DISTRIBUTION OF THE TEMPERATURE AND ENERGY AT INDUCTION HEATING OF WORK PIECE COPPER

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Abstract: *In this paper the results of the research for the distribution of temperature, energy and efficiency in a copper work piece exposed to induction heating are presented. The temperature distribution in the metal work piece based on theoretical and experimental research is analyzed. The theoretical research is supported with the results of the computer simulations made via the ELTA program. The results of the theoretical calculations are compared with the simulation results and the experiments. The experimental results are obtained with induction heating of copper materials in a practical constructed induction device.*

Keywords: TEMPERATURE DISTRIBUTION;EFFICIENCY; METAL MATERIALS

1. Introduction

The process of induction heating of metals is dynamical. Its dynamics is determined by changing the properties of the metal that is heated, [1], [2], [3], [4]. The specific resistance, the relative magnetic permeability and thermal conductivity of metals are temperature dependent. The induction heating of metals is based on the skin effect phenomenon. The distribution of the induced magnetic field and the density of the current in metal exposed to variable magnetic field are concentrated in a small surface area of the metal, i.e. the depth of penetration. The depth of penetration depends of material properties: proportional with the specific resistance, and inversely proportional with the magnetic permeability and the frequency of the magnetic field. The skin effect phenomenon contributes that the induced magnetic field distribution and the induced current density in the metal work piece to be non uniform. Non uniform current density distribution causes non uniform temperature distribution in the work piece, too. In metal melting applications with induction heating, a non uniform temperature distribution doesn't play a significant role. But in the applications where only some area of the work piece needs to be heated or induction welding applications, maintaining a uniform temperature distribution is imperative. Another important factor in the process of induction heating is the power efficiency. The designer of an induction device must endeavor the efficiency of the induction heating process to be as greater as possible. Significant data for improving the induction device efficiency is obtained by using computer simulation programs, [5], [6]. Based on the defined geometry of the system's inductor – work piece by using computer simulations data for the temperature distribution and electromagnetic field parameters can be acquired for the work piece, [7], [8], [9]. In this paper temperature distribution and procedures that improve the energy efficiency of the induction device are analyzed.

2. Thermal analysis

The object of analysis is a symmetrical cylindrical work piece with maximum dimensions r=5.2cm, h=15cm, [9]. The material mass m and its volume V are associated with the specific density δ:

$$m = \delta V \tag{1}$$

For a metal work piece with mass m and temperature T_1, to warm up to the point of melting defined by temperature T_2 energy W should be transferred defined by the equation:

$$W = mC_1(T_2 - T_1) + mC_{lat} \tag{2}$$

where C_1 is specific thermal capacity in J/kg°C, and C_{lat} is the latent heat in J/kg. In the Fig. 1 system inductor - graphite container – work piece, intended for thermal processing, intersection with geometry defined above is given.

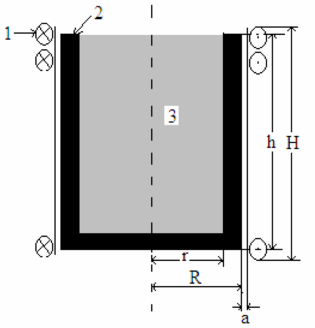


Fig. 1 Intersection of the system inductor graphite container - work piece: 1 – inductor, 2 – graphite container, 3 – work piece

In the Fig. 1, r is the work piece radius, R is the graphite container radius, and a is the thickness of the air gap between the graphite container and the inductor, h is the work piece height, H is the inductor height and $R+a$ is the inductor radius.

In the induction systems analysis, usually the container with the work piece is considered as a work piece with two different materials (two layers of the work piece). According with the defined geometry of the work piece (container plus metal), in the computer simulation program ELTA, [6], can be obtained parameters for the electromagnetic field and temperature distributions along the intersection of the work piece.

Input data:

Work piece: cylindrical form: layer 1 – copper with radius r=3.75cm, length h=13.cm, and initial temperature T=20ºC, layer 2 - graphite with radius R=5.25cm, length h=15cm, and initial temperature T=20ºC.

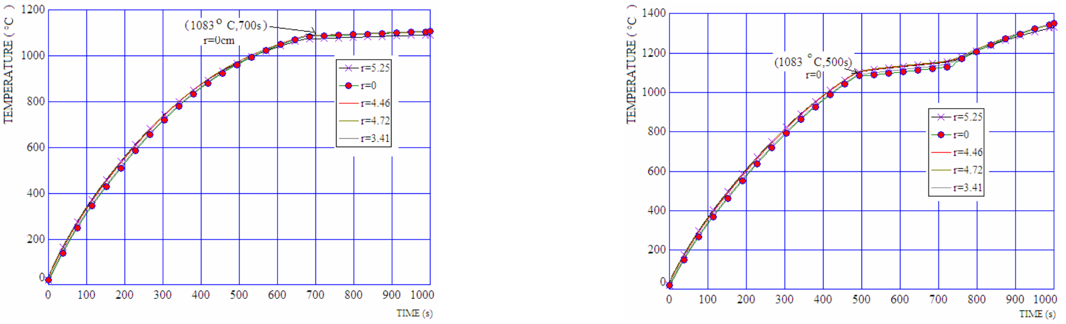
For copper work piece the specific densty is $8.9\cdot10^{-3}$kg/cm^3. From equation (1), for the defined work piece geometry, we calculate that the mass of the metal is 5.3kg.

Inductor: radius R+a=5.75cm and length H=16.5cm, number of coil turns 20, and copper profile with dimensions $\Phi_{ext}/\Phi_{int}=0.8/0.2$.

Power supply: serial resonant converter with resonant frequency and voltage f=6kHz, U=56V. Time cycles is 1000 s.

Our goal is to achieve a liquid state of the copper work piece (layer 1), i.e. all points of the copper piece along its intersection to reach a temperature of 1083 ° C. The upper given input data for the work piece that is our object of analysis in two layers, graphite and copper, with a defined geometry in the ELTA program the magnetic field, the current density, the current, the voltage, the inductance, the impedance, the power, the efficiency, the specific power, the heat losses, the reactive energy, the specific energy, the compensation capacitor and the temperature distribution are acquired. In the Fig. 2a the temperature distribution time dependence for different distances from the surface of the work piece (R=5.25cm) towards its center (R=0cm), for an induction system without magnetic concentrator and refractor is given.

And in the Fig. 2b the temperature distribution in function of time for different distances from the surface of the work piece (*R*=5.25cm) towards its center (*R*=0cm) in the case of induction system with concentrator and refractor is given.



a) b)

Fig. 2 Distribution of the temperature in the work piece in induction device: a) time depending on different distances from the surface of the work piece without concentrator and refractor, b) time depending for different distances from the surface of the work piece with concentrator and refractor

In the Fig. 2a can be noticed that after 700 seconds all points along the intersection of the conductor (*r*=0cm) reached the melting temperature of 1083 °C. And in the Fig. 2b we can see that after 500 seconds all points along the intersection of the metal reached the melting temperature of 1083 °C. The refractor is a material with small thermal conductivity and high specific resistance. The concentrator is a conductive material. The intersection of the system induction coil - work piece with two refractors and a concentrator is shown in the Fig. 3. In the Fig. 3 the refractor 1 is ceramic with thermal conductivity λ=0.05W/cm°C, and the refractor 2 is chamotte with λ=0.012W/cm°C. The concentrator is a conductive material. In the Table 1 the temperature distribution values in function of the time along the intersection of the work piece for induction system without concentrator and refractor (A) and for induction system with concentrator and refractor (B) are given.

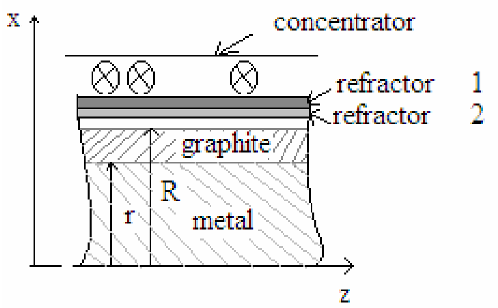


Fig. 3 Intersection on inductor – work piece with concentrator and refractor

Table 1. The values for the temperature distribution in the induction system without concentrator and refractor (A) and with concentrator and refractor (B)

r(cm)	0.5787		1,746		2,914		3,504		4,082		4,671		5,25	
t(s)	A	B	A	B	A	B	A	B	A	B	A	B	A	B
0	20	20	20	20	20	20	20	20	20	20	20	20	20	20
110.2	334,1	357,6	335,6	359,3	338,8	362,7	341	365,1	348,1	373,3	358,3	385,2	362,8	390,7
222.4	574	623,6	575,4	625,2	578,2	628,4	580,1	630,6	587,6	639,5	598,5	652,6	602	657,5
332.7	765,3	844,8	766,5	846,3	768,8	849,2	770,4	851,2	776,8	859,6	785,7	871,9	786,2	874,6
444.9	911,4	1024	912,3	1025	914,2	1028	915,4	1030	920,1	1037	925,8	1047	921,8	1046
555.1	1012	1082	1013	1085	1014	1084	1015	1086	1018	1082	1020	1083	1011	1082
667.3	1081	1106	1082	1109	1083	1110	1083	1111	1084	1112	1083	1112	1081	1111
777.6	1090	1187	1091	1189	1093	1192	1094	1194	1095	1197	1092	1200	1079	1192
889.8	1098	1281	1099	1282	1101	1284	1102	1286	1102	1287	1099	1286	1085	1273
1000	1105	1348	1106	1348	1108	1350	1109	1351	1109	1350	1105	1346	1105	1329

Because the required temperature for copper casting is about 1100 °C, table 1 shows that in the induction system without concentrator and refractor the work piece has reached the casting temperature after 1000 seconds, and in case of the induction system with concentrator and refractor the casting temperature is achieved after 667 seconds. Equation (2) shows that for a work piece with mass *m* for temperature increase from T_1 to T_2 energy W should be transferred. In both analyzed examples the work piece is heated to the same temperature, so the energy needed to achieve the necessary temperature increase is the same, i.e.:

(3) $$W = P_1 t_1 = P_2 t_2$$ or

(4) $$\frac{P_1}{P_2} = \frac{t_2}{t_1} = 67\%$$

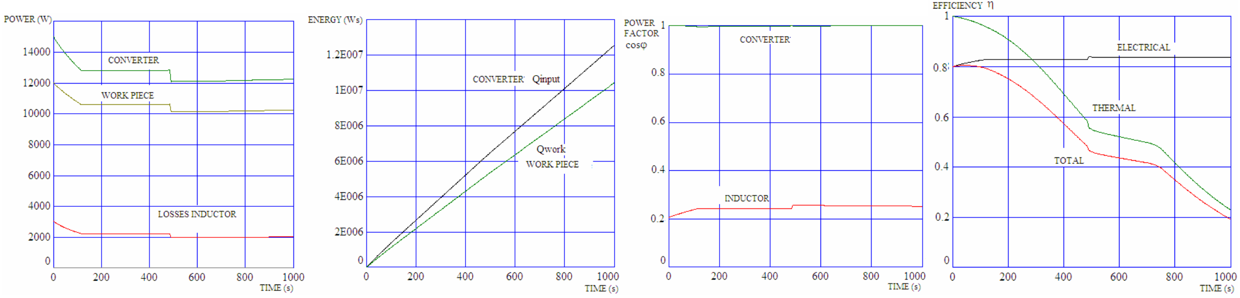
The last equation shows that in case with constant converter power, the topology of the induction system with concentrator and refractor achieves the same effect of heating shortened by 33% in time than the topology of the induction system without concentrator and refractor. Or in other words, if the heating time in both topologies should be the same, then the equation (4) yields:

(5) $$P_2 = 67\% P_1$$

The physical interpretation of the last equation is that in the example of the induction device with concentrator and refractor installed, the converter power can be reduced by 33% from the power of the converter in case of the induction device without concentrator and refractor installed for achieving the same effect (melting the work piece with the same mass for the same time). It means that in an induction device with concentrator and refractor installed the efficiency is greater.

3. Estimation of the Energy Distribution

In the Fig. 4 the power distribution, the energy, the power factor and efficiency in the induction device obtained in the ELTA simulation program is given. In the Fig. 4a the power distribution as a function of the time is given. The Fig 4a shows the diagrams for total converter power, the power deployed to the work piece and the inductor power losses. In the Fig. 4b the total energy distribution in the induction device (obtained by the converter) and the energy in the work piece are shown.



a) b) c) d)

Fig. 4 Distributions in the induction device obtained by simulation: a) power, b) energy, c) power factor, d) efficiency

The distributions in the Fig. 4 are obtained for induction device powered with serial resonant converter with: output voltage 56 VAC, maximum output power 15 kW and resonant frequency 6000 Hz. The capacitor value for reactive energy compensation is 26.6 μF. Based on the analysis in the Fig. 4, in the Table 2 the values for the power, the energy, and the efficiency of the induction device at the moment when the metal is melted, (667 s), are given.

Table 2. The values of the magnitudes in system converter - inductor – work piece at the moment of 667 s

$P_{wp}(kW)$	P_{con}(W)	W_{conv}(kJ)	W_{wp}(kJ)	$\eta_{inductor}$ (%)	$\eta_{thermal}$ (%)	η_{total} (%)	$\cos\varphi$ conv.	$\cos\varphi$ induct.
10.12	12.1	8.464	7.02	83	50	42	1	0.25

In the Table 2 the magnitudes are:

$$\eta_{inductor} = \frac{P_{wp}}{P_{con}} = \frac{W_{wp}}{W_{con}} \tag{6}$$

is the inductor electric efficiency related as a ratio of the work piece energy (power) and the converter energy (power). And from Figure 4d we can see that at the moment 667 s it is 83%. η_{termal} is the thermal efficiency defined as a ratio of the energy required for the work piece melting and calculated from equation (2), and the obtained from the diagram on the Fig. 4b at the moment 667 s. The thermal efficiency value for the energy value in the diagram in the Fig. 5d at the moment 667 s is 50%.

$$\eta_{total} = \eta_{inductor}\eta_{thermal} \tag{7}$$

is the total induction device efficiency. And at the moment 667 s on the Figure 5 d, it is 42%.

$$\cos\varphi = \frac{P_{conv}}{\sqrt{P_{conv}^2 + Q^2}} \tag{8}$$

is the power factor of the induction device. And its value at the moment 667 s is 0.25. From Figure 5c we can see that the total power factor with the compensation capacitor is 1.

4. Energy Distribution Calculation

To bring a work piece of copper with mass 5.3 kg in a liquid state, energy defined with equation (2) should be transferred to it. For copper: the specific thermal capacity is C_{1cu}=384J/kg°C, the latent heat is C_{latcu}=209000J/kg, [10], [11]. So, the required energy for melting the work piece is: W_{cu}=3271117J.

Also, the required energy for heating the graphite container to temperature 1083 °C is calculated from equation (2). And the specific thermal capacity is C_{1c}=880J/kg°C, the density is $\gamma_c=2.6\cdot10^{-3}$kg/cm^3, and the mass with the defined geometry in the Figure 1 is m_c=1.825kg. So, the required energy for heating the graphite container is: W_c=1703848J. In the Table 3 the results from the energy distribution calculation are given.

Table 3. Energy distribution in the induction device for melting 5.3kg copper

$W_{conv}(kJ)$	$W_{wp}(kJ)$	$W_{cu}(kJ)$	$W_c(kJ)$	$W_c + W_{cu}(kJ)$	$\eta_{thermal1}$(%)	$\eta_{thermal2}$(%)	η_{total1}(%)
8.5043	7.0602	3.271117	1.7	4.97	46	71	39

In the Table 3 $\eta_{thermal}$ and $\eta_{therma2}$ are the thermal efficiency, defined as:

$$\eta_{thermal1} = \frac{W_{cu}}{W_{wp}}$$

$$\eta_{thermal2} = \frac{W_{cu} + W_c}{W_{wp}} \tag{9}$$

From the results for energy distribution estimation given in the Table 2, and the calculation results given in the Table 3, we can conclude that the copper work piece thermal efficiency is almost the same for the both cases.

$$\eta_{total1} = \eta_{inductor}\eta_{thermal1} = \frac{W_{wp}}{W_{conv}}\frac{W_{cu}}{W_{wp}} \tag{10}$$

is the total efficiency of the induction device. The calculated value for the total efficiency is almost the same with the value given in the Table 2.

5. Experimental Results

Work piece copper: The experimental results for the efficiency of a practically constructed induction device for melting copper work piece with the features defined above are given here. The induction device operation without built-in concentrator and with built-in concentrator is analyzed. In the Table 4 the magnitude values for the experimental induction device operation for melting copper work piece with mass 5kg is given.

Table 4. Experimental results of the magnitudes in the induction device with capacity of 5kg copper

	$t(s)$	$I_{outrms}(A)$	$U_{outrms}(V)$	$S_{out} \approx P_{out}(kVA)$	$\eta_{total1}(\%)$
without concen.	1620	250	55	13.73	32.6
with concen.	1500	250	55	13.73	38

In the Table 4 the magnitudes are:

$S_{out} \approx P_{out} = I_{outrms}U_{outrms}$ is the output apparent power, and because the induction device operates on the resonant frequency it is same with the active output power.

$\eta_{total1} = \frac{W_{cu}}{W_{conv}} = \frac{\frac{W_{cu5kg}}{t}}{P_{out}\frac{t}{3600s}}$ is the total efficiency of the induction device, as a ratio of the energy required for melting the copper work piece and the energy transferred to the induction device. This efficiency (for induction device with concentrator and refractor), is close to the efficiency obtained in the section 3, equation (7), and in the section 4, equation (10). The induction device topology with concentrator reduces the operating time for 7.5%.

The induction device capacity is:

$$m_{cu} = \frac{3600s}{1500s} = 12kg/h$$

The specific power per kilogram is:

$$\frac{13730}{12} = 1144W/kg$$

Melting copper concentrate

The induction device is used for thermal treatment to melting temperature of copper concentrate obtained by extracting procedure. The copper concentrate is with the features:

Mass 1030 gr, Quality 70 Cu%.

Thermal treatment results: After melting the concentrate a piece of copper is extracted with the features: Mass 730 gr, Quality 99 Cu%.

The results show that via induction heated thermal treatment satisfactory results are acquired when copper concentrate with quality greater than 60 % is used.

6. Results Analysis

Simulation, calculation and experimental analysis show that:

1. The simulation results for copper work piece exposed to induction heating show the temperature distribution and the energy as a function of the distance from the surface and the time. The results show that the temperature distribution in the work piece is not uniform. In the induction device with built-in refractor and concentrator efficiency is greater for 33 %.
2. The diagrams for the power, the energy and the efficiency distributions show that converter efficiency is 83 %, the thermal efficiency is 50 % and the total efficiency is 42 %.
3. The results from the calculations show that converter efficiency is 83 %, the thermal efficiency is 46 % and the total efficiency is 39 %.
4. The experimental results show that for copper work piece without built-in concentrator the total efficiency is 32.6 %, and with concentrator is 38%.
5. The results for the energy distribution and induction device efficiency in the simulations, the calculations, and the experiments are almost the same.
6. The differences in the operating time in simulations and experiments are due to the differences in the quality of the concentrator and the graphite container used, and radiation heat losses in the practically constructed induction device that was used.

7. Conclusion

In this paper the results of the thermal analysis, the energy distribution and efficiency for induction heating of copper and copper concentrate are given. In the analysis computer simulations, calculations and experiments are used. The simulations, calculations and experimental results are identical. The results in this paper can be used for practical construction of induction device for recycling of copper and its alloys and obtaining copper from copper concentrate with quality greater than 60%

8. References

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