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Continuous melting and pouring of an aluminum oxide based melt with cold crucible

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Abstract

A distinctive feature of induction furnaces with cold crucible is the skull melting without introducing any impurities in the melt and overheating of the melt over 3000°C at air. Therefore the technology of induction melting in cold crucible is suitable for high temperature synthesis of oxide materials. This paper describes a new technology for continuous melting and pouring of oxide melts. A new type of cold crucible with two chambers is used for this application. In the first chamber the charged oxide is melted and transferred via a barrier to the second chamber where the oxide is superheated before pouring over a discharging hole. During the transfer of the melted oxide from the melting zone into the superheating zone the transport of non-melted oxide particles has to be avoided. This transport is mainly influenced by the hydrodynamics of the melt flow and the temperature field during melting and pouring. Numerical simulation is used to investigate the heat and mass transfer during the melting and pouring processes in the cold crucible furnace. Both forced and free convections are taken into account in the simulation. Apart from the melt flow inside the cold crucible special attention is also paid to the behavior of the pouring stream. The numerical results are compared with experimental data of melting and pouring experiments in the skull melting installation at the Institute of Electrotechnology. The paper presents a description of the cold crucible setup, the results of the numerical simulation and comparison of them with experimental data.

Key words: Electromagnetic melting, cold crucible melting, skull melting, oxide melting, continuous pouring

Introduction

At the Institute of Electrotechnology (ETP) an inductive skull melting installation is available to conduct experiments with all sorts of low conductive materials. In particular, the installation is used for production of optical glasses, melting of oxides, chemical high temperature reactions and directional solidification or pulling of crystals [1-3]. The needed process temperature, especially in case of oxides, often exceed 2000°C. With the inductive skull melting technology it is possible to handle process temperatures of more than 3000°C by using an inductor crucible when melting glasses or a cold crucible when melting oxides. The inductor crucible can be regarded as a single turn coil combined with a crucible

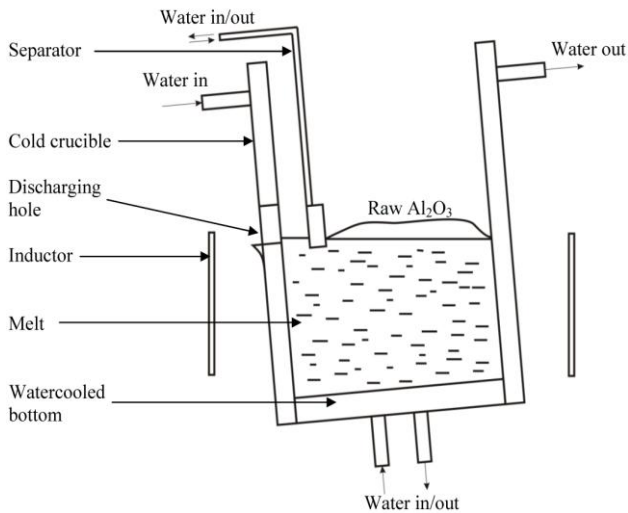


Fig. 1: Principle of cold crucible for continuous pouring

Fig. 2: Design of cold crucible for continuous pouring

into a single unit, whereas a separate inductor is needed when a cold crucible is used. In both cases, massive water cooling of all components is required. Between the hot melt inside the crucible and the water-cooled crucible walls, a layer of solid material is formed, which is commonly referred to as skull layer. The skull layer provides protection against contamination of the melt and damage to the crucible in general.

The existing installation was extended in the last years by a new cold crucible for continuous melting and pouring of high temperature oxides [4]. A special design of the cold crucible with two separated working areas allows continuous melting, superheating and pouring in one device. Fig. 1 shows the principle of the cold crucible with the inductor, the water-cooled bottom, an additional separator to create a separate chamber for superheating and the discharging hole for pouring.

Design of the cold crucible for continuous pouring

Fig. 2 shows the design of the induction furnace. The furnace consists of the single-turn inductor with inner diameter of 340 mm and height of 250 mm. The water-cooled crucible has inner diameter of 250 mm and height of 505 mm.



Fig. 3: Cold crucible with separator

Every section of the crucible is separately water-cooled. The cross section of the crucible is mostly of round shape, only the front sections are mounted in a straight line. The middle front section has a discharging hole. In the upper part the sections are fixed on the pertinax plate by a bolt connection, at the bottom they are fixed by a copper ring. A water-cooled bottom is located inside the crucible.

A barrier (separator) is located inside the crucible in front of the discharging hole. It has no contact with the crucible. The barrier is produced from copper profile and is water-cooled too. The separator provides the division of the crucible into two chambers (Fig. 3) and allows overheating the melt inside the pouring chamber.

The induction system with cold crucible is located inside the water-cooled working chamber (see Fig. 2). The crucible is tilted by a certain angle to allow pouring the melt through the discharging hole.

The inductor is connected to the water-cooled current feeder of the high frequency transistor generator with an output power of 300 kW and an output voltage of 450 V which is doubled by the capacitor

transformation to around 900 V. Frequency can vary in the range from 80 to 350 kHz.

Experiments

Experiments with new designed cold crucible for melting of aluminium oxide have been carried out at ETP. The melting process includes several steps: preparation of the oxide material; starting of the process; induction melting to form the melt and pouring.

The oxide material is filled into the cold crucible up to the level lower than the discharging hole. The oxide in the solid state is good electrical insulator and but its electrical conductivity increases at temperatures near the melting point. Wherein coupling to the electromagnetic field is appearing. For starting of the melting process a little quantity of pure metal is embedded inside the oxide material. The small pieces of this starting metal melt down by induction heating and transfer the induced heat to the surrounding oxide. As soon as the oxide has itself reached high enough for coupling temperature it is able to absorb the electromagnetic energy directly because the electrical conductivity is increased. The melting pool is extended by charging of additional oxide powder.

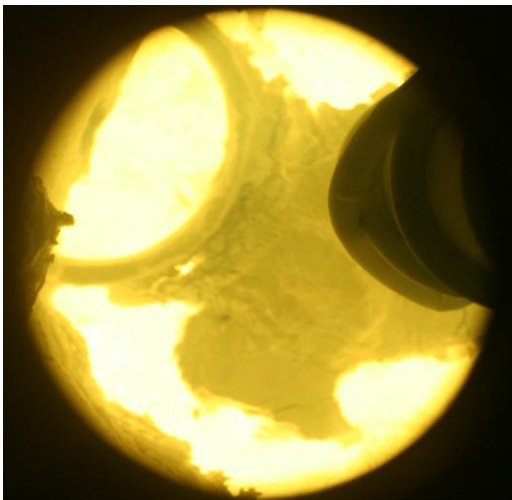


Fig. 4: Melt surface during melting



Fig. 5: Continuously pouring stream

Induction melting is carried out at frequency of 300 kHz with the generator output voltage of 400 V and power of 200 kW.

Fig. 4 shows the top view to the crucible during the melting process before pouring. The oxide powder is permanently charged to the melting zone of the crucible through the water-cooled

charging tube. The barrier prevents flow of non-melted material to the superheating zone during melting. The flow of the melted oxide from the melting zone to the superheating zone takes place under the separator.

The pouring stream of the melt is shown in Fig. 5. The main aim of the pouring process is to receive the continuous melt jet through the discharging hole in the cold crucible. This is mainly influenced by the melt flow and the temperature distribution in the melt. In order to receive the continuous melt jet, permanent transfer of the melted oxide from the melting zone to the superheating zone must be provided. The temperature in the melt must be high enough for melting the charged oxide and the pressure on the melt surface generated by the non-melted oxide must be constant. The melt surface temperature is kept up around 2300°C during the pouring.

Mathematical model

In order to optimize the flow from the melting to the superheating chamber and secondly to optimize also the pouring behaviour, a 3D numerical model for the cold crucible with separator has been developed. Calculation of electromagnetic field based on Maxwell equations was realized in ANSYS software [5]. The obtained electromagnetic forces and Joule heat are imported to the fluid dynamic analysis.

The melt flow is described by the Navier-Stokes equation:

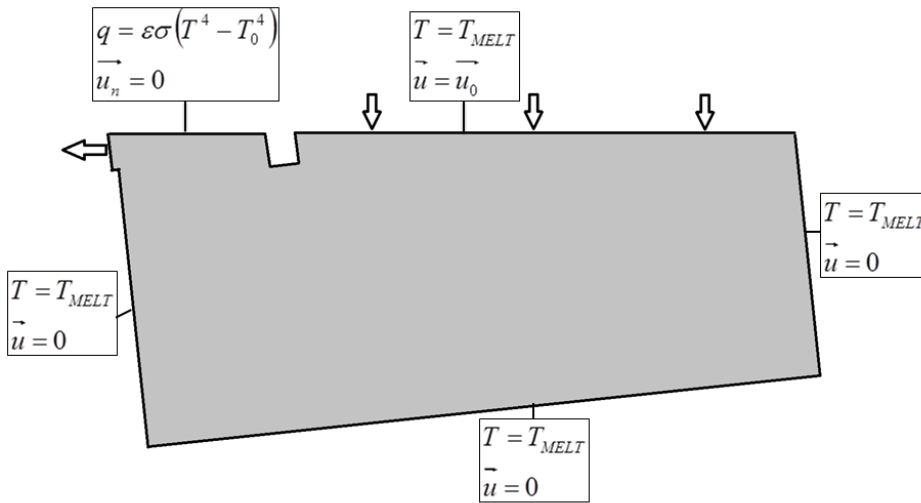
$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \nabla \vec{u} = \frac{1}{\rho} \nabla p + \nu \Delta \vec{u} + \frac{1}{\rho} \vec{f} - \beta T \vec{g}$$

Here u – velocity; p – pressure; T – temperature; f – Lorentz forces density; β – thermal expansion coefficient; ν – kinematic viscosity.

The thermal process in the melt is described by the heat transfer equation:

$$\frac{\partial T}{\partial t} + \vec{u} \nabla T = \frac{\lambda}{c\rho} \Delta T + q$$

Here λ - thermal conductivity, c - specific heat, q - Joule heat density.



Geometry of the melt and the boundary conditions are shown in Fig. 6. Constant temperature $T = T_{MELT}$ was assumed for the bottom and the walls with no slip for the flow field which corresponds to the solid-liquid interface between the melt and the skull. The top surface divided in pouring and melting zones is treated differently. In the pouring zone a radiation boundary conditions with free slip are used. In the melting zone the fixed temperature $T = T_{MELT}$ and flow rate are used.

Fig. 6: Calculation area and boundary conditions

Results of numerical simulation

Fig. 7 shows the temperature distribution in the vertical cross section of the crucible. In the middle part of the crucible the temperature isolines are horizontal. The arrows show the direction of melt flow which is in this zone from right side to the left side. In front of the pouring zone the flow arrows change its direction to the bottom. This effect is explained by temperature differences between the separator and the melt. In the pouring zone the flow arrows change its direction again to the top and then reach the discharging hole.

Fig. 8 shows the streamlines of velocity in the melt. Along the whole perimeter of the crucible buoyancy vortices are observed which are caused by strong radial temperature gradients. These vortices are narrow in radial direction and long in vertical direction. In the region of outflow the vortex is more intensive and larger in radial direction. An additional vortex is formed directly under the surface in the superheating zone, it has velocity vectors directed downwards near the separator due to the cooling of melt.

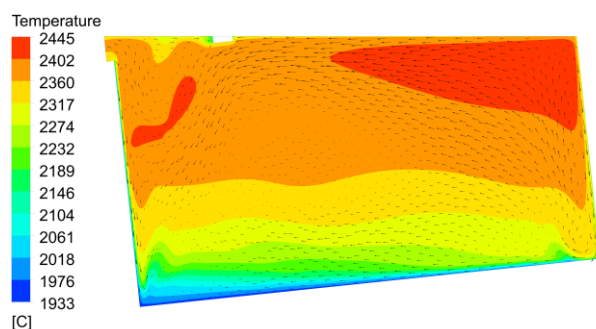


Fig. 7: Temperature field and direction of melt flow

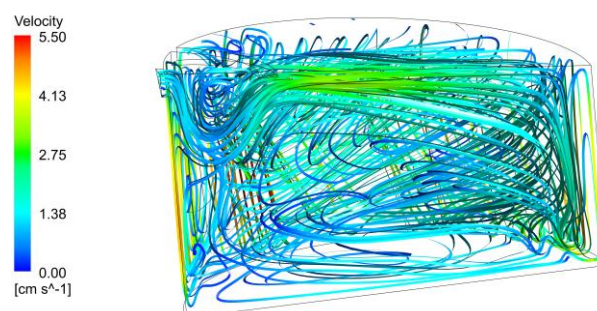


Fig. 8: Streamlines of melt flow velocity

Comparison of experimental and numerical values of power losses

The numerical simulation of the induction melting process in cold crucible allows obtaining the power losses in each induction furnace unit and the induced power in the melt. For this purpose a 3D numerical model of the induction furnace was developed so that the system geometry and dimensions are fully representing the real induction furnace.

The numerical model was used to predict the power losses in the furnace system without any material in the crucible in order to separate the losses in the crucible and the induced power in the melt.

The comparison of obtained experimentally energetical parameters of the induction furnace and results of numerical modelling, presented in Table 1, show very good agreement. Experiment allows measuring the power losses in the cold crucible and in the melt only together, while numerical simulation provides the data separately.

Table 1: Comparison of experimental and numerical data

Parameter	Experiment	Numerical modelling
Diameter of the melt, cm	25	25
Height of the melt, cm	14	14
Frequency, kHz	298	298
Power losses in the inductor, kW	3.4	3.4
Power losses in the cold crucible and melt, kW	76	15.8 (crucible) 63,2 (melt)
Power losses in the bottom, kW	3.8	1.4
Total power losses, kW	83.2	83.8

Conclusions

A new type of cold crucible furnace has been developed for continuous melting and pouring of oxide materials. The furnace has two separate chambers for melting and superheating but it is powered by one induction coil only. The superheating zone in the second chamber is achieved by using an additional barrier which provides the separation but also the superheating of the melt before pouring. With a special numerical simulation model the melt flow inside the double-chamber crucible has been investigated and optimized. The second numerical model is able to calculate the energetical parameters of the furnace and allows optimization of energy efficiency of the melting and pouring processes. The new furnace has been experimentally investigated and meanwhile tested in practice. It confirms that continuous melting and pouring of oxide materials in one cold crucible is feasible and efficient.

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