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Numerical Analysis of Turbulent Flow and Temperature Field in Induction Channel Furnace with Various Channel Design

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Abstract

The paper deals with numerical analysis of low frequency and turbulent oscillations of the temperature field in industrial induction channel furnace (ICF) with different designs of the channel – symmetrical and asymmetrical with one widened branch. The computations of turbulent heat and mass exchange in the melt are performed using 3D electromagnetic (EM) model and 3D transient *Large Eddy Simulation* (*LES*) approach.

Introduction

Two models of industrial ICF with equal electrical power losses in melt (≈ 215 kW) are chosen for the computations:

• ICF with symmetrical channel – the original design of the ICF (fig. 1; 2, left);

• ICF with expressly widened channel – the sectional area of left channel branch (fig. 2, right) is equal to 200% of sectional area of symmetrical channel of original design.

The peculiarities of numerical simulation and computations process are the following:

• computations of EM and hydrodynamic (HD) fields are performed using commercial software packages *ANSYS* and *FLUENT* accordingly;

• initial distributions of melt velocity and temperature are obtained using steady state 3D standard *k*-*ε* model; further computations – using transient 3D *LES* model of turbulence;

• number of mesh elements for HD computations is 3 million for symmetrical ICF and 6 million for asymmetrical ICF;

• time step for transient HD computations was chosen as 0.005 sec;

• computation time to obtain 1 sec of flow time at *PC cluster* with 16 cores is 4–5 hours for symmetrical ICF and 36–42 hours for asymmetrical ICF;

• post-processing of profile files prepared by *FLUENT* is based on own code.

Fig. 1. Original design of ICF with symmetrical channel

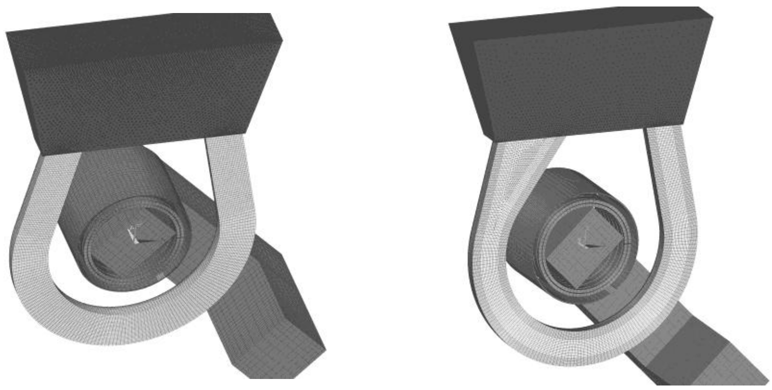

Fig. 2. ICF geometry and mesh for EM modelling: left – symmetrical channel; right – channel with widened branch

1. Melt Maximal Temperature T_{max} and Angle α of its Position in the Channel

The results are shown at fig. 3 and 6 for ICF with symmetrical and widened channel – figures are built using 550 points (every 1 sec of flow time in the range 0–550 sec) and 12,600 points (every 0.005 sec of flow time in the range 0–63 sec) accordingly.

The central angle α of T_{max} position is counting out clockwise starting with vertical plane x = 0, which is perpendicular to vertical plane y = 0 (the only symmetrical plane for both chosen ICF models) – the planes of figures 7, left and 9, left. The central angle α is considered according to curvature centre of channel with coordinates (0; 0; 0).

1.1. Results for ICF with symmetrical channel show the following:

• Melt temperature maximum obtained using *LES* modelling is for 15–20 K lower than temperature maximum obtained in steady-state computations using two-parameter k-ε model of turbulence. Thus melt overheat in ICF channel with respect to melt temperature in ICF bath is consequently lower.

In k-ε model the turbulent viscosity and dissipation of flow turbulent energy near walls are overestimated. That's why the pulsations of velocity are partly suppressed and averaged flow pattern rapidly develops to steady-state velocity distribution. Consequently k-ε model is not describing well the dynamics of anisotropic small- and medium-scale turbulent vortexes and accordingly heat and mass exchange processes.

In *LES* approach local turbulence structure of transient melt flow is modelled more precise and consequently it is resulting with more intensive heat exchange.

• The position of the melt temperature maximum obtained using k-ε model is rapidly stabilized near channel outlet – α ≈ 104°. Accordingly for k-ε model there is high decrease of temperature from zone of temperature maximum to zone of channel entrance, but this effect is not correlating with experimental results [1].

• Distribution of local temperature field obtained using *LES* model of turbulence is rapidly changing according to dynamical changes of turbulent flow. As the result, the significant intensification of heat exchange is obtained in channel in longitudinal direction. This effect is illustrated by fig. 3 for T_{max} and α.

• In addition to short-range pulsations in transition processes the low frequency (or long period) oscillations are obtained as well (fig. 3). There are three ranges of melt flow time with extremely different types of oscillations:

i) for melt flow time in range 0 – 180 sec – amplitude and main period of oscillations of T_{max} are ~ 20 K and 127 sec; the position of T_{max} is oscillating in range of angle α ≈ 0° – 135° (i.e. in the left branch of channel) with main period 95 sec (fig. 4);

ii) for melt flow time in range 180 – 380 sec – all parameter are the similar to case i) except the range of oscillation of T_{max} position – from α ≈ 0° to α ≈ -150°. It means the transition of T_{max} position from left branch of channel to the right;

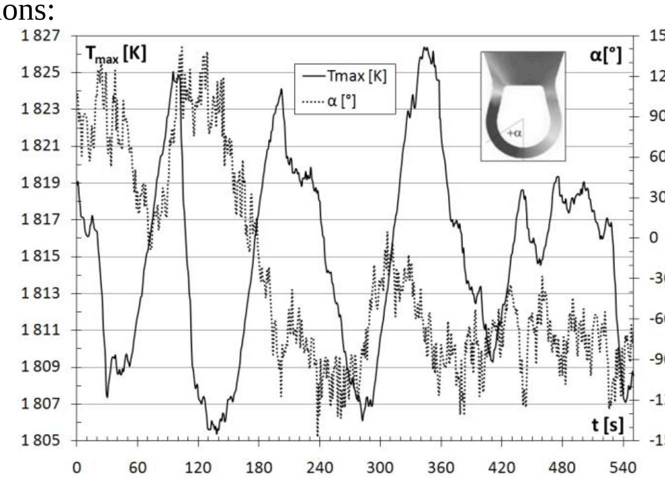

Fig. 3. Maximal temperature T_{max} and angle α of its position in ICF with symmetrical channel (y=0): flow time t = 0–550 sec

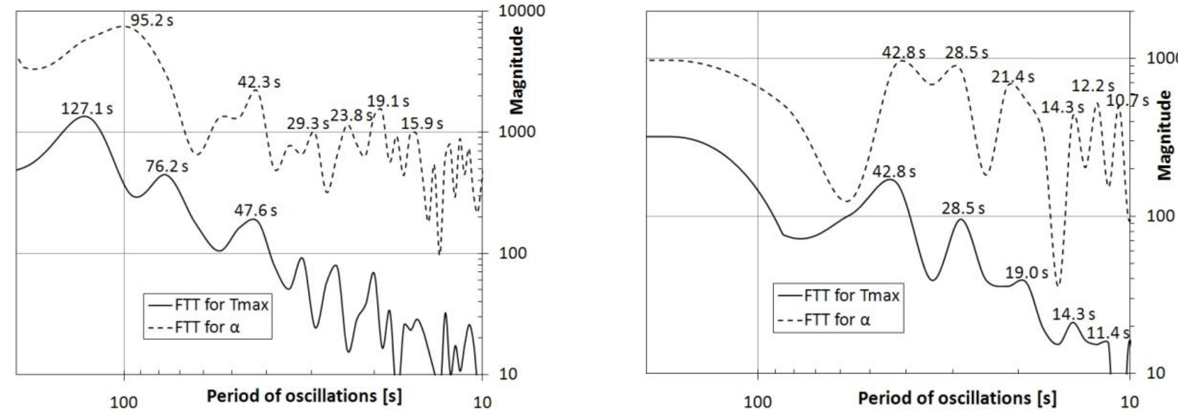

Fig. 4. FTT analysis of maximal temperature T_{max} and angle α of its position showed in fig. 3
left – flow time t = 0–380 sec right – flow time t = 380–550 sec

iii) for melt flow time in range 380–550 sec – amplitude and main period of oscillations of T_{max} are ~12 K and 43 sec; position of T_{max} is oscillating in range of angle from α ≈ -30° to α ≈ -130° with the same main period 43 sec (fig. 4). The position of T_{max} remains in the right branch of channel.

The definite signs of stabilization of oscillations in case iii) may be interpreted as follows. As the vessel with melt for considered ICF model is symmetrical with respect to two mid-planes – x = 0 (or α = = 0°) and y = 0 (fig. 1), the only contributing asymmetry factor is the angle between channel and closed magnetic core α = -45° (fig. 2). That's why T_{max} is stabilizing in zone of maximum of Joule heat power and module of EM forces in melt – see fig. 5, which is build using points at inner surface of channel wall at cross-section y = 0.

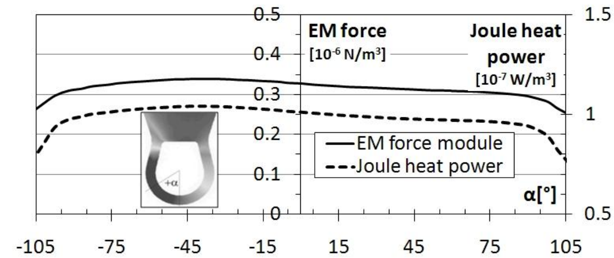

Fig. 5. EM force and Joule heat power in ICF with symmetrical channel (inner surface of channel, cross-section y=0)

As the cause of oscillations in cases i) and ii) may be unfortunate choice of initial condition for computations of melt flow and temperature structure – T_{max} position at t = 0 according to *k-ε* model is in the left branch of channel, but definite stabilization of T_{max} position is reached in the right branch of channel only after 360 sec of flow time.

More precise choice of initial conditions may shorten period of stabilization 3–5 times. It seems that velocity computations from "zero" may be good choice for initial condition versus *k-ε* model, but as to thermal field it is necessary to find proper estimation of melt average temperature.

1.2. The results for ICF with asymmetrical branch of channel are the following:

• In LES modelling T_{max} is stabilizing in channel branch with the greater sectional area at α ~ 48° with deviations ± 20° (fig. 6). The only full

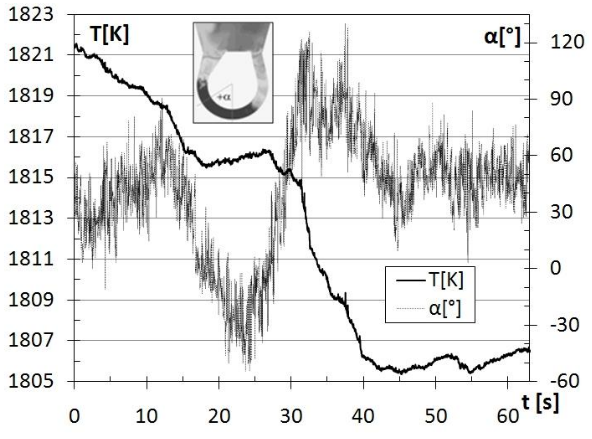

Fig. 6. Maximal temperature T_{max} and angle α of its position in ICF with widened channel (y=0) – flow time t = 0–63 sec

period of low frequency oscillations of T_{max} is ~ 30 sec. The deviations from vertical plane of T_{max} position during low frequency oscillations are from α ~ -55° to α ~130°.

Localization of overheat zone is determined by two factors:

i) resulting EM forces impact difference between two entrance zones of channels [2];

ii) tendency of overheated melt to rise upwards due to thermal convection.

• The results obtained using *k-ε* model for asymmetrical ICF model seems to be more favourable as the initial conditions for computations versus symmetrical ICF model because start position of about ~ 31° for T_{max} (see fig. 6 at t = 0) is placed in the same branch of channel with T_{max} position after stabilization.

2. Structure of flow velocity and temperature fields

For averaging of turbulent transient distribution of flow velocity and temperature fields the following conditions are chosen:

• flow time range from 50 to 290 sec (see fig. 3) – two full periods of low frequency oscillations, which corresponds to transition of temperature maximum from left to right branch of channel for symmetrical ICF (fig. 2, left);

• flow time range from 20 to 60 sec (fig. 6) – the only full period of low frequency oscillations in asymmetrical ICF (fig. 2, right) as well as period of stabilization of temperature maximum in the widened branch of channel.

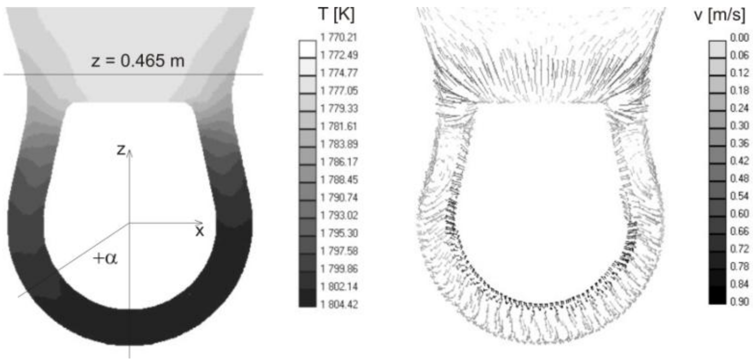

Fig. 7. ICF with symmetrical channel, cross-section y=0 – values averaged for time period 50–290 sec: left – temperature, right – velocity vectors

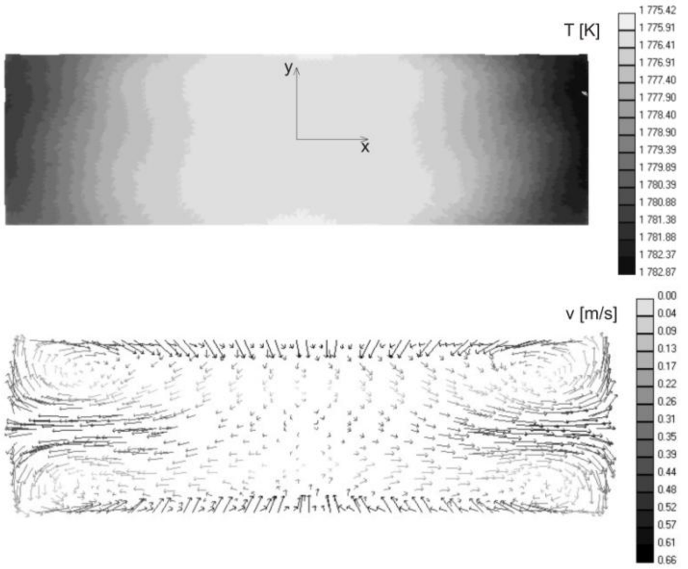

Fig. 8. ICF with symmetrical channel, cross-section z = 0.465 m – values averaged for time period 50–290 sec: above – temperature; below – velocity vectors

2.1. Main results for sym-metrical ICF are the following:

• maximal value of averaged velocity ~ 0.9 m/s in cross-section y = 0 (fig. 7, right) is reached in central zone of the channel near the cross-section x = 0;

• maximal value of averaged overheat between channel and bath of melt is ~ 35 K (fig. 7, left); the distribution in cross-section y = 0 is symmetrical; maximal value of temperature ~ 1,805 K is reached in central zone of the channel near the cross-section x = 0;

• melt circulation at the cross-section z = 0.465 m, which is placed above channel outlets z = 0.395 m (fig. 8, below), is symmetrical relative to both planes – x = 0 and y = 0; circulation has four vortexes with maximal value of averaged velocity ~ 0.65 m/s, which is for $^1/_3$ less than in the channel;

• non-uniformity of temperature at the cross-section, which is placed above channel outlets (fig. 8, above) is ~ 7 K;

• maximal value of total turbulent kinetic energy (TKE) $k \sim 0.26$ m^2/s^2 is reached in cross-section x = 0 in the channel in zone of single vortex circulation of averaged flow. Maximal level of TKE is the cause of intensive heat exchange in this zone.

2.2. Main results for asymmetrical ICF are the following:

• maximal value of averaged overheat between channel and bath of melt is ~ 37 K (fig. 9, left); maximal value of temperature ~ 1,808 K is reached at the position with angle α ~ 40° in widened branch of channel;

• non-uniformity of temperature at the cross-section z = 0.465 m, which is placed above channel outlets z = 0.395 m (fig. 10, above) is ~ 8 K;

• melt circulation has four vortexes (fig. 10, below) and is symmetrical relative to plane y = 0 and asymmetrical relative to plane x = 0 according to different sectional areas of channels' outlets.

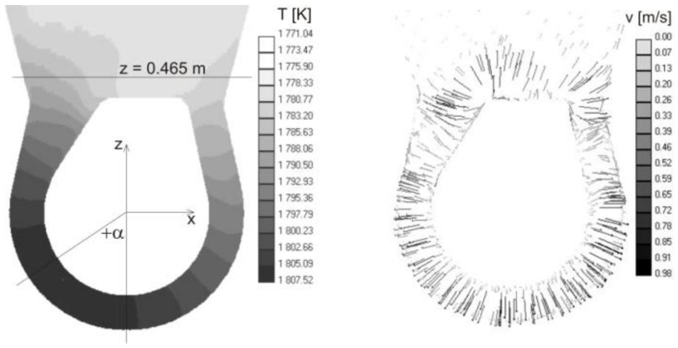

Fig. 9. ICF with widened channel, cross-section y=0 – values averaged for time period 20–60 sec:
left – temperature, right – velocity vectors

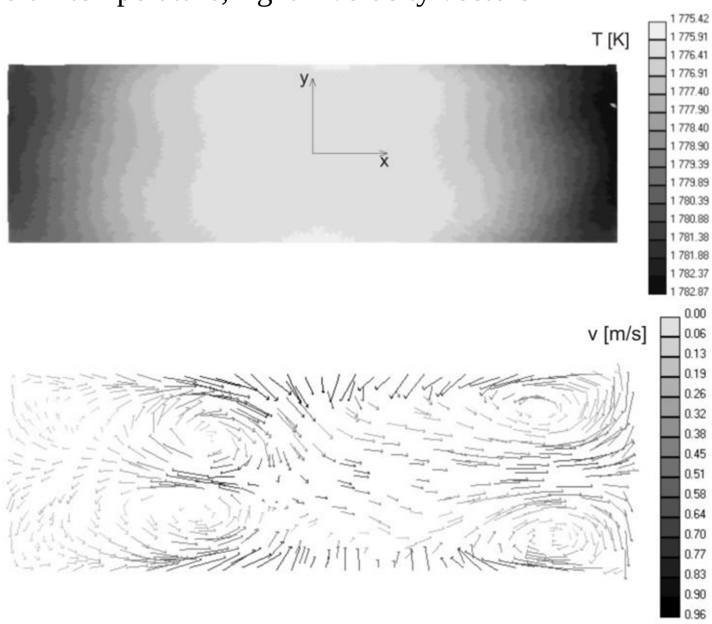

Fig. 10. ICF with widened channel, cross-section z = 0.465 m – values averaged for time period 20–60 sec: above – temperature; below – velocity vectors

• maximal value of averaged velocity in cross-section y = 0 (fig. 9, right) and cross-section z = 0.465 m (fig. 10, below) are the same ~ 0.95 m/s, but maximal value of averaged velocity in cross-section x = 0 (fig. 11, left) is greater ~ 1.3 m/s;

• melt circulation (fig. 11, left) in cross-section x = 0 has two vortexes and is similar to the situation in meridional cross-section of induction crucible furnaces;

• maximum of total TKE $k \sim 1.1$ m^2/s^2 in cross-section x = 0 (fig. 11, right) is reached due to y-component of averaged turbulent pulsations of velocity, which are parallel to the wall; total TKE in zone of two vortexes circulation (fig. 11, left) is ~ 4 times greater than in zone of one vortex circulation in cross-section x = 0 for ICF with symmetrical channel;

• for cross-section x = 0 of the channel the intensity and direction of transit flow is highly changeable (fig. 12).

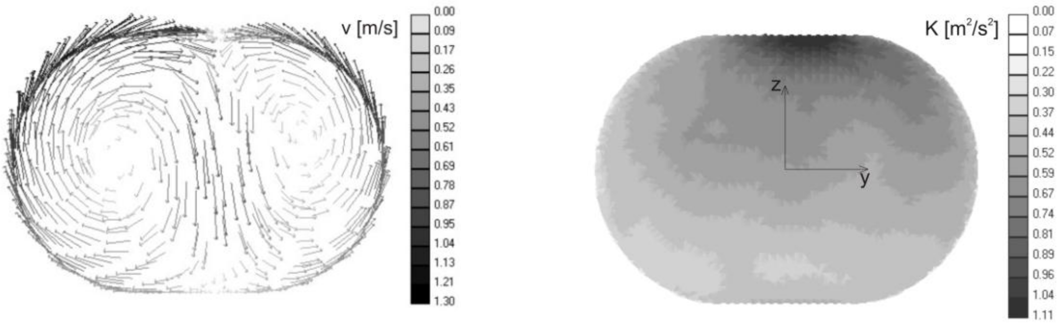

Fig. 11. ICF with widened channel, cross-section x=0 – values averaged for time period 20–60 sec: left – velocity vector; right – total TKE

The averaged (for time period 20 – 60 sec) value of transit flow velocity is ~ -0.035 m/s, but maximum value of transit flow velocity ~ -0.185 m/s is obtained at t ~ 29 sec during period of T_{max} transition from right branch of channel to the left (fig. 6) with rapid decrease of averaged (at cross-section x = 0) value of temperature (fig. 12). Produced by EM forces local vortexes with velocities up to ~ 1.3 m/s are the cause of very intensive homogenization of melt at cross-section x = 0. But this intensive melt circulation is insignificant for heat and mass exchange to x-axis direction, i.e. for resulting transit flow.

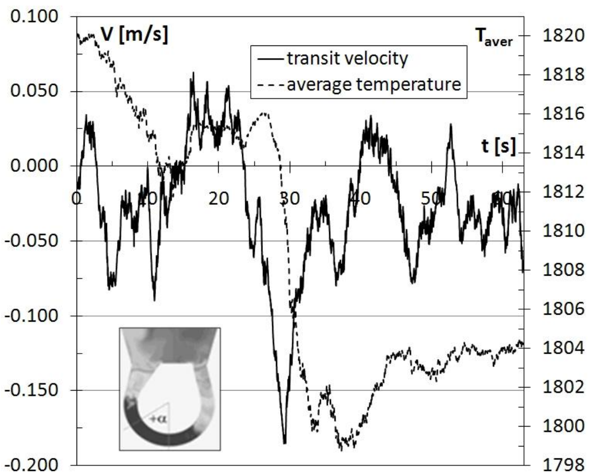

Fig. 12. Transit flow velocity and averaged temperature at cross-section x=0 of ICF with widened channel – flow time t = 0–63 sec

Conclusions

1. *LES* model of turbulence provides more precise results of HD and temperature computations versus *k*-ε model.

2. The long term modelling (several hundred seconds of flow time) is necessary to reach definite stabilization of thermal field distribution in symmetrical ICF because of low frequency oscillations of T_{max} value and position including its transition from one branch of the channel to another.

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