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# Investigation of an Electrical System for Induction Heating of Cylindrical Parts with Different Sizes

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**Abstract.** The article is devoted to the study of an electrical complex, including a high-frequency power source (2400 Hz), a heating inductor and cylindrical parts in the form of hollow cylinders (pipes). An autonomous electric machine power supply based on a high-speed magnetoelectric generator, which provides an output voltage of 950 V with a frequency of 2400 Hz, is considered. The features of inductors during heating of parts made of ferromagnetic steel and non-magnetic steel for low-temperature and high-temperature heating are presented. The results of inductor calculations are shown with a change in the diameters of processed pipes heated from a given inductor, which makes it possible to determine the areas of rational geometric parameters of parts that can be applied for a given inductor.

## 1 Introduction

Currently, the industry uses a large number of technological processes associated with the processing of metal pipes of various diameters and various thicknesses (bending, flaring, applying protective coatings, pipe soldering, creating branches). All of these processes are characterized by the need to preheat pipes. The well-known advantages of induction heating have determined its increasing use in modern installations for thermal and mechanical processing of pipes.

Currently, there are articles devoted to the analysis of the design, electromagnetic and thermal processes in induction installations for processing pipes and pipelines. In [1] describes the features of induction heat treatment of large diameter pipes using modular design inductors consisting of several separated sections, and also proposes a method for rational heating control due to work control of one section.

In [2] a method for making branches in pipes using induction heating is described, as well as a study of thermal processes in a heated pipe. It was determined that for the design

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of such inductors, it is necessary to take into account the electromagnetic characteristics of the pipe material (non-magnetic or magnetic steel), the change in physical parameters with temperature (resistivity, thermal conductivity, heat capacity), hydraulic processes in the inductor (laminar / turbulent mode), mechanical processes [3].

In [4] the equations are presented and computer simulations of electromagnetic and thermal processes are performed during induction heating of a large diameter pipe for its subsequent bending. It has been established that the surface effect, the proximity effect, and the ring effect significantly affect the temperature distribution. Fig. 1 shows the temperature dependences on the surfaces of the pipe obtained by these authors on the frequency, current density, and air gap between the inductor and the pipe. As can be seen, the size of the air gap between the inductor and the part significantly affects the temperatures of the pipe walls, which significantly affects the performance of the induction complex.

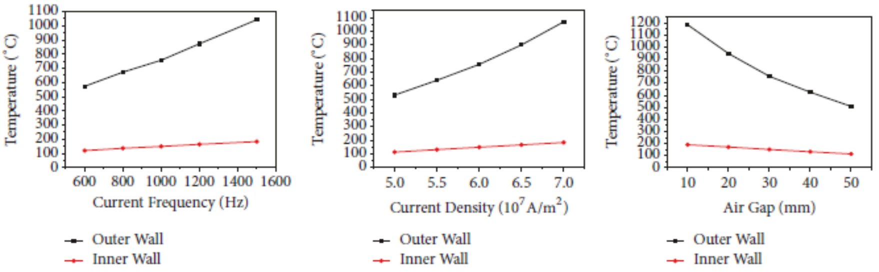


**Fig. 1.** Influence of the parameters of the induction system on the temperature in the pipe.

In [5] the designs of inductors intended for heating pipes used as part of induction water heaters are presented, and the method of electromagnetic calculation of such inductors is also shown. It was found that the inductance of the inductors increases with an increase in the diameter of the heated pipes, while with an increase in the length of the system, the inductance of the inductors decreased.

## 2 Formulation of the problem

The efficiency of induction heating installations for heating pipes (as well as other parts) depends significantly on the electromagnetic and design parameters of the inductor and parts. One of the main factors is: the size of air gap, the value of current frequency of inductor and the value of current density in inductor and parts. Software packages (Ansys, COMSOL Multiphysics, ABAQUS) make it possible to take into account many features of installations when calculating them, but their use is associated with difficulties: difficulty of building a correct model and creating accurate mesh, and a long-time duration of calculations. Therefore, there is a need for engineering methods to take into account the electromagnetic, thermal, hydraulic characteristics of the inductor and parts. Such methods can be built on the basis of equivalent circuits of inductors [6].

Another important aspect of the calculations of induction installations for heating pipes is the choice of the size of the air gap between the inductor and the part, as well as the determination of a rational range for changing the gap. This is due to the fact that in the current calculation methods it is often proposed to choose the appropriate dimensions of the inductor for specific dimensions of parts. In practice, there are often situations when it is necessary to determine which options for parts can be efficiently heated from an existing inductor or how much the efficiency of the process will decrease when the load parameters change. The solution to this problem is important to ensure the matching of the power supply and load.

The parameters of the power source used to power the inductor also significantly affect the efficiency of the process. During heat treatment of pipe blanks, autonomous power sources (mobile power plants) can be used directly near the places of their future operation. This article will consider the operation of an autonomous source based on a magnetoelectric generator that provides an output voltage of 950 V with a frequency of 2400 Hz.

## 3 Study of an autonomous power source based on a magnetoelectric high-frequency generator

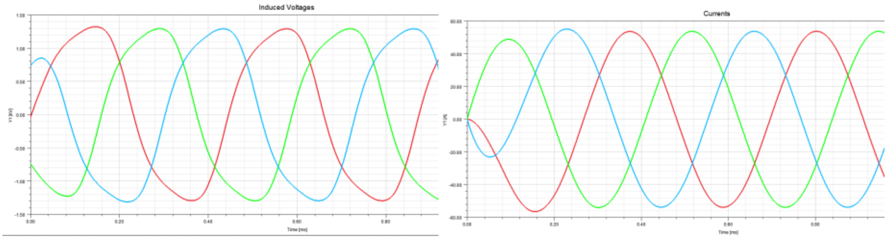
As an autonomous power source for the induction installation, a synchronous generator (SG) with an output power of 100 kW and excitation from permanent magnets of the Sm2Co17 brand 8 mm high will be investigated. To ensure the required frequency, the SG is planned to be driven from a small-sized gas turbine station, with a rotation speed of 70.000 rpm. Similar technologies have been implemented by Capstone, Pratt & Whitney and others. The production lines of serial objects of these firms include systems of a 100 kW capacity or more. As a result of the calculation, the parameters of the SG were obtained, shown in Table 1.

To confirm the calculation results, the simulation of electromagnetic and thermal processes in the generator was carried out using the Ansys software package. According to electromagnetic calculations, the induction in the stator magnetic circuit does not exceed 1.7 T, which is the optimal value for most types of steels, including the Russian steel grade 2421 used. Fig. 2, a shows an oscillogram of the SG phase voltage in the nominal mode, the effective value is 971 V. Fig. 2, b shows the SG current in the nominal mode. The effective value of the SG current is 39.7 A, which corresponds to a current density of 12.5 A/mm2.

The cooling system was implemented as a flow system, transformer oil was used as a coolant, with a temperature of 40 °C, and a mass flow rate of 11 l/min. The results of thermal calculation are presented in fig. 3. The temperature on the active elements does not exceed the permissible values, so the temperature on the magnets is 157 ºC, and the temperature of the windings does not exceed 187 ºC.

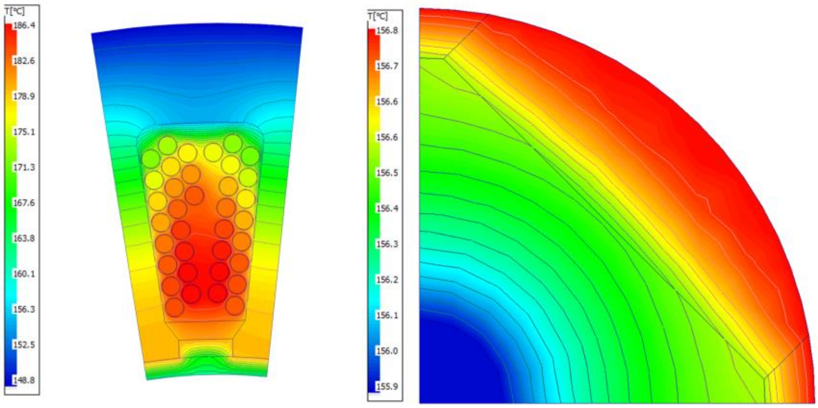
**Table 1.** Parameters of high-frequency generator.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Rated power | 99.7 kW | Current density | 12.5 A/mm$^2$ |
| Rotation frequency | 70000 rpm | Linear load | 505 A/cm |
| Number of poles | 8 | Magnetic induction in the air gap | 0.57 T |
| Active length | 170 mm | Magnetic induction in stator teeth | 1.61 T |
| Stator outer diameter | 90 mm | Losses in the stator winding | 36121.8 W |
| Current frequency | 2333 Hz | Losses in stator steel | 13316.8 W |
| Phase voltage | 971.2 V | Mass of permanent magnets | 1.1 kg |
| Phase current | 39.7 A | Active mass | 6.9 kg |
| Efficiency | 97.7 % | Specific power | 14.4 kW/kg |
| Power factor | 0.89 | | |



a b

**Fig. 2.** Oscillograms of SG: a - voltage, b – current.



a b

**Fig. 3.** Temperature distribution in parts of the SG: a - slot, b - area of magnets.

# 4 Investigation of the influence of the air gap on the efficiency of induction heating of pipes

Consider the influence of the air gap in induction installations for heating pipes on the heater. We will take into account two types of installations:

1. Installations for low-temperature heating of pipeline pipes for subsequent application of a protective coating on their outer surface. In this case, heating is carried out to a temperature of 300 ºC, and the pipes are made of ferromagnetic steel and retain magnetic properties throughout the process.
2. Installations for high-temperature heating of pipes up to a temperature of 1100 ºC. Such pipes are made of heat-resistant non-magnetic steel, for example, AISI 310S steel (Russian analogue - steel 20X23H18). Such installations are used, for example, for thermal diffusion galvanizing of metal parts.

A feature of calculation of induction systems with a ferromagnetic load (pipe) is a relatively low penetration depth, as well as a significant change in the specific heating power p0 as the temperature of the pipe rises. In this case, the magnetic field strength (according to the first harmonic) in the heated steel He can be determined by the formula (Slukhotskiy 1981):

$$H_e^2 \cdot \sqrt{\mu_e} = 3.67 \cdot 10^2 \cdot \frac{p_0}{\sqrt{\rho \cdot f}}, \quad (1)$$

where μe is the relative magnetic permeability on the pipe surface corresponding to He; ρ is the resistivity of the pipe material, Ohm·m; f is the frequency, Hz.

The calculation begins with setting a certain value p0. Further, the magnetic field strength can be determined from the dependence $H_e^2 \cdot \sqrt{\mu_e} = f(H_e)$. According to the magnetization curve $B_e = f(H_e)$, where $B_e$ is the magnetic induction (first harmonic), the induction and the permeability μe are determined.

The distribution of heat T along the pipe wall is described by a differential heat conduction equation, the solution of which is written as [7]:

$$\frac{T_2}{T_3} = \frac{\tau + S_1(\alpha,0,\tau)}{\tau + S_1(\alpha,1,\tau)}, \tag{2}$$

where T2, T3 are the temperatures on the outer and inner walls of the pipe, °C; τ = a·t/h2 is the Fourier criterion; S1 is the special function defined by reference tables, for example, in [7]; a is the thermal diffusivity of the pipe material, m2/s; t is the heating time, s; h is the pipe thickness, m.

Specific power (kW/cm2) with a ferromagnetic part is determined by:

$$p_0 = (1.2 \div 1.3) \cdot \frac{\lambda \cdot T_2}{10^7 \cdot h \cdot (\tau + S_1(\alpha,0,\tau))}, \tag{3}$$

where λ is the thermal conductivity of steel, W/(m·°C).

The value of the τ is determined by successive approximations with verification of the obtained ratio T2/T3. In many practical cases, τ >> 0.3. It is more convenient to calculate τ with the construction of a graph T2/T3 = f(τ) [6].

Recalculation of the inductor for a different number of turns (to assess the effect of the number of turns) can be performed based on the formula:

$$P = P_{init} \cdot \left(\frac{w}{w_1}\right)^2, \tag{4}$$

where Pinit is the calculated power, W; w is the calculated number of turns; w1 is the modified number of turns.

Currently, in installations for induction heating of pipes, it is proposed to use sets of inductors for heating pipes of a certain range of diameters, for example: 57-114 mm, 159-168 mm (h = 4 mm or less), 219-273 mm (h = 4...6 mm), 377-426 mm (h = 4...8 mm), etc. Let us consider the effect of the air gap on the installation parameters for the two above types of heating. So, for the installation for low-temperature heating, we set the parameters indicated in Table. 2. The range of outer diameters of pipes will be D2 = 700-100 mm. Table 3 shows the results of the calculation of the inductor for the case D2 = 700 mm. Method of calculation for a non-magnetic pipe are given in [6].

**Table 2.** Initial parameters of the inductor for low-temperature heating.

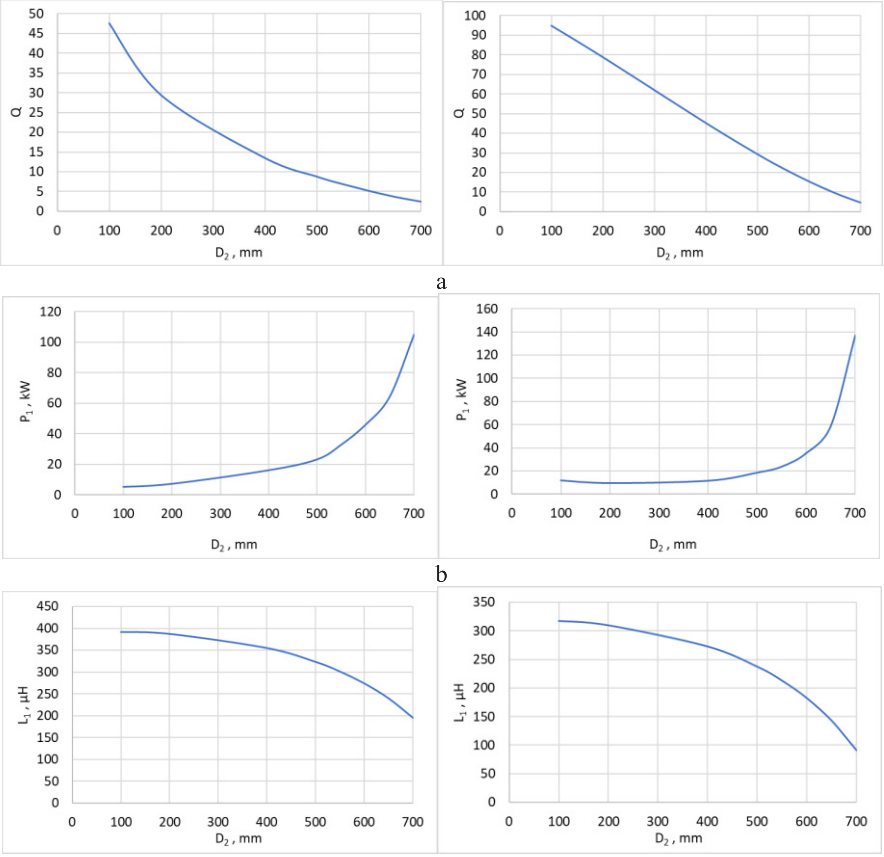
| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $T_2$ | 300 °C | Current frequency | 2400 Hz |
| Inductor inner diameter | 750 mm | Supply voltage | 950 V |
| Pipe length | 1 m | Inductor tube thickness | 2 mm |
| Inductor coil length | 300 mm | $T_3$ | 290 °C |
| h | 10 mm | $w = w_1$ | 21 |

**Table 3.** Calculation results of the inductor for low-temperature heating.

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Heating time of the section/part | 116.5 s / 388 s | Inductor current | 297 A |
| Inductor active power | 104.9 kW | Inductor movement speed | 2.6 mm/s |

| | | | |
|---|---|---|---|
| Total efficiency of the inductor | 0.6 | Q-factor | 2.5 |
| Power factor | 0.38 | Inductor inductance | 195 μH |

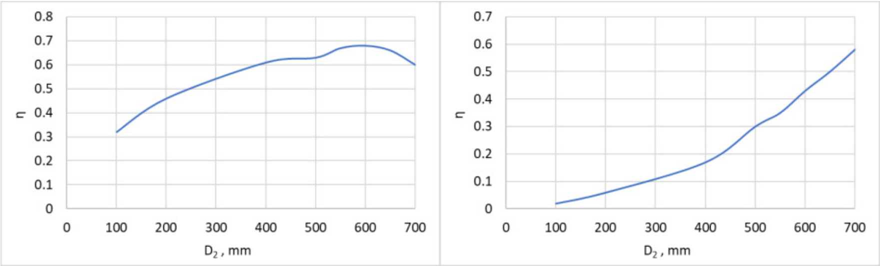
Fig. 4 (left graphs) shows the dependences of the main parameters of the inductor with a change in D2. As can be seen, even at D2 < 400 mm, the Q-factor becomes more than 10, which causes the inductor power to drop to less than 20 kW. The inductor inductance increases as D2 decreases and asymptotically tends to the value of the inductance of the "empty" inductor L1 ≈ 400 μH. For a given inductor diameter, there is a maximum point of its total efficiency equal to 0.68 at D2 = 620 mm, after which the total efficiency drops to 0.3 at D2 = 100 mm. Fig. 4 (right graphs) shows the calculated parameters of the inductor for high-temperature heating of a non-magnetic tube to temperatures T2/T3 = 1100/1090 °C with a tube length of 300 mm and w1 = 19 (other initial parameters correspond to Table 2). As you can see, the Q-factor increases to a much greater extent and becomes more than 10 already at D2 < 650 mm. The power of the inductor also drops more sharply and is less than 20 kW at D2 = 500 mm. L1 tends to 325 μH. The total efficiency of the inductor drops sharply as D2 decreases and is 0.3 at D2 = 500 mm.



a

b

c



d

**Fig. 4.** Results of calculations of inductors: a - Q-factor; b - power supplied to the inductor; c - inductance of the inductor; d - total efficiency of the inductor.

## 5 Conclusions

A study was made of an electrical complex with a high-frequency power supply (2400 Hz) based on a high-speed magnetoelectric SG designed to power an induction heating installation. It was found that the calculated dimensions of the SG active parts ensure its performance at an output power of 100 kW and an induction in the air gap of 0.57 T, while the temperatures of the SG active parts (windings and magnets) do not exceed the permissible values. A study was made of the operation of an induction heater for heating pipes made of ferromagnetic steel and non-magnetic steel. Calculation of heating inductors for different diameters of pipes was made. For the case of frequency of 2400 Hz and an inner diameter of 750 mm and low-temperature heating, the rational values for the diameters of heated pipes with h = 10 mm are D2 = 700–400 mm, and for high-temperature heating of a non-magnetic pipe, the outer diameters of the pipes where 700-600 mm. Heating of the ferromagnetic tube provides higher process efficiency values.

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