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Numerical Simulation of Mass and Heat Transport in Induction Channel Furnaces

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Abstract

The induction channel furnace (ICF) is widely used in industry for melting, holding and casting of metals. But up to now there are still open questions regarding the heat and mass exchange in the inductor channel itself and between the channel and the bath. In this paper the melt flow velocities and the temperature distribution in the melt of the ICF are modelled using 3D electromagnetic model and a 3D transient LES approach. The numerical results are verified by temperature and velocity distributions measured in an experimental full scale inductor channel furnace operating with Woods metal, as a low temperature model melt. After successful validation of the numerical model it is applied to industrial ICFs of different power scales, operating with cast iron, aluminium and zinc.

1. Introduction

The induction channel furnace (ICF) is used for holding and casting of ferrous and non-ferrous metals and due to its good efficiency for melting of non-ferrous metals. Fig.1 shows the principle design of a one loop ICF, which is typically used for holding and casting of grey cast iron. The ICF basically consist of a ceramic lined furnace vessel and one or several inductors. In principle, the inductor 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 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 avoid a local overheating in the channel.

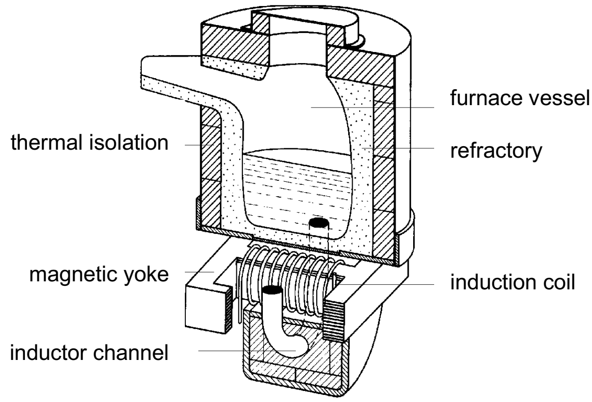

Fig.1. Principle design of an one loop induction channel furnace [2]

Although the ICF is well established for many years, up to now there are still open questions and room for improvements regarding the operation life time of the inductor, which is strongly limited by wear and tear damages like erosion, clogging and infiltration of the ceramic lining in the inductor channel. Practical experience in grey cast iron foundries have shown, that the operation life time of the typical used single loop channel inductors are sometimes only a few weeks due to fast growing build up formations, which lead to insufficient heat exchange and local overheating of the melt in the channel. This channel overheating significantly influences the wearing of the ceramic lining.

The melt flow in the channel itself and in the transition zone between the channel and the bath, the so-called inductor-throat, is very complex, highly turbulent and influenced in some regions mainly by electromagnetic forces but in other regions additionally by buoyancy forces. In order to investigate the operation behaviour of the ICF heat and mass transfer processes in the melt have been analysed applying the Large Eddy Simulation (LES) approach. The simulation results are verified by already existing data of melt flow velocity and temperature measurements.

2. Numerical Modelling

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 three-dimensional (3D) electromagnetic (EM) model performed with the Finite Element (FEM) package ANSYS®. Taking into account the symmetry of the geometry, only half of the full furnace is modelled for the EM calculations (Fig.2). All regions, which are relevant for the EM simulation are taken into account, these are the channel itself and the bath with Wood´s metal, the slitted cooper cooling cylinder between coil and channel, the copper 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 electromagnetic simulation results show a very symmetrical heat source and *Lorentz* force distribution in the 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 electromagnetic 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.

The results of the EM simulation are the input data for the second step, the hydrodynamic and thermal numerical calculations using the ANSYS-CFX® CFD package. A steady state 3D k-ε model or a Shear Stress Transport (SST) model is used for the initial calculations of the melt flow and temperature field, where the calculations are performed using half of the full channel geometry with symmetry boundary conditions.

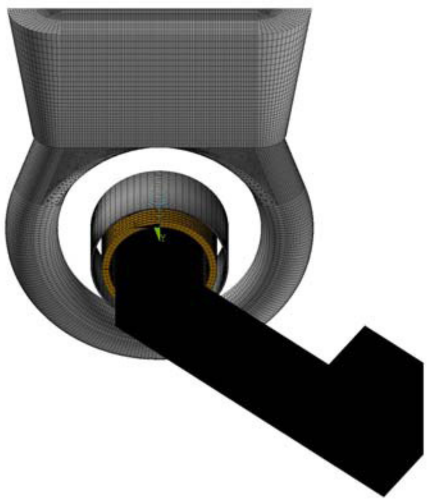

Fig.2. Geometry and mesh of the channel furnace for electromagnetic modelling

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 turbulent main vortices in the cross-sections of the channel is not modelled correctly. Therefore, the Large Eddy Simulation (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 [5, 6]. 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 a time steps of about 5 ms. The channel has adiabatic thermal boundary conditions while the metal bath has fixed temperature of about 80°C due to the water cooled jacket. The free surface of the melt has convection power losses with heat transfer coefficient a = 20

W/(m^2·K). The LES simulations are starting from the steady-state converged results calculated by the mentioned two parameter models or from homogeneous melt temperature of 80°C and zero velocity field. The total simulation time can achieve more than 60 sec.

3. Experimental set-up

The experimental data, used in this paper for the verification of the simulation results, have been carried out by Eggers in 1993 [3]. The experimental set-up consists of an industrial sized channel inductor 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. The local flow velocities have been measured in all three components using a well proved potential probe (*Vivés* probe) [4]. Temperature profiles along the channel as shown in Fig.3 were measured simultaneously using a number of thermo-couples. During the experiments the channel inductor was operating with a power of 60 kW and a frequency of 50 Hz.

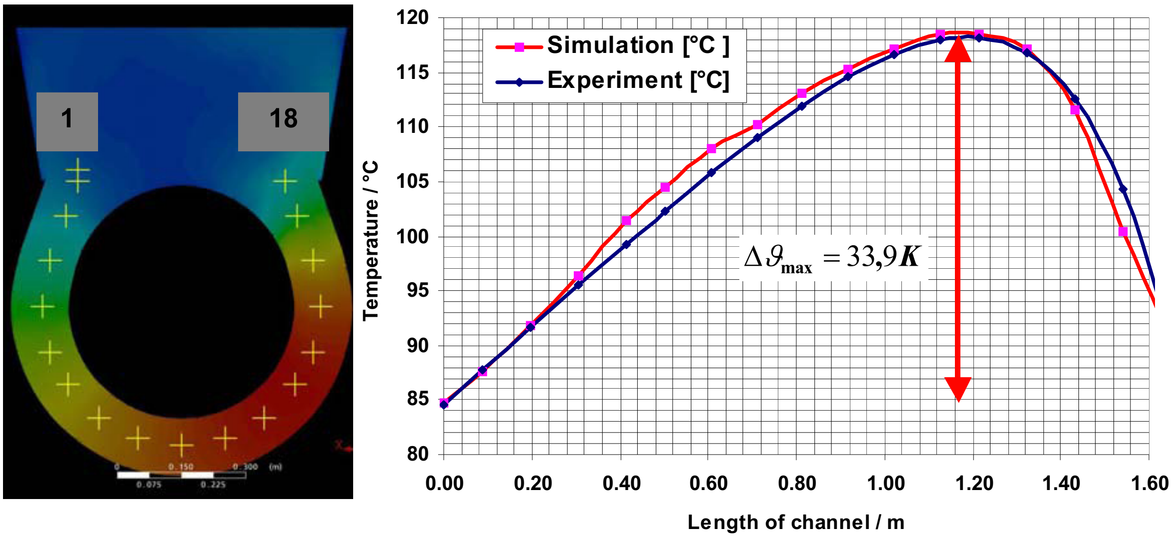

Fig.3. Temperature distribution in the experimental channel furnace. Left: position of thermo-couples, right: comparison between simulation (LES) and experiment

As shown in Fig.3 the temperature distribution calculated with the LES model fits very well with the experimental data, especially with a view on the position and the level of the maximum temperature. Similar results could not be achieved by standard turbulence models, because the turbulent energy transport was not modelled with correct order of magnitude. This problem was solved, in many cases by introduction of an effective turbulent thermal conductivity. With this artificial parameter calculations could be adapted to measurement results. With the LES-model it is possible to calculate temperature and velocity distributions with physically correct material properties.

3. Investigated ICFs

During this work many different ICFs have been investigated. Numerical models for symmetric and non-symmetric single-loop ICF used for cast iron and aluminium, as well as for double-loop ICF used for zinc are established. The symmetry relates to the design of the

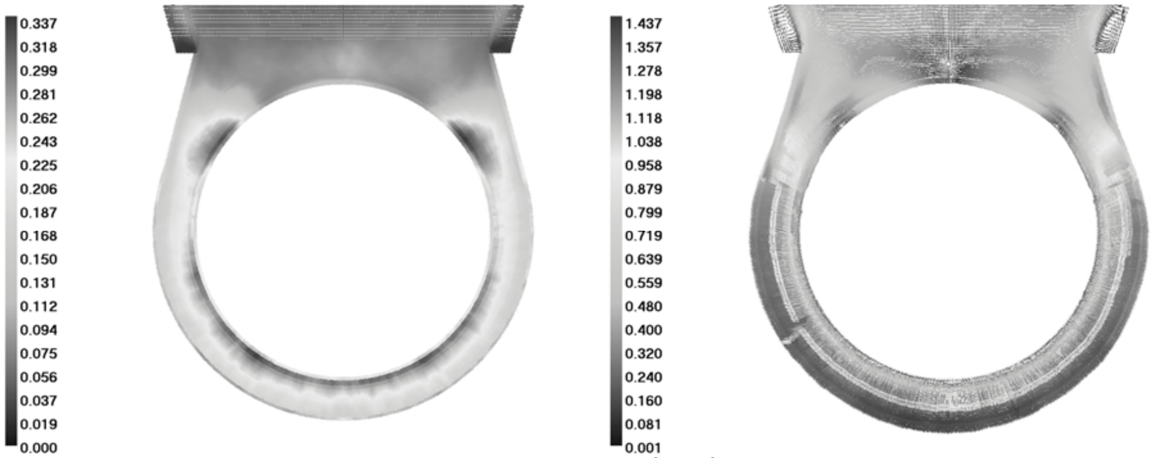

Fig.4. Turbulent specific kinetic energy (left [m^2 /s^2]) and time-averaged velocity (right [m/s]) in symmetric ICF for cast iron

throats. The electric power ranges from 80kW to 1.2MW to get wide spread comprehension for the physics and hydrodynamics in ICFs. This paper sums up the most important and new results of this investigation.

In Fig.4 the specific turbulent kinetic energy and the time-averaged velocity at the symmetry plane is shown for a symmetric ICF. Regions with higher probability for build up formation have typically high turbulent specific kinetic energy together with low average velocities. The laminar sub-layer in this area is not stable and the particles can enter the walls. One of the open questions concerning ICF is the location and the height of maximum temperature in the channel. The local overheating and the pinch-effect limit the power of ICFs. The location of the temperature maximum is affected by a transitional flow through the channel. Calculations show that the transitional velocity through the channel is one order of magnitude below the averaged velocities in the channel. In consequence the transitional flow through the channel cannot be held responsible for the thermal exchange between channel and bath. During transient analysis the location of the maximum temperature is not stable. It moves from one side of the loop to the other side and back at different time-scales depending on the parameters of the ICF. The Fig.5 shows this behaviour. The stationary calculation with standard turbulence model and artificial Nusselt number shows the temperature maximum at the left neck.

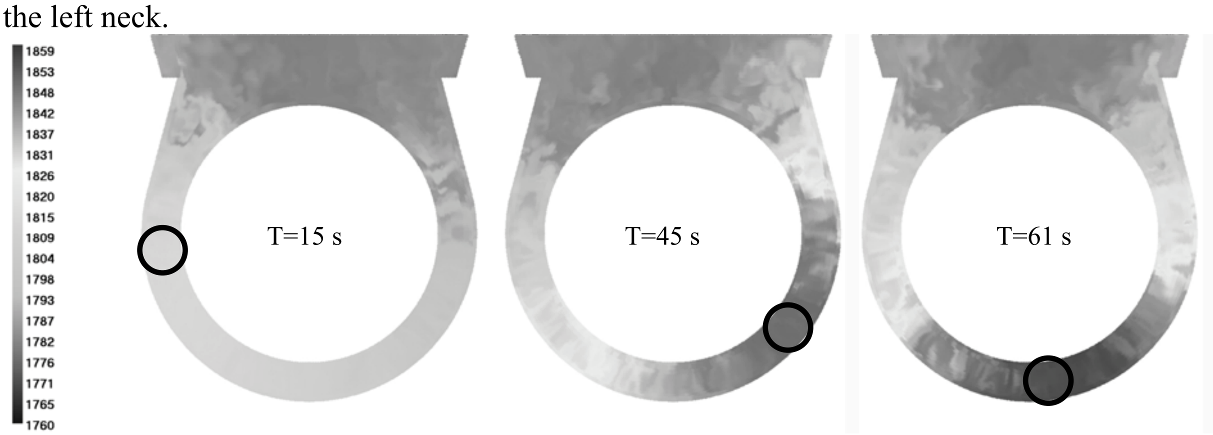

Fig.5. Temperature distribution at different times during operation

After 15s the maximum is moving counterclockwise to the right arm of the channel, where it reaches the end position after 45s. Another 16s later the maximum is again at the lowest point of the channel and is still moving to the left arm. Similar results are achieved for non symmetric channels with different power ranges. The temperature difference was calculated between 34K for the model furnace to 150 K for an inductor for zinc. But for all inductors instable location could be observed.

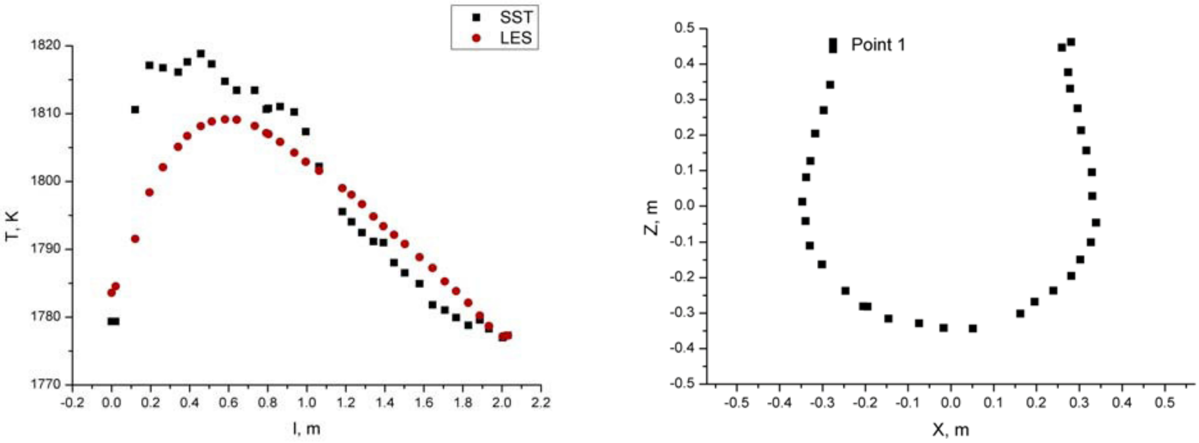

Fig.6. Temperature track along the channel for SST and LES calculations (left) and locations of trackpoints

The calculations have been performed stationary with the SST-k-omega turbulence model. The result was the starting condition for the transient LES calculation. In Fig.6 the result of temperature tracking is shown for both, the stationary and the transient model. As expected the overheating calculated with the SST model is higher. The turbulent heat and mass transport is very important for operation of ICF. This transport could not be modelled precise enough with stationary turbulence models.

4. Conclusion

The LES approach has been successfully applied for highly turbulent melt flow and temperature calculations in ICF of different power scales. With these models numerical investigations for improved design of inductor channels will be carried out.

		Electromagnetic					Thermal
	material	P [kW]	S [MA/m2]	B[mT]	p [MW/m3]	f [kN/m3]	dT [K]
ICF 1	woods metal	60	1.9	30	5	200	34
ICF 2	cast iron	1040	7.0	350	30-80(edges)	1250	90
ICF 3	cast iron	220	3.5-4.8 (edges)	200	13-25(edges)	117	40
ICF 4	cast iron	291	5.19	245	25	665	70
ICF 5	zinc	474	13.4	374	37.6	2210	150

Tab.1. Overview of electromagnetic and thermal parameters of the investigated ICF

In Tab.1 some of the electromagnetic and thermal results are shown for five ICF. The total power induced in the melt is in the 3.rd column. Highest temperature difference was calculated for double loop zinc inductor ICF5. This inductor has almost the highest induced current and power density with 13.4 MA/m2 and 37.6 MW/m3. Some of the investigated inductors have sharp edges and the current density and the power density are up to two times higher there than in the remaining regions. In the table ICF2 and ICF3 belong to this group.

These edges are the source for turbulent eddies and can be used to improve the heat exchange but also can accelerate build up formation.

For a better operation, higher power rates and improved heat exchange between channel and bath are required to limit the maximum temperature in the channel. Regions with high turbulent specific kinetic energy and low averaged velocity should be eliminated to avoid build up formations especially for grey cast iron applications.

5. Acknowledgement

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