Temperature and flow distribution of liquid metal fin in refractory of induction crucible furnaces

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***Abstract*—The melting process in induction crucible furnaces causes permanent erosion at the refractory. Apart from the fact that liquid metal may infiltrate the refractory, mechanical strains may also cause cracks. Liquid metal can enter the cracks and the metal can penetrate the refractory and reach the water cooled induction coil. If the induction coil is insufficiently cooled by water, it is possible that the hot liquid metal fin melts the copper coil. Should this happen, water would vaporize and produce hydrogen. An explosion with possibly fatal results would occur. Here, we numerically simulate the transient behavior of such a liquid metal fin in the refractory of induction crucible furnaces. We include the description of the boundary conditions, of the materials, of the arrangement, of the simplifications, and of the parameter variations used for the simulations. The results of the numerical simulations will be presented and finally some liquid metal fin characteristics will be interpreted.**

Keywords—induction, heating, crucible, temperature, flow, metal, fin, safety

I. INTRODUCTION

The simulated section of the furnace wall (Fig. 1) consists of seven vertical regions. Here we find the furnace wall, the induction coil, and the environment. We assume a liquid melt is in the inner region of the furnace. The crucible wall consists of 60 mm refractory and an electrode panel which is 0.3 mm thick and of layer silicate. The electrode panel is simplified as mica and will be directly glued onto the 20 mm coil grout. The copper coil follows the coil grout after 0.3 mm coil isolation. The coil profile is a rectangular hollow profile with 12 mm x 20 mm edge length and an inner cutout of 6 mm x 14 mm for cooling water. To insulate the coil windings, a 10 mm layer of coil isolation will be used. Air is assumed to be the induction furnace environment. The liquid metal fin with 4 mm height is inserted horizontally into the refractory and then different cases are calculated. We expect a strong influence of the melt flow on the heat transfer in the metal fin. Numerical simulations are the only way to obtain information about the heat transfer conditions in these types of metal fins, since the hostile environment of a working furnace makes real measurements impossible.

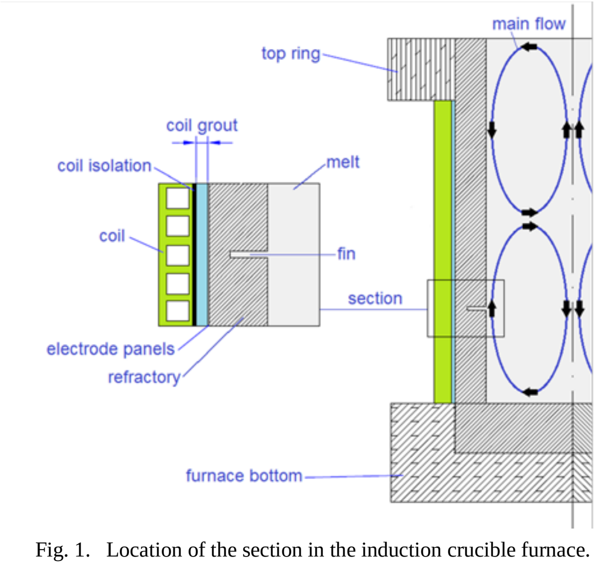

Fig. 1. Location of the section in the induction crucible furnace.

II. NUMERICAL SIMULATION

Simulating the entire furnace including the necessary environment is exceedingly expensive and time-consuming. Thus, we assume symmetry and we define a section with useful boundary conditions at the boundaries. Fig. 2 shows three coils and the melt with the penetrating fin of the section. Magnetic boundary conditions and thermal boundary conditions for the stationary temperature field calculation will be assumed to respect the symmetry conditions. Inside the crucible we have hot liquid iron with a temperature of 1600°C. In such induction crucible furnaces we find a strong turbulent flow with velocities of 1 meter per second or higher [2]. Normally we find two vortices of melt flow inside an induction crucible furnace. We consider a worst case position for our section where the flow moves vertically from the bottom to the top. For our simplification we use a melt flow velocity of 1 meter per second (Fig. 2). Detailed information about boundary conditions, material properties, and simulation results without metal flow can be found in [1].

ANSYS WORKBENCH is used for the coupled simulation of the electromagnetic field (MAXWELL) together with the flow and temperature field (FLUENT). MAXWELL is used to calculate the heat sources and the time averaged Lorentz forces for FLUENT. It is a one-way coupling, because we assume a constant electrical

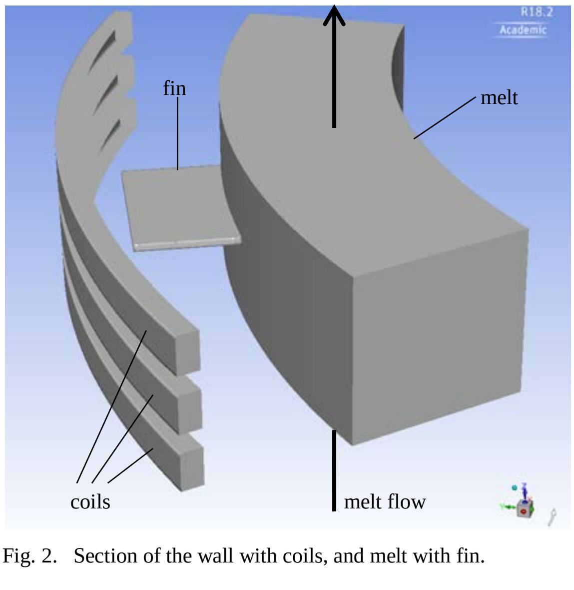

Fig. 2. Section of the wall with coils, and melt with fin.

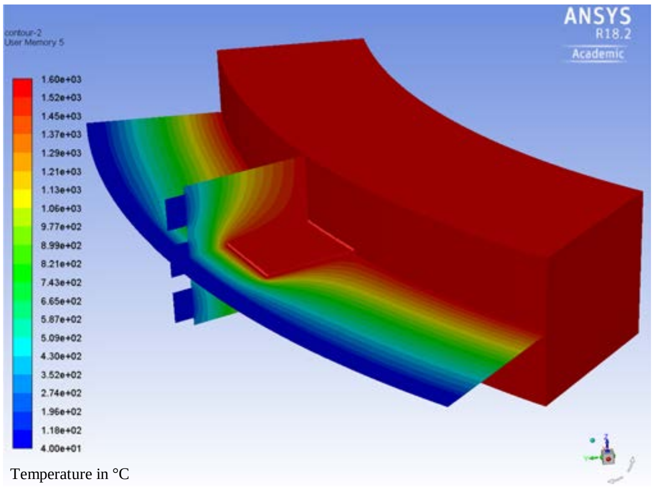

Fig. 3. Temperature distribution of the melt with fin and two cut planes, fin width: 100 mm.

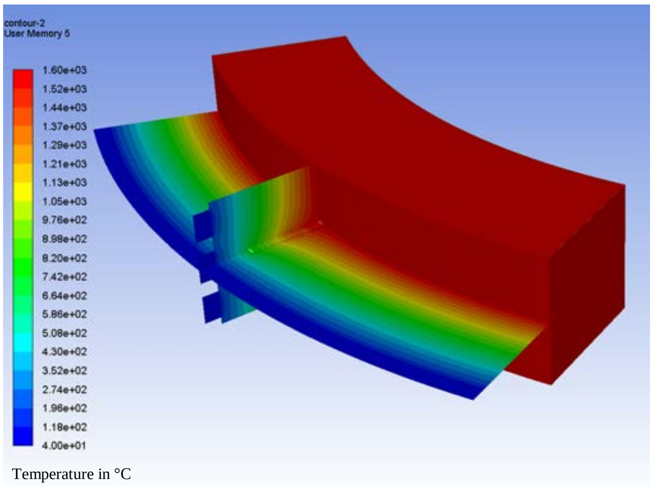

Fig. 4. Temperature distribution of the melt with fin and two cut planes, fin width: 10 mm.

conductivity not depending on temperature. That’s why the temperature isn’t needed for MAXWEL. ANSYS is able to transfer the heat sources from MAXWELL to FLUENT, but it is not possible to transfer the time averaged Lorentz forces on the WORKBENCH to FLUENT automatically. That’s why the coupling must be performed by hand. We use the so called User Defined Functions of FLUENT to save the coordinates of the FLUENT mesh in a file. The powerful MAXWELL field calculator is able to read this coordinate file to calculate the time averaged Lorentz force density and to save the data in a file for FLUENT. Now FLUENT can read and use the Lorentz force density for the flow calculation. To calculate the strong turbulent flow, we chose the Transition SST (4eqn) turbulent model. The Reynolds number has a value of about $4 \cdot 10^6$.

III. RESULTS

The numerical model is able to calculate different fin types under the influence of heat sources and Lorentz forces including the global melt flow in the crucible. In this research we investigate horizontal metal fins with a length of about 60 mm and a thickness of 4 mm. The top of the fin is located near the electrode panel.

A fin width of 100 mm (Fig. 3) leads to a nearly constant temperature distribution in the fin which has the level of the liquid metal in the crucible (1600°C). The temperature at the top of the fin decreases only by about 50 K, which is not to be seen in Fig. 3. This nearly constant temperature distribution in the fin can only be explained by a powerful metal flow in the fin. A detailed view to the flow in the fin shows a velocity up to 1.86 m/s near to the side walls of the fin. This could explain the erosion effect of the refractory. Solid thin horizontal metal fins are occasionally found at the end of the lifetime of the induction crucible furnace in the refractory.

A fin width of 10 mm (Fig. 4) leads to a temperature distribution in the fin which is similar to the temperature of the undisturbed case without fin in the refractory. The metal flow is not able to develop in this small fin. That’s why the heat transfer is mainly generated by heat conduction. A detailed view of the flow in the small fin only shows a very small melt flow velocity. This could explain that horizontal small solid fins are not found at the end of the lifetime of the induction crucible furnace in the refractory.

We can change the axial position of the fin in our model by varying the velocity of the vertical melt flow. The position of the section in the middle is an interesting case where we assume the velocity of the main flow is equal to zero. In this case only the Lorentz forces push the flow in the fin, and we get a similar temperature distribution in the metal fin like shown in Fig. 3. Simulation results show that the influence of the velocity of the vertical main flow is low.

IV. CONCLUSIONS

Former numerical investigations [1] of metal fins didn’t consider the melt flow. In these cases the heat sources in the metal fin near to the inductor lead to temperatures much higher than 1600°C. From a certain fin width between 10 to 50 mm, flow vortices occur in the fin which lead to an intensive heat transfer and finally to a nearly constant temperature of 1600°C (temperature in the crucible). The conclusion is that the fluid flow can’t be neglected in the metal fin.

In this investigation we only use a static contour of the metal fin. But to summarize our findings, we assume that the melt fin needs a minimum width in order to grow into the refractory. If the fin is too narrow the heat transfer is too small. Then the temperature decreases below the melting point and the liquid metal becomes solid. The induced eddy currents are not strong enough to prevent the cooling. Small fins which have a width lower than a certain limit value can’t exist.

V. OUTLOOK

Further interesting questions can be investigated using our new coupled simulation model. Open questions are: What happens with the melt fin if it is located vertically? What is the influence of frequency, eddy currents, Lorentz forces and global melt flow on the heating and growing process of the liquid metal fin? Is it possible to simulate the growing process of the metal fin?

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