Optimization of Cold Crucible Shape with Different Number of Rectangle Segments

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Abstract — **The beginning of the article briefly describes the principle and construction solution of the cold crucible. The next part is devoted to the numerical simulation of the cold crucible with different number of rectangle segments. The calculation considers the electrically non-conductive material (Al2O3 in melted form) as the load at normal temperature. Based on the obtained results (Joule losses), it is possible to determine the distribution of power losses in the individual parts of the cold crucible and efficiency of the system. Finally, the best construction solution is selected.**

Keywords — cold crucible, induction melting, ANSYS, numerical simulation, power losses

I. Introduction

The method of induction melting in a cold crucible is used for melting electrically conductive and electrically non-conductive materials. One of the biggest advantages is the ability to reach temperatures above 3000 °C. Due to high temperatures the impurities in the load are eliminated. The other advantage is homogenization of the melted material. The classic furnace uses the ceramic crucible which does not reach so high temperatures. The ceramic crucible can also negatively influence purity of the load. The cold crucible is appropriate for vitrification of radioactive waste.

II. Principle of the Cold Crucible

The AC current goes through the copper inductor. The frequency is usually between 90 kHz and 5 MHz. Lower frequencies are used for electrically conductive materials. Higher frequencies are used for electrically non-conductive materials. The electromagnetic field induces eddy currents in the load or in the starting material. The eddy currents cause heating of the load or starting material. The load is placed inside the segmented crucible. In this application, the inductor and segmented cold crucible are intensively cooled by water. Due to intensive cooling of the cold crucible a hardened layer is created. The hardened layer is called “skull”. The temperature of the “skull” is approximately 100 °C but the temperature in the melted material can be up to 3000 °C. The hardened layer is transparent to electromagnetic waves. The fact that the electromagnetic field pushes the melt from the edges inward by the Lorentz force contributes to efficient cooling, which ensures mixing of the load.

III. Melting of Non-Conductive Materials

Melting of the electrically non-conductive materials is technologically difficult in comparison with melting of the electrically conductive materials and can be divided into several phases. First, it is necessary to increase the conductivity of the melted material using the starting phase. It is followed by melting of the load and formation of the “skull” on the inner surface of the segmented cold crucible. The last phase is the crystallization of the melted material (load) and its solidification.

The technical practice uses a range of different workflows which can increase the electrical conductivity of the melted material. The most common procedures are:

A. To insert an Electrically Conductive Ring to the Load

The ring is most often made of graphite, carbon or iridium. The inserted ring is intensively heated by electromagnetic induction and heat is transmitted to the load by conduction. Then the electrical conductivity of the load starts to increase. The conductive circle can be removed when the electrical conductivity of the load is sufficient.

B. To insert Small Amount of Metal in the Form of Powder or Small Pieces to the Load

The inserted metal is heated by eddy currents. Then the inserted metal is mixed with the load and it leads to its oxidation. As in the previous case, the electrical conductivity of the load will increase with the increasing temperature. This procedure can be applied to the following materials: Al_20_3, ZrO_2, Y_2O_3. It is useful for metal oxides which are available in their metallic form.

C. To Act Direct Thermal Performance by Burners to the Load

The heat of burners causes change of the electrical conductivity of the load. The main problem is a chemical reaction between the flame of burner and load which may cause an undesirable contamination.

The evaporation of impurities can be performed due to the high temperatures of the load and melting without a protective atmosphere. During this process a large amount of impurities can be reduced. The impurities are sulphur, chlorine, nitrogen and alkali metals.

IV. Shape of Segment

The segment of the cold crucible can have different cross section. The cross section significantly influences the distribution of power losses in the construction parts of the cold crucible. The cross section is the most commonly cylinder, rectangle or trapezoid.

Based on the previous numerical simulation and own production of the cold crucible we know that the cylinder shape is optimal. The cold crucible with the cylindrical segment which was manufactured by us for our laboratory is shown in Fig. 1.

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The cylindrical segment has slightly lower power losses in comparison with other types of segments and it is easy to create the cold crucible from this shape.

The construction solution with the trapezoid segment is appropriate for small sizes of the cold crucible because it is easy to keep 0,5 mm distance between the segments. This construction solution is very difficult to manufacture. The functional sample which we created for our laboratory is shown in Fig. 2.

Sometimes it is also necessary to use the rectangle segment. Rectangular segments are used for large diameters of the cold crucible to reduce the spacing of the inductor from the load.

Fig. 1. The cold crucible with cylindrical tubes for HFG160.

Fig. 2. The experimental cold crucible with trapezoid segment.

In our case, segment means two hollow rectangular profiles (tubes) connected in the upper part of the cold crucible (Fig. 3).

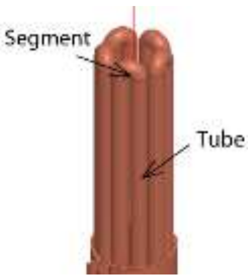

Fig. 3. Segment and tube.

V. Mathematical Model

The purpose of this article is to compare different construction solutions of the segmented cold crucible. The study considers the cold crucible with different number of hollow rectangular profiles (tubes). The load is Al_20_3 (in melted form). The steady state is considered in this simulation. The working frequency of the source is 1 MHz and current through the inductor is 1 kA. This setup is appropriate for melting of the electrically non-conductive materials such as Al_2O_3 or ZrO_2. The study investigates power losses in the construction parts of the cold crucible and efficiency of the whole induction system. All material parameters and solution setup are shown in Tab. I.

TABLE I.
Material Properties and Solution Setup

Component	Material	Electrical parameters		Solution setup	
		μ_r [-]	ρ_e [Ω.m]	Current [kA]	Frequency [MHz]
Inductor	Copper	1	1,75e-8	1	1
Load	Al_20_3	1	1e-3	-	-
Tube	Copper	1	1,75e-8	-	-

The whole geometrical arrangement is shown in Fig. 4. The problem has to be solved like 3D. The smallest symmetric sector of the cold crucible has been chosen to decrease the number of elements in the model.

The complete model with boundary conditions adjustment and dimensions is shown in Fig. 4. The size **b** remains constant and size **a** changes. The inductor is replaced by the current layer of 3 depth of penetration.

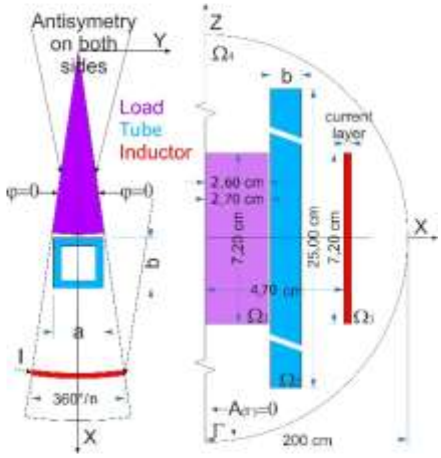

Fig. 4. Complete model with boundary conditions.

The distribution of the electromagnetic field in the whole model is described by the equation (1) for magnetic vector potential [3, 4].

The Dirichlet boundary condition (**A** = 0) is considered on the outer boundary of the model (radius 2 m). In the axis of symmetry is **A** = 0 too. On both load sides (X-Z planes) there is the electric potential $\varphi = 0$. On one side of the inductor (X-Z plane) there is also the electric potential $\varphi = 0$ and on the opposite inductor side (X-Z plane) there is the electric current loaded.

The anti-symmetry boundary condition is considered on both sides of the X-Z plane. The meaning of the symbols is described in Tab. II.

$$\mathrm{rot}\left(\frac{1}{\mu}\mathrm{rot}\,\underline{\mathbf{A}}\right)=\gamma\cdot(-j\omega\underline{\mathbf{A}})+\underline{\mathbf{J}}_{\mathrm{S}} \quad (1)$$

where
$$\mathbf{J}_{\mathrm{S}}=-\gamma\cdot\mathrm{grad}\,\varphi \quad (2)$$

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While considering the boundary conditions which are shown in Fig. 4.

TABLE II.
USED ABBREVIATIONS

Symbol	Units	Description
$\underline{\mathbf{A}}$	$Wb.m^{-1}$	Magnetic vector potential
μ	$H.\ m^{-1}$	Permeability
γ	$S.m^{-1}$	Electric conductivity
$\underline{\mathbf{J}}_S$	$A.m^{-2}$	Source current density
I	A	Current
φ	V	Electric scalar potential

The numerical electromagnetic model was realized by utilizing the software ANSYS using language programming APDL [4]. The example of discretization of the hollow rectangular profile (tube) and load is shown in Fig. 5. The areas where eddy currents are induced are meshed precisely. On the contrary to the areas where no eddy currents are induced, the mesh is very rough. This simplification leads to faster calculations while maintaining accuracy of the calculation.

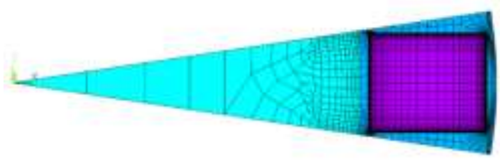

Fig. 5. Detail of mesh (load and tube) in ANSYS.

VI. RESULTS

The power losses in the segments, load and inductor are to be compared to find the optimal dimensions of the hollow rectangular profile (tube). The aim is to achieve a maximum power in the load with minimum power losses in the cold crucible tubes.

The numerical simulation is carried out for seven different numbers of tubes. The simulation for 64 tubes is made only from a theoretical point of view. This shape is not possible to manufacture with respect to cooling.

The used dimensions are shown in Tab. III. The size **b** remains constant and size **a** changes.

TABLE III.
USED DIMENSIONS

Tubes [pcs]	b [cm]	a [cm]	S [cm^2]
12	0,9	1,39	1,255
16	0,9	1,02	0,920
20	0,9	0,8	0,724
24	0,9	0,66	0,594
28	0,9	0,55	0,502
32	0,9	0,48	0,433
64	0,9	0,21	0,193

Table IV shows total losses in different construction parts of the cold crucible (full model) and efficiency depending on the number of tubes. The results show that the power losses in the inductor will be almost constant for all calculations. The losses in the segments are lower with increasing number of tubes. Distribution of the power losses in the construction parts of the cold crucible are shown in Fig. 6.

TABLE IV.
POWER LOSSES AND EFFICIENCY
IN THE CONSTRUCTION PARTS OF THE COLD CRUCIBLE

Tubes [pcs]	Losses inductor [W]	Losses segment [W]	Losses load [W]	Efficiency [-]
12	1175	3977	24858	0,828
16	1143	3757	26305	0,843
20	1139	3579	27377	0,853
24	1139	3433	28057	0,860
28	1146	3307	28690	0,865
32	1147	3221	29124	0,870
64	1154	3263	30854	0,875

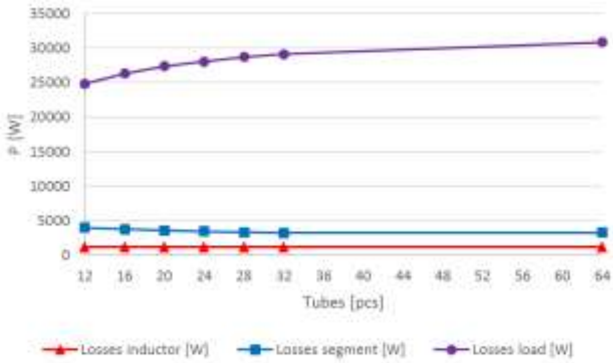

Fig. 6. Distribution of power losses in the construction parts of the cold crucible.

The power losses as a ratio value are shown in Tab. V. The losses for 32 tubes were chosen as the reference because it is the optimum number for this construction solution. Distribution of the power losses as a ratio value P/P_{32} is shown in Fig. 7. The efficiency of the induction system is shown in Fig. 8.

TABLE V.
DISTRIBUTION OF THE POWER LOSSES AS A RATIO VALUE (P/P_{32})

Tubes [pcs]	Losses inductor P/P_{32} [W]	Losses segment P/P_{32} [W]	Losses load P/P_{32} [W]
12	1,03	1,23	0,85
16	1,00	1,17	0,90
20	0,99	1,11	0,94
24	0,99	1,07	0,96
28	1,00	1,03	0,99
32	1,00	1,00	1,00
64	1,01	1,01	1,06

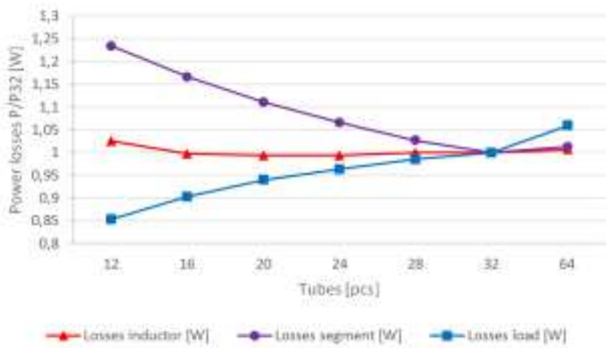

Fig. 7. Distribution of the power losses as a ratio value (P/P_{32}).

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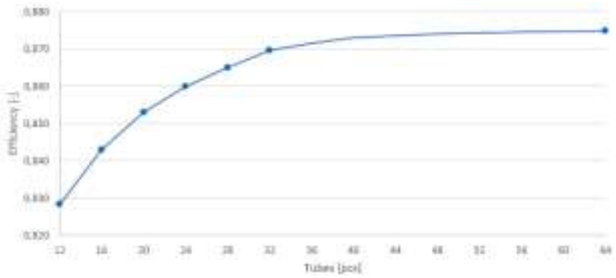

Fig. 8. Efficiency of the induction system.

VII. Conclusion

The numerical simulation shows that the higher number of tubes leads to higher efficiency of the induction system. These results are true for melting non-conductive materials with higher frequencies of the power source. The optimum number is 32 tubes for this solution setup. The cold crucible has a quite high efficiency and it is possible to manufacture it. From the technological point of view it is not possible to use more than 32 tubes for considered dimensions of the cold crucible.

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