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Analysis of Experimental and Simulation Data for Liquid Metal Flow in a Cylindrical Container

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Abstract

The paper has two parts. The first part introduces experimental Wood's metal velocity measurements with a permanent magnet sensor in a crucible induction furnace (ICF) and their frequency analysis. The second part describes LES modelling results of this flow. Introduced wave number spectrums are in accordance with Kolmogorov's theory. Computed characteristic velocities are compared to be close to measured in experiments. Particle tracing results introduce the effect of gravitational interaction to the particle trajectories.

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Introduction

Electromagnetic heating and melting is one of the most effective methods for conducting material processing and production. The melt flow in induction furnaces and electromagnetic stirrers is formed by Lorentz forces and usually consists of one or several recirculated vortices. The maximal intensities of the flow have characteristic values larger than 1 m/s in industrial equipment. Due to strong interaction between vortices measured in experiments temperature distribution inside the melt is very homogenous without large temperature gradients, which can improve quality of the final product. Depending on material properties different types of induction furnaces are suitable for production of high purity metal alloys, ceramics and glasses. Such materials often have very high melting temperature. Experimental measurements of temperature and velocity fields in such high temperature melts are very difficult and even impossible. Computer modelling allows to study parameters of induction equipment before it is built and to improve energy efficiency of melting process. The aim of this work is to study physical parameters of velocity oscillations in the melt flow

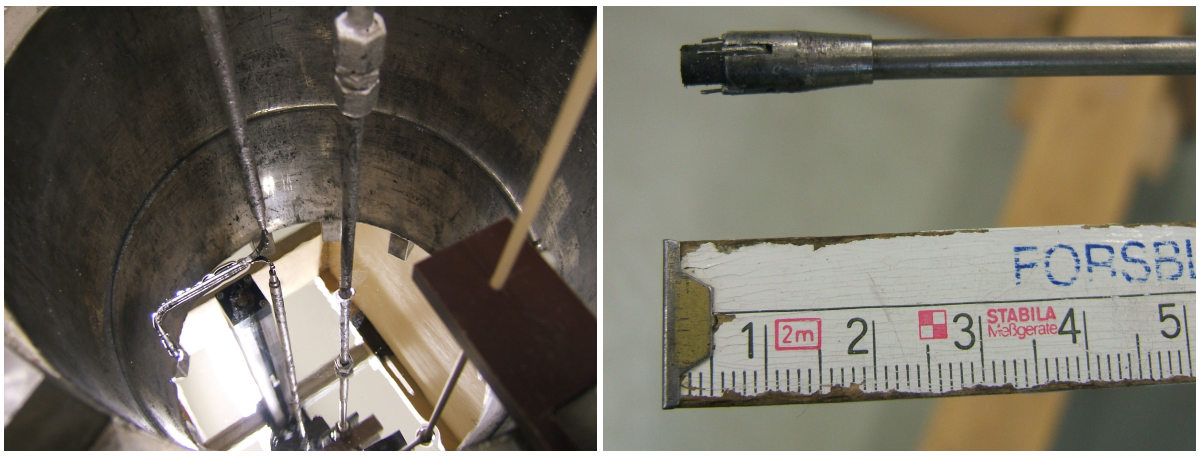


Fig. 1. Filled crucible with two probes and thermocouple for temperature control and example of probe used in experiments

and to check LES model, which can be used to predict velocity and temperature fields in real induction facilities.

1. Experimental setup and results

Velocity measurements of Wood's metal flow in ICF were made in 90-ties [1] and new in January 2006 at the Institute for Electrothermal Processes in Hannover. The electromagnetically driven flow of Wood's metal was studied in a steel crucible (d = 31.6 cm) for different inductor currents and material filling level (fig. 1 left). Due to relatively low melting temperature ($T_{melt} \approx 70^oC$) Wood's metal can be good model fluid for EM industrial equipment and it allows usage of all modern velocity and temperature measurement techniques in every point of the melt. During experiments instantaneous velocity values were measured on a discrete grid. Permanent magnet probes (fig. 1 right) were used to measure axial and radial velocity components. New velocity measurements were performed with two probes, which were placed in one half-plane of the crucible. Sensors were moved independently using their own coordinate systems. The minimal possible distance between the probe sensors was 2 cm.

There are old measurement results with 20 Hz measurement frequency and modelling results, which allow us to make frequency analysis described in the next chapters. Digital measurement complex Delphin was used in the last experiments for signal measurements. Three Delphin channels for two probe velocity measurements were used and stable results were achieved with 4 Hz measurement frequency, which is not enough for analyses of turbulent properties of the flow. Last experiments give more information about low-frequency

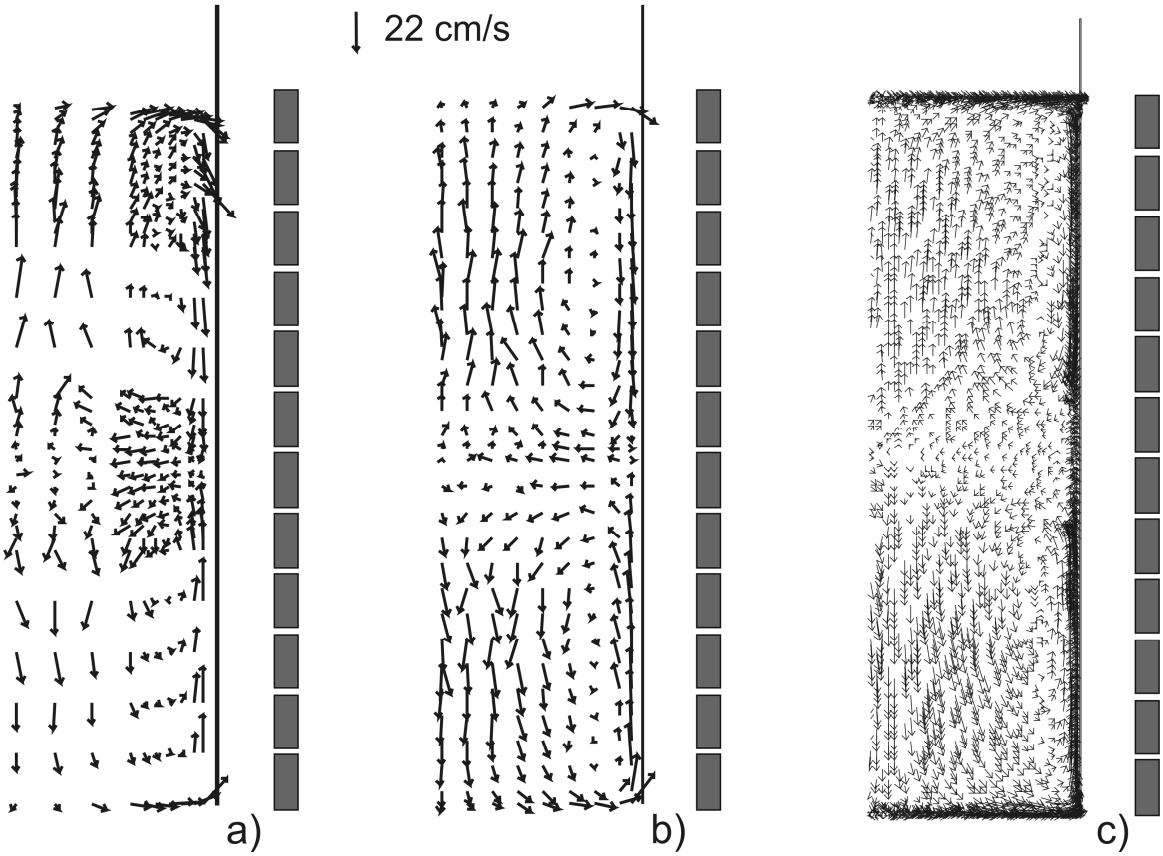
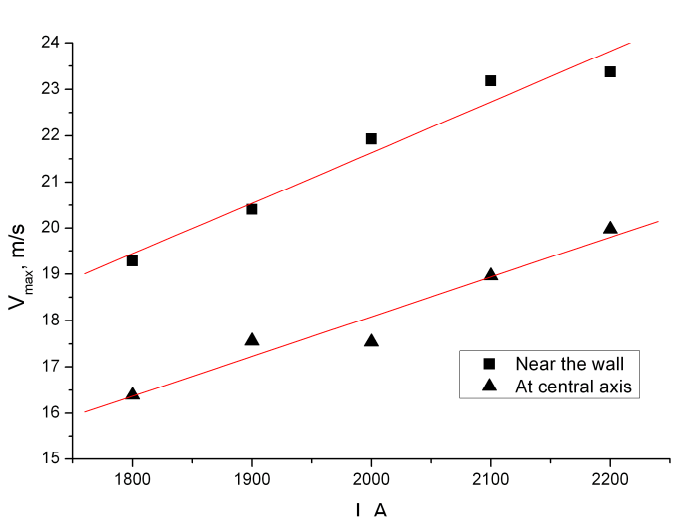
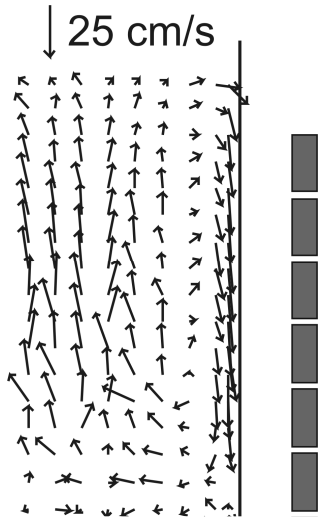


Fig. 2. Experimental old a), experimental new b) and calculated c) velocity distributions for H=57 cm crucible filling in the middle crossection of the melt. (a – I=1999 A, f=396 Hz, 1992; b – I=1999A, f=384 Hz; c – I=1989A, f=396 Hz).





velocity oscillations because velocity in each point was measured at least for two minutes. But in some characteristic points additional five minute measurements were performed to approve older results. Two setup types were used in these measurements: the melt's standard filling level H=57 cm, which is equal to the inductor height (12 turns); H=62 cm filling level, the first inductor turn from the bottom is disconnected and inductor is placed symmetrically over the height.

Experimental velocity distributions for the 57 cm melt height are comparable (fig. 2a and 2b). Averaged flow consists of two toroidal vortices, which are placed symmetrically in the melt. Vortex eyes are placed on the relative radius about 0.76. Induced Lorentz forces are concentrated in the near wall zone of the melt and has maximum in a middle region. In this place flow comes to the centre of the crucible from the all sides. Then it interacts and divides into two parts. One goes to the top part and another to the bottom along symmetry axis and then near the crucible wall comes back to the middle. Due to the mass conservation law and cylindrical geometry the flow achieves its maximal velocity near the crucible wall. For I=2000A the maximal measured velocity is about 22 cm/s.

Measured maximal axial velocities for different current values (fig. 3 left) are proportional to the current *I*, as it should be. However, linear fit of *V(I)* dependence shows that *V*=0 cross point with *I* axis should be in a range from 20 to 120 A and for very small inductor currents maximal velocity dependence on inductor current is not linear.

For H=62 cm experiment one inductor turn was disconnected and inductor current was increased to 2180A (fig. 3 right). Measured velocity distribution in the melt for 62 cm is symmetrical and has the same structure as for 57 cm and we have shown only upper vortex to economy place. Radial coordinate of the vortex centre is again 12 cm as for 57 cm case. Maximal measured velocity is about 25 cm/s and the law *V~I* applies again. This experiment data seems very important to us because H/d ratio is closer to 2 and extensive experiments with 62 cm filling level were not made yet.

2. Simulation methods and results

Computer simulation of the flow was performed in commercial FLUENT package. EM field and forces for given geometry were calculated using 2D axis symmetric ANSYS model. Then forces were transferred to FLUENT model using UDF. FLUENT grid had characteristic mesh size about 0.3 cm, boundary regions were specially refined for more accurate calculations.

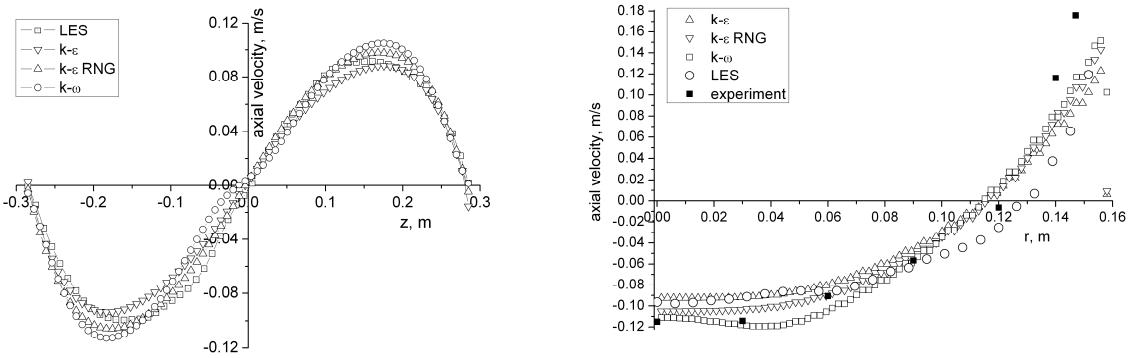


Fig. 4. Axial velocity profiles at symmetry axis r=0 (left) and on radius z=-0.165 (right),

For our simulation we have tried different turbulence models, starting from well known half-empirical 2D k-ε model and finishing with 3D LES calculations on 1.7 million element grid. Different model results are compared on several lines inside the melt and are in agreement with each other (fig. 4). Some difference from experimental results is observed in the near wall region (fig. 4 right). There can be two reasons: computational effects and velocity measurement difficulties in near wall region (geometry and EM field effects). For averaged flow velocity distribution calculations 2D models can be used with good precision. However to predict turbulent parameters of the flow transient modelling should be used and as a good compromise between computational time and model results we propose to use LES. Using LES we have calculated 60 and 40 s flow development from zero state with 5 ms time step for H=57 cm and H=62 cm correspondingly. 60 s averaged LES flow (fig. 2c) has another scale then experimental results (fig. 2a and 2b).

Frequency analysis of velocity oscillations was performed making inverse Fourier transform of autocorrelation coefficients $R_{ii}(\tau) = \langle V_i(\vec{r},t)\, V_i(\vec{r},t+\tau)\rangle$, where V_i is instantaneous velocity component and angle brackets denote averaging. All three spectrums were added together to get full energy time spectra. Experimental results contain data only for axial and radial velocities and its spectra were multiplied by 3/2 using isotropic turbulence approximation. However analysis shows [2] that turbulence is close to isotropic only in a part of the flow. Frequency spectra were converted into wave number spectra using Taylor's hypothesis: $k = \omega/V$, where V is averaged velocity at current point. Regions with high enough averaged velocity were selected ($V \approx 9.5$ cm/s) for spectral analysis in the wave number space.

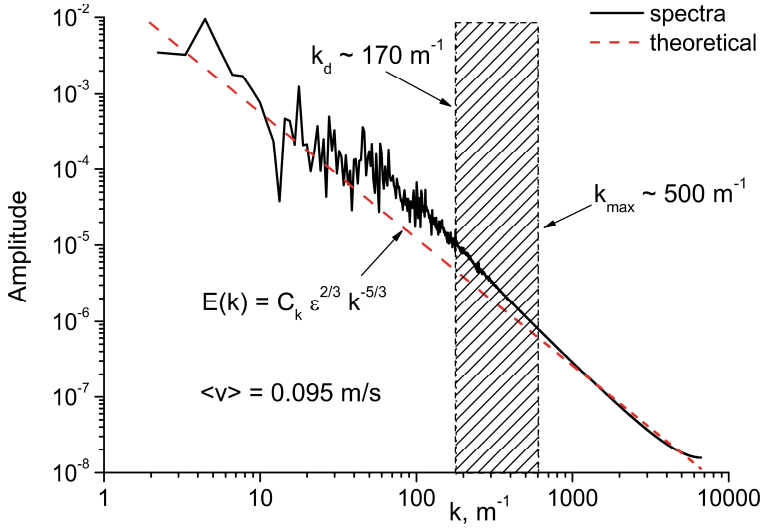


Fig. 5. Turbulent energy spectra in wave number space near the crucible wall.

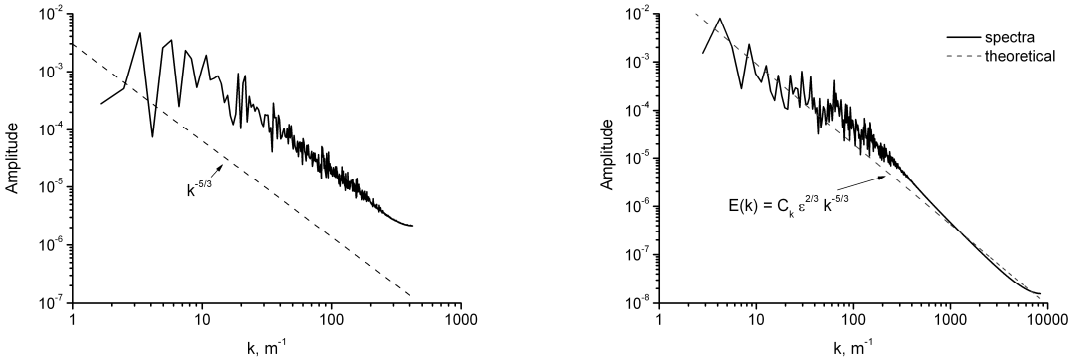


Fig. 6. Experimental (left) and calculated (right) turbulent energy spectra at symmetry axis (H=57 cm).

Experimental measurement frequency was 20 Hz and distinction ability in space did not exceed $k_{max} \approx 500$ m^{-1} (with 9.5 cm/s average velocity). Computational time step is 5 ms, which corresponds to 10 times better resolution. However we must take into account space discretization of the models with characteristic element size $\Delta x = 0.3$ cm. The numerical cut-off wave number can be estimated as $0.5/\Delta x$ [3] (for uniform mesh). In our case cut-off wave number k_d is about 170 m^{-1}. Therefore our model can not calculate turbulent structures with larger wave numbers then 170 m^{-1} (fig. 4). There are several spectral zones with relatively equal energy levels and therefore high pulsation intensity in the small wave-number regions ($k < 10$ m^{-1}), which can be best noticed on fig. 6 (left). Computed and experimental spectra can be compared with the theoretical Kolmogorov spectrum in the inertial sub-range [4]:

$$E(k) = C_k \varepsilon^{2/3} k^{-5/3},$$

where turbulent dissipation rate ε can be computed taking the integral:

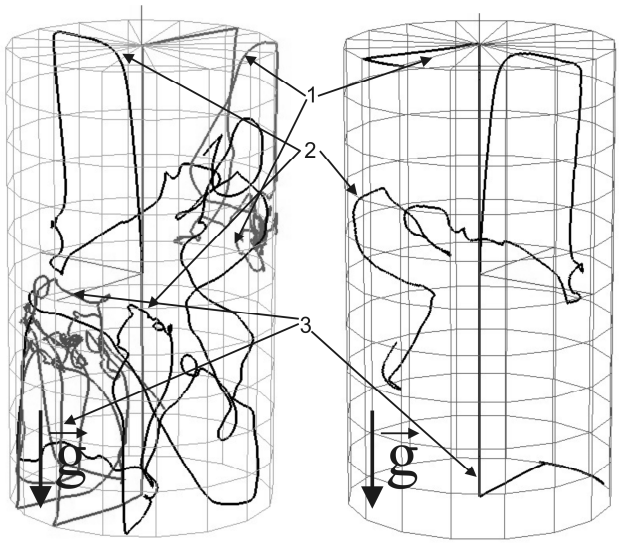


Fig. 7. Particle tracks with 1.1 density ratio (left) and with 5 density ratio (right), H=57 cm

$$\varepsilon = 2\nu \int_0^{+\infty} k^2 E(k)\, dk$$

from the energy spectrum $E(k)$, where kinematical viscosity $\upsilon = 4.5 \cdot 10^{-7}$ m^2/s for the melt. The theoretical Kolmogorov's constant C_k is usually taken to be 1.5. Dashed lines on spectrum figures 5 and 6 (right) represents theoretical curves calculated by these formulas. Observed zone with equal slope corresponds to the inertial range. The inertial range is narrow because our mesh and selected time step restrict observation of small scale oscillations with the large wave numbers. Decay of computational curve at high k values is more rapid because subgrid viscosity and numerical effects.

To investigate the convective transfer mechanism in the simulated flow Lagrangian approach for particle tracking was used (fig. 7). Three particles of 1 mm diameters with different densities were placed in the symmetry point of the melt at t=0. Particle motion is determined solving next equations [5]:

$$\frac{dV_p}{dt} = F_D(V - V_p) + \frac{g(\rho_p - \rho)}{\rho_p}, \qquad F_D = \frac{18\mu}{\rho_p d_p^2}\frac{C_D \mathrm{Re}_d}{24}, \ \mathrm{Re}_d = \frac{\rho d_p (V_p - V)}{\mu},$$

where μ is molecular viscosity of fluid, V_p is particle velocity, ρ_p is particle density, d_p is particle diameter and C_D is drag coefficient that depends on particle shape. Gravitational force has large influence to particle motion. Depending on the particle density ratio to the melt density, particle motions are different (fig. 7). Particle size is 1 mm and all particles "accept" momentum from the melt. Reaction to this momentum is different: the most heavy particle does not feel high frequency flow oscillations while lightweight particle motion is more controlled by the flow and its trajectory is defined by small velocity perturbations. Gravitation plays important role if density difference is large. For 5 times different densities comparing to the melt density "heavy" particle is drowned, but "light" flows on the surface of the melt. Particle, which density is the same as in the melt, flows together with the liquid metal.

Conclusions

LES model is proved to be very good tool to describe heat and mass transfer details and make statistical analysis of turbulent flows. Turbulent flow modelling limitations are mainly connected with mesh size and time step selection. The lack of LES method can be large computational time and sizeable amount of results for post-processing. LES model averaged flow has nearly the same characteristics as measured mean flow and 2D calculated mean flow. Wavenumber space experimental and computational spectrums are in accordance with Kolmogorov's theory. Particle tracking shows that gravitational interaction can be much stronger then the drag force affected motion.

Acknowledgements

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