HEAT AND MASS TRANSFER IN A RECIRCULATED FLOW UNDER EM CONVECTION

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Summary The main objective of this paper to develop and verify hydrodynamical and thermal numerical model for mathematical simulation of different induction melting furnaces. The melt flow is formed by several recirculated vortices in the selected class of induction furnaces. Often used two-equation turbulence models gives contradictory temperature distribution in the melt with large inner gradients comparing to available experimental data. The authors propose to use Large Eddy Simulation turbulence model for hydrodinamic calculations to homogenize temperature distribution. These models are initaly tested using experiments on laboratory scale Induction Crucible Furnace (ICF) and Induction Channel Furnace (CF).

1. INTRODUCTION

The induction melting process is widely used today in metallurgical industry; hence it is a good object for investigation. 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 and to predict velocity and temperature fields in the real induction facilities using LES modelling.

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. This flow is turbulent and usually consists of one or several averaged recirculated vortices. The maximal intensities of the flow have characteristic values larger than 1 m/s in industrial equipment. Two types of induction furnaces are presented in this paper: Induction Crucible Furnace (ICF) and Induction Channel Furnace (CF). The Lorentz force driven flows in ICF consists of the two toroidal averaged flow vortices, which sizes and position depends on geometry and electromagnetic field distribution in the melt. These averaged vortices provides very rigorous melt stirring [10], which sometimes needs to be damped [11]. CF furnaces can be used in steel casting. The most interesting thing there is heat and mass transfer between the channel and a metal bath.

It was established in experiments that measured temperature distribution in ICF is very homogeneous in the whole melt volume. This fact well corresponds to LES modelling results. Temperature gradients in CF are even greater, but temperature homogenisation and higher superheat should be obtained for melt alloyage with additions, which can have higher melting temperature. Therefore calculation of average superheat is one of the tasks for computer simulation. From the other side alloyage species transport (for example carbon or silicon), homogenisation or sedimentation are actual problems both for ICF and CF, which can substantially influence quality of the final product or lifetime of the installation (ceramic
channel erosion is another well-known problem of CF). Our experience shows that LES approach together with the particle tracing can be effectively used to solve such problems.

2. FLOW VELOCITY MEASUREMENTS IN WOOD'S MELT

Experiments on Wood's melt flow velocity measurements in the Induction Crucible Furnace (laboratory scale) were performed at the Institute for Electrothermal Processes. Well-known Vive's probes (permanent magnet probes) [1,2] were used as velocity sensors. Experimental facility consists of large scale laboratory crucible (R = 15.8 cm, H/D = 1.8) with 12 winding inductor. Melt filling level is equal to the inductor height H in a “standard” experiment where effective inductor current I = 2000 A at f = 395 Hz produces B = 0.05 T magnetic field. Velocity probes were connected to high frequency (till 2 kHz) digital data acquisition system with high precision amplifiers and independent signal channels. Crucible walls were water cooled with ability switch on heating system and keep Wood’s melt in a liquid state without working AC convertor for a long time. It also allowed to keep constant temperature 80°C of the crucible walls and avoid temperature fluctuations influence on the flow. In this case melt temperature in the crucible was about 115°C.

Several series of experiments were performed. Sometimes two velocity components (axial and radial) were measured instantaneously [2], but in the last experiments all velocity components were measured separately. Every component was measured for 120 s with sampling frequency 32 Hz. Detailed analysis of experimental data are performed in [2,3]. Averaged velocity distributions for “standard” flow regime introduces two main vortices, but in reality instantaneous flow is highly turbulent (Re >10^6). Result analysis show that the flow structure is a double-torus (Fig. 1 left) with a common flow directed radially inwards at half the height of the melt load. Then the flow is carried up and down in the central region, goes radially outwards at the top and bottom lids, and closing accordingly along the sidewalls. In other words

![Fig. 1. Averaged velocity patterns taken from experiments for 570 mm filling level (left), 400 mm (middle) and from LES simulation for 570 mm (right).](image-url)
the mean flow is formed by two recirculated vortices. The inward direction of the flow in the middle region is determined by the Lorentz force distribution in the melt. The maximal Lorentz force density can be found in the thin border layer at the half height of the inductor, e. g. the middle part of the melt. This region is also characterized by the strong flow coming from the top and the bottom to the center along the wall, which can be imagined as a collision of two fluid jets, which come from opposite directions. Due to the turbulence and different boundary conditions at the top free surface and at the bottom wall the intensity of the wall jets varies in time, creating instability and secondary turbulent vortices of a considerable scale, which can annihilate later introducing low-frequency velocity oscillations in the whole melt.

The averaged flow structure for 400 mm filling level (Fig. 1 middle) is also represented by large toroidal vortex, which is higher than a half-height of the inductor.

The characteristic average velocity values are also higher till about 30 cm/s. The top surface of the melt is located in the maximal Lorentz force action region and its deformations and strong oscillations were clearly observed in the experiments. A small vortex also seems to be present near the top surface and crucible wall, which makes all the flow there very unstable.

Spectral analysis of velocity time series (Fig. 2) introduce very high level of specific kinetic energies \(0.5v_i v_j\) in low frequency region. Pulsations, which produce such energy peaks, can also be identified on velocity time charts. They introduce low frequency velocity oscillations with characteristic periods about 10 s. The intensity of the velocity oscillations in the melt is comparable with the average flow velocities. This spectra is also in good accordance with Kolmorov’s theoretiocal curve \(E \sim (f/\overline{v})^{-5/3}\), where \(\overline{v}\) is a constant characteristic velocity.

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Taking a look on turbulent energy charts (Fig. 3) the maximums of turbulent kinetic energy can be identified. The turbulent energy maximum is located approximately at half height of the inductor near the crucible wall. For 570 mm filling level axial velocity component introduces the largest part into turbulent kinetic energy. For 400 mm melt filling the maximal value of the turbulent energy is approximately two times higher comparing to the 570 mm case. The energy maximum here is shifted closer to the top surface and is more sharp. The flow is more determined (stable) in other crucible regions for 400mm.

All above mentioned experimental facts let us say that there is a strong heat and mass exchange between the averaged flow vortices in the flow, which leads to fast homoginization of temperature and possible alloying particles in the melt.

3. LES MODEL VERIFICATION

Our LES approach was already previously published [4,5], therefore only main objectives will be shortly described. The melt flow in all our experiments and simulations is EM driven. Therefore we start with the EM model, which is usually build in ANSYS. Depending on the model geometry the model can be 2D axisymmetric or 3D (usually not full). Free surface deformation is also taken into account if necessary. Calculated EM forces and Joule heat sources are transferred to HD model in FLUENT or CFX. HD model usually has about 2 million elements with sizes not larger than 3 mm.

LES simulation starts from converged k-ε solution or from zero velocity field. Usually we need to calculate about 5 s of the flow to get fully developed turbulent flow. Then averaging starts. Second order central difference approximations are used for equations. Depending on the model geometry and characteristic flow velocities 0.005 s or 0.01 s time steps are used. The total simulation time can achieve more than 60 s.

Typical LES averaged flow for “standard” ICF case (Fig. 1 right) represents two vortex structure, which corresponds to experimentally determined. However velocity magnitudes and turbulent kinetic energy values are a little lower. It can be explained by large complication of studied phenomena (3D transient simulation) and by possible additional limitations, which are introduced by fixed free surface and finite size of the elements. From the other side this approach was successfully used for TiAl flow simulation in Induction Furnace with Cold Crucible [6] and other industrial projects.

4. INDUCTION CHANNEL FURNACE (CF)

CF with large electrical and thermal efficiency are used for melting and stirring of iron and other metal alloys. Heat is generated in narrow channel and is transferred to metal bath through the neck. The melt flow is very complex and is influenced not only by the EM forces, but also by bouyancy [7,8]. There are available experimental data [8] on laboratory CF, which size is close to industrial and which is filled with the Wood’s melt. This CF was selected for transient 3D LES simulation.

4.1. EM simulation

Electromagnetic simulation of CF was performed in ANSYS Classic v.10 FEM package using APDL script. The script is fully parametric and allows easy modifications of model geometry and mesh. Taking into account symmetry of geometry, only half of the full furnace is
EM modeled (Fig. 4). The model has several regions defined, where material electrical properties are important:

- channel itself and a bath with the Wood's metal;
- copper cooling jacket between the inductor and the channel;
- copper inductor;
- iron core for EM field amplification;
- surrounding air with infinite boundary.

Introducing laminated iron core its electrical conductivity can be taken to be zero, because electrical power losses in the core are not taken into account. Each region consists of several volumes and brick meshing was adapted everywhere except air and a part of channel neck. A special layer of infinite elements was extruded in air to obtain correct EM field distribution far from the model.

Built model has a little shorter inductor (one turn less) then it is in the real experimental

![Fig. 4. Geometry and fine mesh (760k elements) of EM model.](image)

![Fig. 5. EM force distribution on symmetry plane.](image)

![Fig. 6. Total power losses and power losses in the melt depending on amplitude of inductor current.](image)

\[
y = 4.320E-05x^2 - 3.347E-05x + 1.853E-02
\]

\[
R^2 = 1.000E+00
\]

\[
y = 0.000040x^2 + 0.000961x - 0.576923
\]

\[
R^2 = 0.999999
\]
facility. Inductor consists of 32 (16 for half model) circles with rectangular cross-sections. Current is calculated including skin effect. The magnetic field is homogenized by presence of the laminated core. The model was verified using total electrical power on two grids (coarse and fine) for \( I_{\text{amp}} = 1200 \, \text{A} \) (50 Hz). Calculated total electrical power and power losses in the melt (Joule heat) were almost equal for two different grids. Inductor current – total power curve was constructed using the coarse model (Fig. 6), which illustrates quadratic dependence of the power losses in the system on inductor current (\( P \sim I^2 \)). Amplitude current 1200 A, which produce about 62 kW total power, was also selected to be a model current for EM force and Joule heat calculation on large grid.

Simulation results show very symmetrical Lorentz force (Fig. 5) distribution in the channel. The maximal values of Lorentz forces are noticed on the inner bottom surface of the channel, which is the closest to the inductor. Lorentz force direction is collinear to the radii direction on a symmetry plane and force intensity in the bath is much lower than in the channel. EM force distribution in the channel crosssection should lead to two-vortex structure inside the channel. It also should ensure upflow directly above the channel in the symmetry plane (e.g. Fig. 8).

4.2. CF hydrodynamics

Hydrodynamics was simulated in ANSYS CFX CFD package. 3D k-\( \varepsilon \) model was used for the first calculations on the half of the full geometry with symmetry boundary conditions, which grid had about 1.3 tetrahedral million elements (unstructured mesh) and refined near wall boundary. 3D transient LES simulation was performed on the full geometry.

No slip boundary conditions were used for hydrodynamics on channel and bath walls, top surface was left to be free, but without fluid-air interface deformations. Channel had adiabatic thermal boundary conditions while metal bath had fixed temperature 80°C on the walls and convection conditions with heat transfer coefficient \( a = 20 \, \text{W/(m}^2\cdot\text{K)} \) on free surface. The model included buoyancy with temperature dependent melt density: \( \rho = \rho_0(1-\alpha(T-T_0)) \), where \( \alpha = 0.0001 \, \text{1/K} \) is the thermal expansion coefficient and \( \rho_0 = 9400 \, \text{kg/m}^3 \) at \( T_0 = 70 \, \text{°C} \). Gravity vector is directed to negative z. High resolution numerical schemes were selected for

Fig. 8. Calculated steady and instantaneous velocity distribution on symmetry plane.
precise calculations. LES simulation used 0.01 s time step and convergence was achieved with RMS error less than $10^{-4}$.

$k$-$\varepsilon$ model calculated velocity distribution in the symmetry plane (Fig. 8) satisfies EM force distribution in the melt. Flow is directed radially outwards in the channel and there is upflow just above the channel forming two vortex loops in the bath. These loops have complex structure and are closed on front wall of the bath. This flow structure and absolute values of velocities are very close to those, which are observed in experiments (Fig. 9). There is less intensive upflow near the left and right side of symmetry plane. Different intensity of this side flow can be explained by the buoyancy, because $k$-$\varepsilon$ model calculated temperature distribution in the channels (Fig. 10 left) is not symmetrical. Both in experiments and in numerical simulation there can be specific factors, which can disturb ideally symmetrical but not stable temperature distribution. Consequently,
a prior direction of the flow in the channel can develop even in steady simulation.

This temperature distribution in the channel introduces 40 K temperature difference along it (Fig. 10 left). Such large temperature gradient in the channel seems to be abnormal. Channel walls are adiabatic and all induced heat should go to the melt bath. However flow intensity in the bath is lower than in the channel and there are vortex interaction zones near the channel exit, which are similar to the ICF averaged vortices. Hence temperature in the bath is just above the wall temperature.

Instantaneous velocity pattern calculated with LES model (Fig. 10 right) shows highly turbulent structure of the flow. However even here the regions of more or less constant direction flow can be determined. Looking at the instantaneous temperature distribution, it can be noticed that temperature distribution in the channel is much more homogeneous with characteristic temperature about 367 K and heat comes from it to the bath where temperature is about 354 K. We expect less temperature difference between the channel and the bath, which more correspond to the real situation. These expectations are based on existence of low-frequency velocity oscillations in the channel. Velocity distribution in the channel can form vortices along it and possibly these vortices can have a long life time.

Velocity distribution inside the channel is represented by two-vortex structure (Fig. 11), which also is in accordance with Lorentz force distribution and experimental measurements (Fig. 12). Characteristic velocity magnitudes in the channel are approximately the same for both models (0.5 – 0.7 m/s in maximum). The distance between the vortex centers is about channel radius.

5. CONCLUSIONS

Presented results provide a short overview on heat and mass transfer processes in two types of induction furnaces. It is shown that low-frequency and turbulent velocity oscillations play an important role in transfer processes and often used two-equation turbulence models can give abnormal temperature distributions with very large temperature gradients in the melt. LES
approach can be successfully used for complicated flow, heat and mass exchange modelling in
different industrial facilities. Received results are in accordance with experimental data not only
for ICF but also for CF with much more complicated geometry.

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NOMENCLATURE

\( v \) melt velocity, m/s,
\( v' \) velocity pulsation, m/s,
\( \text{Re} \) Reynolds number,
\( a \) heat transfer coefficient, W/(m\(^2\)·K),
\( k \) turbulent kinetic energy, J/kg,
\( I \) electrical current, A,
\( T \) temperature, K,
\( P \) electrical power, W.

Greek symbols

\( \alpha \) thermal expansivity,
\( \varepsilon \) energy dissipation,
\( \rho \) melt density.

Subscripts

ampl amplitude value.

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