IMPROVEMENT OF THE COLD CRUCIBLE MELTING PROCESS USING LES MODELLING

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Introduction. The induction furnace with cold crucible (IFCC) offers various technological and economical advantages, like high-purity cast products as well as melting, alloying and casting in one process-step [1]. Practical experiences show that the overheating temperature of the entire melt, which is determined by the electromagnetic, hydrodynamic and thermal behaviour of the cold crucible installation is one of the key parameters of this technological process.

Former experimental investigations in induction crucible furnaces (ICF) carried out that, at any given time moment, the velocity field is far from symmetrical. The analysis of experimental and numerical results shows that the flow fluctuations contain also low-frequency component which may have significant influence on the heat and mass transfer processes in the melt. Considering the transient and three-dimensional character of this phenomenon, it was expected, that steady-state or 2D modelling, without implementation problem-specific modifications, will be not able to describe correctly such flow parameters as temperature and concentration distributions. That's why the Large Eddy Simulation (LES) numerical technique was approved to be an alternative for the models based on Reynolds Averaged Navier-Stockes (RANS) equations. The results of the transient 3D LES simulation contained the large scale periodic flow instabilities similar to those obtained from the experimental data.

Due to these positive results, transient 3D calculations using the LES model were carried out in order to investigate the possibilities to increase the overheating temperature of the melt in the IFCC. These numerical studies were concerned with influence of various design and operation parameters. The commercial CFD software package FLUENT was used for the application of LES to the hydrodynamic and thermal problem, but the external electromagnetic forces and the shape of the melt surface were calculated using the commercial software package ANSYS and self-developed FEM codes.

Aluminium served as a model melt for the experimental validation of the numerical results for the temperature and melt flow velocity field. Suitable measuring methods were selected, improved and realised, particularly with regard to the high melt temperature ($\sim 700°$C) and very aggressive behaviour the aluminium melt.

1. Experiment. The experimental investigations 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

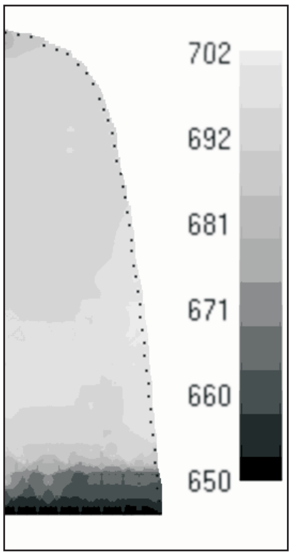

Fig. 1. Measured temperature distribution.

very aggressive aluminium environment during long-lasting experiment. However, due to this protection, the thermal inertia of the thermocouple was quite long ($\sim$ 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 (see Fig. 4), 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.

The melt flow velocity was measured with electromagnetic sensor [2]. 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, which has melting temperature of 72°C. The measured sensitivity of the sensors varied through the range 0.3–0.8 μV/(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 field inside the crucible is not fully axis-symmetrical, due to the conductive slit walls. Therefore, an approximation should be used for 2D distribution of heat sources and volume forces in the melt.

2.1. Steady-state 2D simulation. We have chosen the RNG modification of the $k-\varepsilon$ model for the 2D simulation of the KIT process. According to our previous numerical studies, it has delivered more accurate predictions about turbulence properties in the recirculated flows than the standard model. But, both of them usually underestimated the heat transfer intensity between the two time-averaged main flow eddies formed by the external electromagnetic forces [3, 4]. 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. The rest of the heat is carried away with the cooling water through the crucible bottom and walls. As far as the heat exchange between the two parts was underestimated, the 2D steady-state simulation predicted too high

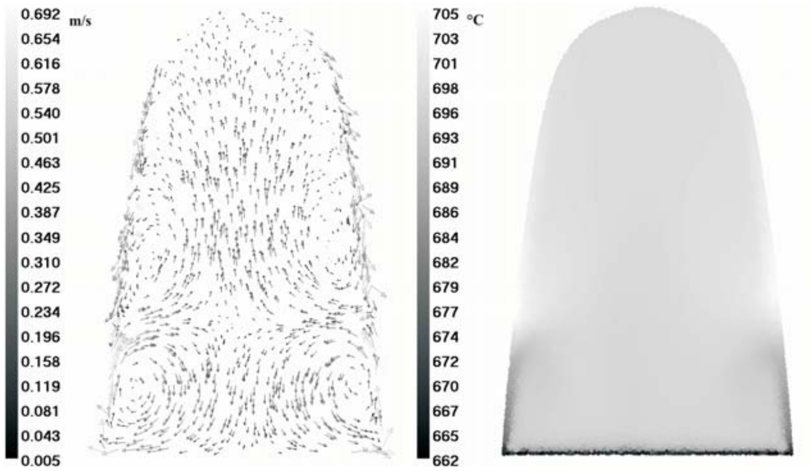

Fig. 2. Time averaged velocity and temperature distribution in Aluminium.

temperature difference between upper and lower vortexes, which is not confirmed by experimental data.

2.2. Transient 3D simulation. 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) [5].

The resulting time-average velocity field (Fig. 2) looks very similar to the one predicted with 2D steady-state calculations, as well as quite good agrees with experimental observations. However, 3D transient approach allows to model accurately the heat transfer processes in such flows, where two or more recirculated eddies are interacting. The calculated flow pattern at the each time-step is not symmetrical, and simulation shows, that the flow is intensively oscillating. Those oscillations provide convective heat transfer mechanism, which is possible to simulate numerically only using transient three-dimensional calculation techniques. The time-averaged temperature distribution calculated with LES (Fig. 2) is more homogeneous, than in case of 2D modelling and resembles the measured temperature field (Fig. 1). 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.

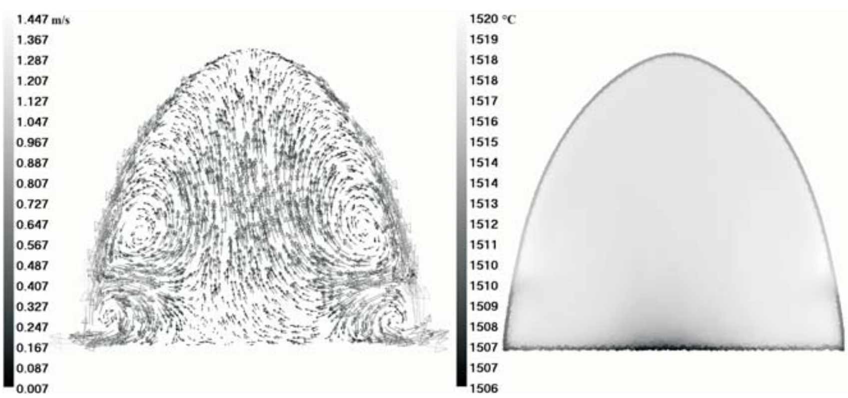

Fig. 3. Time averaged velocity and temperature distribution in TiAl alloy.

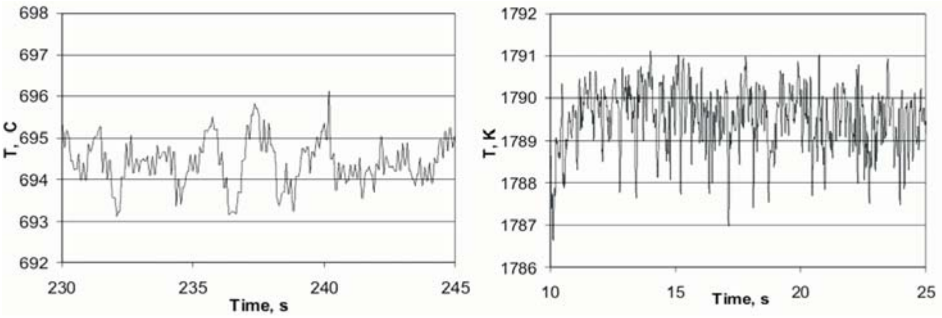

Fig. 4. Temperature oscillations on the axis measured in aluminium (left) and calculated for TiAl alloy (right).

The 3D numerical investigations of TiAl melting process produced similar results in terms of flow pattern (Fig. 3), although the meniscus height in this case is lower due to the increased density of the material. The flow velocities are slightly higher (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 higher R/H 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.

3. Conclusions. Measurements of the temperature and velocity fields in the aluminium melting process in the cold crucible show typical recirculating flow structure with an axial symmetry and with presence of intensive three-dimensional flow field oscillations, which are responsible for effective mixing and temperature homogenisation of the entire melt. The modelling results show, that only the 3D transient LES is able to model correctly these heat and mass transfer processes.

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REFERENCES

1. M. Vogt, F. Bernier, A. Mühlbauer, M. Blum, G. Jarczyk. Experimental Investigations of Temperature Field and Energy Flows in Induction Furnace with Cold Crucible and a practical Application of the Results. In *Proc. of Int. Symp. Electromagnetic Processing of Materials* Nagoya, Japan, 2000, pp. 289–294.

2. E. Baake, B. Nacke, F. Bernier, M. Vogt, A. Mühlbauer, M. Blum. Experimental and numerical investigations of the temperature field and melt flow in the induction furnace with cold crucible. In *Proc. of the Int. Seminar on Heating by Internal Source* Padua, Italy, September 12-14, 2001, pp. 21–28.

3. E. Baake, B. Nacke, A. Umbrashko, A. Jakovics. LES Modelling of Heat and Mass Transfer in Turbulent Recirculated Flows. In *In Proc. of the 5^{th} Int. PAMIR Conference* Ramatuelle, France, Sept. 16-20, 2002, vol. I, pp. 173–178.

4. E. Baake, B. Nacke, A. Umbrashko, A. Jakovics. Turbulent flow dynamics, heat transfer and mass exchange in the melt of induction furnaces. In *In Proc. of the Int. Seminar on Heating by internal sources* Padova, Italy, 2001, pp. 47–53.

5. J.S. Smagorinsky. General circulation model of the atmosphere. *Monthly Weather Review*, vol. 164 (1963), pp. 91–99.