

## DEVELOPMENT AND INVESTIGATION OF A SYMMETRIC INDUCTION HEATING UNIT FOR SPHERICAL SHAPE METAL WARE

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*Received 15 March 2018  
Accepted 15 June 2018*

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### ABSTRACT

*The present communication considers a symmetric induction heating unit for spherical shape metal ware. It analyzes the corresponding electromagnetic processes, determines the inductor optimum frequency and amperage values and provides results of the experimental investigation.*

*Keywords: induction heating, spherical item, temperature, electromagnetic field, frequency, magnetic field strength.*

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### INTRODUCTION

The creation of energetically efficient continuous-acting equipment for symmetric heating to a given depth of spherical metal products with no oxidation and decarburization is a challenging problem for some industries. The latter include mass production of milling bodies for ore-dressing, balls for rolling bearings and valves in hydraulic systems, and wear-resistant balls in the back-water gates of deep-well pumps for oil production, etc.

This combination of heating qualities which is in demand in industry is most thoroughly met by the induction method with its direct and high-speed (of the order of fractions of a second) conversion of an electrical energy into a thermal energy. This conversion is characterized by a simple regulation of the temperature and the heating depth, thus making it possible to obtain, after quenching and tempering, the optimum combination of products high surface hardness (back-to-back endurance) and a relatively elastic core (anticracking).

However, despite all advantages of this method, it is only applied to produce articles of a continuous or near-continuous cross section of ensured heating symmetry of heating.

### INDUCTOR DESIGN AND MATHEMATICAL MODEL

The choice and calculation of the inductor begins with determining its geometric configuration. Copper tubes are the common material used in its making. It is worth adding that the inductor must be cooled by running water during its operation. The inductor shape and dimensions depend on the heating conditions, on the size and configuration of the heated billet, as well as on the supply power and frequency. In the case under consideration, spherical items are used as billets, including grinding balls and rolling elements of ball bearings. Therefore, it is most appropriate to use an inductor of a multi-turn ring configuration, i.e. of a round cross section minimizing the air gap between the inductor turns and the billet. Thus, its efficiency is increased.

Usually, the inductor is made of a round or rectangular copper tube. The use of rectangular copper tubes gives an efficiency gain of 2 - 3 percent [1-3], which is appropriate for high-power plants. However, copper tubes of a round cross-section are more widespread and less costly.

An induction heating unit (IHU) with a vertical symmetry axis consists of several inductors (section-

alization), is with a transporting profile [4] inside it. The sectionalization is performed in order to increase the efficiency of the unit and the ability to operate the heating parameters within wide limits. In order to ensure uniform heating of spherical billets, it is necessary to distribute the electromagnetic field energy transmitted to them uniformly along the transporting profile. Since the resistivity and permeability of the billets change in the course of heating, the inductor current must also vary along the length of the transporting profile. The inductor current frequency must also vary, because it is necessary to maintain a given heating depth. These requirements – the inductor current and frequency varying along the profile length – can only be guaranteed by dividing the inductor into sections.

In order to carry out the research, it is necessary to develop one section of the inductor, as the electromagnetic processes of heating the moving spherical billets in the different sections is identical. Furthermore, the inductor will be seen as one section only. At the same time, the choice of the inductor geometric dimensions, in particular the length  $L$ , depends on the total number of sections, the kinematics of spherical billets moving along the transporting profile (the geometry of the transporting profile, the mass-dimensional parameters of the spherical metalware), the required power and the billet heating depth. Because at this stage of the research the whole IHU does not need to be calculated, the inductor length  $L$  will be taken as equal to five times the diameters  $d$  of the spherical billet.

The inductor internal diameter  $D$  depends on the billet diameter and the wall thickness of the transporting profile. The wall thickness is determined by the selected material of the transporting profile. The high melting temperature (because the temperature of the spherical billets will reach the required quenching temperature of 700°C - 800°C), the low thermal expansion coefficient, the high electrical resistivity (in order to avoid heating the material by induction eddy-currents), the relatively high mechanical strength and the non-magnetization of the material refer to the profile material requirements.

A high-strength quartz glass tube is used as a spherical billet to move inside the inductor of the experimental unit. The geometric configuration of the inductor is shown in Fig. 1.

The specific power  $P_{sp}$  at the surface of the heated article is usually in the range of 0.5 kW/cm<sup>2</sup>-1.5 kW/cm<sup>2</sup>,

mainly around 1 kW/cm<sup>2</sup> [5] in case short of induction quenching of cylindrical bodies geometrically close to the ball quenching. The estimated power  $P$  of the experimental unit is about 3 kW. Rolling bearing balls made of constructional bearing steel 100Cr6 (for European community) are used as billets. The approximate diameter of the ball must not exceed:

$$d \leq \sqrt{\frac{P}{\delta P_{sp}}} \leq \sqrt{\frac{3}{\delta \cdot 1}} \approx 0.955 \text{ cm} \quad (1)$$

According to ref. [6], the appropriate maximum diameter of the ball is 9.525 mm. This value will be used for further calculations. Thus, a quartz tube is selected according to TU 21 - 54598235 - 560 - 2001 with an external diameter  $D = 12$  mm and wall thickness  $a = 1$  mm.

The electrical parameters of the inductor are further calculated. The required inductor current frequency  $f$ , is determined by the surface effect and depends on the required active depth of heating the ball,  $\Delta_b$ , as well as on the properties of the ball material:

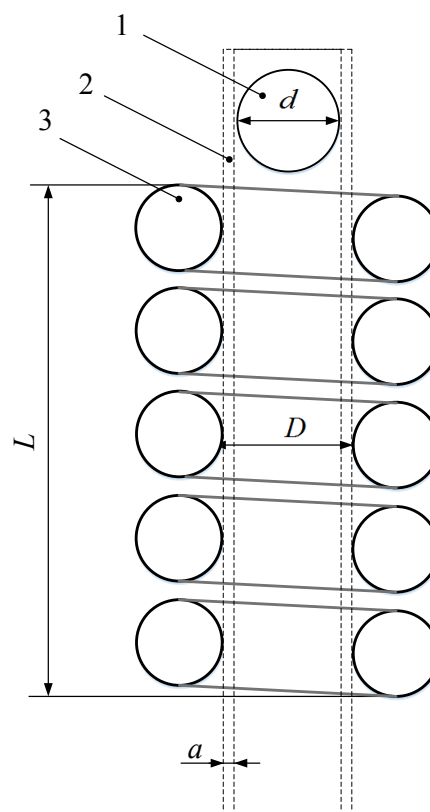


Fig. 1. Geometric configuration of the inductor: 1 – a billet (ball), 2 – a quartz tube, 3 – inductor copper turns.

$$f = \frac{1}{\pi \mu_0 \mu_b \frac{1}{\rho_{sr}} \Delta_b^2}, \quad (2)$$

where  $\mu_0 = 4\pi \cdot 10^{-7}$  H/m (it is the magnetic permeability of vacuum),  $\mu_b$  is the relative magnetic permeability of the billet, while  $\rho_{sr}$  is the billet specific resistance (according to Table 1).

The specific resistance of carbon steels, in this case of 100Cr6 (for European community), depends on the temperature according to Table 1. Its relative magnetic permeability depends on the temperature,  $T$ , as well as on the magnetic field strength,  $H$ . An approximation of the dependences is used:

$$\mu_b = 1 + \frac{3.11 \cdot 10^5 \cdot H^{-0.852}}{\left[1 + \left(\frac{T}{T_k - T}\right)^{1.7+0.02 \ln(H)}\right]^{-0.03+0.02 \ln(H)}} \quad (3)$$

where  $T_k$  is the Curie temperature.

The required active depth of heating the ball must be in the range of 1%- 5% of the spherical billet diameter.

For the selected billet it is 0.1mm-0.5 mm. In order to calculate the frequency according to Eq. (2), it is necessary to know the value of the magnetic field strength,  $H$ , determined by Eq. (3). This value can be finally determined by performing the electric calculation of the inductor. So, first the range of values  $H = 20$  kA/m - 100 kA/m is chosen with its subsequent refinement after determining all inductor parameters.

The graphs (Fig. 2) demonstrate the dependences of the required current frequency on the temperature in the form of a range on the basis of the heating depth limitations for two values of the preselected magnetic field strength of 20 kA/m and 100 kA/m. The intersection area of the two ranges is optimum for frequency selection. The latter should be done in view of almost no changes with temperature variation. This in turn provides unchanged inductor parameters.

Fig. 2 shows a line representing the selected optimum frequency. The range of the optimum frequency at temperature change lies between 75 kHz and 132 kHz. It will be used in the further calculations.

The current depth,  $\Delta_c$ , of the copper conductors in the optimum frequency range can be determined at 100 °C according to the equation:

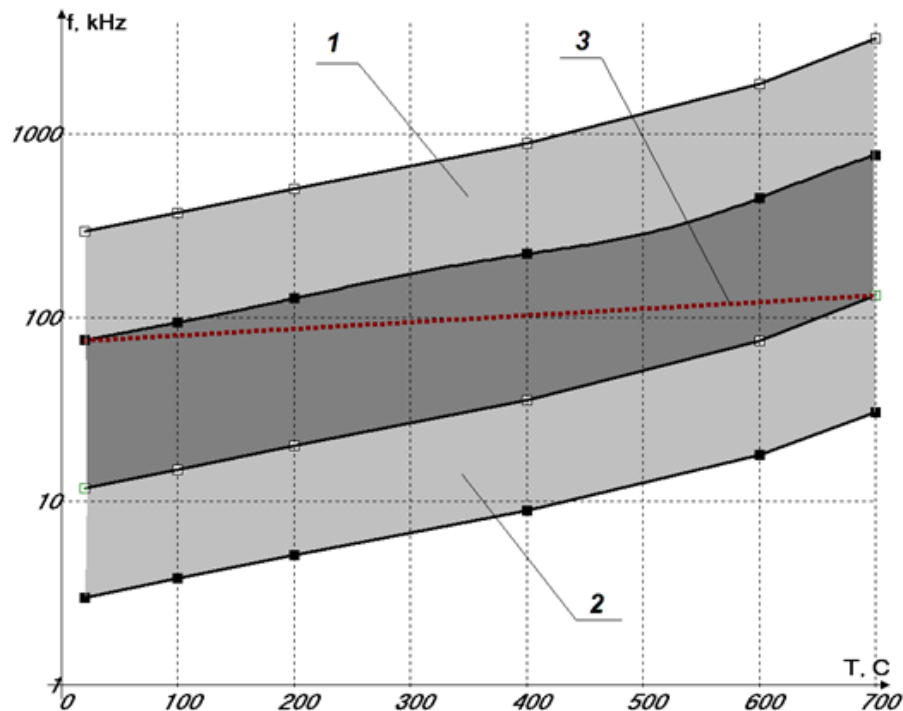


Fig. 2. Temperature dependence of the required current frequency: 1 – a range of frequencies at a strength of  $H = 20$  kA/m; 2 – a frequency range at a voltage of  $H = 100$  kA/m; 3 – an optimum frequency.

Table 1. Temperature dependence of steel resistivity.

t, °C	20	100	200	400	600	800	1000	1200	1300
$\rho_{sr}, 10^{-6} \Omega \cdot m$	0.2	0.25	0.33	0.52	0.79	1.18	1.22	1.26	1.3

$$\Delta_c = \sqrt{\frac{\rho_c}{\pi \mu_0 f}} = 0.22 \dots 0.29 \text{ mm}, \quad (4)$$

which determines the minimum required thickness of the inductor copper tube.

The dependence of the external diameter of the copper tube,  $d_c$ , on the active cross-sectional area,  $S_a$ , can be estimated according to the equation:

$$d_c = \frac{S_a + \pi \cdot \Delta_c^2}{\pi \cdot \Delta_c}. \quad (5)$$

The maximum allowable inductor current density,  $J_{max}$ , under cooling conditions should not normally exceed 150 A/mm<sup>2</sup> [1]. Hence the dependence of the required external diameter of the copper tube on the inductor current,  $I$ , is:

$$d_c = \frac{\frac{I}{J_{max}} + \pi \cdot \Delta_c^2}{\pi \cdot \Delta_c}. \quad (6)$$

The indicated dependence of the previously determined frequency range is shown in Fig. 3. Diameters above 10 mm are impractical because it is difficult to bend the tube to an internal diameter of 12 mm. The values of 6, 8 mm and 10 mm (a wall thickness 1 mm) are selected among standard copper tube diameters, and a comparative analysis is performed. The value of the heating power released in the spherical billet will serve as the evaluation criterion of the analysis.

In order to calculate the heating power, it is necessary to use numerical methods. It is most appropriate to apply the finite element method (FEM) in this case.

Further, an FEMM program package will be used providing the given method implementation. FEMM is a free set of programs (freeware) for solving electromagnetic, current and thermal problems in two-dimensional flat and axisymmetric areas.

The program is used to solve:

- linear and non-linear magnetostatic problems;
- harmonic linear and non-linear quasistatic magnetic problems;
- thermal problems in a steady thermal state.

Via FEMM, inductor mathematical models with a billet and with three variants of copper tube diameters are developed: 6 mm, 8 mm and 10 mm (Fig. 4). Next, the values of the heating power are calculated depending on the inductor current provided that the optimum frequency is maintained as shown in Fig. 5. Hence, the value of the inductor copper tube diameter equal to 8 mm is selected because the transition to a larger diameter of 10 mm practically does not yield any power gain. The average power value is 1.6 kW accounting the surface area of the spherical billet. It yields a specific power of 0.533 kW/cm<sup>2</sup>, which is in the recommended range of 0.5 kW/cm<sup>2</sup> - 1.5 kW/cm<sup>2</sup>.

The final inductor parameters are as follows: (i) the configuration of the conductors of the inductor - a hollow tube, an external diameter - 8 mm, an internal diameter - 6 mm, a number of turns - 5, distance between turns - 2 mm; (ii) the inductor configuration - an exter-

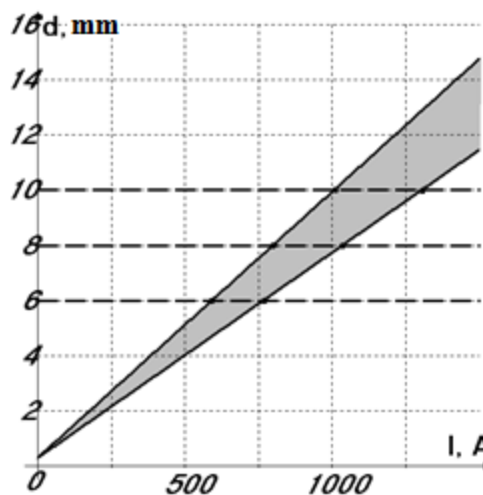


Fig. 3. A dependence of the required external diameter of the copper tube on the inductor current within the optimum frequency range.

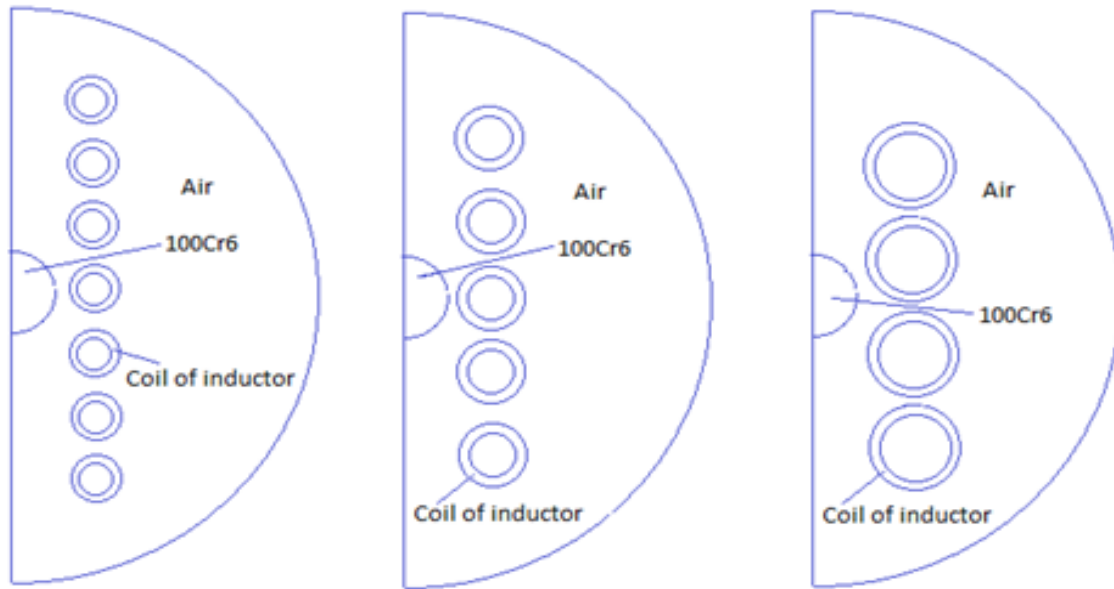


Fig. 4. FEMM program variants of the inductor configuration for different diameters of the copper tube used.

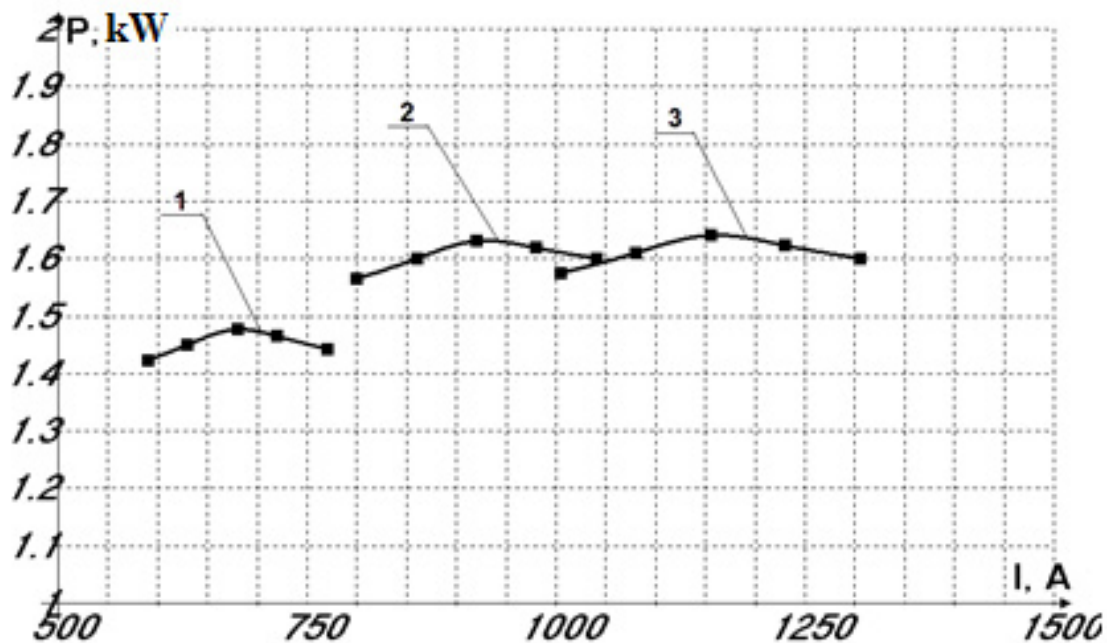


Fig. 5. Billet heating capacity for inductor tube diameters of: 1)  $d_c = 6$  mm; 2)  $d_c = 8$  mm; 3)  $d_c = 10$  mm.

nal diameter - 28 mm, an internal diameter - 12 mm, an inductor length - 48 mm. Fig. 6 shows the pattern of the electromagnetic field for a given configuration. The application of FEMM provides also the calculation of the parameters of the electric circuit of the inductor. The main parameters taken down in presence and absence of

a spherical billet in the inductor are summarized in Table 2. Further, the magnetic field strength,  $H$ , is plotted as a function of the distance between the surface and the billet according to Fig. 7. As seen from the graphs, the values of the intensity are close to those of the previously accepted interval  $H = 20$  kA/m - 100 kA/m.

Table 2. Parameters of the electric circuit of the inductor.

	with billet				empty	
	20°C		700°C			
	75 kHz	132 kHz	75 kHz	132 kHz	75 kHz	132 kHz
I <sub>2</sub> , A	1040	800	1040	800	1040	800
U <sub>2</sub> , V	20,1	26,3	21,6	28,3	11,1	13,8
P <sub>2</sub> , W	2423	2581	2025	2149	656	545
Q <sub>2</sub> , Var	20755	20880	22393	2501	15559	15455
S <sub>2</sub> , VA	20896	21039	22484	22603	15573	15465
r, Ω	0,002244	0,004033	0,001872	0,003358	0,000607	0,000852
L, H	4,0721E-08	3,934E-08	4,39E-08	4,239E-08	3,0528E-08	2,9118E-08

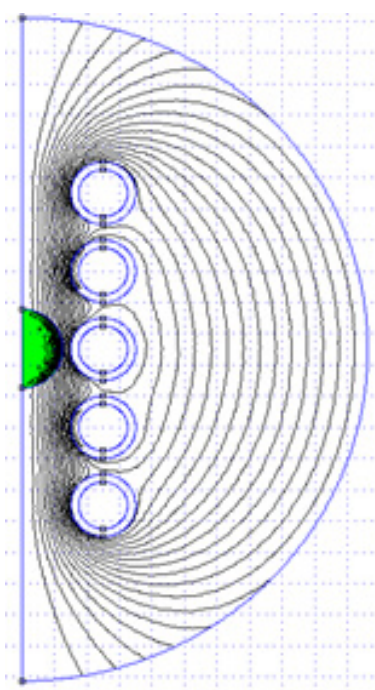


Fig. 6. An electromagnetic field pattern of the inductor size selected.

The optimum inductor frequency and amperage will be determined according to the criterion of the maximum possible rate of heating the ball. In this case, the allowable frequency range  $f_{\min} - f_{\max}$  must be limited on the basis of the allowable ball heating depth range:

$$\left\{ \begin{array}{l} f_{\max} = \frac{1}{\pi \times \Delta_{\min}^2 \mu_0 \mu_b \frac{1}{\rho_b}}; \\ f_{\min} = \frac{1}{\pi \times \Delta_{\max}^2 \mu_0 \mu_b \frac{1}{\rho_b}}, \end{array} \right. \quad (7)$$

where  $\Delta_{\min}$  is the minimum depth of ball heating,  $\Delta_{\max}$  is the maximum depth of ball heating,  $\mu_b$  is the relative magnetic permeability of the billet material,  $\mu_b$  is the electrical resistivity of the billet material, while  $\mu_0 = 4\pi \cdot 10^{-7}$  H/m is the magnetic permeability of vacuum.

## EXPERIMENTAL

The metal ball used in the experiments was 10 mm in diameter. The required active depth of ball heating must was in the range of 1 % - 5 % of the spherical billet diameter [7]. For the selected billet, the range was 0.1 % - 0.5 mm, which corresponded to the frequency range of 75 kHz - 132 kHz.

The ball heating time was estimated at three frequencies of 75 kHz, 100 kHz, and 120 kHz. In this case, for all three measurements, the current from the rectifiers

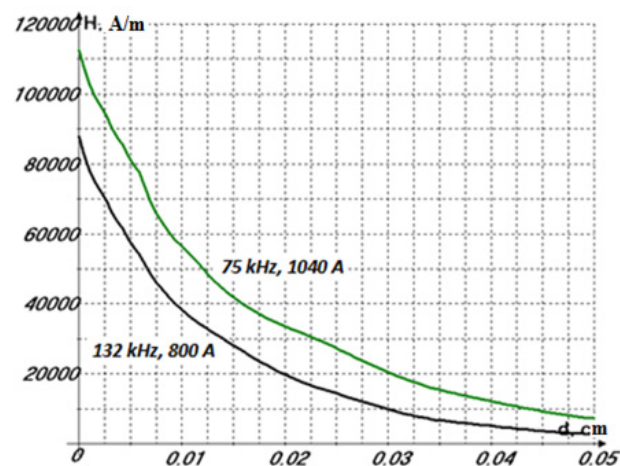


Fig. 7. Dependence of the magnetic field strength of a spherical billet on the distance from the surface.

Table 3. Measurement of the ball heating time at different current frequencies.

Inductor current frequency, kHz	Rectifier-supplied current, A	Rectifier-supplied power, W	Inductor current, A	Bank capacity C, $\mu\text{F}$	Time of heating up to 500°C, s
75	2,5	500	130	25,5	25
100	2,5	500	100	14,25	27
120	2,5	500	80	9,75	29,5

Meanwell SE-600-48 [8], i.e. the constant active power was maintained constant. The rectifier amperage was determined according to the criterion of the inductor current reaching the value equal to the capacitor bank allowable current of 85A for frequency 120 kHz. It was equal to 2.5 A, which corresponded to the power consumed by 500 W rectifier. In order to maintain the constant rectifier current [9], the inductor current was regulated by changing the value of the effective output voltage.

The ball was heated from 20°C to 500°C [10]. The temperature was measured using the infrared pyrometer CEM DT-8865 with the following characteristics: temperature measurement range from -50°C to +1000°C; an accuracy  $\pm 1\%$  (from +20 to +300°C),  $\pm 1.5\%$  (from +300 to +1000°C); a response time of 0.15 s.

The results of the measurements carried out are summarized in Table 3.

As seen from the table, the heating at a lower frequency of 75 kHz was faster at a constant power consumption value. This could be explained by an increase of MOSFET heating at a higher frequency and, hence, by a decrease of the unit efficiency. The final choice was made for the optimum frequency of 75 kHz, the heating time at which (at the inductor current of 130 A) was 25 seconds.

## CONCLUSIONS

As a result of the conducted research, an optimum inductor design was calculated for heating the selected billet – ball-bearing balls with a maximum diameter of 9.525 mm. The main elements of the power circuit were calculated and selected for an inductor supply. They included a balancing capacitor, a matching transformer and a MOSFET inverter. A control system was developed for heating both fixed balls and those moving through the inductor in the electrical engineering heating complex

[11]. The electrical engineering complex performance analysis was described in detail in ref. [12].

The experiments were conducted on heating the ball at which (i) the inductor current optimum frequency and intensity were determined; (ii) the stationary ball heating time was estimated, and (iii) the graphs of the transient processes when working with a moving ball were obtained. The obtained results provided the advancement of a concept for designing a spiral chute unit with a set of inductors.

The conducted research gave reason to expect a decrease in the production cost of spherical metal ware due to a significant decrease in the energy intensity of their heat treatment (direct heating at a set depth) by about 11.2 %. According to the results of a series of experiments, there was also a twofold increase of the lifetime of these items (surface heating – relative to an elastic core, i.e., the anticracking effect was achieved along with the symmetry of the impact) compared to items heat-treated according to a traditional technology. These aspects afford grounds for forecasting a high demand for these items from ore-dressing and processing enterprises plants (non-ferrous and ferrous metal ore preparation), the construction industry (production of silicates, cement), the ball-bearing industry (rolling bearing balls), and oil production (check valves of deep-well pumps).

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