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Transient 3D Simulation of Recirculated Melt Flow

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Abstract

Transient 3D calculations with Large Eddy Simulation (LES) turbulence model were performed to investigate numerically the melt flow dynamics in an induction crucible furnace. The comparison of the numerical simulated results with collected experimental data, carried out, that there is good agreement between calculated and measured periods of low-frequency oscillations and heat transfer between the toroidal flow eddies. It was not possible to get such conformity using two-dimensional modifications of the k-ε turbulence model.

Introduction

Experimental investigations in induction crucible furnaces (ICF) show large intensity of low-frequency oscillations, which are oriented perpendicular to the averaged flow in the zone of interaction between the toroidal flow eddies [4]. These pulsations play significant role in heat and mass transfer between flow vortexes. Therefore, this aspect of flow dynamics has to be taken into account when modeling concentration and temperature distributions in such systems.

Numerical calculations of the heat and mass transfer processes in similar axial symmetrical systems with several recirculated flow eddies, which are based on various 2D stationary k-ε models and commercial codes, e.g. ANSYS and FLUENT, lead to results, which are significantly different from experimental data. This is in spite of the fact that calculated averaged flow patterns usually are in good agreement with the experiment [2, 3]. Considering technological importance of the numerical modeling of such widespread industrial processes like melting and homogenization of alloys, several ways were developed to solve this problem. One of the realized approaches, which was oriented to practical use, is the 2D modeling with extended k-ε model by additional empirical thermal conductivity, which is caused by the mentioned low frequency flow oscillations [5]. Also, the numerical studies of the flow dynamics were performed using transient 3D models for the calculation of the turbulent flow velocity and temperature distribution in order to investigate the eddy dynamics from the scientific point of view.

For three-dimensional calculations we chose Large Eddy Simulation (LES) turbulence model, which is an alternative to the k-ε model. LES method is implemented in commercial computational fluid dynamics package FLUENT, which was used for the calculations presented in this paper. Typical finite element mesh consisted of about three millions cells and there were calculated more than one minute of the flow development with time-step of 10 milliseconds. There were carried out intensive numerical studies on the subject how the calculation results depend on temporal and spatial discretization, as well as on subgrid turbulence model choice. Analysis of the latest results shows that calculated flow oscillation frequencies are in a good agreement with experimental data.

1. Model Parameters

The model induction crucible furnace [1] has a radius of 158 mm and a height of 756 mm, where the inductor height is 570 mm. Wood's metal, which has a melting point of 72°C and a dynamic viscosity of $4.2 \cdot 10^{-3}$ kg/m·s, was used as a model melt. There are a lot of experimental data for various filling levels, frequencies and inductor currents. For numerical modeling was chosen the following combination of parameters: the crucible was filled at 100% of the inductor height, the operating frequency was 400 Hz and the inductor current was 2000 A. The characteristic velocity magnitude measured on the symmetry axis was about 16 cm/s, therefore the flow is considered to be highly turbulent ($Re \sim 5 \cdot 10^4$).

Two turbulence models were applied during the numerical investigations. First of them is the well-known k-ε model, which has relatively low mesh requirements and is widely used in various numerical engineering applications. This model usually produces good results for the time-averaged velocity distribution in case of stationary 2D calculations, but fails to describe correctly the heat and mass transfer quantities when system contains at least two dominating flow eddies. Most probably it happens because of incorrect calculation of the turbulent kinetic energy distribution. Analysis of the experimental data reveals that maximums of turbulence kinetic energy are located between the toroidal flow eddies, but not in the eddies centers as shown in the results of the numerical calculations. By the way, such distribution is characteristic for k-ε model even when moving to the 3D transient simulation, as will be shown below (Fig. 2).

Large Eddy Simulation (LES) model needs much finer mesh and can be considered as some kind of compromise between k-ε model and DNS (Direct numerical simulation) method, which is based on non-averaged Navier-Stokes equations. Large eddies are resolved directly, therefore turbulent viscosity shows dissipation of eddies smaller than grid element size. There are two options for calculating subgrid turbulent viscosity: either Smagorinsky-Lilly or RNG method. Both of them produced similar results, which are in better agreement with the experiment than results of k-ε turbulence model.

The crucible volume was meshed in several ways with different mesh sizes, to examine the influence of the level of grid resolution on solution stability and reliability. Several meshes were built with various numbers of elements from 250 thousands up to 6.5 millions, and with two of them (0.4 and 3.5 mil.) were performed transient calculations for more than 60 seconds of the flow time. Three-dimensional calculations need a lot of time and computational resources even when using parallel processing on 4 or 8 processors; that's why it was not possible to analyze prolonged flow development with more different grid sizes up to now.

Each transient calculation started with non-initialized velocity field, so to avoid waste of time calculating formation of the flow pattern, first ten seconds were calculated with time-step 1 second. Formed velocity field (Fig. 7) was symmetric and resembled results of 2D steady-state calculations with k-ε model. Further, simulation went on with time-step of 10 ms. There were chosen three control points along the crucible radius at half-height of the inductor. Velocity magnitude values in these points were written to the output file after each time-step. Therefore it was possible, to analyze the oscillations and compare the time-depended behavior of the velocity components with the experimental results.

2. Results of Transient Numerical Simulation

2.1 Turbulent Heat Transfer between Dominating Flow Eddies: Experiment and Modeling

As described before, experimental velocity measurements in induction crucible furnaces show presence of low-frequency flow oscillations (Fig. 1). Auto-correlation analysis shows, that most intensive of them has characteristic period about 8-12 seconds depending on inductor current, $T \sim 1/I \sim 1/v_{ch}$ [5]. Observed oscillations most probably are the result of two dominating toroidal eddies periodic expanding and the oscillation frequency depends on the eddies turnover time: the rotation speed of the flow eddy is proportional to the oscillation frequency. During experiments were measured all three velocity components, and it turned out that flow in azimuthal direction is well developed together with radial and axial components.

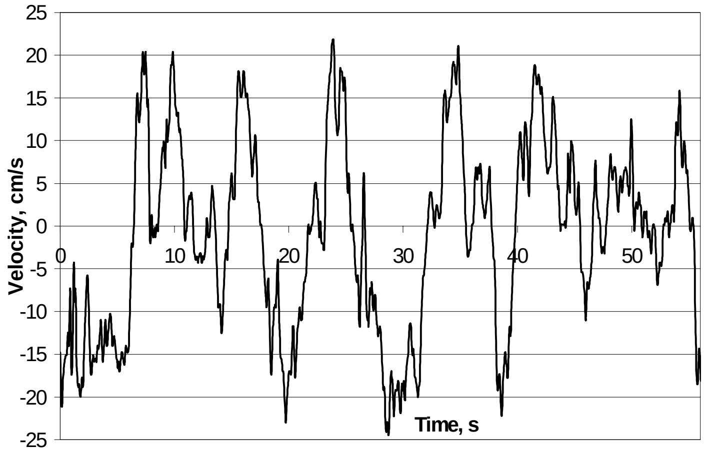

Fig. 1. Axial velocity oscillations measured in experimental ICF in the region between the dominating flow eddies near the crucible wall

Consequent analysis of the experimental data and numerical results leads to the idea, that heat and mass exchange between upper and lower crucible regions is mostly caused by these long-period flow oscillations. This conclusion was made because turbulent together with molecular thermal conductivity are not able to provide sufficient heat transfer through the exchange zone between the flow vortexes and to predict comparable values, carried out by estimations based on experimental data (estimated effective thermal conductivity $\lambda_{eff} \sim 5 \cdot 10^3$ W/m·K) [5]. The use of the 2D k-ε model leads to calculated maximums of turbulent kinetic energy located in the centers of the eddies, but minimum is in the zone of eddies interaction. Therefore, turbulent viscosity and turbulent thermal conductivity magnitudes in this zone are comparable with molecular values ($\lambda_t \sim \lambda_m \sim 20$ W/m·K), and much smaller than estimated. Time averaged axial velocity components are approximately zero in this region and the main flow is mainly in radial direction, so the vertical convective transfer mechanism in this region is negligible also.

When LES turbulence scheme is used, the subgrid viscosity distribution significantly differs, i.e. maximum now is located near the crucible wall and between the recirculated flow eddies (Fig. 3). But at the same time highest viscosity values are usually one order of magnitude less than in case of k-ε turbulence model. The reason of this is, because only small vortexes are responsible for the subgrid viscosity calculation, while large eddies are resolved directly. As result, effective thermal conductivity still doesn't fit experimental estimations. If the heat and mass between eddies are mainly transferred with long time-scale oscillations, then only transient simulation can help calculating correct temperature and concentration distributions.

2.2 Dynamics of Recirculated Flow

Two-dimensional axial-symmetric transient calculations with various turbulence models and time steps did not show any flow oscillations. This was expected considering the three-dimensional character of concerned phenomenon and absence of the azimuthal velocity component in such kind of analysis. In it's turn 3D simulation using k-ε turbulence model produced symmetric flow pattern with almost unnoticeable velocity fluctuations. Such results can be caused by incorrect turbulent viscosity distribution, when oscillations of the large-scale vertexes are damped by the high viscosity values distributed like in case of 2D steady-state calculations.

First numerical experiments with 3D LES turbulence model and relatively rough mesh produced flow instabilities similar to the observed in experimental induction furnace. To investigate the reliability of these results, the mesh was several times refined, then were calculated up to two minutes of the flow development with time-step 10 milliseconds. Examining results, it was found out that axial velocity oscillates with the amplitude of approximately 20 cm/s near the crucible wall in the region of eddies interaction (Fig. 4), but at the half-radius of the crucible these oscillations are approximately two times less intensive. This amplitude remains the same for different mesh discretization levels and quite good agrees with experimental data. Oscillation periods for two grid sizes and subgrid models are provided in the Tab.1.

Tab. 1. Oscillation periods from experiment and different numerical model parameters

Approximate number of grid elements, $x10^6$	Subgrid turbulence scheme	Total calculated flow time, seconds	Low-frequency oscillation's period, seconds
0.4	Smagorinsky-Lilly	130	14
3.5	Smagorinsky-Lilly	60	12
3.5	RNG	60	10.5
Experimental data		56 (measured)	9

Examining graphs with the Fourier analysis of experimental and numerical data (Fig. 5 and 6), one can see that calculations contain not only the main frequency, but they also with good conformity reproduce several additional pulsations with higher and lower frequencies. On the presented graph spectrum of the numerical results is shifted in the direction of the lower frequencies in comparison with the experimental data. This tendency remains when decreasing spatial grid resolution. Unfortunately, further experiments with mesh refinement are confronted with too high time and computational resources consumption.

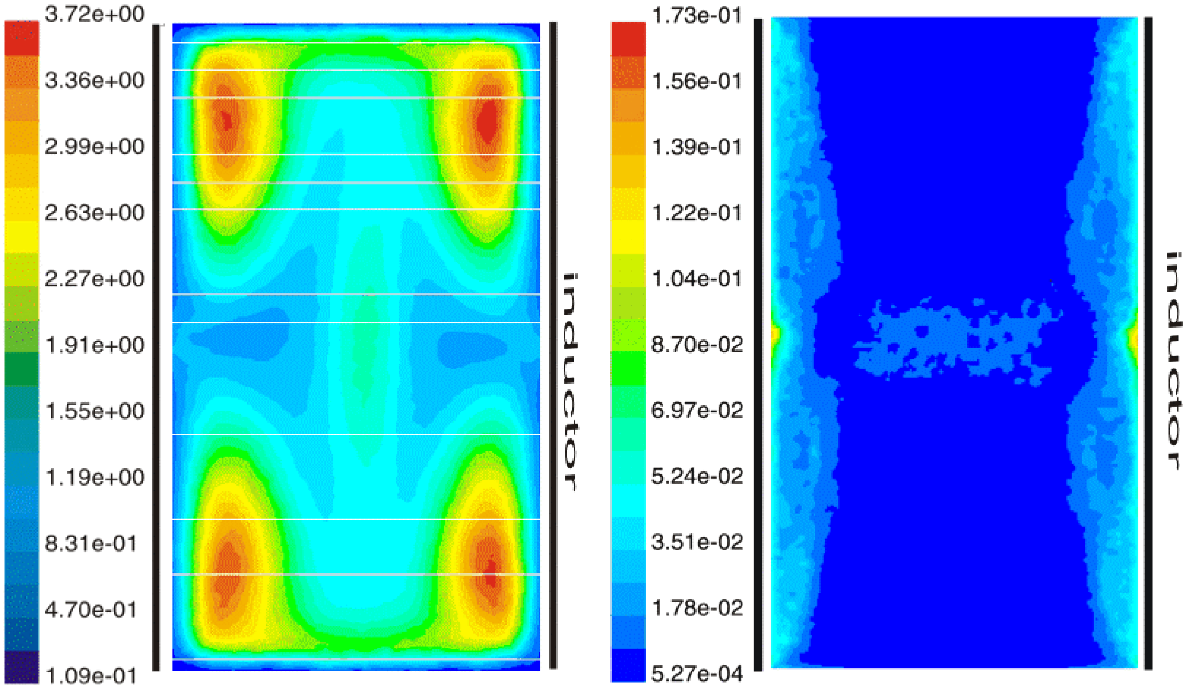

Fig. 2 and 3. Characteristic turbulent viscosity distribution in [kg/m·s] calculated with 3D k-ε and LES turbulence models

Three movies were made with different crucible cross-sections to get visual interpretation of the three-dimensional flow development during numerical simulation (included on colloquium's CD). First two of them display velocity vectors in, consequently, vertical and horizontal symmetry planes; and the third shows contours of the velocity magnitude on the melt surface. Last one have prototype filmed above the industrial ICF and in this film can be seen periodic regions with relatively high flow intensity, which rotate around the central point. It is noticeable that numerical movie has common details with the movie taken from real furnace.

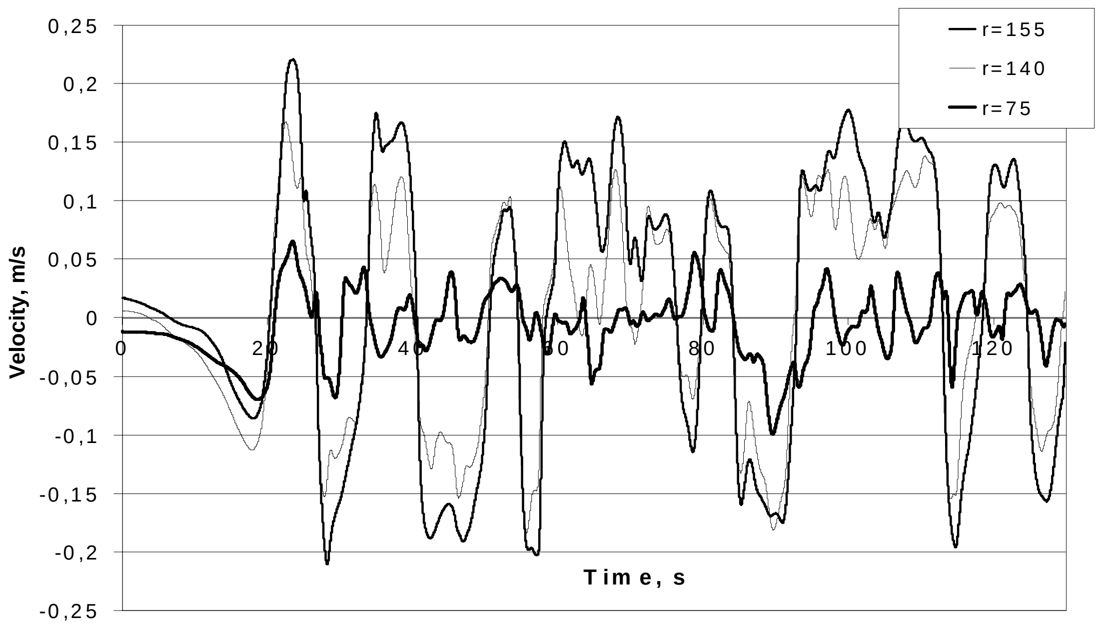

Fig. 4. Axial velocity oscillations at the middle-height of the inductor calculated with 3D LES turbulence model (mesh contains 400 thousands elements)

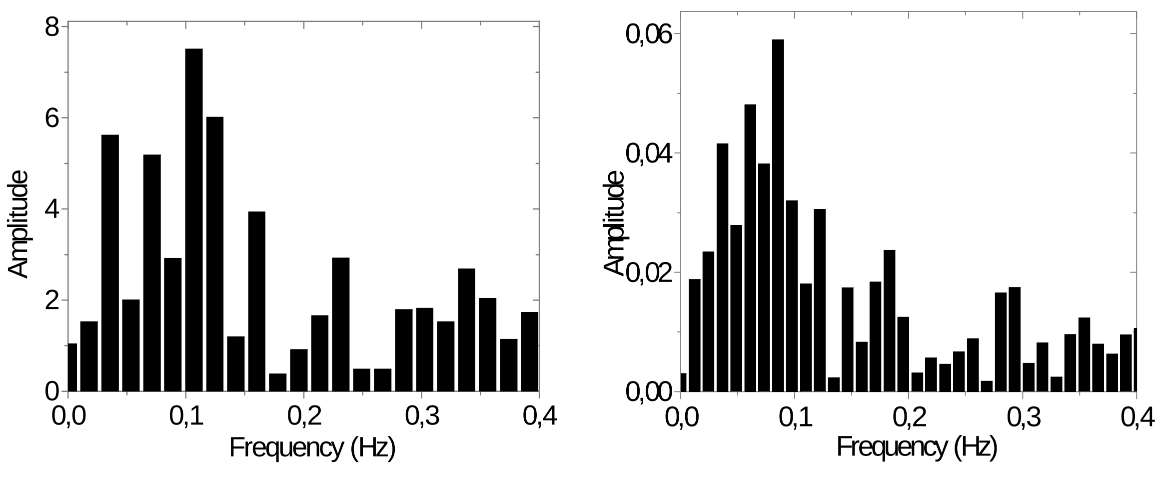

Fig. 5 and 6. Fourier analysis of the measured (left) and calculated with 3.5 mil. elem., time-step 10 ms (right) oscillation of the axial velocity components near the crucible wall at half-height of the inductor. Amplitudes are in [cm/s] on the left and in [m/s] on the right graph.

3. Conclusions

Large Eddy Simulation turbulence model was applied for three-dimensional transient calculations and it proved to be a very promising tool for numerical simulation of complex turbulent flows. Produced results are in good agreement with experimental data collected in model induction furnaces, and this fact gives the premises of future modeling of the turbulent flows and heat and mass transfer processes in real industrial furnaces.

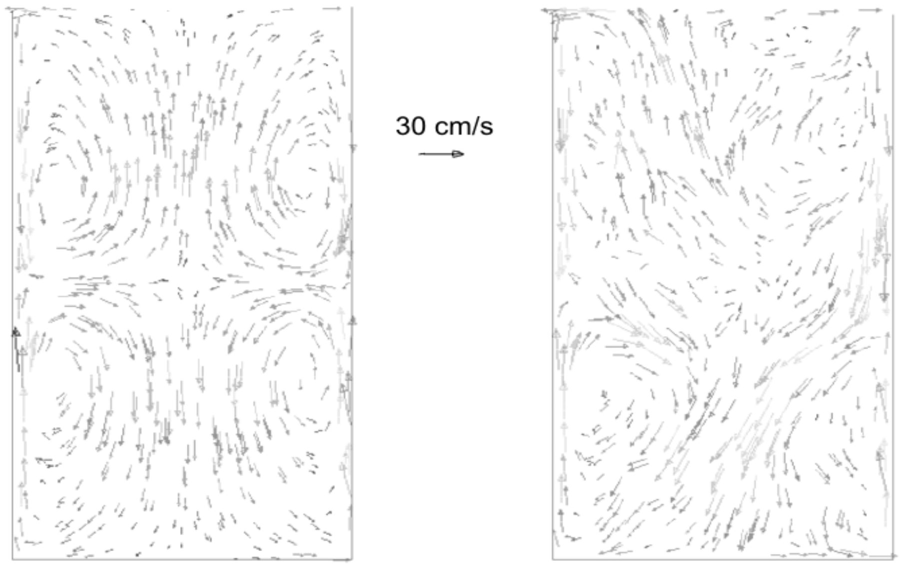

Fig. 7 and 8. Calculated with LES turbulence model flow pattern with symmetric dominating flow eddies and after 30 seconds of transient simulation with the time-step 10ms

References

[1] Baake, E.: *Grenzleistungs- und Aufkohlungsverhalten von Induktions-Tiegelöfen.* VDI-Verlag, Düsseldorf, 1994

[2] Mühlbauer, A., Baake, E., Jakovics, A.: *Influence of the filling level on the turbulent material exchange in the melt of induction crucible furnaces*. Second International Conference on Energy Transfer in Magnetohydrodynamic Flows, Aussois, France, 1994, Vol.1, pp. 349-358

[3] Baake. E., Mühlbauer, A., Jakovitsch, A., Andree, W.: *Extension of the k-ε model for the numerical simulation of the melt flow in induction crucible furnaces*. Metallurgical and Material Transactions, Vol. 26B, (1994), pp. 529-535

[4] Baake, E., Mühlbauer, A., Nacke, B.: *Heat and mass transfer in the turbulent melt flow of the crucible inductor furnace*. International Colloquium on Modeling of Material Processing, Riga, Latvia, 1999, pp. 98-103

[5] Baake, E., Nacke, B., Jakovics, A., Umbrashko, A.: *Heat and mass transfer in turbulent flows with several recirculated flow eddies*. Fourth International PAMIR Conference, Presquile de Giens, France, 2000, pp. 71-76

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