

# Calculation and research of electrical characteristics of induction crucible furnaces with unmagnetized conductive crucible

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**Abstract.** Calculation methods for induction crucible furnaces with a conductive crucible have been reviewed and compared. The calculation method of electrical and energy characteristics of furnaces with a conductive crucible has been developed and the example of the calculation is shown below. The calculation results are compared with experimental data. Dependences of electrical and power characteristics of the furnace on frequency, inductor current, geometric dimensions and temperature have been obtained.

## 1. Introduction

Induction crucible furnaces (ICF) are widely used in the industry for melting ferrous and non-ferrous metals and alloys, which require special purity, homogeneity and accuracy of chemical composition. Depending on the electrical properties of the crucible material, one can distinguish ICF with a non-conductive and conductive crucible.

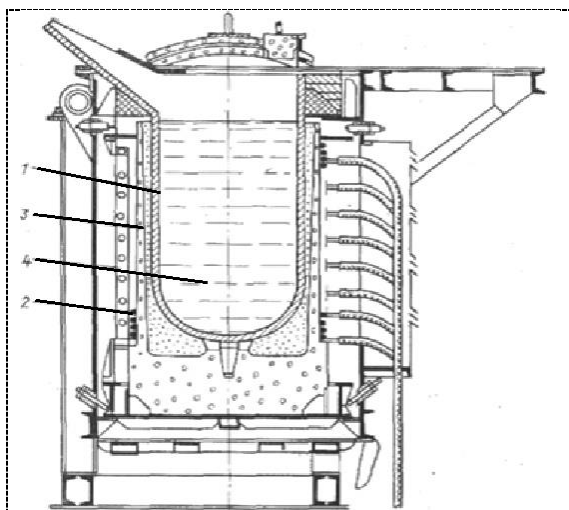


Figure 1. ICF with a conductive crucible: 1- conductive crucible; 2 - inductor; 3 - charge; 4 - thermal insulation

In ICF with a non-conductive ceramic crucible the metal (charge) is heated by the electromagnetic field produced by the inductor current. The crucible is almost equivalent to the air gap because of the large value of the electrical resistivity. In ICF with a conductive crucible (further ICF with CC) made from steel, graphite or graphite-chamotte in the electromagnetic field both the crucible and the charge are heated (Fig.1). ICF with CC are used for melting copper and magnesium alloys, uranium, gold, as well as non-conductive materials [1 - 4].

If the thickness of the crucible wall exceeds 2-3 times the penetration depth of the current into the crucible material, one can consider that the induced current is concentrated in the crucible wall. The load is heated only by heat transfer and may not have electrical conductivity. With a smaller wall thickness of the crucible the electromagnetic field gets into the charge, and

energy is also released in it. In this case it is possible to speak about induction heating of a double-layer body which is formed by the crucible and the charge. Each layer has its own values of electrical resistivity and relative magnetic permeability, which affects the distribution of the released energy. The fact that under certain conditions the charge of ICF with CC represents a two-layer body is a significant difference between calculation of the ICFs with CC characteristics and the calculation of conventional

ICFs with a non-conductive crucible. At the same time, the calculation of the electrical and energy characteristics of ICFs with CCs is substantially complicated because it must be taken into account that during the heating the electrophysical parameters of the crucible material and the charge which are depend on the temperature and the strength of the magnetic field also change.

ICFs with conductive crucibles are widely used in Russia and abroad. They are made of ferromagnetic steel for melting of magnesium with the capacity of 0.3-8 ton and the power of 120-1200 kW and are also made of graphite for melting copper with the capacity up to 6 tons and the power up to 1500 kW [5-7].

## 2. Calculation of electrical characteristics of the ICF with CC in the ELCUT package.

The ELCUT package allows us to calculate ICFs with CCs which have magnetic properties and also to take into account the edge effects, the presence of the bottom and collar, as well as its versatility and the possibility of further solving of related problems (thermal problem, calculation of forces). It can be concluded that FEM realized in ELCUT is the most appropriate solution for the tasks set out in the article.

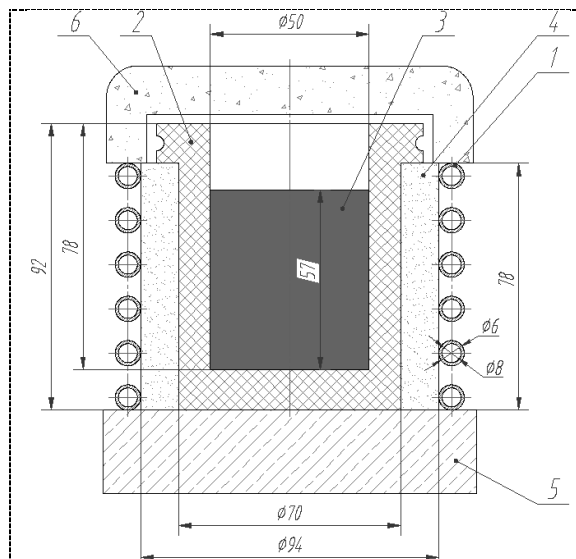


Figure 2. ICF with a conductive crucible: 1 - inductor; 2 - conductive crucible; 3 - charge; 4 - thermal insulation

As an example, ICF with a graphite crucible for melting copper with a mass of 1 kg was calculated. The furnace is powered by a high-frequency transistor converter with the power of 2.5 kW and an operating frequency of 22 kHz. Fig. 2 shows a drawing of the "inductor-charge" system of a furnace with geometric dimensions. The crucible is made of the FGG graphite.

Electric calculation of the furnace has been carried out in the universal finite-element program package ELCUT 6.0 (professional version) by solving the problem of magnetic field of alternating currents.

The analysis of magnetic field of alternating currents consists in electric and magnetic fields calculation excited by the applied variable currents (sinusoidally varying with time) or an external variable field. The change of the field with time is assumed to be sinusoidal.

The total current in the conductor is considered as the sum of the external current caused by the

externally applied voltage and the eddy current induced by the alternating magnetic field

$$\mathbf{j} = \mathbf{j}_{ext.} + \mathbf{j}_{e.c.} \quad (1)$$

Where the electrical conductivity  $\gamma$  and the components of the magnetic permeability tensor  $\mu_z$  and  $\mu_r$  are constant within each block of the model.

The problem is formulated as a partial differential equation relatively to the complex amplitude of the vector magnetic potential  $A$  ( $B = \text{rot } A$ ,  $B$  is the vector of magnetic induction).

The magnetic induction vector is assumed to lie in the plane of the  $zr$  model (Figure 3), while the vector of the electric current density  $j$  and the magnetic vector potential  $A$  are orthogonal to it.

The equation for the axisymmetric problem can be written as:

$$\frac{\partial}{\partial r} \left( \frac{1}{r\mu_r} \cdot \frac{\partial}{\partial r} rA \right) + \frac{\partial}{\partial z} \left( \frac{1}{\mu_z} \cdot \frac{\partial}{\partial z} A \right) - i\omega\gamma A = -j_{ext} \quad (2)$$

Where the electrical conductivity  $\gamma$  and the components of the magnetic permeability tensor  $\mu_z$  and  $\mu_r$  are constant within each block of the model.

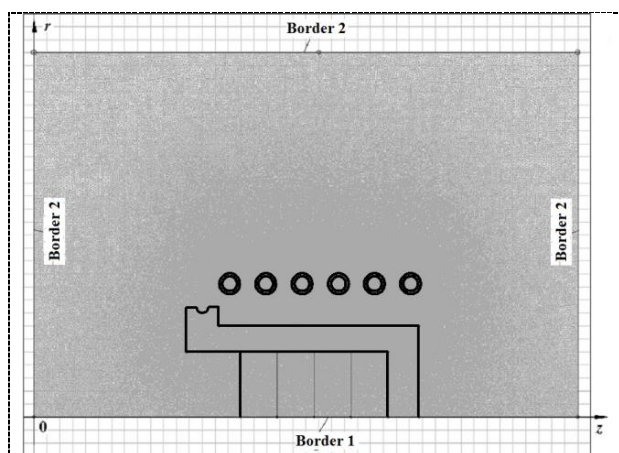


Figure 3. Calculation area in the ELCUT package

In Fig. 3 shows the calculated area divided by the finite elements. The number of grid nodes is about 350,000. Grid irregularities can be achieved by setting different values of the sampling step for different subareas of the calculating area and directly at nodes marked with dots in Fig. 3. The model allows performing calculations for the cases of a graphite crucible without metal and a crucible with different levels of metal by changing the properties of blocks. The Neumann boundary condition  $dH/dr = 0$  (the absence of a tangential component of the magnetic field strength) is given on the axis of symmetry (boundary 1 in fig. 3); on the outer boundaries

(boundary 2) is the zero Dirichlet boundary condition  $A = 0$  (the value of the magnetic potential is assumed to be zero, i.e. the field is localized within the computational domain).

Table 1. The main results of calculation of ICF with CC without metal and with copper

Inductor-charge" system parameter	Crucible without metal		Copper crucible	
	Var. 1	Var. 2	Var. 1	Var. 2
Inductor voltage $U_1$ , B	62.7	63.8	64.1	65.5
Power in the inductor $P_1$ , W	147	146	147	146
Power in crucible $P_{2.1}$ , W	1278	1286	1040	997
Power in copper $P_{2.2}$ , W	-		50	55
Total power in the load $P_{2\Sigma}$ , W	1278	1286	1090	1052
Total active power $P_\Sigma$ , W	1425	1432	1237	1198
Impedance of the system is $z$ , $\Omega$	0.348	0.354	0.356	0.364
Active resistance of the system $R$ , $\Omega$	0.044	0.044	0.038	0.037
Inductive resistance of the system $xL$ , $\Omega$	0.345	0.351	0.354	0.362
Electrical efficiency $\eta$	0.897	0.898	0.881	0.878
$\cos \varphi$	0.126	0.125	0.107	0.102

Practice shows that the radius of the calculation area (the distance along the  $r$  axis in Figure 3) should be set 2 to 2.5 times greater than the internal radius of the inductor of the furnace, and the distances along the  $z$  axis from the bottom of the crucible to the right to boundary 2 and from the collar to the left to the boundary 2 should be set approximately equal to the internal radius of the inductor.

Practice shows that the radius of the calculation area (the distance along the  $r$  axis in Figure 4) should be set 2 to 2.5 times greater than the internal radius of the inductor of the furnace, and the distances along the  $z$  axis from the bottom of the crucible to the right to boundary 2 and from the collar to the left to the boundary 2 should be set approximately equal to the internal radius of the inductor.

As a result of solving the problem of the magnetic field of alternating currents the integral results have been obtained (shown in the Table 1) for the case of a graphite crucible without metal and a crucible with copper (copper mass about 1 kg) with the inductor current  $I_1 = 180$  A and the frequency  $f = 22$  kHz. In Table 1, for each case, the values in the left column correspond to the real crucible; the values in the right column correspond to the crucible without the bottom and collar.

So, the results of the calculation show that if we do not take into account the influence of the bottom and the collar of the CC on the electrical and energy characteristics of the furnace with the CC, it makes a small error in the calculation - no more than 10%. Fig. 4 shows the calculated distributions of the volume power density of heat release for both these cases.

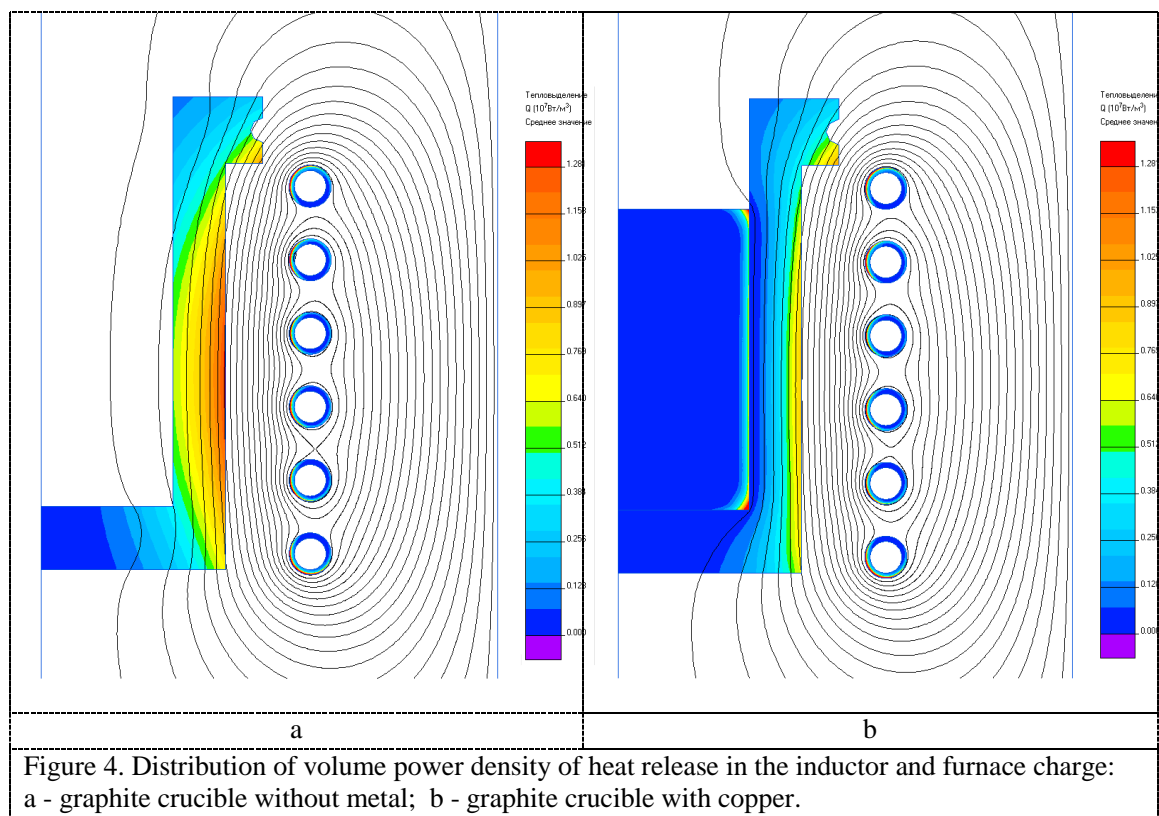


Table 1 and Fig. 4 show that the presence of liquid copper in the graphite crucible (in the calculations, the resistivity  $\rho$  of copper was assumed to be  $2.15 \cdot 10^{-7} \Omega \cdot m$ ) has a significant effect on the parameters of the "inductor-charge" system. So, the heat release in a graphite crucible with copper in it decreases by almost 20% with the same inductor current, while the heat release in copper itself is insignificant - about 50 W.

This can be explained by the fact that the depth of electromagnetic wave penetration into the wall of a graphite crucible 10 mm thick, the inductor current of 22 kHz, is about 13 mm. Therefore, the integral value of the induced current in copper is comparable with the total current in the crucible (about 400 A and 780 A, respectively). This leads to the appearance of a backward electromagnetic wave reflected from the boundary between media with different values of  $\rho$ . So the distribution of the magnetic field strength  $H$  in the thickness of the crucible wall is changed (Fig. 5a) [1, 3, 11]. Thereby, the values of the volume power density of heat release  $p_{0V}$  in each point along the wall thickness of the crucible decrease (Fig. 5b), which leads to a significant decrease of power in the crucible. In this case, the internal heat sources in the inner layer of the two-layer charge contribute insignificantly to the total active power in the charge as a consequence of relatively small values of  $\rho$  for the inner layer. Fig. 6 shows the area which is limited by two vertical lines corresponds to the wall of the crucible.

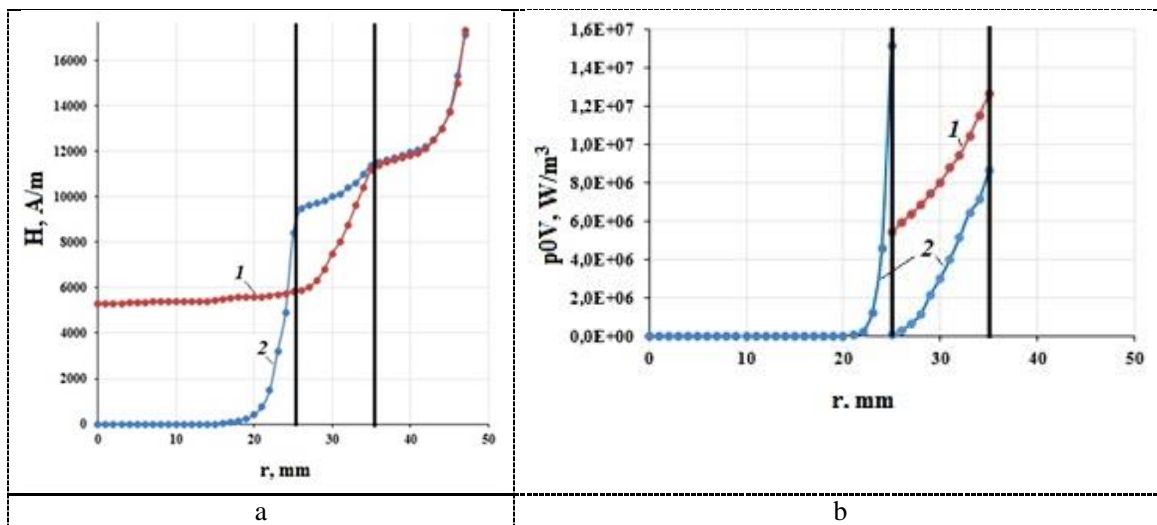


Figure 5. The distribution of the magnetic field strength  $H$  (a) and the volume power density  $p_{0V}$  (b) along the radius  $r$  for the empty crucible (1) and the crucible with liquid copper (2) at the inductor current  $I_l = 210$  A

As a result of the calculations, it was also found that the value of  $\rho$  copper present in the graphite crucible had little effect on the parameters of the "inductor-charge" system (the value of  $\rho$  varied from the value corresponding to liquid copper at the temperature of  $1100^\circ\text{C}$ ,  $72 \cdot 10^{-8} \Omega \cdot \text{m}$  at  $20^\circ\text{C}$ ), because it still remains substantially smaller in comparison with the value  $\rho$  of graphite, which varies slightly with heating. All this makes special specific requirements for the operation of the power supply - transistor voltage inverter [12 - 13].

Since at the initial stage of the technological process of metal smelting in ICF with CC the crucible charge represents a lump charge, some pieces of which are electrically unrelated, the induced currents are closed mainly within each piece, and the equivalent resistance of such lumpy charge in several times exceeds the analogous value for liquid copper. At this stage, the presence of a metallic (in particular copper) charge in the crucible can be neglected and one can use the results obtained for the crucible without metal. It was confirmed experimentally [12].

Calculation parameters of  $\rho$  graphite:  $7.14 \cdot 10^{-6} \Omega \cdot \text{m}$  at  $20^\circ\text{C}$ ,  $7.6 \cdot 10^{-6} \Omega \cdot \text{m}$  - at  $1100^\circ\text{C}$ .

### 3. Conclusion

1. The review and comparison of the methods for calculating ICF with CC has been carried out. It is shown that the most appropriate option for calculation of the electrical characteristics of ICF with CC is MCE, implemented in ELCUT.
2. A methodology for determining the electrical characteristics of ICF with CC has been developed and corresponding studies have been carried out.
3. It is established that in the case when the CC is partially transparent to the electromagnetic wave, the total power of heat release in the crucible with the molten metal becomes less than the power of heat release in the CC without metal with the same inductor current and frequency.

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