MODELLING VELOCITY PULSATIONS IN A TURBULENT RECIRCULATED MELT FLOW

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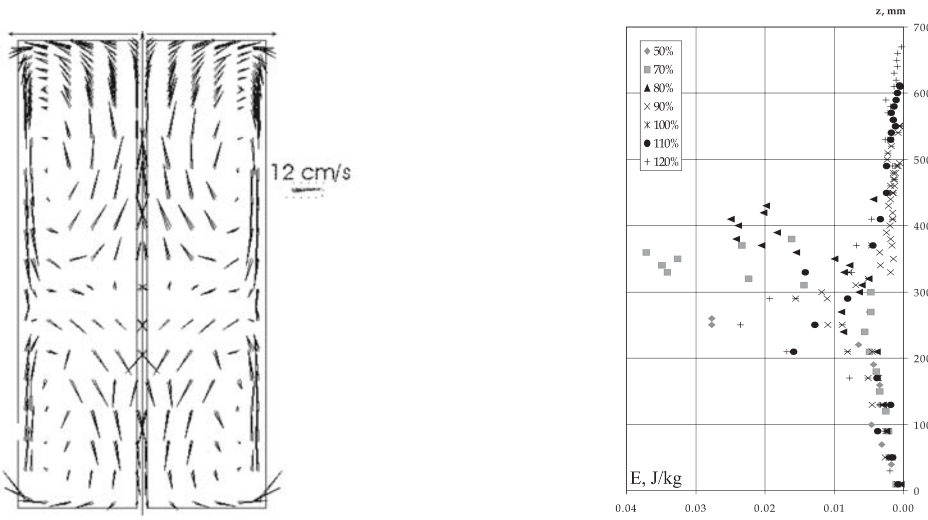
Introduction. To improve electromagnetic furnaces it is necessary to achieve a technologically defined superheat of the melt that is needed for doping and casting [1] with the lowest energy consumption. Characteristics of the melt flow in such processes are very important because they determine the heat-and-mass transfer in the melt. There are known experimental data on Wood's alloy flows in a conventional crucible [2], which can be used to tests computer models. Well-known and fast semi-empirical computer models used in engineering calculations often give results that differ from experimental [3]. More complicatred 3D models (LES, DNS) should be used for better quantitative agreement of calculations with the experimental data.

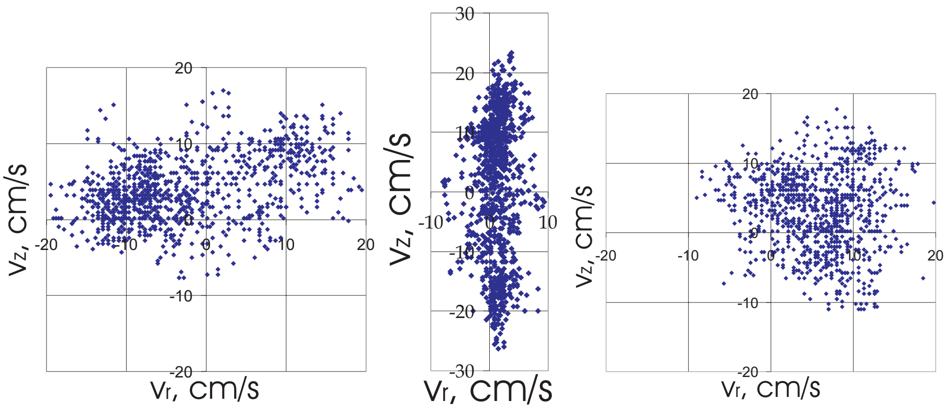
1. Experimental results and discussion. In the experiments, an electromagnetically driven flow of Wood's metal was studied in a cylindrical crucible ($r = 57\,\text{cm}$, $\oslash = 31.6\,\text{cm}$) [2]. The current of a 10-coil inductor varied from 1000 A to 2200 A and the frequency varied from 300 to 1500 Hz. The filling level of the melt was changed from 50 to 120% of the inductor height.

Analysis of experimental data shows that the average flow consists of two dominating toroidal vortices (Fig. 1*a*). The momentum, heat and mass are mainly transferred from one vortex to the other with low-frequency and turbulent flow velocity oscillations, which are observed in the turbulent flow between the main vortices in the middle zone of the melt (Fig. 1*b*).



(*a*) (*b*)

Fig. 1. (*a*) Averaged flow (experimental data, crucible filling level is 110%). (*b*) Kinetic energy of pulsations vs the height near the crucible wall.



a *b* *c*

Fig. 2. Velocity components, (*a*) $r = 0$, $z = 250\,\mathrm{mm}$; (*b*) $r = 147\,\mathrm{mm}$, $z = 250\,\mathrm{mm}$; (*c*) $r = 90\,\mathrm{mm}$, $z = 250\,\mathrm{mm}$.

First, some well-known dependences were verified to make sure that the measured velocity values correspond to the previous theoretical conclusions [2]: $v_{z\max} \sim I$ and $v_{\mathrm{ch}} \sim 1/\sqrt{F}$ (it can be suggested that v_{ch} is almost frequency-independent in the working frequency region). The flow intensity varied from 4 to 22 cm/s ($\mathrm{Re} > 10^4$), hence, the flow is highly turbulent.

The analyzed turbulent flow is higly anisotropic. The changes in axial velocity are 2–3 times greater than the radial velocity oscillations $|v'_z|/|v'_r|_{\max} \approx 2.5$ near the wall (Fig. 2*b*). The axial velocity has very expressive oscillations there, which are influenced by two melt jets going near the crucible wall in opposite directions. The radial velocity pulsations are dominating in the central region between the vortices (Fig. 2*a*): $|v'_z|/|v'_r|_{\max} \approx 0.6$. The wall effects at the crucible center are negligible and the flow there is mainly determined by inertia, while the disbalance of radial and axial velocity pulsations is smaller. The turbulence is nearly isotropic only near the central zones of the crucible (Fig. 2*c*).

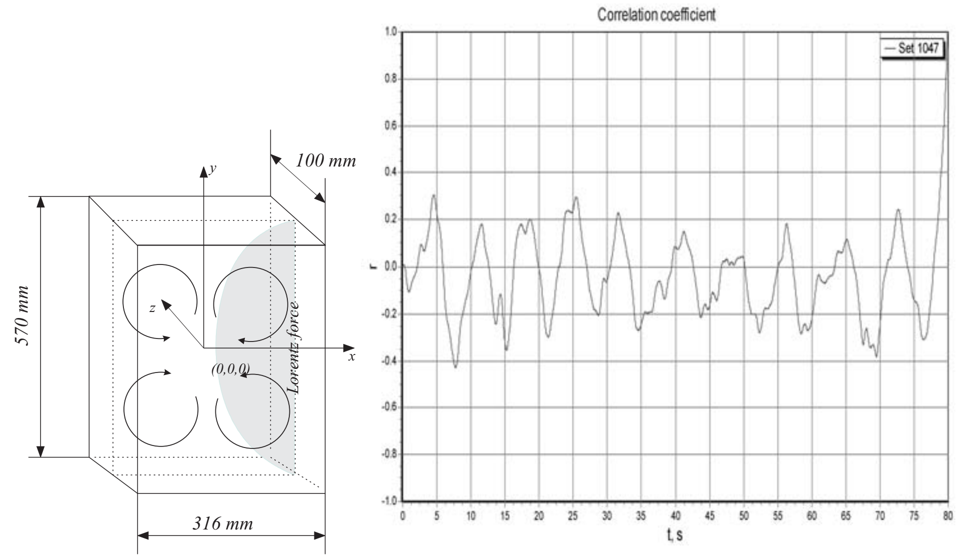
The maximum energy of pulsations between the vortices can be 10 times greater than in other regions near the wall (Fig. 1*b*). This difference is smaller when both vortices are more or less equal (filling level is about 90÷100%). The energy level of pulsations increases when the intensity of the vortices has a larger disbalance (filling level is less than 70% or greater than 120%).

The values of pulsation periods are of the same order as those of the circulation periods (Table 1).

2. Modeling of low-frequency oscillations. The model's geometry was simplified to obtain smaller number of elements and to perfom the LES simulation on a laboratory PC in *FLUENT 6.1.22* environment. The model had a rectangular tank form (Fig. 3*a*). The number of elements in the model was 216000. The front, back and upper planes had free surface boundary conditions. For the rest of the walls no slip boundary conditions were used. The *ANSYS* calculated

I, A	F, Hz	Eddy period, s	Pulsation period, s	$\langle v \rangle$, cm/s
1068	1444	12.6	13	5.50
1260	1470	10.5	15	6.62
1670	990	6.4	8	10.84

Table 1. Characteristic velocities and periods of the flow and velocity pulsations.



(*a*) (*b*)

Fig. 3. (*a*) Design of a model for LES. (*b*) Correlation spectra at the point near the wall between vortices. Force is 80% of rated.

force was applied using *FLUENT*'s UDF functions. This force varied for different calculation sets. Time step values were selected between 0.01 s and 0.05 s.

3. Results of computations. Nine minutes of the real flow were calculated with the time step of 0.04 s and a small Lorentz force (16% of the rated, which corresponds to the 1400 A inductor current). The characteristic velocities of such flow were below 1 cm/s (Re $\sim$ 3400). The melt was at rest at zero time and the motion of the melt began when force was applied. The velocity values

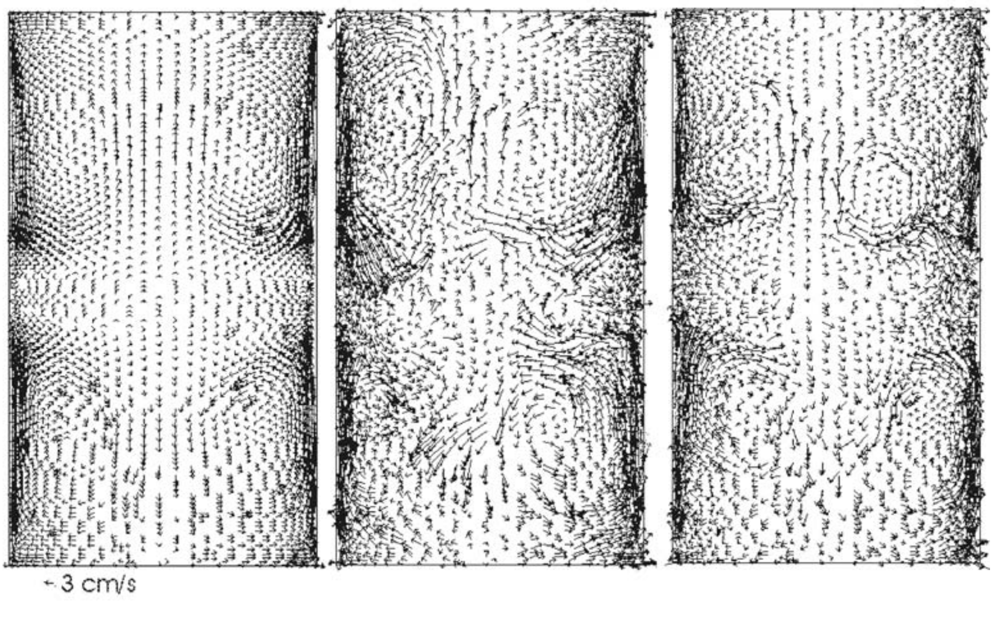


Fig. 4. Flow pattern in the middle plane (averaged, at 20, 100 s. Force is rated and corresponds to the current of 1400 A.

f/f_{nom}	Eddy period, s	Pulsation period, s	$\langle v \rangle$, cm/s (calc)	Discretization	$\langle v \rangle$, cm/s (exp)
0.16	115.0	40	0.6	First order	
0.80	20.9	20	3.3	Centr. dif.	5.92
1.00	13.8	17	5.0	First order	8.36
1.00	14.7	10	4.7	Centr. dif.	8.36

Table 2. Calculated flow parameters

achieved their maximum after about 70 flow second. Then the melt flow stabilized and approximately in 240 s low-frequency oscillations began, and the spectra of this stage are typical of the turbulent flow containing lots of frequencies. The intensity of such turbulent spectrum is at least one order of magnitude greater than that in the flow development stage. Our numerical approach gives a good qualitative pattern of the flow development.

The following calculations were performed with a force, which is 80% of the rated value. The maximum flow velocity near the wall is about 7.5 cm/s in this case (Re ∼25000). The stationary k-ε solution was selected as the initial state for the LES model. The flow pattern at every time step is not symmetric because of high turbulence (Fig. 4), but the averaged flow is fully symmetrical. The computed averaged flow shows a zone in the middle of the tank, between vortices, where the flow intensity is low. The height of this zone is about 10 cm. Correlation analyses gives the basic frequencies of pulsations (for example, the basic frequency of pulsations in Fig. 3*b* is about 7 s).

The calculations with the rated force corresponding to the 1400 A current were performed in the order with different schemes for the momentum equations. The FFT analysis for both calculations show that the difference in the spectra when using the first-order upwind and central differences schemes for the momentum equations is about 5–10 times at the region of low frequencies.

The pulsation period is of the same order as the eddy circulation period (Table 2). The calculated averaged velocities are smaller than the equivalent velocities from the experiments because of different model geometry. The maximum flow velocities are of the same order as the measured averaged velocities at the symmetry axis.

4. Conclusions. The calculated results are in qualitative agreement with experimental and literature data. The low-frequency velocity oscillations have been computed using different momentum discretization schemes. Each approach leads to the pulsations, but the calculated flow parameters are different. The proposed model makes it possible to work out a qualitative approach to the development of the turbulent flow from the state of rest to the state of high turbulence; it also can be used to perform the heat-and-mass transfer analysis of real systems.

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REFERENCES

1. V. Bojarevics, R. A. Harding, K. Pericleous, and M. Wickins. *Metallurgical and materials transactions B*, vol. 35B (august 2004), pp. 785–803.
2. E. Baake. *Grenzleistungs- und Aufkohlungsverhalten von Induktions-Tiegelöfen*(VDI, Düsseldorf, 1994)
3. E. Baake, B. Nacke, A. Umbrashko, A. Jakovics. *Magnetohydrodynamics*, vol. 39 (2003), no. 3–4.