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Abstract

Purpose – The purpose of this paper is to present in-depth numerical modelling of heat and mass exchange in industrial induction channel furnace (ICF).

Design/methodology/approach – The turbulent heat and mass exchange in the melt is calculated using a three-dimensional (3D) electromagnetic model and a 3D transient large eddy simulation method. The simulation model has been verified by flow velocity and temperature measurements, which were carried out using an industrial sized channel inductor operating with Wood's metal as a low temperature model melt.

Findings – The ICF is well-established for melting, holding and casting in the metallurgical industry. But there are still open questions regarding the heat and mass exchange in the inductor channel itself and between the channel and the melt bath. Different new designed channel geometries have been investigated numerically in order to find an optimized shape of the channel, which leads to an improved heat and mass transfer.

Originality/value – Long-term computations for the industrial ICF have been performed. Low frequency oscillations of the temperature maximum and its position in the ICF channel are considered.

Keywords Simulation, Modelling, Numerical analysis, Experiment, Furnace

Paper type Research paper

Introduction

The induction channel furnace (ICF) is widely used for holding, casting and melting of metals. Figure 1 shows the principle design of a one loop ICF (Baake *et al.*, 2007), which is typically used for holding and casting of grey cast iron. The ICF basically consists of a ceramic lined furnace vessel and one or several inductor units. In principle, the inductor unit can be regarded as a transformer with iron yoke, where the induction coil is the primary circuit and the melt filled inductor channel represents the secondary short-circuited current loop. For the safety and efficient operation of the ICF the heat transport from the channel, where the Joule heat is generated, to the melt bath in the furnace vessel is important in order to prevent a local overheating in the channel.

Comprehensive knowledge of the heat and mass transfer processes in the melt of the ICF is required to realize an efficient and safety melting or casting process.

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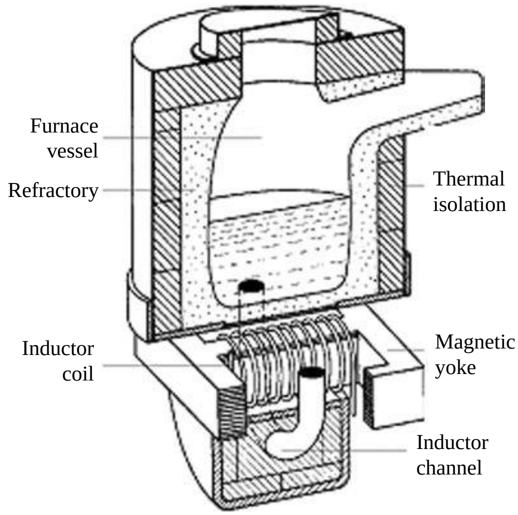


Figure 1.
Principle design of a one loop ICF

The heat transport from the channel, where the Joule heat is generated, to the melt bath in the furnace vessel is the most crucial feature of the ICF in order to prevent a local overheating and wearing and finally destroying of the ceramic lining. The heat and mass transfer processes in the melt of the ICF are three-dimensional (3D), in-stationary and very complex. The melt flow in the channel itself and in the transition zone between the channel and the bath is highly turbulent and influenced mainly by electromagnetic (EM) forces and additionally by buoyancy and inertia forces.

Previous investigations have shown that the channel design plays an important role for improvements of the heat and mass exchange and finally for the operation life time of the inductor unit (Baake *et al.*, 2009). Steady-state simulations of the melt flow and temperature distribution predicted by 3D k-ε model or share stress transport (SST) model differs with the measured temperature distribution, because the heat exchange caused by the interaction between the local turbulent vortices in the channel is not modelled correctly. Therefore, the large eddy simulation (LES) approach is applied in order to investigate and to analyse the influence of the channel design on the heat and mass transfer processes.

Experimental investigations

The experimental data, used in this paper for the verification of the simulation results, have been carried out by Eggers (1993). The experimental set-up consists of an industrial sized channel inductor unit operating with Wood's metal as a low temperature model melt, with a melting point of 72°C. The furnace vessel has been water cooled in order to keep the level of melt temperature constant during the melt flow velocity and temperature measurements. All three velocity components have been locally measured using a well-proved potential probe designed by Vivés (Ricou and Vives, 1982). Temperature profiles along the channel as shown in Figure 4 were measured simultaneously using a number of thermocouples. The channel inductor was operating with a power of 60 kW and a frequency of 50 Hz during the experiments.

Numerical simulation model

In the first step of the numerical simulation procedure, the induced Joule heat and the Lorentz forces in the melt of the ICF are calculated using a 3D EM model performed in package ANSYS – the equation for complex vector potential of quasi-stationary magnetic field is solved by finite element method. Taking into account the symmetry of the geometry, only half of the full furnace is modelled for the EM calculations (Figure 2). All regions, which are relevant for the EM simulation are taken into account, these are the channel itself and the bath with metal, the slitted cooper cooling shield between the coil and the channel, the cooper coil and the magnetic yoke. The surrounding air has infinite boundary. The precision of the EM model is checked by mesh refining and the final EM model consists of about 800,000 elements.

The EM simulation results show a very symmetrical Joule heat source and Lorentz force distribution in channel. The maximum values of Lorentz forces are noticed on the inner bottom surface of the channel, which is closest to the induction coil. The direction of the EM forces is collinear to the radial direction on a symmetry plane. The Lorentz force distribution in the channel cross-section should cause obviously a two-vortex structure inside the channel (Figure 3(a)). The results of the EM simulation are the

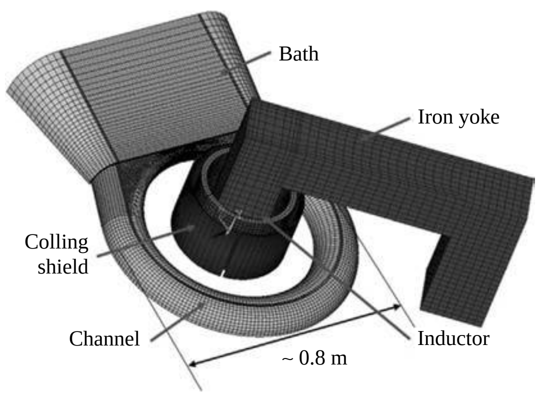
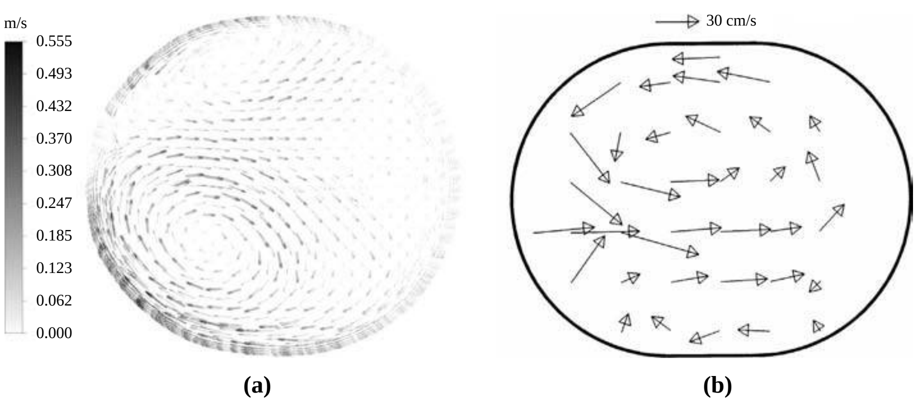


Figure 2.
EM model of the ICF



Notes: (a) Time averaged distribution over 60s (LES); (b) measurements

Figure 3.
Melt flow velocity distribution in the cross-section of channel

input data for the second step: the hydrodynamic (HD) and thermal numerical calculations using the CFD package ANSYS-CFX. A steady-state 3D k-ε model or SST model is used for the first calculations of the melt flow and temperature field, where the calculations are performed using half of the full channel geometry with symmetry boundary conditions or complete 3D geometry.

The steady-state temperature distribution predicted by these two-equation models differs with the measured temperature distribution, because the heat exchange caused by the interaction between the main turbulent vortices in the cross-sections of the channel is not modelled correctly. Therefore, the LES turbulence model is applied to ensure better time and space resolution of small vortices and to take into account more precisely the interaction between the turbulent macroscopic vortices (Baake *et al.*, 2007). This full 3D transient model is used to simulate the development of the flow and temperature distribution in the melt. The LES model of the experimental channel furnace consists of 3.2 million elements and the transient calculations are carried out with time steps of about 0.01 s. The total simulation time can achieve more than 60 s.

Results of the experimental channel furnace

The simulation results obtained using the two parameter or LES model show highly turbulent 3D dynamic flow vortex structures, with flow velocities up to 70 cm/s. In comparison to these high local melt flow velocities, which are driven by EM forces, the integral transition flow through the channel, caused mainly by buoyancy forces, is very small in the range of 5 cm/s and therefore only secondarily responsible for the heat transfer processes from the channel into the bath. The velocity distribution in the cross-section inside the channel is represented by two-vortex structure (Figure 3(a)), which also is in accordance with experimental measurements (Figure 3(b)). Characteristic velocity magnitudes in the channel are approximately the same for both simulation models (0.5-0.7 m/s in maximum). The distance between the vortex centres is approximately equal to the channel radius.

The transition flow in the channel depends on the unsymmetrical temperature distribution along the channel, where the maximum of the overheating temperature of about $\Theta \approx 34$ K in case of the model furnace, is located in the upper part of the one loop channel, which is in good agreement with measurements. As shown in Figure 4, the temperature distribution calculated with the LES model is in a good agreement with the experimental data, especially with a view on the position and the level of the maximum temperature.

Simulation results of industrial ICFs

Different designed channel geometries have been investigated numerically. In this paper, the following three models of the ICF are considered, where the induced electrical power in melt is approximately 215 kW and equal in all three models. The design can be described as follows:

(1) with symmetrical channel (the original model, Figure 5);

(2) with narrowed channel (the sectional area of left channel branch is equal to 90 per cent of sectional area of symmetrical channel of original model, Figure 7); and

(3) with expressly widened channel (the sectional area of left channel outlet is equal to 200 per cent of sectional area of symmetrical channel of original model, Figure 8).

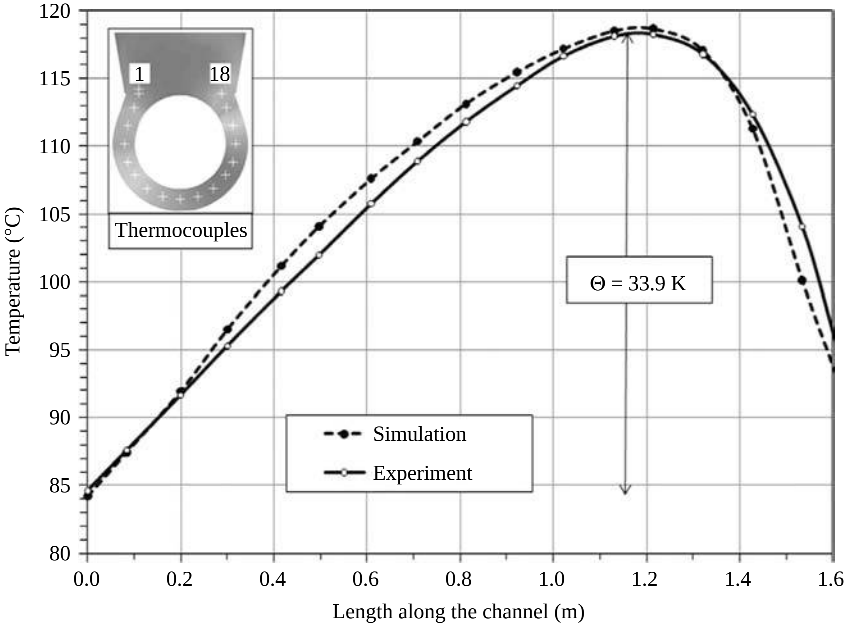


Figure 4.
Temperature distribution in the experimental channel furnace: comparison between simulation (LES) and experiment; positions of thermocouples

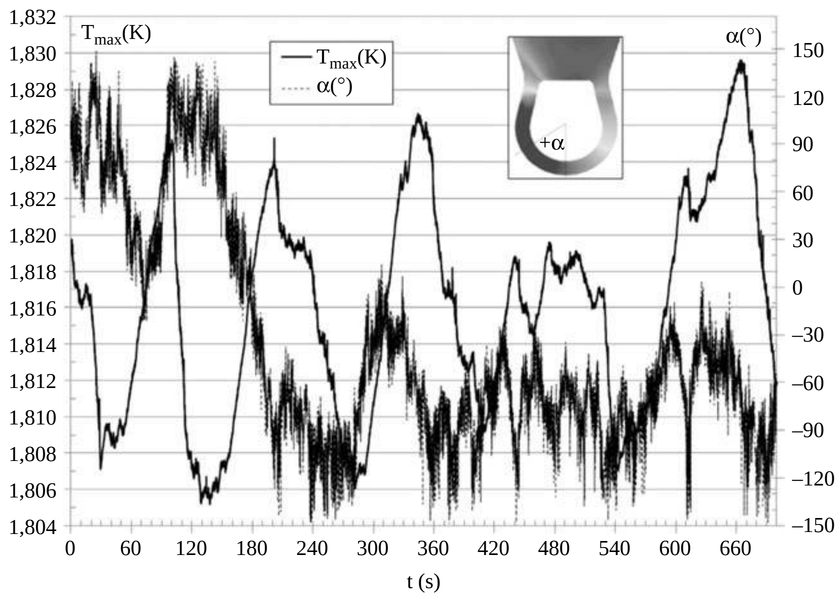


Figure 5.
Maximum temperature T (K) and the angle α (°) of the position as a function of flow time t (s) for the symmetrical channel of the ICF (original model 1)

For these three models the numerical simulations are performed using ANSYS for the EM field and FLUENT for the HD and temperature fields. Initial distributions of the melt velocity and temperature are obtained using the steady-state 3D standard k-ε model. For further computations, a transient 3D LES model of turbulence is used.

The mesh for HD computations consists of approximately 3,000,000 elements for a symmetric ICF and of 6,000,000 elements for asymmetric ICF. The time step 0.005 s was chosen for transient HD computations. The computation time to obtain 1 s of the flow time using the PC cluster with 16 processor cores is 4-5 h for the symmetric ICF and 36-42 h for the asymmetric ICF. For post-processing of profile files prepared by FLUENT a self-developed code is used.

Maximum values of instantaneous and averaged temperatures are important characteristics of the technological processes in the ICF because they determine melt overheating in the channel with respect to the melt temperature in the bath, which must be minimized for a higher efficiency of the melting and a longer lifetime of the ICF channel.

The results on maximum values T_{max} of instantaneous temperature in the ICF with the symmetric, narrowed and widened channels, which are shown in Figures 5, 7 and 8, are plotted using 140,000, 10,000 and 25,000 points, i.e. every 0.005 s of the flow time in the range 0-700, 0-50 and 0-125 s, accordingly.

The Cartesian coordinate system, where the *x*-axis corresponds to the long side of the channel, the *y*-axis to the short and the *z*-axis indicates the vertical direction placed at the geometrical centre of the channel loop. In such a case, the vertical plane $y = 0$ is a symmetry plane for all three studied ICF models. Intersection of this plane with the channel provides an origin for calculating the central angle α of the T_{max} position, which is counted clockwise starting with the perpendicular cross-section $x = 0$ (this coordinate system is shown in models in Figures 5, 7 and 8).

Fast Fourier transform (FFT) analysis for T_{max} and α fluctuations in Figure 6 for the ICF with a symmetric channel is performed for 700 s time series signals with 1 Hz

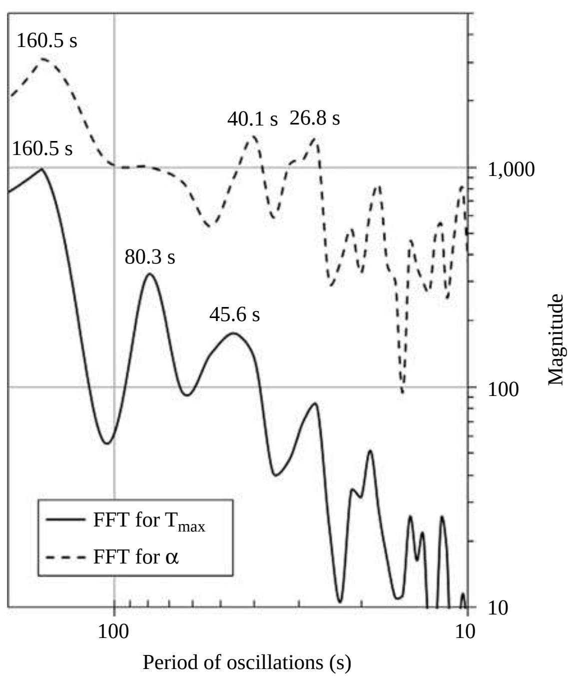


Figure 6.
FFT analysis of the maximum temperature T_{max} and angle α of its position shown in Figure 5 for flow time $t = 380\text{-}700$ s

resolution. The selected time resolution is sufficient to determine main periods of the low-frequency oscillations for T_{max} and α. For α fluctuations in Figure 9 for the ICF with a widened channel is performed for 125 s time series signals with 200 Hz resolution.

The results obtained for ICF with a symmetric channel (model 1) using the k-ε model of turbulence, which are the initial conditions for LES computations, are shown in Figure 5 at $t = 0$. The melt temperature maximum $T_{max} \approx 1{,}819$ K is located near the left outlet of the channel at $\alpha \approx 104°$. This high position of T_{max} determines a large temperature gradient between the temperature maximum and the channel outlet, but this result obtained using the k-ε model does not correlate with the experimental results (Eggers, 1993).

With the k-ε model, the turbulent viscosity and the dissipation of flow turbulent energy near the walls are overestimated because this model assumes a homogeneous and isotropic turbulence structure. The velocity pulsations are partly suppressed and an averaged flow pattern rapidly develops to a steady-state velocity distribution. Hence, the k-ε model does not describe well the dynamics of anisotropic small- and medium-scale turbulent vortices and, accordingly, the heat and mass exchange processes.

With the LES approach, the local turbulence structure of transient melt flow is modelled more precisely accounting for smaller anisotropic vortices in the nearwall regions and, hence, the results show a more intensive heat exchange along the channel. Distributions of the instantaneous temperature fields obtained by the LES model of turbulence evolve according to dynamic changes in the turbulent flow. As a result, the heat exchange, which is obtained inside the channel in the longitudinal direction, is significantly intensified. This effect is shown in Figure 5 for T_{max} and α. In addition to short-range pulsations in transition processes, the low-frequency (or long-period) oscillations of T_{max} and α are obtained as well (Figure 5).

During the whole period of computation (flow time 0-700 s), the amplitude of the T_{max} oscillations reaches maximum and minimum values of $\sim$ 22 K and $\sim$10 K for time ranges of $\sim$540-670 s and $\sim$400-470 s, accordingly. An absolute maximum value of $T_{max} \approx 1{,}829$ K is obtained at $\sim$667 s (Figure 5) and it is larger than T_{max} predicted by the k-ε model.

The main period of T_{max} oscillations varies from $\sim$127 s for a flow time range $\sim$0-380 s to $\sim$161 s (Figure 6) for a flow time range $\sim$380-700 s. If a shorter time range 380-550 s is selected, then the main period of T_{max} oscillations is about four times smaller ($\sim$43 s) than for the $\sim$380-700 s time range. This example clearly demonstrates the importance of long computations and experiments for a more accurate estimation of the characteristic parameters of the low-frequency temperature oscillations.

Figure 5 shows that the character (amplitude and intensity) of T_{max} oscillations is practically independent on T_{max} localization in different branches of the channel. Regarding the position of T_{max}, there are two ranges of the melt flow time with extremely different types of oscillations:

(1) *The position of T_{max} is in the left branch of the channel.* For a melt flow time ranging 0-180 s, the position of T_{max} is oscillating within $\alpha \approx$ 0-145°. Only at a minor range of $\sim$70 s the angle α varies from 0 to $\sim -20°$, i.e. in the right branch of the channel (Figure 5). The main period of oscillations of the T_{max} position is $\sim$95 s.

(2) *The position of T_{max} migrates from the left branch of the channel and remains in the right branch of the channel.* For a melt flow time ranging 180-700 s, the T_{max} position oscillates from $\alpha \approx 0$ to $\alpha \approx -150°$ (Figure 5).

The main period of the T_{max} position oscillations varies with the flow time range. With 180-380 s, the main period of the T_{max} position oscillations is $\sim$ 95 s (the same as in case (i). With 380-700 s, the period of the T_{max} position oscillations is about 161 s, i.e. the same as the main period of T_{max} oscillations (Figure 6).

The fact that the position of the temperature maximum has migrated from the left branch of the channel and oscillates in its right branch might be interpreted as follows. As the vessel with a melt for the considered ICF model is symmetrical with respect to two mid-planes $x = 0$ (or $\alpha = 0$) and $y = 0$, the only contributing asymmetry factor is the angle $\alpha = -45°$ between the channel and the closed magnetic core yoke (Figure 2). Thus, T_{max} is located in the zone of the maximum of Joule heat density and module of EM forces in the melt.

The oscillations of the T_{max} position in the left branch of the channel for the initial period of computations (flow time 0-180 s) and the migration of the T_{max} position to the right branch of the channel might be explained by an unfortunate choice of the initial condition: according to the k-ε model at $t = 0$ the position of T_{max} is $\alpha \approx 103.5°$. A more precise choice of the initial conditions can shorten the period of stabilization of the T_{max} position in the right branch of the channel.

The maximal difference $\Delta T = T_{\max}^{aver} - T_{\min}^{aver}$ between the maximum time-averaged melt temperature $T_{\max}^{aver}$, which is reached in the channel, and the minimum time-averaged melt temperature $T_{\min}^{aver}$, which is reached near the free surface in the bath, obtained by LES – ΔT_{LES} – can be both greater and smaller if compared with the result by the k-ε turbulence model – $\Delta T_{k-\varepsilon} \approx 49.9$ K. ΔT_{LES} depends on period of time-averaging – $\Delta T_{LES} \approx 47.4$ K for period 290-700 s, $\Delta T_{LES} \approx 45.1$ K for period 500-550 s and $\Delta T_{LES} \approx 52$ K for period 570-700 s. Note, that time-averaged temperature difference obtained by LES depends on instantaneous temperature difference, which at certain time periods can be as well both greater and smaller than the time-averaged temperature difference computed by the k-ε model (Figure 5).

For ICF with narrowed branch of the channel (model 2), melt maximum temperature in LES simulations decreased till $T_{max} \sim$ 1,829 K (Figure 7), but T_{max} position is rapidly relocated from left narrowed branch of the channel to the right one.

It may be assumed that the oscillations of T_{max} position will be located mainly in the right branch of the channel, where HD resistance for transit flow is lower than one in the left narrowed branch, and where zone of the maximum of Joule heat density and module of EM forces in the melt is located.

For ICF with widened branch of the channel (model 3), LES simulations show that melt maximum temperature is stabilized at the $T_{max} \sim$ 1,806 K with ± 2 K deviations (Figure 8).

The oscillations of T_{max} position are located mainly in the channel branch with the largest cross-section area with deviations from the vertical plane from $\alpha \sim -55°$ to $\alpha \sim 130°$. The main period of the low-frequency oscillations of T_{max} position is $\sim$64 s (Figure 9).

As the HD resistance in the left widened branch of the channel is lower than in the right one, the influence to T_{max} position of this asymmetry factor is more strong in

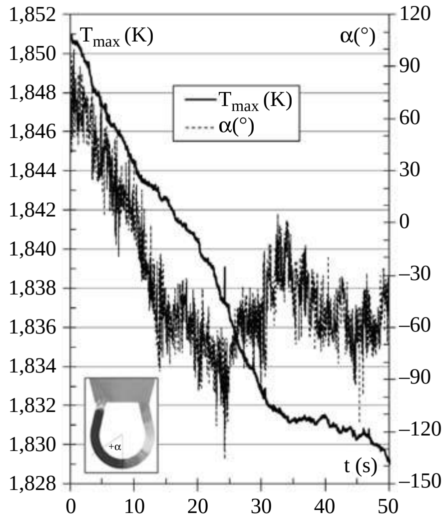


Figure 7.
Maximum temperature T (K) and the angle α (°) of the position as a function of flow time t (s) for the narrowed channel of the ICF (model 2)

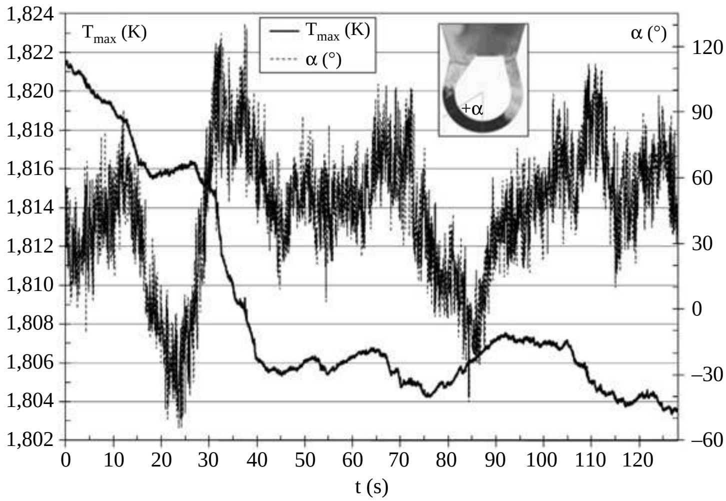


Figure 8.
Maximum temperature T (K) and the angle α (°) of the position as a function of flow time t (s) for widened channel of ICF (model 3)

comparison with the asymmetry factor, which is similar to ICF with symmetrical channel (model 1) and which concern with location of the zone of the maximum of Joule heat density and module of EM forces in the melt.

The results obtained with the k-ε model for the ICF widened channel seem to be more favourable as the initial conditions for computations versus the ones for the symmetrical ICF model because the start position of $\alpha \sim 31°$ for T_{max} (results obtained by the k-ε model are shown in Figure 8 – $t = 0$) is placed in the same branch of the channel as for the T_{max} position after stabilization.

The maximum value of the averaged overheating temperature Θ is $\sim$ 36.5 K. Thus, the melt overheating temperature in the ICF channel obtained by LES is consequently

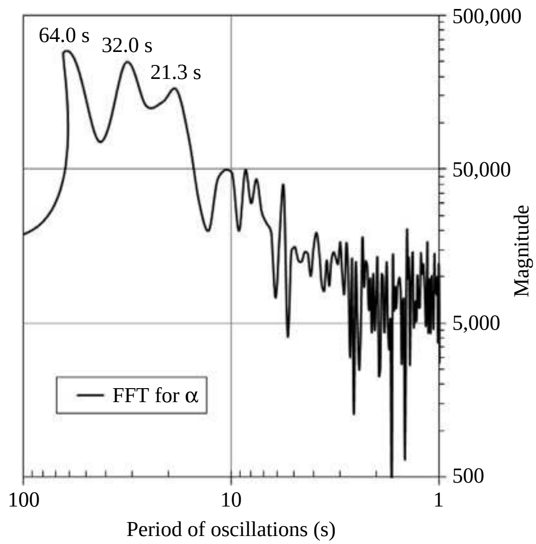


Figure 9.
FFT analysis of the angle α of position of maximum temperature T_{max} shown in Figure 8 for flow time $t = 0\text{-}125$ s

lower than the melt temperature in the ICF bath obtained by the k-ε turbulence model for the considered flow time period. In general, the overheating zone localization is determined by two factors:

(1) the resulting EM forces affect the difference between two entrance zones of the channels (Arefyev *et al.*, 1981); and
(2) the overheated melt tends to run upwards due to thermal convection.

For the selected cross-section of the channel (symmetry plane at $x = 0$), the intensity and direction of the transit flow is changing as shown for example in Figure 10 for the model with widened channel (model 3). The averaged (for a time period of 20-125 s) value of the transit flow velocity is -0.033 m/s, but the maximum value of the transit flow velocity about -0.185 m/s is obtained at $t \approx 29$ s during T_{max} migration from the right branch of the channel to the left (Figure 8) with a rapid decrease of the averaged (at $x = 0$) value of the temperature (Figure 10). The local recirculating vortices with velocities up to 1.3 m/s (Figure 11), which are produced by EM forces, are the cause of a very intensive homogenization of the melt at transverse cross-sections. However, this strong melt circulation is insignificant for heat and mass exchange in the azimuthal direction, i.e. for the resulting transit flow.

The results of LES HD computations show in general similar tendencies in all three cases:

- maximal value of turbulent kinetic energy (model 3) is for y component – 1.15 m^2/s^2, for x and z components intensity of pulsations is three times lower – 0.32 and 0.36 m^2/s^2 accordingly;
- the position of turbulent kinetic energy maximum value is near the inner wall (Figure 12(b) and (d)) intensity between two oppositely directed vortices of averaged flow in perpendicular cross-section of channel – this situation is similar to the induction crucible furnace (Kirpo *et al.*, 2007);

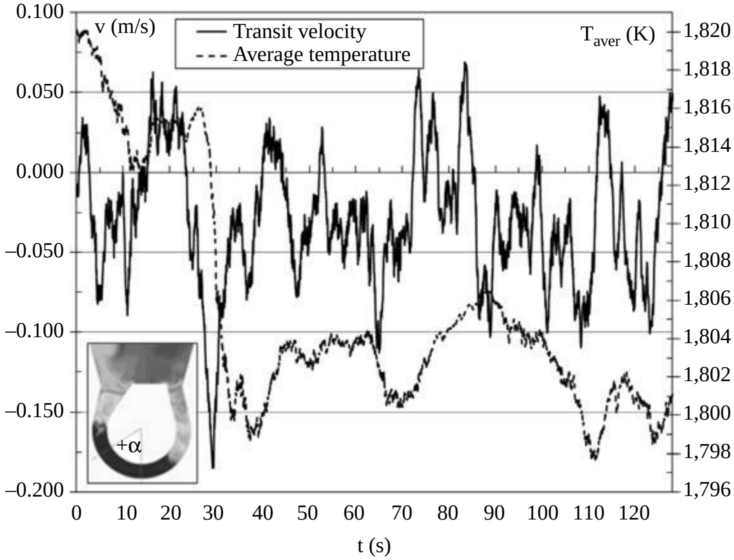


Figure 10.
Averaged (for cross-section x = 0 of channel) transit flow velocity and temperature for model 3

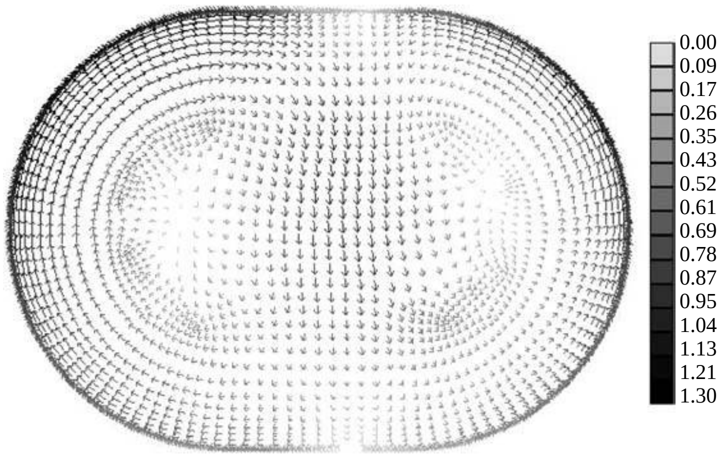


Figure 11.
Averaged (for a time period of 20-60 s) flow velocity in cross-section x = 0 of channel

- high values of turbulent kinetic energy are reached at the sharp corners of channel outlet too as result of electromagnetically initiated very intensive flow motion in that corner regions (Figure 12(a) and (c)); and
- high level of turbulent flow pulsations cause remarkable additional hydraulic resistivity for transit flow in the channel and can be one of important limiting factors for intensity of transit flow (Figure 10).

Conclusions

The 3D transient turbulent melt flow velocity and temperature distribution in different experimental and industrial ICFs have been investigated applying the two-parameter

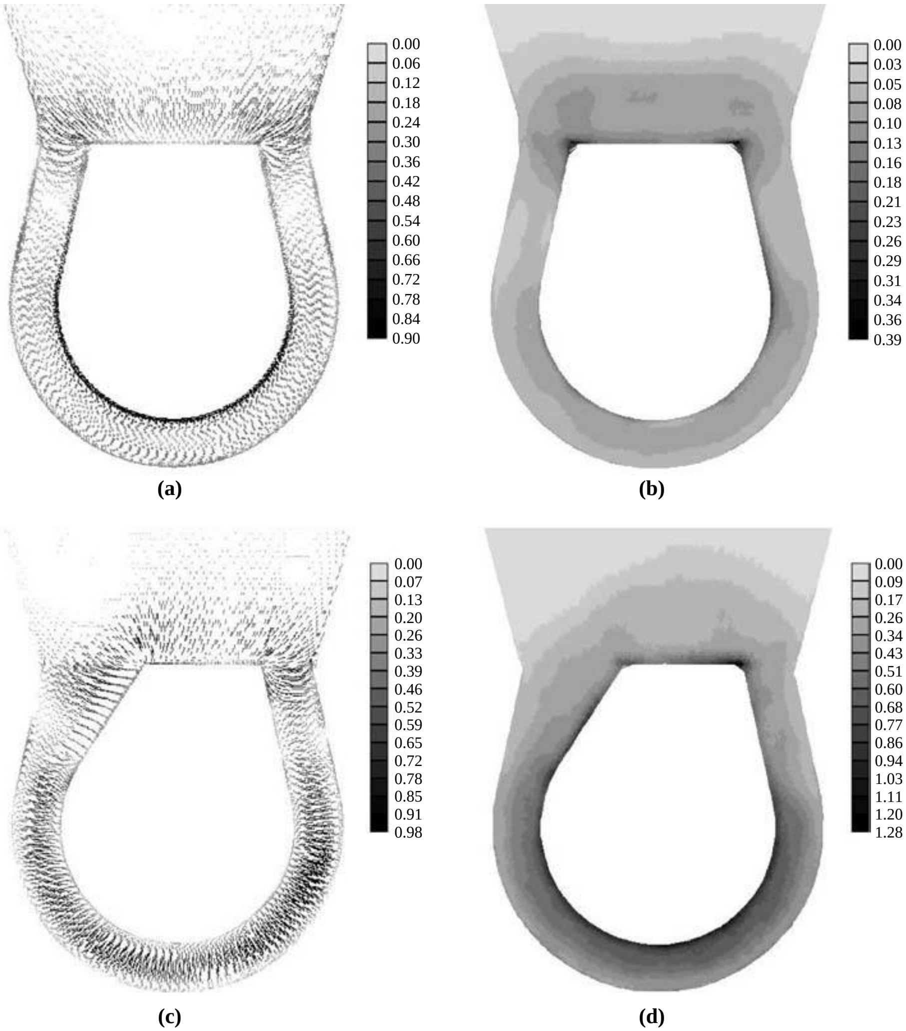


Figure 12.
LES calculated averaged flow velocities (a, c) and total turbulent kinetic energy (b, d) at y = 0 for the model 1 (a, b) and model 3 (c, d) of ICF

and LES turbulence models. The LES simulation results have been successfully verified by measurement data. The temperature distribution along the channel, calculated with the LES model shows a temperature maximum located unsymmetrical in the upper part on one side of the one loop channel, like it has been measured in the experimental furnace.

Performed LES simulations in symmetrical channel have shown also low-frequency oscillations of the temperature maximum and its position due to thermal instable situation with maximal Joule heat generation in the lower part of channel and connected changes in the velocity of transitional flow.

The long-term modelling of about several hundred seconds of flow time is necessary to achieve the quasi-stable state of thermal field distribution in the symmetrical ICF because of the low-frequency oscillations (with period approximately 160 s) of the T_{max} value and position including its migration from one branch of the channel to the other.

The LES model of turbulence provides substantially more thorough results for HD and temperature distributions, which considerably differ from the results obtained by the k-ε model – the quasi-stable state of temperature distribution for the symmetrical ICF obtained by the LES model greatly differs from the temperature distribution computed by the k-ε model of turbulence.

Asymmetrical branches of the channel show that the temperature maximum tends to stabilize in those channel branches which have a greater sectional area at the outlet.

The typical hydrodynamical and flow pulsations effects in the channel cross-section with two oppositely directed vortices are very similar to the carefully experimentally and numerically studded situation in the vertical cross-section of induction crucible furnace.

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