application.

Acknowledgments
The study was supported by the Government of Perm Region (Program for the support of Scientific Schools of Perm Region, grant C-26/788).
Figure 4. The velocity $z$-component as a function of time, in the center of the cell. The number of electrodes is: $a$ — 5, $b$ — 4, $c$ — 3, $d$ — 2

Figure 5. Wavelet diagrams of the velocity $z$-component in the cell center. The number of electrodes is: $a$ — 5, $b$ — 4, $c$ — 3, $d$ — 2
Figure 6. The EVF frequencies, obtained from the wavelet analysis.
References

[1] Rabiger D, Zhang Y, Galindo V, Franke S, Willers B and Eckert S 2014 Acta Materialia 79 327–338
[2] Kazak O 2013 Metallurgical and Materials Transactions B 44 1243–1250 ISSN 1543-1916
[3] Sneyd A D and Wang A 1996 Magnetohydrodynamics 32 487–493
[4] Weber N, Galindo V, Stefani F and Weier T 2014 Journal of Power Sources 265 166–173
[5] Weber N, Galindo V, Priede J, Stefani F and Weier T 2015 Physics of Fluids 27 014103
[6] Kelley D H and Weier T 2018 Applied Mechanics Reviews 70
[7] Bojarevics V, Freibergs Y, Shilova E and Shcherbinin E 1989 Electrically induced vortical flows (Kluwer Academic Publishers, Dordrecht.)
[8] Vinogradov D A, Teplyakov I O, Ivochkin Y P and Klementeva I B 2017 Journal of Physics: Conference Series. 899 082006
[9] Pedchenko A, Molokov S, Priede J, Lukyanov A and Thomas P J 2009 EPL (Europhysics Letters) 88 24001
[10] Khripchenko S Y 1991 Magnetohydrodynamics 27 77–83
[11] Kolesnichenko I, Khripchenko S, Buchenau D and Gerbeth G 2005 Magnetohydrodynamics 41 39–51
[12] Weber N, Nimtz M, Personnettaz P, Salas A and Weier T 2018 Applied Thermal Engineering 143 293–301
[13] Stefani F, Galindo V, Kasprzyk C, Landgraf S, Seilmayer M, Starace M, Weber N and Weier T 2016 IOP Conference Series: Materials Science and Engineering 143 012024
[14] Davidson P A and Lindsay R I 1998 Journal of Fluid Mechanics 362 273–295
[15] Weber N, Beckstein P, Herreman W, Horstmann G M, Nore C, Stefani F and Weier T 2017 Physics of Fluids 29 054101
[16] Weber N, Beckstein P, Galindo V, Herreman W, Nore C, Stefani F and Weier T 2017 Magnetohydrodynamics 53 3–13
[17] Zikanov O 2015 Physical Review E 92
[18] 1999 Wavelets: An Analysis Tool (Oxford Mathematical Monographs no Paperback: pages Publisher: (July 29, 1999) Language: English) (Oxford University Press) ISBN 0198505213
[19] S M 2008 A wavelet tour of signal processing, third edition: the sparse way 3rd ed (New York: Academic Press)
[20] Kolesnichenko I, Pavlinov A, Golbraikh E, Frick P, Kapusta A and Mikhailovich B 2015 Experiments in Fluids 56
[21] Mandrykin S D, Kolesnichenko I V, Losev G L and Frick P G 2018 Bulletin of Perm University. Physics 40 20–27
[22] Mandrykin S, Kolesnichenko I and Frick P 2019 Magnetohydrodynamics 55 115–124