COMPARISON OF EXPERIMENTAL AND NUMERICAL VELOCITIES FOR MELT ELECTROVORTEX FLOW IN CYLINDRICAL MULTI-ELECTRODE FURNACE

S.Pavlovs(1), A.Jakovics(1)

(1)Laboratory for mathematical modelling of environmental and technological processes, University of Latvia, Jelgavas Str. 3, Riga, LV-1004, Latvia

ABSTRACT. Paper presents the comparison of experimental and computation results for velocity of electrovortex flow (EVF) of mercury in cylindrical vessel, which is driven with alternating electrical current (AC), supplied over three non-submerged electrodes or two fully submerged electrodes. Time-averaged velocity of liquid metal, computed with *LES* model of turbulence, qualitatively and quantitatively agree with measured profiles of axial velocity for considered experimental setups.

INTRODUCTION

The numerical researches by authors are concerned with LES-study of melt flow patterns and heat transfer in metallurgical MHD devices with combined power supply by inductor and over electrodes [1,2].

Up to now the experimental verification of authors' computational approach has been successfully performed partly, that is for MHD devices with inductive power supply [3]. The measurements have been held for cylindrical experimental setup where the liquid *Wood*-metal flow is driven by inductor and recirculation flow patterns are toroidal vortices (electromagnetic convection – EMC). Melt velocity field has been obtained by *Vives* probe. The experimental verification has been performed also for industrial scale MHD devices [4], where measured melt flow turbulent energy distributions have been compared with experimental distributions.

The current paper fills a gap in verification of computational results for MHD devices with conductive power supply by means of comparison with velocity field of mercury EVF, which has been measured in [5] by means of single-component fibre-optic flowmeter.

Experimental setups

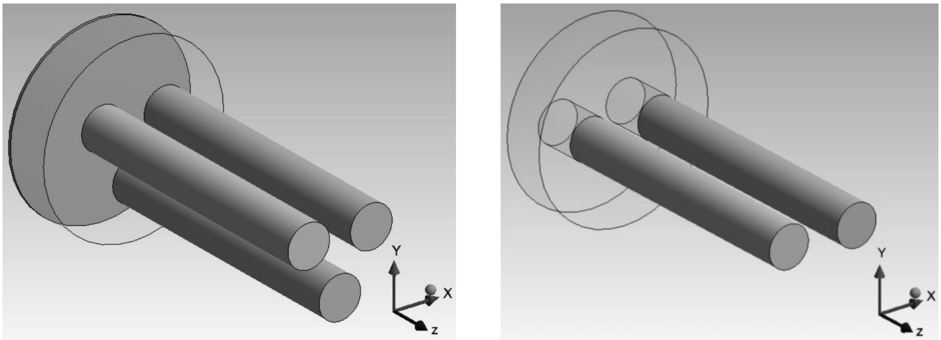
Experimental setups [5] consist of cylindrical bath with mercury (Fig. 1). Origin of coordinates is placed in the centre of bath base, thus axis z of symmetry is directed horizontally. Gravity vector is directed opposite to vertical y-axis.

In considered setups the conductive power supply is performed:

- with three cooper AC electrodes, which are not submerged into mercury, – Fig. 1 (a);
- with two cooper AC electrodes, which are fully submerged into mercury, – Fig. 1 (b).

The first setup has a cooper disk, which is placed at the base of mercury bath.

Geometry of bath and mercury parameters are collected in Table 1; geometry of cooper electrodes and disk as well as parameters of conductive power supply – in Table 2.



(a) (b)

Figure 1. Computational models according to experimental setups, described in [5]:
(a) three cooper AC electrodes are non-submerged into mercury; cooper disk is placed at the base of mercury bath; (b) two cooper AC electrodes are fully submerged into mercury.
Origin of coordinates is placed in the center of base of cylindrical bath
with symmetry axis *z* (horizontal). Gravity vector is directed opposite to *y*-axis (vertical).

Table 1: geometry of bath and mercury parameters

Radius of melt – r_{melt} (m)	0.065
Thickness of melt – L_{melt} (m)	0.032
Electrical conductivity – σ (*S/m*)	$1.041 \cdot 10^{6}$
Density – ρ (kg/m^3)	$1.36 \cdot 10^{4}$
Dynamic viscosity (laminar) – η $\left(\frac{kg}{m \cdot s}\right)$	$1.564 \cdot 10^{-3}$

Table 2: geometry of cooper electrodes and disk; parameters of conductive power supply

Number of cooper electrodes – k_{el} ( )	3 or 2
Radius of electrode – r_{el} (m)	0.015
Length of electrodes outside of melt – $l_{el}(m)$	0.2
Length of submerged part of two electrodes – l_{el}^{sub} (m)	0.032
Radial positions of electrodes' axes – r_k^{el} (m)	$r_1^{el} = r_2^{el} = r_3^{el} = 0.026$ or $r_1^{el} = r_2^{el} = 0.026$
Azimuthal positions (around *z*-axis) of electrodes' axes – φ_k^{el} (°)	φ_1^{el} =0°; φ_2^{el} =120°; φ_3^{el} =240° or φ_1^{el} =0°; φ_2^{el} =180°
Frequency of AC – f_{cond} (Hz)	50
Effective value of AC – I (A)	490 or 1000
Phases of AC in electrodes – α^{el} (°)	α_1^{el} =0°; α_2^{el} =120°; α_3^{el} =240° or α_1^{el} =0°; α_2^{el} =180°
Electrical conductivity – σ (*S/m*)	$5.9 \cdot 10^{7}$
Radius of cooper disk – r_{disk} (m)	0.065
Thickness of copper disk – $l_{disk}(m)$	0.002

Peculiarities of numerical computations

Quasi-stationary electromagnetic (EM) field for multi-electrode models supplied with AC as well as time-averaged *Lorentz* force in liquid metal has been computed with commercial package *ANSYS Maxwell*.

Transient hydrodynamic (HD) field in the liquid metal has been computed with *ANSYS FLUENT*. Both isotropic (k-ε) and anisotropic (*LES*) models of turbulence have been used – the estimations of *Reynolds* number with liquid metal parameters (Table 1) and measured velocity values (Figs. 2, 4) give $Re \sim 10^4$.

Computational mesh for HD field has ~200K elements with inflation at wall in immediate proximity to non-submerged electrodes or near submerged electrodes.

COMPARISON OF COMPUTED AND MEASURED RESULTS

Setup with three non-submerged electrodes – Fig. 1 (a)

Fig. 2 shows the comparison of time-averaged measured (circles) [5] and computed profiles of axial velocity v_z (horizontal direction) of liquid metal along y-axis (vertical direction) for x=0 and z=15 mm. Both *qualitative* and *quantitative* agreement is obtained with *LES* (solid line) and k-ε (dotted line) models of turbulence in the case of fine mesh with inflation at the wall in immediate proximity to non-submerged electrodes and base wall of bath.

Comparison of axial velocity as function of time in case of sudden switch on of electrical current shows that computed characteristic time of velocity increase till its maximum value for quasi-stationary state is smaller in comparison with measured [5, Fig. 4 (d)] because of inertia of voltage supply, where value of nominal current reaches in several (5–8) seconds.

In contrast to experimental investigations, which in most cases present only characteristic profiles of fields under research, the numerical simulation provides comprehensive 3D distribution of EM field in multi-electrode model as well as 3D patterns of turbulent flow – both instantaneous and time-averaged.

3D vectors in Fig. 3 (a) for cross-section z=0.031 m as well as in Fig. 3 (b) for cross-section x=0 show the rotational symmetry of *Lorentz* force distribution, which, in its turn, is the cause of corresponding melt flow time-averaged patterns with rotational symmetry – the illustration for zone near electrodes see in Fig. 3 (c) and illustration for cross-section x=0, which is one of three symmetry planes of model plane, see in Fig. 3 (d).

Setup with two fully submerged electrodes – Fig. 1 (b)

Fig. 4 shows the comparison of time-averaged measured (circles) [5] and computed profiles of axial velocity v_z (horizontal direction) of liquid metal along z-axis (horizontal direction) for x=0 and y=0. The *quantitative* agreement is obtained with *LES* (solid line) for maximum values of axial velocity.

As to *qualitative* agreement there are definite contradictions between computed and measured profiles.

According to comments in [5] for measurement results [5, Fig. 2 (a)] profiles of axial velocity are similar for different values of y. This fact is explained with presence of two jets with opposite direction of mercury flow.

Computational results show that for x=0 and y=0 there is only single jet of mercury with direction opposite to z-axis – see Fig. 5 (b), (c), – which corresponds to *Lorentz* force direction in Fig. 5 (a). Flow pattern for plane z=0.016 m, shown in Fig. 5 (d), has mirror symmetry to plane x=0. Computed melt circulation is similar to flow character for experimental setup [6], where observation has been held at melt free surface.

Two jets with opposite direction of melt flow are obtained relatively far from inter-electrode zone – for x=0 and y=-0.025 m – see Fig. 4, dotted line.

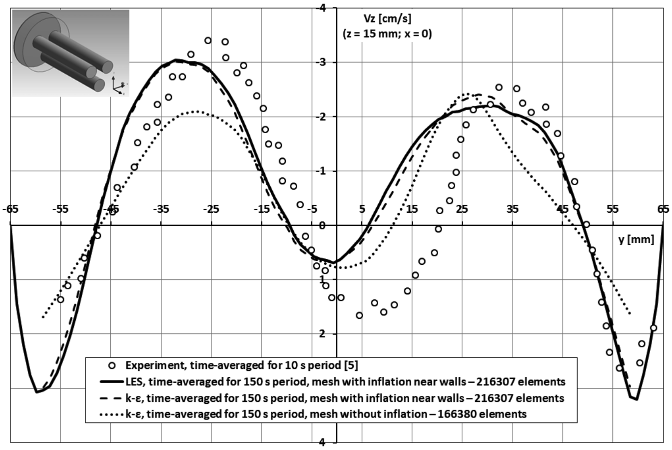


Figure 2. Vertical distribution (along *y*-axis for *x*=0 and *z*=15 mm) of axial velocity v_z of liquid metal for experimental setup [5] with three non-submerged electrodes – Fig. 1 (a). Comparison of measurement (circles) [5] and computation results obtained with LES (solid line) and *k-ε* (dotted line) models of turbulence for mesh with and without (points) inflation.

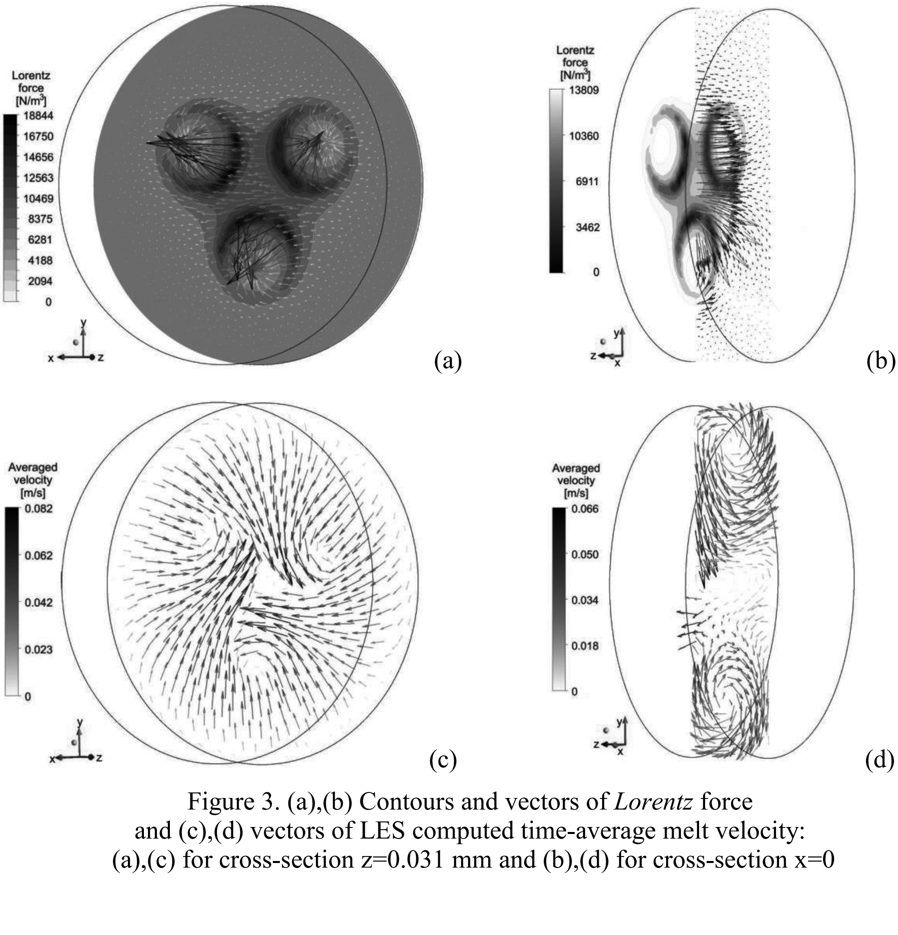


Figure 3. (a),(b) Contours and vectors of *Lorentz* force
and (c),(d) vectors of LES computed time-average melt velocity:
(a),(c) for cross-section z=0.031 mm and (b),(d) for cross-section x=0

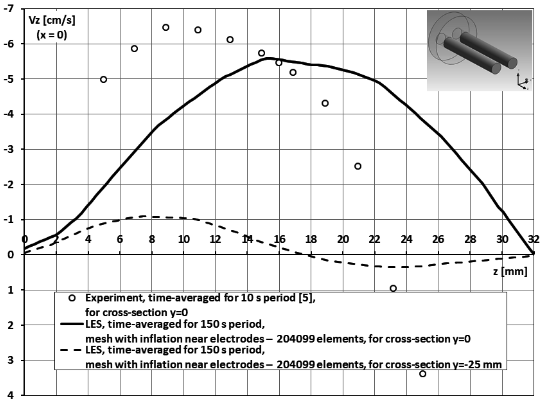


Figure 4. Horizontal distribution (along z-axis for x=0) of melt axial velocity v_z
for experimental setup [5] with two submerged electrodes.
Comparison of measurement (circles) [5] and computation results obtained with LES models
of turbulence for y=0 (solid line) and y=25 mm (dotted line).

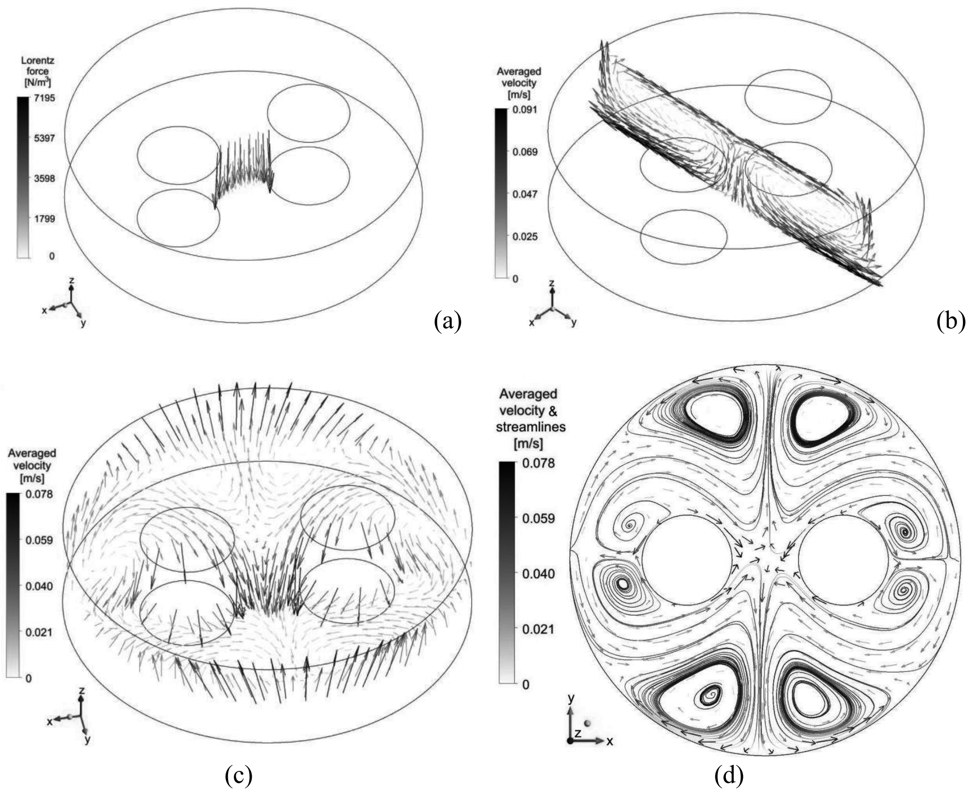


Figure 5. (a) Vectors of *Lorentz* force
and LES computed time-average (b),(c),(d) velocity vectors and (d) streamlines of melt:
for cross-sections (a) x=0, (b) y=0; (c),(d) z=0.016 m

CONCLUSIONS

Performed comparison of results show that maximum values in computed and measured [5] axial velocity profiles of liquid metal agree well *quantitatively* for both considered experimental setups [5].

Qualitative agreement of axial velocity profiles agree for installation with three non-submerged electrodes.

For installation with two fully submerged electrodes *qualitative* agreement of axial velocity profiles is obtained for cross-section, which is not documented in considered source of experimental results [5] and is placed relatively far from inter-electrode zone.

The results of comparison make possible to state that developed numerical approach is suitable for models not only with inductive, but also with conductive power supply and thus consequently with combined power supply.

As numerical simulation provides comprehensive 3D distribution of EM field and turbulent flow patterns for models with multi-electrode conductive power supply, the combination with results of limited experiments can provide wider research of MHD devices under consideration.

OUTLOOK

The further research is concerned with comparison of measured [7] and computed melt velocity profiles for experimental setups with three partly submerged electrodes.

Measurement and computation results (with possible use of physical similarity approach) will be applied for the further research of alloys and melts flows in industrial scale MHD devices for such electrotechnological processes as electroslag welding and complex treatment of steel in ladle, etc.

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