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Numerical Modelling of Recirculated Liquid Metals Flows in Practical Applications

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Abstract

The experimental and numerical investigations of the turbulent melt flow are carried out in various laboratory and industrial sized induction furnaces, like induction crucible furnace and induction furnace with cold crucible. The results of the transient 3D LES simulation of the turbulent melt flow revealed the large scale periodic flow instabilities and the temperature distribution in the melt, which both are in good agreement with the expectations based on the data from the experiments. In order to investigate convective heat and mass transport mechanisms in the considered flow the discrete particle tracing approach has been carried out. The studies, presented in this paper, contain the numerical simulation of turbulent melt flow of experimental and industrial size induction furnaces and demonstrate the possibility of using the three-dimensional transient LES approach for successful simulation of heat and mass transfer processes in metallurgical applications.

Introduction

Industrial metallurgical processes like melting of alloys in induction furnaces has become a subject of numerical modeling since many years. A wide range of different modeling approaches for the simulation of the turbulent melt flow and the heat and mass transfer processes have been developed. But up to now a universal and always reliable modeling approach which can be used for the development and design of industrial metallurgical applications is not available.

Melting of alloys in induction crucible furnaces can be mentioned as a wide spread example of numerical modeling, because this process can be approximated with two-dimensional (2D) axial-symmetric model. The flow pattern in these installations is formed by the influence of electromagnetic forces and usually comprises of two or more toroidal dominating recirculating vortices. Flow patterns obtained with two-dimensional solvers based on Reynolds Averaged Navier-Stokes (RANS) equations usually are in good agreement with estimated and measured time-averaged flow velocity values. But, they often fail to describe correctly the heat and mass transfer processes between the main vortices of mean flow. Therefore, the resulting spatial distribution of the temperature and alloys compound concentration may differ significantly from experimental observations.

At the present time, different modeling techniques are being used to achieve better agreement with the experiment [1-3]. Our own engineering approach developed for this problem is described in [4], however, it is necessary to investigate advanced simulation methods for more generic and therefore universal flexible solutions. Due to the permanent growth of accessible high powerful computational resources, nowadays, it is possible to run more complicated transient and three-dimensional (3D) numerical calculations of fluid dynamic problems using advanced turbulent models with higher time and volume resolution requirements and to get reliable results in reasonable time.

Concluding all these preconditions the calculations presented in this paper were devoted to the application of Large Eddy Simulation (LES) method for turbulent recirculating flows, which often occur in various industrial processes where liquid metal is acting by electromagnetic forces.

1. General Information

The experimental investigations of the melt flow and temperature distribution in the induction furnace with cold crucible (IFCC) were performed using 6 kg pure aluminium (99.5%) in the cold crucible with a radius of 7.8 cm and a height of 26 cm. The output power of the generator was 200 kW at the frequency range 8-10 kHz. The meniscus height reached up to ~22.5 cm under those conditions. With these process parameters the meniscus shape of the melt surface is quite stable and therefore it is possible to perform detailed investigations of the free melt surface itself, the temperature field and the turbulent melt flow.

The temperature distribution was measured using NiCr-Ni thermocouples, which were placed in a protective ceramic tube to avoid their destruction in the very aggressive aluminium environment during long-lasting experiment. However, due to this protection, the thermal inertia of the thermocouple was quite long (~2.8 s), therefore, it was possible to measure only time-averaged temperature values. In order to investigate temperature oscillations in several characteristic points of the melt, the thermocouple was used without ceramic protection. In this case the response time became approximately 0.8 s, but the operational time for one thermocouple decreased to the 10-15 minutes.

The time-averaged temperature field as it was measured is shown on the Fig. 1. There is clearly seen how temperature distribution is influenced by the thermal boundary conditions. The lowest temperatures are at the water-cooled bottom, where was detected the solid skull layer with thickness about 10 mm. Also the radiation losses from the free surface lead to the formation of relatively cold area at the top. And the highest temperatures are observed in the intensive inductive heating region. The temperature distribution in the rest of the melt is more or less homogeneous.

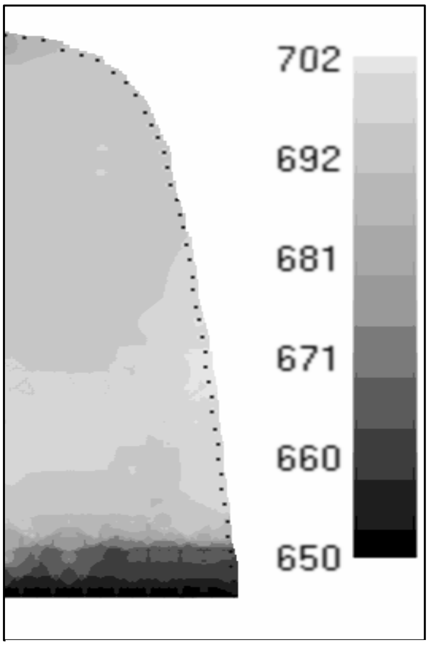

Fig. 1. Measured temperature distribution in aluminium melt in IFCC [˚C]

The melt flow velocity was measured with electromagnetic sensor [5]. Low corrosion durability of the flow velocity measuring sensor in the aluminium melt appeared to be the greatest problem in the measurements performed. After 10-20 minutes of operation the magnetic steel core and the steel case were so greatly corroded that the sensor became unfit for the further operation. All sensors were calibrated in the induction crucible furnace with Wood's metal (Figure 1). The measured sensitivity of the sensors varied through the range 0.3 – 0.8 $\mu V/(cm \cdot s^{-1})$. The main results of our velocity measurements in the liquid aluminium show, that flow pattern consists of two vortexes and the zone of their interaction is located between z = 7 and z = 9 cm. The maximum axial velocity detected in the upper vortex on the symmetry axis was 40±5 cm/s. In overall, these observations are in quite good agreement with numerical predictions.

2. Numerical modelling

The electromagnetic part of cold crucible modelling was resolved with commercial software ANSYS using 3D model, which represents a half-slit wide sector-cut of the complete geometry. Because of acceptable run-times of these calculations, it was possible to couple them with the self-developed code, which calculates free-surface shape of the melt. The use of 3D electromagnetic model also was advantageous since it gives the non-symmetrical (real) Lorentz force and Joule heat distribution in the melt.

For the numerical investigations of the turbulent melt flow as well as the heat and mass transfer two turbulence models were applied. The first was the well-known k-ε model, which has relatively low mesh requirements and is widely used and verified in various numerical engineering applications. This model usually produces fast good quantitative results for the time-averaged velocity distribution in case of stationary two dimensional calculations, but fails to describe correctly the heat and mass transfer quantities in the melt when the system contains at least two dominating recirculating flow eddies.

3D calculations were based on Large Eddy Simulation (LES) turbulence modelling method, which can be described as a compromise between the solving of RANS equations and Direct Numerical Simulation (DNS). Main flow structure is resolved directly like in the DNS approach, but small eddies, which size is comparable with grid size, are modelled additionally. Therefore, finer meshing and, as result, more computational resources are required in order to get an advantage over two-equation models, e.g. k-ε turbulence model, but still less than it is necessary for the application of the DNS.

2.1. Aluminium melt flow and temperature distribution

As it is shown on the velocity plot (Fig. 2) the time-averaged flow pattern, calculated with 2D k-ε model, consist of two vortexes. The thermal boundary conditions for upper and lower vortexes significantly differ - we have the radiation from the free surface above and water-cooled bottom below. The estimated heat flux distribution shows that only 6% of the thermal energy are lost due to the radiation (emissivity coefficient $\varepsilon = 0.3$). The rest of the heat is carried away with the cooling water through the crucible bottom. As far as the heat exchange between the two parts was underestimated, the 2D steady-state simulation predicted too high temperature in the upper region of the melt, which is not confirmed by experimental data.

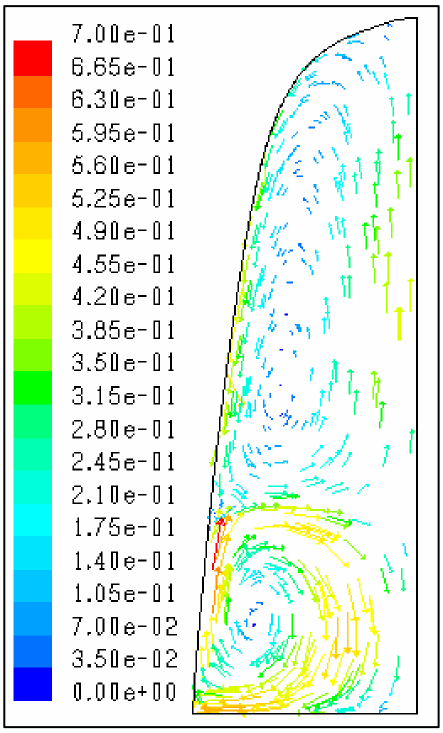

Fig. 2. Velocity vectors calculated with 2D RNG k-ε turbulence model [m/s]

The resulting time-average velocity field of LES looks very similar to the predicted with 2D steady-state calculations, as well as quite good agrees with experimental observations. But, at the same time, the time-averaged temperature distribution calculated with LES is more homogeneous, than in case of 2D modelling and better agrees with the measured temperature field. In the pictures series with temperature filed at the consequent time-steps it can be observed how relatively cold melt masses from below penetrate into upper vortex area and are dissolved there.

The discrete particle tracing approach has been carried out additionally in order to visualize convective mass transport mechanism in the considered flow. Particles trajectories in transient flow show, that the mass exchange between the vortexes is quite effective and homogenisation time should not exceed several eddy turnover times, but the same particles in the mean flow (time-averaged of LES results or predicted with RANS models) move in the closed loop and do not penetrate into the another vortex.

2.2. Parameter studies for TiAl melt

The 3D numerical investigations of TiAl melting process produced similar results in terms of flow pattern (Fig. 3). The melt mass was the same 6 kg, but the meniscus height in this case is lower due to the increased density of the material. The flow velocities are slightly higher (maximal average velocity at $r = 0$ is about 55 cm/s), therefore the temperature distribution is more homogeneous, than in aluminium. Calculated temperature oscillations have similar amplitude (3 - 4 K) as these measured in aluminium (Fig. 4). It should be taken into account here, that higher frequencies in measured oscillations are “filtered” by thermocouple, while the time step in the calculations was 0.01 s.

Due to the noticeably lower H/D ratio of the melt shape, the low-velocity zone exists in the middle of the bottom region, which may lead to the thicker skull layer above the water-cooled base. Therefore, the modification of the crucible’s geometry or load is considered as a possible way to improve the efficiency of the process.

There were performed calculations for the three different H/D ratios, but the power induced in the melt was kept the same. The Fig.5 shows the results for two ratios: 1.20 (left) and 1.67 (right) additionally to the 0.84 ratio shown on Fig. 3. As it can be seen, the flow is more intensive near the central axis in case of smaller diameter crucible. This can prevent the

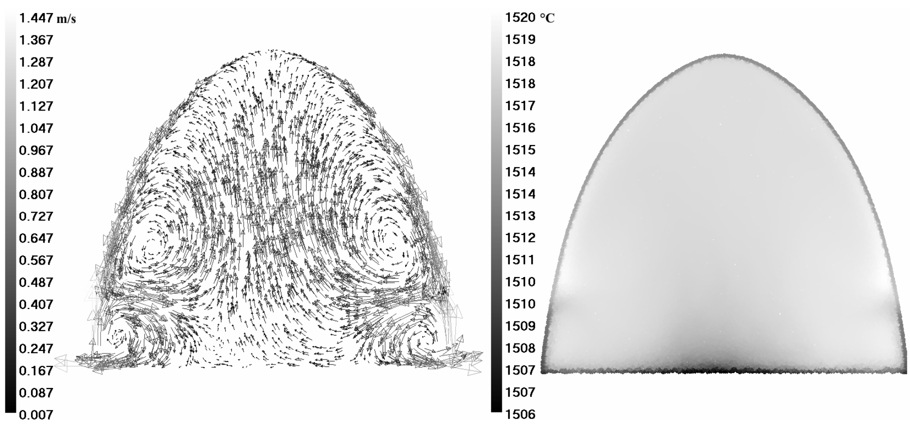

Figure 3: Time averaged velocity and temperature distribution in TiAl alloy.

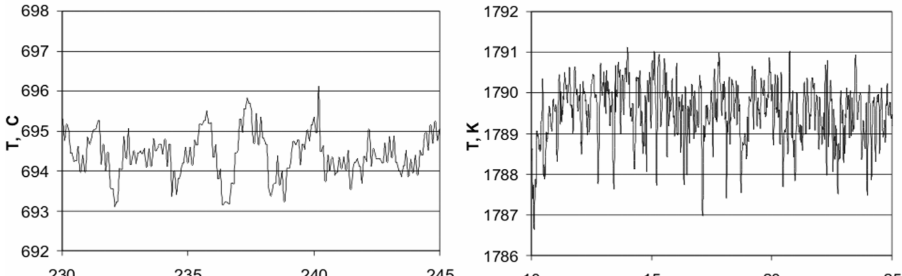

Figure 4: Temperature oscillations on the axis measured in aluminium (left) and calculated for TiAl alloy (right).

formation of the thick layer of the solidified material at the bottom. But, at the same time, the melt has larger contact area with the crucible walls, which can lead to the changes in the electromagnetic forces and Joule heat sources distribution in the melt, as well as to increased heat flux to the water-cooled slits. But, the comparison of electrical efficiency of these systems show (Tab. 1), that only about 18% of the full power are induced in the melt in case of H/D=0.84, while for the larger ratio it is ~36%. Therefore, the same amount of Joule heat can be generated with significantly lower total energy consumption.

Tab.1 Parameter studies with TiAl melt in IFCC.

Ratio of the melt H/D	Inductor current, kA	Total power, kW	Power in the melt, kW	Power in the melt, %
0.84	4.6	275.3	50	18.2
1.20	4.0	188.0	50	26.6
1.67	3.7	138.6	50	36.1

Also, the influence of the electromagnetic field frequency was studied. The Fig. 6 demonstrates the melt shape and the time-averaged flows for two cases: 5 and 20 kHz. The melt height decreases at higher frequencies (the induced Joule heat was kept constant). The velocities are noticeably smaller in the 5 kHz case (almost twice on the axis), which may lead to the less intensive mixing. These particular calculations show, that maximum temperature for 20 kHz is by 7 K (or 28% from temperatures range in the melt) higher then for 5 kHz. This can be considered advantageous, because increasing of the overheating temperature is useful for practical applications.

Conclusions

The results of the LES modelling of aluminium melting process are in good agreement with the experimental investigations.The comparative modelling results show, that the configurations with higher H/D ratio of the melt are more efficient. Also the lower frequencies provide better mixing of the melt, but are less effective from the practical point of view. Considering, that change of any parameter (frequency, power and ratio) influences the melt

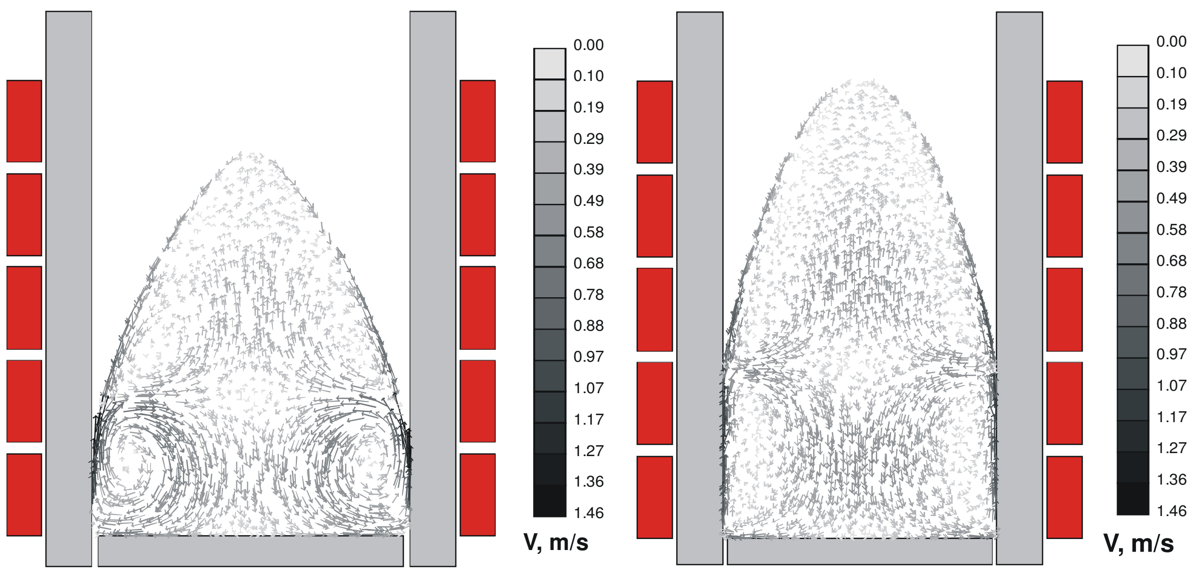

Fig. 5 Velocity vectors of TiAl melt in cold crucible with H/D ratios 1.20 (left) and 1.67 (right).

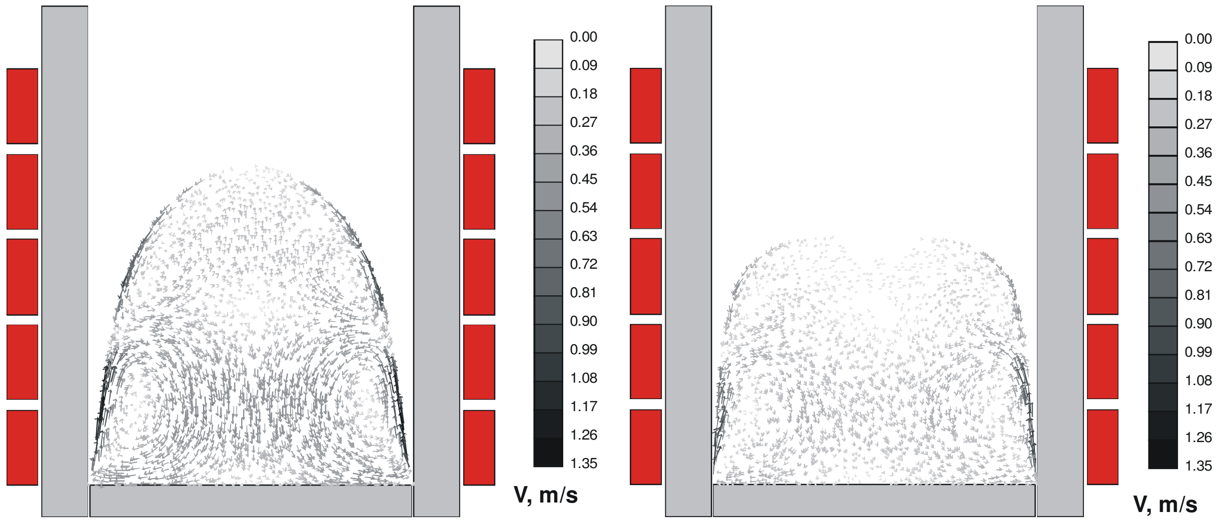

Fig. 6 Velocity vectors of TiAl melt in cold crucible with EM field frequency 5 kHz (left, H/D=0.99) and 20 kHz (right, H/D=0.77).

shape and, therefore, the electromagnetic coupling and temperature distribution, further investigations are required to obtain the optimal IFCC configuration.

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