THE OSCILLATIONS APPERING DURING THE PROCESS OF PARTICLE HOMOGENIZATION IN EM INDUCED FLOW OF ICF

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Abstract : The large oscillations of the axial component of liquid velocity in the middle zone of induction crucible furnaces (ICF) are observed. These pulsations produce the oscillations of particle transport appearing during the process of homogenization, which is important step of industrial processing of metals. The experimental and numerical results of the liquid oscillation and simulation of the pulsations of the particle distribution in the middle zone of ICF are analyzed in the paper.

1. Introduction

Induction crucible furnace (ICF) is the typical electroheat equipment, which is used for melting and overheating of conductive materials. The melt flow is formed by the Lorenz force and usually consists of two toroidal mean recirculated vortices. However, as far as the Reynolds number is high, developed turbulent flow with numerous dynamic vortices appears in the ICF. This flow pattern is well analyzed (see e.g. [1]).

The ICF is also often used for the mixing of different components of an alloy. Many components are put in the melt as solid particles and homogenized by turbulent flow thereafter. Widespread example of such technique is the processing of the steel, the carbon particles are mixed in the iron alloy like that.

The electric well-conductive materials have high melting temperature and are not optically transparent, but transparent liquids have low conductivity. Electromagnetic (EM) field produced not only induced flow motion but also heat up the liquid within penetration depth. Thereby thermal convection dominates in the low-conductive transparent liquids. Therefore, till nowadays there is no experimental technique to investigate the process of the particle motion and homogenization in EM induced flow, like in the ICF. So, more and more scientific and engineering problems are solved by means of numerical simulations.

It is known that two parametric turbulent models (k-ε, k-ω, etc.) are not able to simulate the intensive anisotropic pulsations of the velocity in the middle zone of the crucible, facing the maximum of the Lorentz force; only the Large Eddy Simulation (LES) model is able to do this [2]. It was also shown that only careful resolutions of these pulsations ensure the physically correct description of heat and mass transfer in ICF [2]. Therefore the LES approach for the flow simulation is used in this paper. The pulsation of axial velocity between two mean eddies were investigated experimentally and numerically in [3].

Table 1: The parameters of the laboratory scale ICF.

Parameter	value
Inductor frequency	365 Hz
Inductor current	2000 A
Melt and inductor height	570 mm
Crucible radius	158 mm
Number of inductor turns	12

It was pointed out [4], that the process of the particle homogenization in ICF, which is progressed by the particle exchange between the zones of upper and lower mean eddies (see fig 1), also have the oscillation nature.

This paper contains the analysis and comparison of macroscopic axial flow and particle oscillations that have an effect on the particle homogenization process. Small angular oscillation of particle distributions near the wall of crucible was also observed [5], but they are not so interesting from the industrial point of view. So the present research is done on the basis of the technique of data analysis for the homogenization process proposed in [4]. According to this technique the number of the particles in the zones of eddies and in the middle zone of intensive velocity pulsations was analyzed. The number of the particles, which are entrapped on the wall due to the balance of EM, buoyancy and drag forces, is excluded from the middle zone account. The physical processes that take place in this zone and that are important for the understanding of the present research were also discussed in [4].

So, the present paper will discuss the influence of the velocity pulsations in the middle zone of the ICF (see fig 1), between mean eddies, on the oscillations of the particle distribution that appears during the process of the homogenization. For the purpose of comparison with experimental data of the velocity distribution in ICF [1,3,5] the laboratory scale crucible, which is operated in ETP, University of Hanover, is simulated. The parameters of this experimental equipment are shown on tab 1; Wood's metal is used as the model liquid.

2. Mathematical model

As it was mentioned above, the LES approach should be used for the flow simulation to ensure the appearance of the anisotropic low-frequency velocity pulsations. The mesh, which consists of approximately 3 million elements and is refined in radial direction near the wall to resolve the viscous boundary layer, is used for the flow and the particles simulation.

As fare as the significant part of alloying admixtures is inertial particles, the particle motion is simulated within the Euler-Lagrange two phase model. The biggest part of alloying elements are pure conductive and a great transition resistance appears on the surface between the particle and the conductive liquid, hence, we can consider non-conductive particles; and the Lagrangian equation is as follows [4]:

$$\underbrace{\left(1+\frac{C_\mathrm{A}}{2}\frac{\rho_\mathrm{f}}{\rho_\mathrm{p}}\right)\cdot\frac{\mathrm{d}\boldsymbol{u}_\mathrm{p}}{\mathrm{d}t}}_{\mathrm{d}\boldsymbol{u}_\mathrm{p}/\mathrm{d}t+\text{added mass force}} = \underbrace{C_\mathrm{D}\cdot\boldsymbol{U}}_{\text{drag force}} + \underbrace{\left(1-\frac{\rho_\mathrm{f}}{\rho_\mathrm{p}}\right)\cdot\boldsymbol{g}}_{\text{buoyancy force}} - \underbrace{\frac{3}{4}\frac{1}{\rho_\mathrm{p}}\boldsymbol{f}_\mathrm{em}}_{\text{EM force}} + \underbrace{\frac{\rho_\mathrm{f}}{\rho_\mathrm{p}}C_\mathrm{L}\boldsymbol{\xi}}_{\text{lift force}} + \underbrace{\left(1+\frac{C_\mathrm{A}}{2}\frac{\rho_\mathrm{f}}{\rho_\mathrm{p}}\right)\cdot\frac{\mathrm{D}\boldsymbol{u}_\mathrm{f}}{\mathrm{D}t}}_{\text{acceleration + added mass}}, \quad (1)$$

where $\boldsymbol{U}=\boldsymbol{u}_\mathrm{f}-\boldsymbol{u}_\mathrm{p}$, $\boldsymbol{u}_\mathrm{f}$ and $\boldsymbol{u}_\mathrm{p}$ are liquid (flow) and particle velocities respectively, ρ_f and ρ_p are liquid and particle density respectively, $\boldsymbol{g}$ is free fall acceleration; $\boldsymbol{f}_\mathrm{em}=\frac{1}{2}\left[\boldsymbol{j}\times\boldsymbol{B}^*\right]$ is the averaged Lorenz force density, $\boldsymbol{j}$ is the current density, $\boldsymbol{B}^*$ is complex conjugated magnetic field induction, $\boldsymbol{\xi}=\left[\boldsymbol{U}\times\left[\nabla\times\boldsymbol{U}\right]\right]$; acceleration coefficient $C_\mathrm{A}(\mathrm{d}U/\mathrm{d}t, U)=2.1$ is approximated in the extreme Odar-Hamilton form [6], $C_\mathrm{D}(U)$ and $C_\mathrm{L}(U)$ are drag and lift coefficients in the Schiller-Naumann [7] and the McLaughlin-Legendre-Magnaudet [8] approximations respectively. The volume fraction of particles in liquid is less than 1%, therefore the one-way coupled model is used. The particles also are expected spherical form.

According to the present model the individual trajectories of the particles are calculated (fig 2). As fare as the results of the flow simulations in each individual area point and each moment of time can be not similar to the real values, but at the same time the common flow pattern corresponds well to experiment, we are not sure about veracity of the individual trajectories of the particles. However, the statistical approach, which consolidates all trajectories into the data of the particle distribution dynamics, should be adequate to the industrial processes. Therefore, the statistical approach is used in the present paper, as it will be shown below.

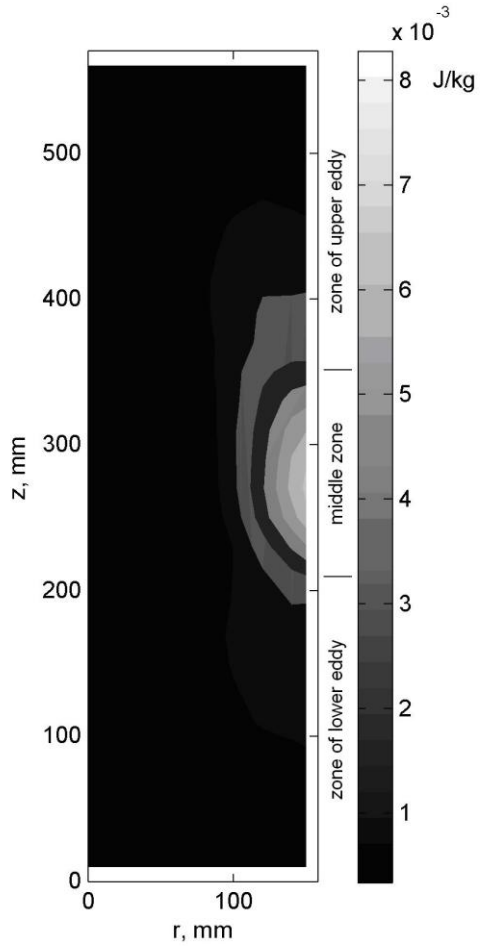


Figure 1: The axial part of turbulent kinetic energy. Experimental results [1].

The simulation is done by means of the self-improved *OpenFOAM* free code software.

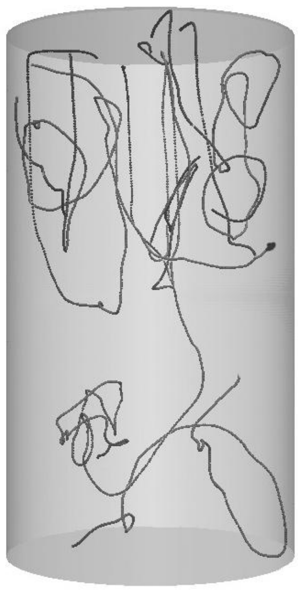


Figure 2: The example of the trajectories of certain particles in ICF.

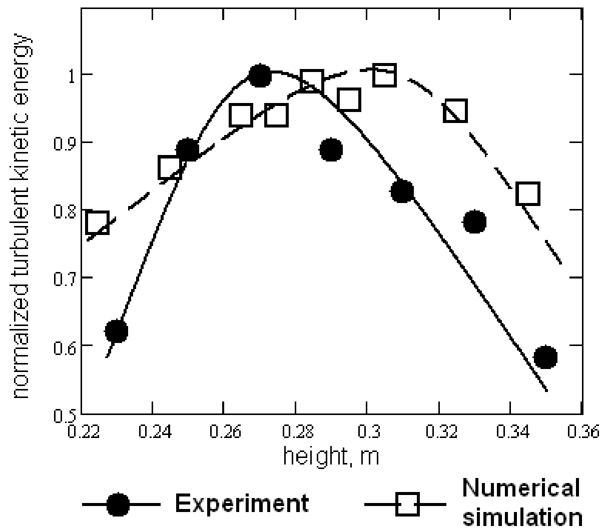


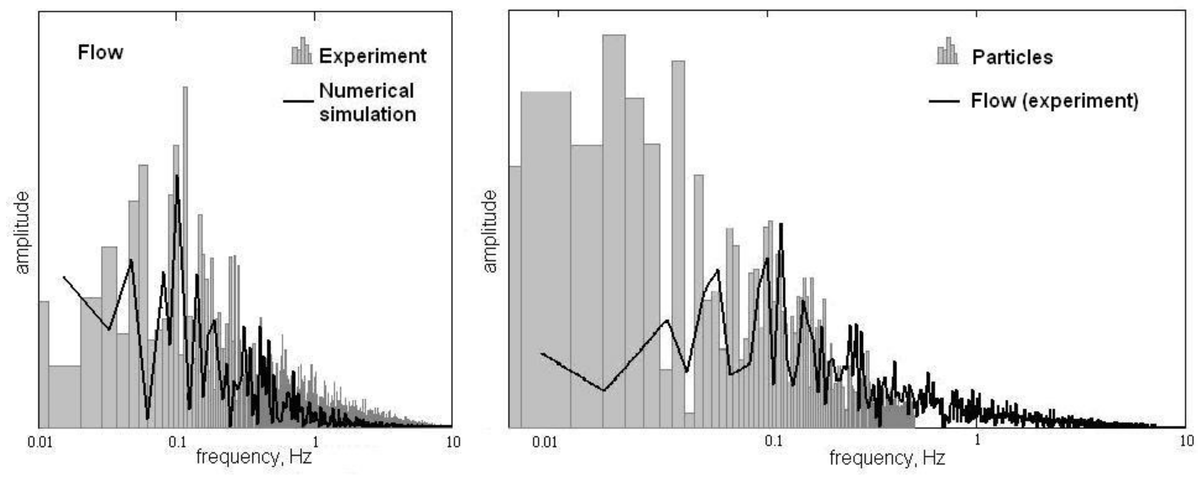
Figure 3: The axial distribution of the axial part of turbulent kinetic energy, integrated in radial direction.

2. Flow oscillations

In this paper we review the experimental data of velocity measurements in the flow of the Wood's metal in ICF [3] and obtain unpublished results, matched to the peculiarities of the particle homogenization process.

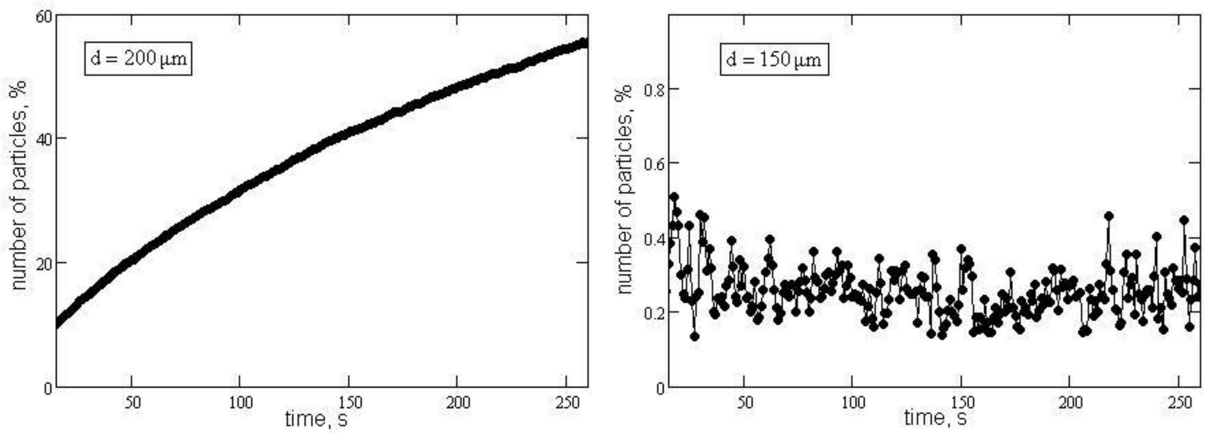
Firstly we should discuss the distribution of turbulent kinetic energy in the ICF. The experimental and numerical results [1,2] definitely states the maximum of the axial part of the energy of velocity pulsation ($< u_{\mathrm{f}\,z}^{'\,2} > /2$) in the middle zone of the crucible by the wall (fig 1). At the same time the pulsations in radial and angular directions are much weaker.

Within the bound of the method for analysis of the homogenization process [4] the axial motion of the particles in the whole horizontal plane is important; therefore we integrated the energy in the radial dimension. Such results are shown on fig 3. The experimental and numerical results are quite similar, and the difference between the experimental and numerical maxima is within the errors.



(a) (b)

Figure 4: (a) spectrum of the axial pulsations of flow velocity in the middle zone of ICF; (b) spectra of the particles and flow (experiment) oscillations in the middle zone of ICF.



(a) (b)

Figure 5: Percentage of particles, which are entrapped on the wall in the middle zone. $\rho_f / \rho_p = 1.5$; (a) the size of the particles is $200\,\mu m$; (b) $150\,\mu m$ particles.

Radial component of the Lorenz force has maximal value in the middle zone of the crucible, so the liquid rotates in different direction from this maximum. Hydrodynamic instabilities disturb the EM induced flow pattern and produce large axial pulsations in the middle zone by the wall. These oscillations have the main frequency, which is roughly defined as 0.1 Hz [2]. However, such clear spectrum can be observed only in one point exactly facing the maximum of the force; moving away from this point the spectrum becomes more and more fuzzy.

To compare the flow oscillations and the pulsations of the particle number during the process of the homogenization we should draw the common spectrum for the analyzed zone. The intensive pulsations are observed in the middle zone of the crucible between 0.22 m and 0.36 m from the crucible bottom (fig 1,3), therefore this zone is chosen for the pulsation analysis. Fig 3a certifies that the spectra of the pulsations, calculated from the experimental data, correspond well to the numerical results.

3. Particle oscillations

Initially particles are injected on a horizontal plane near the top surface of the crucible: such initial position of the particles roughly corresponds to the industrial case. After initial motion of the particle cloud (see [4]) the particles are distributed between zones of the upper and the lower eddies; the homogenization progresses by exchange between these zones through the middle zone of the intensive pulsations. As it was mentioned above, according to the technique of the analysis of the homogenization process [4], the number of the particles in the middle zone of intensive oscillations is counted. Fig 5 shows the percentage of the particles, which are entrapped on the wall due to the balance of EM, drag, buoyancy and lift forces. The EM force tries to press the particles to the wall, the lift force moves the particle away from the wall, the buoyancy force carries out axial motion of the particles, and the drag force makes the particles follow the flow (see [4]). In the case of big particles (fig 5a) the EM force is larger than the others, and the part of the entrapped particles increases monotonous. But fig 5b shows the case, when the forces are in the balance and small oscillations of drag and lift forces (due to the rippling of flow velocity) produce the pulsations of the part of the entrapped particles.

If we exclude the entrapped particles from the account in the middle zone, we can compare the oscillations of the liquid and the particles (fig 4b). The oscillations of the particles coincide with the flow pulsations in the part of the spectrum with high frequencies. But the low frequencies have greater amplitude in the particles spectrum. This fact can be explained with inertial motion of particles. The low frequency oscillations of the flow, as fare as they have longer period of influence on the particles, have more chances to take the particle away from the middle zone of the intensive pulsations.

4. Conclusion

The pulsations of the flow velocity in the middle zone have great influence on the particle homogenizations process in ICF. The distribution of the turbulent kinetic energy and the spectra of the flow velocity oscillations are quite similar for the experiment and the results of the numerical simulation. The comparison of the particle and the flow spectra in the middle zone points out the increased significance of the low frequency pulsations for the particle homogenization process. And the coincident high frequency part of the spectra can indirectly indicate the relevance of the numerical model for the particle motion in ICF.

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6. References

[1] Kirpo, M.; Jakovičs, A.; Baake, E.; Nacke, B.: Analysis of experimental and simulation data for the liquid metal in a cylindrical vessel. Magnetohydrodynamics. 43 (2007) 161-172.

[2] Umbrashko, A.; Baake, E.; Nacke, B.; Jakovics, A.: Modelling of the turbulent flow in induction furnaces. Metallurgical and Materials Transactions B. 37B (2006) 831-838.

[3] Kirpo, M.; Jakovičs, A.; Baake, E.: Characteristics of velocity pulsations in turbulent recirculated melt flow. Magnetohydrodynamics. 41 (2005) 199-211.

[4] Ščepanskis, M.;. Jakovičs, A.; Nacke, B.: Homogenization of non-conductive particles in EM induced metal flow in a cylindrical vessel. Magnetohydrodynamics. 46 (2010) 413-423.

[5] Kirpo, M.; Jakovičs, A; Baake, E.; Nacke, B: LES study of particle transport in turbulent recirculated liquid metal flows. Magnetohydrodynamics. 45 (2009) 439-450.

[6] Odar, F.; Hamilton, W. S.: Forces on a sphere accelerating in a viscous fluid. J. Fluid Mech. 18 (1964) 302-314.

[7] Schiller, L.; Naumann, Z.: Uber die grundlegenden Berechnungen bei der Schwekraftaufbereitung (in German). Ver. Deut. Ing. 77 (1933) 318-320.

[8] Legendre, D; Magnaudet, J.: The lift force on spherical bubble in a viscous linear shear flow. J. Fluid Mech. 368 (1998) 81-126.