SIMULATION-DRIVEN DESIGN AND OPTIMIZATION OF A NEW TWO-COIL CRUCIBLE INDUCTION FURNACE USING THE ALTAIR FLUX3D® SOFTWARE

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Abstract: A new two-coil crucible induction furnace with a lateral coil connected to the one-phase electric power supply and a bottom coil connected to a capacitor bank with an appropriate value of the capacity is able to realize a desired balance between the induction heating of the lateral face and of the bottom face of the furnace bath. The evaluation of the optimum value of the capacity, which corresponds to the same mean value of the induced power density on the respective faces, represents an example of simulation-driven optimal design. Finite element models are used to study many variants of the new furnace related the number of turns of the two coils and related the diameter of the furnace bath for imposed bath volume.

Keywords: CRUCIBLE INDUCTION FURNACE, FINITE ELEMENT ANALYSIS, TWO-COIL INDUCTOR, OPTIMAL DESIGN

1. Introduction

The induction furnace of crucible type continue to be one of the most wide-spread device for melting, alloying, holding of the metallic and of the non-metallic materials like glasses, salts and oxides, which in the molten state are electro-conductive enough [1, 3, 8, 11].

Taking into account the evolution in the last decades of the hardware and software for numerical computations, the deeper investigation of phenomena associated with induction furnaces operation, the study of new configurations and the optimal design are becoming more and more accessible to peoples involved in research and industrial developments [2, 4 - 7].

In the usual induction furnaces the molten bath / the furnace charge is placed in a cylindrical volume surrounded by the inductor. The inductor produces the AC magnetic field, whose penetration in the furnace charge is associated with the generation of induced currents in the electro-conductive material of the furnace bath. The inductor of the furnace [9] usually consists in one or many circular turns, series connected. Each turn of the inductor can consist in many conductors connected in parallel through one input and one output terminals.

The usual induction furnaces are one-phase electrically supplied. The one-phase inductor with one turn or many turns series connected is called also the furnace coil. In fact, the term furnace inductor is associated with the phenomenon electromagnetic induction and the term furnace coil defines a correspondent physical component of the device.

If together with the induction heating effect of the electromagnetic field, a controlled electromagnetic stirring and/or the levitation of the molten bath is desired [2, 10], the inductor has more than one coil and the furnace is multi-phases supplied. In both cases, one-coil one-phase inductor and multi-coils multi-phases inductor, the inductor is placed around the lateral face of the furnace bath. In such a configuration the density of the induced currents on the circular face of the bath’s bottom has the maximum value on the circle between the lateral face and the bottom face and decrease in an exponential manner to zero value zero in the bath axis. The mean value of the power associated with the Joule effect of the induced currents is much lower on the bottom face than on the lateral face of the furnace bath. As consequence, the induction heating of the bath bottom face is much less intense than the heating of the lateral face.

The novelty of the two-coil inductor configuration studied in this paper consists in the simultaneous action of two coils, a lateral coil, electrically supplied, and a bottom pancake coil, connected to a capacitor bank. The optimum design of such a two-coil one-phase inductor ensures the same mean value of the induced power on the lateral face and on the bottom face of the furnace bath.

All applications in this paper correspond to the frequency supply 300 kHz, volume of the molten glass bath 110.8 dm³, reference value of bath radius 275 mm and the gap 45 mm between the furnace bath and the coils.

2. Geometry and mesh of a one-turn LATERAL coil and three-turns BOTTOM coil

The images in the figure 1 show the main components of the new two-coil crucible induction furnace with cylindrical bath. The inductor contains the one-turn LATERAL coil, with eight conductors parallel connected, and the three-turn BOTTOM coil.
The finite element analysis of the electromagnetic phenomena associated with furnace operation uses Flux3D models [12] with the meshing presented in the figure 2.

**Fig. 2.** Finite element meshing of regions with current density in the electromagnetic field computation domain.

### 3. Volume density of induced power in the usual one-coil inductor induction furnace

If the terminals of the BOTTOM coil are free, or if the coil is connected on a high resistance resistor, for example a voltmeter, Fig. 3 a), this coil is not involved in the induction heating of the furnace bath when the LATERAL coil is connected to the power supply source. The furnace operates as a usual one-coil one-phase furnace. The distribution of the volume density of the induced power in this case, Fig. 4, shows that the heating of the bath bottom face, heating in direct connection with this density, is much lower than the heating of the lateral face of the furnace bath. The ratio of the mean values of the induced power volume density \( dJp \) related to the lateral face and to the bottom face of the furnace bath, \( \text{LATERAL}_dJp/\text{BOTTOM}_dJp = 5.337 \), is much higher than one. Consequently, there is a week contribution to the induction heating of the entire furnace bath of the bath volume in the bottom neighboring.

**Fig. 3.** Circuit models of the studied furnace: a) BOTTOM coil connected on a high resistance resistor; b) BOTTOM coil connected on a capacitor.

**Fig. 4.** Volume density of induced power in the usual one-coil one-phase induction furnace

### 4. Influence of the capacity connected to the BOTTOM coil terminals in the two-coil furnace

The figure 5 presents the dependence of the ratio \( \text{LATERAL}_dJp/\text{BOTTOM}_dJp \) on the value of the capacity of the capacitor bank CAPA, Fig. 3 b), connected to the terminals of the BOTTOM coil. This operational parameter of the new two-coil furnace reflects the balance between the contributions of the cylindrical face and of the circular bottom face of the furnace bath to the induction heating determined by the diffusion of the AC electromagnetic field through the respective faces.

**Fig. 5.** Dependence on CAPA capacity of the operational parameter \( \text{LATERAL}_dJp/\text{BOTTOM}_dJp \)

The optimal value \( \text{LATERAL}_dJp/\text{BOTTOM}_dJp = 1 \) in the figure 5, respectively the same mean value of the induced volume power density on the lateral face and on the bottom face of the furnace bath, corresponds to the values of the CAPA capacity \( C1 = 232.49 \text{ nF} \) and \( C2 = 294.67 \text{ nF} \).
The dependences on the capacity of CAPA of the power induced in the furnace bath and of the voltage and current related to this capacitor are presented in Figs. 6 and 7.

Fig. 6. Dependence on capacity of the power induced in the furnace bath.

Fig. 7. Dependence on the capacity of CAPA voltage and current

The volume density of induced power in figure 8 corresponds to the optimal value C1 of the CAPA capacity and to a value of the current in the LATERAL coil for which the power induced in the furnace bath is 400 kW. It is obvious from both images the contribution of the BOTTOM coil of the new two-coil furnace to the induction heating of the furnace bath bottom.

Fig. 8. Volume density of the induced power for optimal value C1 of the CAPA capacity, NEord1 and NEord2 results.

The maps of the volume density of induced power in the figure 9 for the two values C11 = 221 nF and C12 = 240 nF of the CAPA capacity, under and over the optimal value C1, correspond, the first, to the case in which LATERAL_dJp/BOTTOM_dJp = 1.3428, when the heating of the lateral face of the furnace bath is more intense than the heating of the bottom face, and, the second, to LATERAL_dJp/BOTTOM_dJp = 0.7734, when the heating of the lateral face of the bath is less intense than the heating of the bottom face. In the first case the bottom of the furnace bath it is underheated and in the second case this area is overheated.

Fig. 9. Density of the induced power for two values of CAPA capacity C11 = 221 nF and C12 = 240 nF, under and over the optimum C1.

5. Two-coil furnace variants with different number of turns

In the SIMULATION-DRIVEN OPTIMAL DESIGN context, there are presented in Table 1 results for three optimal C1 variants of the new two-coil furnace with different numbers of turns of the LATERAL and BOTTOM coils. One from the three variants can be selected based on the criteria (1) maximum of furnace electric efficiency, (2) minimum of BOTTOM coil losses, or (3) minimum of voltage of LATERAL coil and/or of BOTTOM coil. Taking into account globally all three criteria, the variant 1 turn LATERAL coil and 5 turns BOTTOM coil should be selected. The drawback in comparison with other two, related the high value of the BOTTOM coil voltage, should be compensated by the reduced value of the current in this coil.

Table 1: Different number of turns of LATERAL and BOTTOM coils. The optimal values of CAPA capacity are C1 = 233.9 nF, 233.9 nF, 13.1 nF

<table>
<thead>
<tr>
<th>LATERAL coil / BOTTOM coil</th>
<th>1 turn / 3 turns</th>
<th>2 turns / 3 turns</th>
<th>1 turn / 5 turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge induced power [kW]</td>
<td>399.9</td>
<td>399.7</td>
<td>398.8</td>
</tr>
<tr>
<td>LATERAL coil losses [kW]</td>
<td>1.060</td>
<td>1.398</td>
<td>1.029</td>
</tr>
<tr>
<td>BOTTOM coil losses [kW]</td>
<td>37.05</td>
<td>34.41</td>
<td>23.71</td>
</tr>
<tr>
<td>Furnace electric efficiency [%]</td>
<td>91.30</td>
<td>91.36</td>
<td>94.16</td>
</tr>
<tr>
<td>LATERAL coil voltage [V]</td>
<td>1387.4</td>
<td>2853.7</td>
<td>1383.6</td>
</tr>
<tr>
<td>LATERAL coil current [A]</td>
<td>1367.5</td>
<td>683.8</td>
<td>1361.6</td>
</tr>
<tr>
<td>BOTTOM coil voltage [V]</td>
<td>2807.9</td>
<td>2822.5</td>
<td>3877.1</td>
</tr>
<tr>
<td>BOTTOM coil current [A]</td>
<td>1238.0</td>
<td>1215.1</td>
<td>607.53</td>
</tr>
<tr>
<td>LATERAL_dJp/BOTTOM_dJp</td>
<td>0.989</td>
<td>1.001</td>
<td>1.000</td>
</tr>
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</table>
6. Different diameters, same volume of the furnace bath of two-coil furnace

In the same SIMULATION-DRIVEN OPTIMAL DESIGN context, the results in Table 2 correspond to different values of the furnace bath diameter: 430 mm, 550 mm and 670 mm. Fig. 10. The variant 1 turn LATERAL coil 5 turns BOTTOM coil is considered. Maximum of the furnace electric efficiency and minimum values of the BOTTOM coil losses and of the voltages of the two coils of the furnace correspond to the first value of the bath diameter.

![Fig. 10. Different diameters, the same volume.](image)

### Table 2: Different bath diameters, the same volume, 110.8 dm³. The optimal values of CAPA capacity are C1 = 106.1 nF; 83.13 nF; 68.92 nF

<table>
<thead>
<tr>
<th>Charge Diameter [mm]</th>
<th>430</th>
<th>550</th>
<th>670</th>
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<tr>
<td>Charge induced power [kW]</td>
<td>399.1</td>
<td>398.8</td>
<td>399.7</td>
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<tr>
<td>LATERAL coil losses [kW]</td>
<td>1.687</td>
<td>1.029</td>
<td>0.7224</td>
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<tr>
<td>BOTTOM coil losses [kW]</td>
<td>21.60</td>
<td>23.71</td>
<td>25.91</td>
</tr>
<tr>
<td>Furnace electric efficiency [%]</td>
<td>94.49</td>
<td>94.16</td>
<td>93.74</td>
</tr>
<tr>
<td>LATERAL coil voltage [V]</td>
<td>1181.4</td>
<td>1383.6</td>
<td>1574.4</td>
</tr>
<tr>
<td>LATERAL coil current [A]</td>
<td>2365.8</td>
<td>1361.6</td>
<td>919.4</td>
</tr>
<tr>
<td>BOTTOM coil voltage [V]</td>
<td>3242.3</td>
<td>3877.1</td>
<td>4500.1</td>
</tr>
<tr>
<td>BOTTOM coil current [A]</td>
<td>648.7</td>
<td>607.53</td>
<td>584.6</td>
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<tr>
<td>Lateral_dJp/Bottom_dJp</td>
<td>1.003</td>
<td>1.000</td>
<td>0.9995</td>
</tr>
</tbody>
</table>

7. Volume density of induced power along a path

The curves in figure 11 show the variation of the volume density of the induced power along a path consisting in a vertical line of the lateral face of the furnace bath and the correspondent radius of the bottom face. The first map in Fig. 11 corresponds to the usual one-coil furnace, the second to the new two-coil furnace. The results correspond to the 550 mm diameter of the furnace bath.

![Fig. 11. Volume density of induced power along a path](image)

8. Conclusions

The new two-coil crucible induction furnace one-phase supplied, with a capacitor bank connected to the bottom coil, represents a better solution than the usual one-coil furnace in what concern the distribution of the induction heating on the lateral and bottom faces of the furnace bath. Through the value of the capacity connected to the bottom coil, the intensities of the induction heating on the lateral face and on the bottom face of the furnace bath can be coordinated with furnace operation requirements.

In the context of optimal design of the new two-coil inductor, solutions to reduce the Joule losses in the bottom coil, respectively to increase the furnace electric efficiency, are under study.

### References


