NUMERICAL CALCULATION OF THE TEMPERATURE DISTRIBUTION IN THE MELT OF INDUCTION CRUCIBLE FURNACES

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INTRODUCTION

In induction furnaces, power losses from the eddy currents in the melt are used to heat the charged metal. Nearly all of the induced heating power is generated inside the melt within the small depth of penetration. On the other hand, the electromagnetic Lorentz forces on the molten metal cause heat transport by forced convection. Figure 1 shows a cross section of an induction furnace. The question is wether the influence of convection is strong enough to homogenize the temperature of the melt. This paper deals with a method to calculate numerically the steady state temperature distribution within the melt, taking into account the heat transport by conduction, convection and radiation. The calculations below were done for a 800kg steel furnace with a filling level of 125%, an induced power of 50 kW at 500 Hz; any other combinations can be calculated.

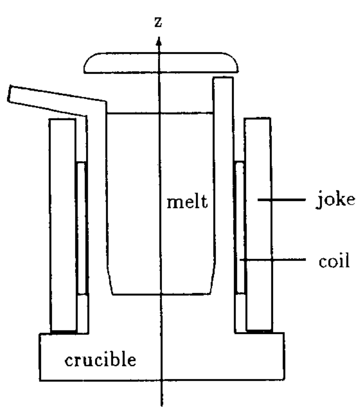

Figure 1: induction furnace (cross section)

CALCULATION CONCEPT

The calculation of the temperature distribution consists of three main parts: In the first step a FEM eddy current solver package is used to calculate the density fields of induced power and electrodynamic forces. In a second step the flow field within the melt is computed. Having now obtained the strength and location of the heat sources as well as the data

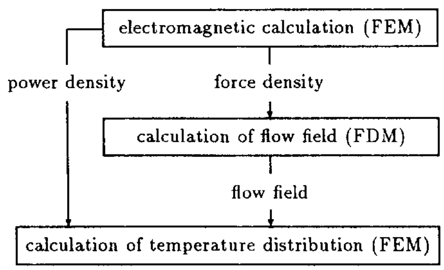

Figure 2: Flow chart of calculation steps

concerning heat transport by forced convection, the calculation of the temperature field can take place in the third step.

ELECTROMAGNETIC ANALYSIS

Figure 1 shows the cross section of an induction furnace. To obtain the model for the FEM analysis, all non-interesting parts are removed. Relevant parts of the furnace are the melt, the coil and the joke. Because induction furnaces have cylindrical geometry, the problem is quasi-two-dimensional; the model can be reduced to the resulting structure in figure 3. Boundary conditions for the electromagnetic calculation are:

- The melt has homogenous conductivity σ and permeability μ
- The joke is assumed to enclose the whole furnace circumference and to have homogenous permeability μ
- The coil is free of losses (conductivity is zero)

A FEM package developed by *Shen* [4][5] at the Institute of Electrical Machines is used for the electromagnetic analysis. An exciting current density $\underline{J}^e$ is impressed in the coil; the resulting vector potential only includes the φ-component and is computed in the form $\underline{U} = \underline{A} \cdot \underline{r}$. In a postprocessing function, the power density field is computed following the equation

$$p = \frac{1}{2}\omega^2\sigma\left(\mathrm{Re}\{\underline{A}\}^2 + \mathrm{Im}\{\underline{A}\}^2\right) \qquad (1)$$

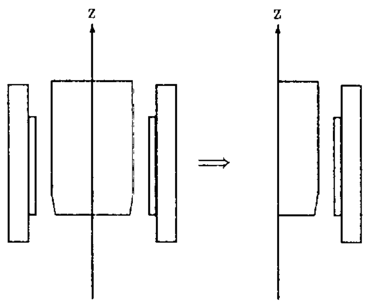

Figure 3: Model for electromagnetic calculation

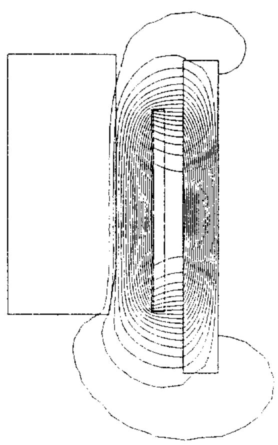

Figure 4: Flux density

Figure 4 shows the calculated flux density.

CALCULATION OF THE FLOW FIELD

The behaviour of the fluid is described by the equation of Navier-Stokes. Turbulence effects are taken into account by the effective viscosity η_W [1]. For the free turbulent circle vortex is

$$\frac{\eta_W}{\eta} = \frac{Re}{Re_{min}} \tag{2}$$

where Re is the Reynolds number and Re_{min} has been determined by experiment. In this case, a value of $Re_{min} = 30$ fits well [6].

The electromagnetic forces $\vec{f}_{el}$ in the melt couple the magnetic field and the fluid field. Not the absolute value of the forces but their curl determines the intensity of the fluid flow. It can be obtained using the equation

$$\begin{aligned} \mathrm{rot}(\vec{f}_{el}) &= -\frac{2}{r}\mathrm{Re}\{\underline{J}_\varphi \underline{B}_r^*\} - 2\omega\sigma\mathrm{Im}\{\underline{B}_r \underline{B}_z^*\} && (3) \\ with\ \underline{\vec{B}} &= \mathrm{rot}\underline{\vec{A}} = -j\omega\sigma\underline{\vec{A}} + \mu\underline{\vec{J}^e} && (4) \end{aligned}$$

Leurs [6] programmed a FDM package for the calculation of the flow field in the melt of an induction furnace. The FDM grid of 50 x 100 = 5000 nodes covers the area of the melt. The values for rot$\vec{f}_{el}$ are interpolated from the FEM mesh to the FDM grid using the method of weighted distance. Considering the turbulent vortex of the fluid flow one has to find the equivalent viscosity η_W by repeating the computation of the fluid field with different viscosities until condition (2) is satisfied. The final computation result (Fig. 5) shows the two typical whirls which are observed at a single-phase fed furnace.

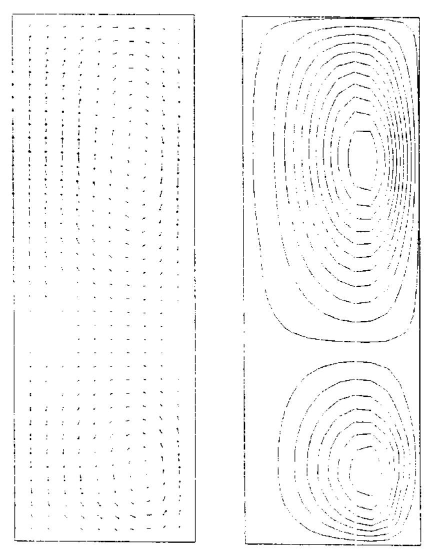

Figure 5: Flow field: strength (arrows) and main flow direction (lines)

TEMPERATURE FIELD

The calculation of the temperature distribution takes place using a solver adopted from a FEM package, which was developed by *Conraths* in [2]. The solver uses Newton-Raphson iteration to solve the nonlinear problem. The model for the temperature analysis must have a different mesh and structure than the one for the electromagnetic analysis, since now we have to regard all heat-conducting parts of the furnace. In addition, the whole melt must have an extremely fine mesh in order to obtain a small Peclet number for each Element. If the element

Peclet number grows too large, the algorithm tends to be instable. Figure 6 shows the outline of the used model.

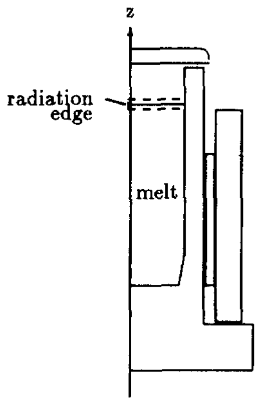

Figure 6: Outline of the model for temperature calculation

The power density is assumed to be constant within a single element of the target mesh. It is interpolated to the new mesh using a linear formulation:

$$p(r,z) = d_1 + d_2 \cdot r + d_3 \cdot z$$

which is applied to the nodes of the source mesh element (123) that encloses the centre of gravity of the target mesh element (abc) to get the values for d_i; with the known constants d_i the power density for the target element is obtained by calculating the power density at the center of gravity S_{abc}.

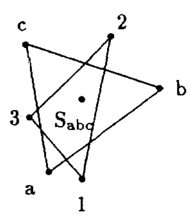

Figure 7: Interpolation between the two FE meshes

The flow field values from the FD-solver are interpolated in a similar way. The formulation is

$$v(r,z) = c_1 + c_2 \cdot r + c_3 \cdot z + c_4 \cdot r \cdot z$$

Figure 8 illustrates the interpolation from FDM to FEM meshes. In both cases, the interpolation error is less than 3 percent.

Heat transport by radiation must be taken into account at the surface of the melt. Therefore, this edge is constrained to have radiation properties. The emissivity of this edge can be choosen freely; for a steel melt $\varepsilon \approx 0.3$ is a typical value that was used here. The temperature at the coil is bound to 80 °C. At a distance of 3 meters from the furnace and also at the bottom of the crucible temperature is assumed to be 20 °C. The furnace cover can be "opened" or "closed" by assigning different thermal properties to it. In the following example the cover was open. Figure 9 illustrates the resulting temperature distribution in the melt. Plotted are isothermal lines. The temperature varies from 1340 °C in the lower right corner of the melt to 1365 °C.

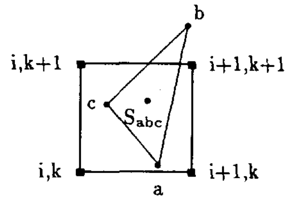

Figure 8: Interpolation from FD grid to FE mesh

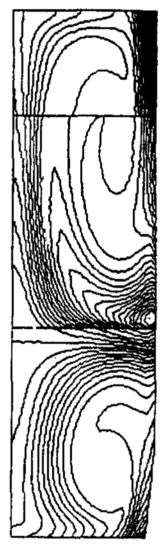

Figure 9: Temperature field in the melt

The two whirls from the flow field calculation are represented in the temperature field. In the upper whirl, the melt flows clockwise into the area of power induction, where it is heated up. After leaving this region, it cools down, delivering heat to the rest of the melt by convection and conduction and, at the surface of the melt, by radiation. Except radiation, the same procedure takes place in the lower whirl, which rotates counterclockwise. The temperature is nearly homogenous. A slight increase in temperature can be observed in the depth of penetration between the two whirls. This is caused by low transport speed and high induced power density in this region.

CONCLUSION

A method for numerical calculation of the temperature distribution in the melt of induction furnaces has been presented. The calculation takes place in three steps:

- electromagnetic analysis
- computing of the flow field caused by forced convection
- calculation of the temperature field using the results of the two previous steps.

The obtained results have to be regarded under the following boundary conditions:

- Up to now, only steady state temperature distributions can be calculated.
- The calculated flow field represents the effective flow speed in main flow direction. Turbulence effects causing heat transport transversal to the main flow are neglected.
- Thermal contact resistances are not enclosed.
- Radiation and convection at the outer surface of the furnace are neglected.
- All material parameters are assumed to be constant.

The presented method allows to detect regions with superheating as well as such with high heat losses and to improve the form and material of the thermal insulation parts of a furnace. In addition, steady state losses of a furnace model can be calculated.

*

References

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