Numerical Analysis and Experimental Verification of the Behaviour of Solid Inclusions in Induction Crucible Furnaces

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Abstract: **The paper refers to the dynamics of solid inclusion in the turbulent flow of liquid metal in induction furnaces. The numerical analysis is carried out adopting LES-based Euler-Lagrange approach in the limit of dilute conditions. The admixing of carbon particles in induction crucible furnace from the open surface of a melt is simulated. The behaviour of the particles in the bulk of the flow is illustrated as well as compared with the industrial observation of the open surface of the alloy. The paper also contains the description of the novel experimental technique, which is proposed for the verification of the numerical model. The experiment deals with ferromagnetic particles in the flow of Wood's metal in the small induction crucible furnace. This experiment confirms the satisfactory agreement with the numerical results.**

Key words: **induction furnaces; turbulent flow; solid inclusions; carbon; LES, experimental verification.**

1 Introduction

The present paper deals with the transport of solid inclusions in a recirculated flow of metal melt in the induction metallurgical furnaces. All of them (induction crucible furnace – ICF, channel induction furnace – CIF, and others) have the same physical principle of operation and, consequently, the similar flow distribution in the active region. This turbulent flow has unsteady structure with two mean vortices and intensive pulsations between them. Umbrashko et al. [1] showed that these pulsations are responsible for the exchange of heat and mass between the zones of the eddies and generally ensure the homogeneity of temperature in the furnace. Moreover, the two parametric turbulent models (k-ε, k-ω at alias) cannot simulate these instabilities, but the Large Eddy Simulation (LES) method should be used for solving fluid dynamics and thermal problems in practical applications. Later Kirpo et al. [2] and Ščepanskis et al. [3] analyzed the redistribution and the homogenization of solid alloying admixtures on the basis of the same hydrodynamic model. Both papers carried out the particle tracking using LES-based Euler-Lagrange approach in the limit of dilute conditions (one-way coupling). However, the set of the forces in the Lagrange equation in the paper [3] is extended in comparison with the model in [2] by adding additionally lift, acceleration and added mass forces. The significance of such model's extension is statistically proved in [4]. The simulated results of the present paper are obtained using the same model as in [3,4].

In spite of the numerous numerical results of the particle motion in the flows of the metal melts, until now there was no confident experimental investigation and, consequently, verification. The main obstacle is the fact that the materials that conduct electricity well are not optically transparent. The only known method, yielding comparative success, has been developed in Taniguchi's group (see e.g. [5]). It provides an opportunity to experimentally investigate experimentally the rate of the particle deposition in a turbulent flow of liquid metal under EM force. However, because the results are obtained by cutting solidified liquid,

it is impossible to receive any information about the dynamics of the process inside the melt using such experimental technique. Finally, the present paper proposes the experimental technique, which is based on the use of ferromagnetic particles. The technique and the results are described in detail below.

2 Admixing of the Carbon Particles in the Steel Alloy in ICF

Steel is produced by admixing the carbon and some other elements in an iron alloy. According to widespread induction technology the carbon particles are placed on the open surface of the liquid metal in the same ICF, where it was previously melted. Then the intensive turbulent flow of alloy mixed the solid particles into the melt in spite of their low density. Apparently, it is important to achieve the homogeneous distribution of the inclusions to ensure high quality of the alloy. Furthermore, it is desirable to reduce the time of mixing in order to decrease the energy consumptions and prevent the melt from excessive overheating. The carbon has a low conductivity, moreover, transitional resistance appears on the surface. Therefore the EM force is applied in the Lagrange equation as for a non-conductive particle. Other details of the model are discussed in the Introduction.

Fig.1 compares the simulation of the carbon admixing process in steel with the appropriate industrial observations, which were made by Otto Junker GmbH. As the liquid steel is not transparent, we can compare only the behaviour of the particles on the open surface of the steel during the initial stage of the process (Fig.1 (a) and (b)). The results qualitatively agree, so we can analyze the motion in the bulk of the crucible, which is invisible (Fig.1 (c)). Initially the flow drives the cloud of inclusions to the corner between the free surface and the wall, after that the intensive turbulent flow takes it inside and moves along the wall to the middle zone of the crucible. As it is shown in [1], the most intensive axial turbulent pulsations are observed exactly in this region. These pulsations carry out the exchange of the particles between the two mean eddies and thereby homogenize the distribution of the inclusions with the lapse of time. The homogenizations of the particles with different densities and sizes between the eddies has been carefully analyzed in [3].

3 Experimental Verification of the Model

The small 9 cm wide and 10 cm high crucible (that is a height of the melt) and the 4 kHz generator were used for the experiment. The inductor had 6 turns and was the same height as the crucible. The 432 A current was applied in the inductor that corresponds to the induced power of 1.3 kW. The crucible was filled with the Wood's metal (50% Bi - 26.7% Pb – 13.3% Sn – 10% Cd eutectic), which becomes liquid at 70°C.

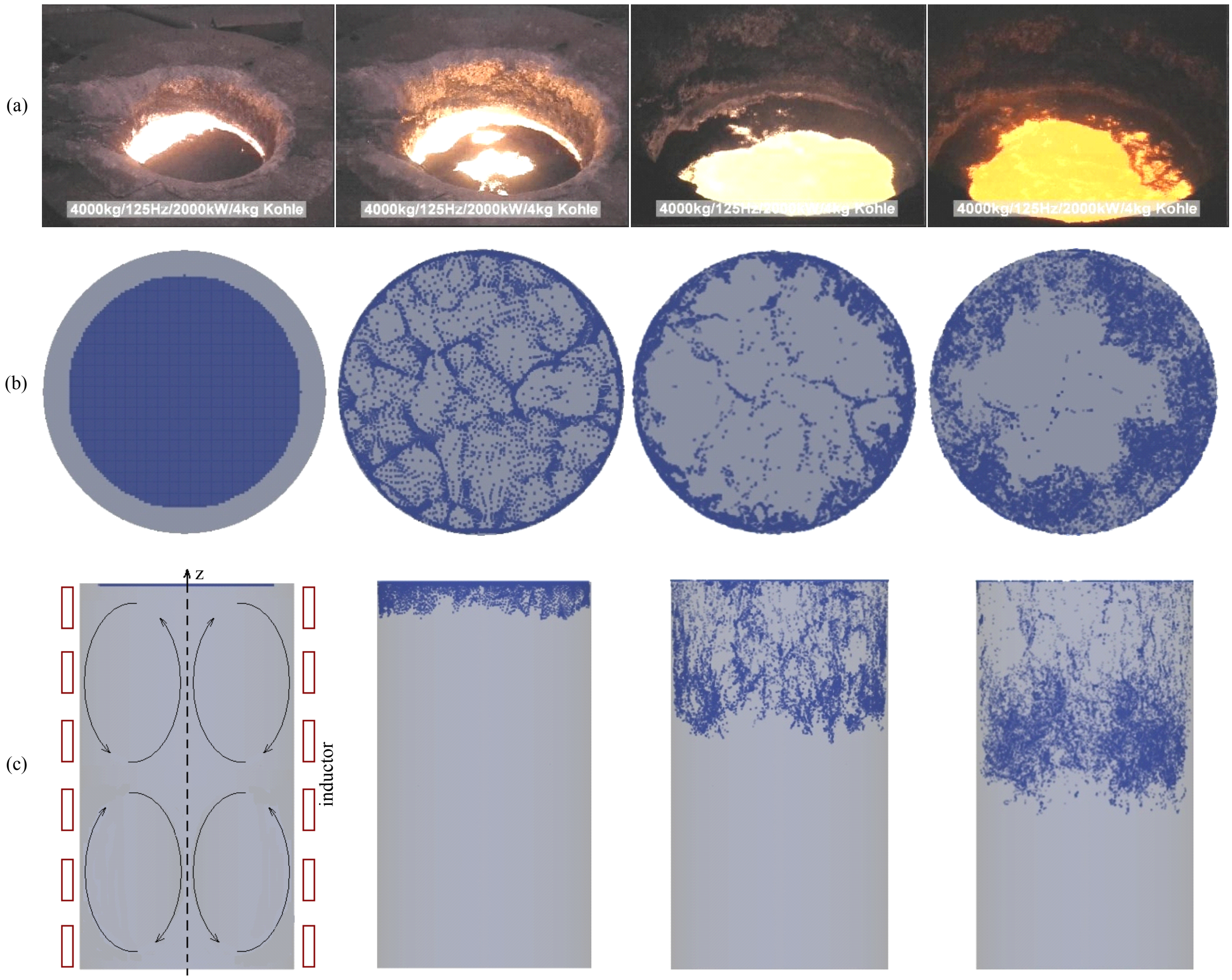
10.5 g of the spherical iron particles with diameter 250-350 μm were put on the open surface of the liquid metal that corresponds to the industrial case. The power of ICF was switched on when the particles were already on the surface, it was done in the attempt to reduce the operation time of the furnace and thereby avoid the Wood's metal from dangerous overheating. Obviously, this case differs from industrial conditions, where the inclusions are usually put on the surface of the already stirring metal. However, the measurements of the particle concentration were done at 11 s, when the transition regime was already passed. The local 4 ml probes of the particle laden Wood's metal were taken. The iron particles were collected from the liquid sample using strong permanent magnet and counted after that.

Generally the influence of EM field on the particles is included in the Lagrange equation as following force:

$$\boldsymbol{f} = -\frac{1}{2}\frac{3}{2}\frac{\sigma'' - \sigma'}{2\sigma'' + \sigma'}\mathrm{Re}\left[\boldsymbol{j}_0 \times \boldsymbol{B}_0^*\right] + \frac{\mu - \mu_0}{4\mu\mu_0}\,\mathbf{grad}\,B_0^2, \tag{1}$$

where $\boldsymbol{j}_0$ and $\boldsymbol{B}_0$ are the amplitudes of induced current and magnetic flux, σ'' and σ' are the conductivity of the liquid and the particle respectively, μ and μ_0 are the magnetic permeability of the particle and a vacuum respectively. The poor conductive ($\sigma' \ll \sigma''$) inclusions are usually used in the metallurgical applications, and they are non-magnetic ($\mu = \mu_0$). Thereby the equation (1) is reduced to the following expression:

$$\boldsymbol{f}_1 = -\frac{1}{2}\frac{3}{4}\mathrm{Re}\left[\boldsymbol{j}_0 \times \boldsymbol{B}_0^*\right].$$



(a) Snapshots of industrial process (courtesy Otto Junker GmbH);

(b) Simulated results, view from the top of the furnace; (c) Particles in the bulk of the flow, view from the side of furnace.

Fig. 1 The admixing of the 100 μm carbon particles into the steel alloy in ICF

However, the iron particles are used in the experiment. Iron is a good conductor ($\sigma' > \sigma''$) and a ferromagnetic material ($\mu \gg \mu_0$). It should be pointed out that the conductivity of iron is several times higher than the conductivity of Wood's metal, but due to the partial wetting and the transitional resistance we can assume the equal conductivity of the particle and the liquid. Therefore (1) for this type of particles can be reduced to

$$\boldsymbol{f}_2 = \frac{1}{4\mu_0}\,\mathbf{grad}\,B_0^2\,.$$

As it is shown on **Fig.2**, the magnitude of EM force for the non-conductive inclusions (f_1) almost coincides with the force for the ferromagnetic particles (f_2). Therefore the iron particles can be used like a physical model of the typical metallurgical inclusions in the induction furnaces.

Fig.3 compares the experimental results and the appropriate simulation. The conditions and the EM parameters in the simulation are the same as in the physical experiment. 3 curves on the Fig.3 correspond to the radial distribution of the inclusions at different depths: 3 cm (upper eddy), 5 cm (middle of the crucible) and 7 cm (lower eddy) from the surface. The experimental and simulated curves are in the satisfactory agreement to each other in all points except one: on the axe of symmetry in the zone of the upper eddy (the left point on Fig.3a).

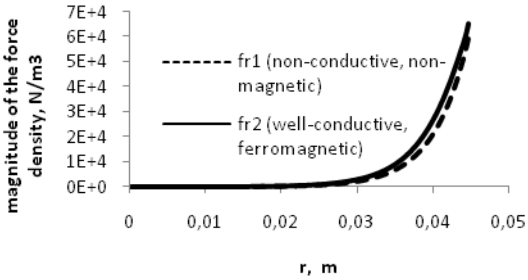
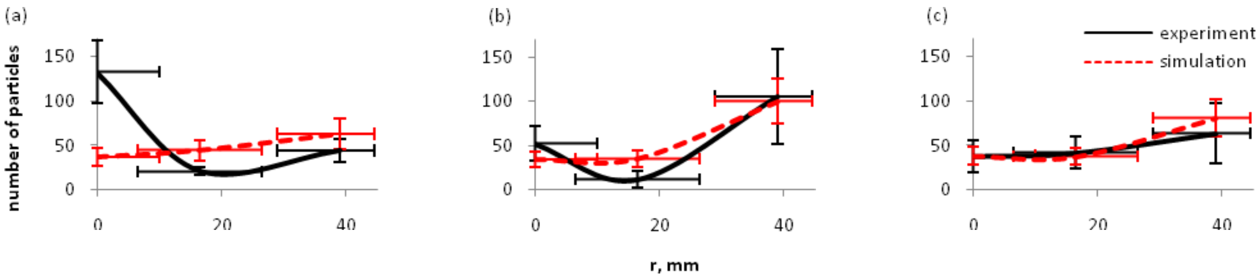


Fig. 2 Magnitudes of the radial component of the EM force density for non-conductive & non-magnetic (f_1) and for well-conductive & ferromagnetic (f_2) particles at the middle of the small crucible.



(a) 3 cm from the surface (upper eddy); (b) 5 cm from the surface (middle); (c) 7 cm from the surface (lower eddy).

Fig. 3 The distribution of spherical 300±50 μm inclusions in ICF at 11±2 s from the beginning of stirring (quasi-stationary regime). The volume of the sample is 4±1 ml.

4 Conclusions

(1) The numerical results of the carbon admixing from the open surface of the steel melt in ICF are in a good qualitative agreement with the industrial observation of the particle dynamics on the surface of the melt. Therefore the calculations can also give a relevant conception of the redistribution of the inclusion in the bulk of the melt.

(2) The iron particles can be used as a physical model for the tracking of non-conductive inclusions in ICF. The experimental results are in a satisfactory agreement with the simulations. However, the experimental investigation and verification will be continued.

References:

[1] Umbrashko A et al. Modeling of the turbulent flow in induction furnaces. Metall Mater Trans B [J], 2006, 37B: 831-838.

[2] Kirpo M, Jakovičs A, Baake E, Nacke B. LES study of particle transport in turbulent recirculated liquid metal flows. Magnetohydrodynamics [J], 2009, 45(3): 439-450.

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

[4] Ščepanskis M, Jakovičs A, Baake E. Statistical analysis of the influence of forces on particles in EM driven recirculated turbulent flows. J Phys: Conf Ser [J], 2011, 333: 012015.

[5] Taniguchi S, Brimacombe J K. Application of pinch force to the separation of inclusion particles from liquid steel. ISIJ International [J], 1994, 34: 422-731.

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