Calculation of electrical parameters for different schemes of ferromagnetic pipe

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Abstract **Problems of simulation of electromagnetic field taking into account hysteresis effect, at low-temperature heating of ferromagnetic steel, are considered in the present paper. Methods of numerical calculation of induction, resistive, and induction-resistive systems for ferromagnetic steel heating are developed. Comparison of electromagnetic field parameters in ferromagnetic steel for induction, resistive, and induction-resistive heating units is made, based on the methods obtained. The hysteresis effect contribution into the total heat output in the heated ferromagnetic material is estimated.**

Keywords **low-temperature heating, ferromagnetic steel, hysteresis effect, equivalent electric circuit.**

I. INTRODUCTION

There are processes in which heating of steel parts is mostly used for heat loss compensation, these are heat tracing of pipelines, vessels, hoppers, etc., at that low surface outputs are required (up to 5 kW/m^2) and, accordingly, low levels of magnetic field strength (H < 4000 A/m). At that the electromagnetic field parameters begin noticeably influenced by power loss caused by hysteresis effect [1, 2].

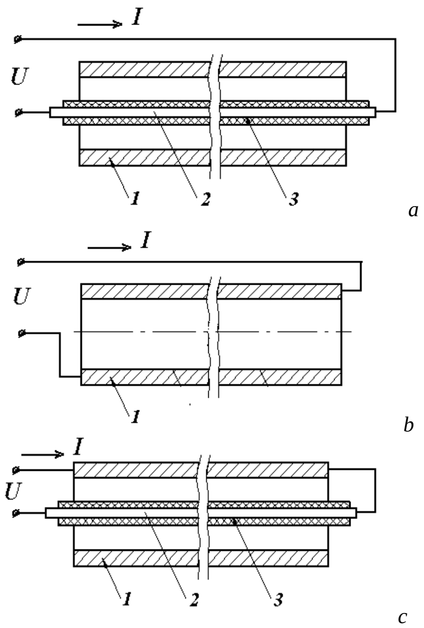

Figure 1. Schematics of induction (a), resistive (b) and induction-resistive (c) heating:
1- ferromagnetic tube, 2 – rod inductor, 3 – electric insulation

In this case the problem appears to take into account power loss due to alternating magnetization of steel (hysteresis) when calculating devices for induction, resistive and induction-resistive (combined) heating of steel parts at industrial frequency, in particular tubes (Figure 1).

II. ALGORITHM FOR COMPUTING THE ELECTROMAGNETIC FIELD IN FERROMAGNETIC STEEL

The article is concerned with the method for electromagnetic field parameters calculation in ferromagnetic steel using electric equivalent circuits [3, 4].

Let us consider the model based on electrical equivalent circuit as applied to the ferromagnetic tube with inner diameter *d* and thickness δ, in which flows the current *I* having frequency *f*. As an example, the plate division to 4 layers through its thickness (to *n* layers in general case) is accepted. At that it is accepted that the current in each layer flows through its middle (Fig. 2). The predetermined values are: electric resistance of the plate material ρ, the basic *B(H)* curve and the dependence of the hysteresis loss w_r on the magnetic field strength *H* and frequency *f*.

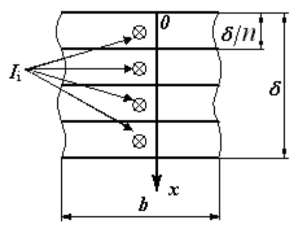

Figure 2. A fragment of the wall of the tube with division into layers with current values I_i

The equivalent electric circuit for calculation of electromagnetic field parameters in ferromagnetic tube is presented in Fig. 3 for induction-resistive heating. The following key symbols are used in the diagram: U – the supply voltage, $\dot{I}_i$ - the layers' currents; R_i – active resistances of the layers, taking into account losses caused by induced currents; L_i – self-inductances of the layers ; R_{gi} – active resistances of the layers, taking into account hysteresis losses; *i* – the current layer number.

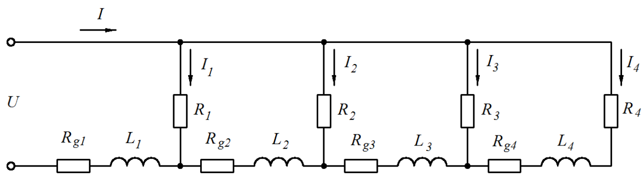

Figure 3. Electrical equivalent circuit for induction-resistive heating unit

The active resistance and inductance of the layer *i* are calculated by formulas:

$$R_i = \rho \cdot \frac{1}{\pi \cdot h \cdot (d_i + h)}, \quad (1)$$

$$L_i = \mu_i \cdot \mu_0 \cdot h \cdot \frac{1}{\pi \cdot d_i}, \quad (2)$$

where d_i and μ_i are inner diameter and relative magnetic permeability of the layer number *i*; $h = \delta/n$ – the layer thickness, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m.

The active resistance of the layer *i* taking into account the hysteresis loss and depending on *H* is:

$$R_{gi} = \frac{P_{gi}}{I_i^2} \quad (3)$$

Calculation of electromagnetic field in the wall of the tube is performed by iteration method: nonlinear dependences of $\mu(H)$ and $P_{gi}(H)$ are taken into account. At each iteration a system of linear algebraic equations is set up on the first and the second Kirchhoff's laws in accordance with the diagram presented in Figure 3.

III. RESULTS OF CALCULATION

Using the developed methods, electromagnetic field parameters in ferromagnetic steel taking into account the hysteresis effect have been calculated.

It is established also that variation of the magnetic field in tube's wall is different for induction, resistive and induction-resistive heating units that is reflected on distribution of the magnetic field strength, current and output heat power throughout the wall layers. The distributions of the magnetic field strength (a) and relative magnetic permeability (b) in the tube's wall for induction (1), resistive (2) and induction-resistive (3) heating units are presented in Figure 4. The simulation had been made using the following input data: cross-section of the inner centralized copper conductor – 15 mm^2, outer conductor – tube 32x3 mm (material type: steel 10), current *I* = 100 A.

The difference integral electrical parameters depend on the differences of the electromagnetic field distribution parameters for the systems of heating (table 1).

Table 1. Integral electrical parameters

	R*10-3, Ohm/m	X*10-3, Ohm/m	Z*10-3, Ohm/m
Induction heating	6.14	3.61	7.13
Resistive heating	3.05	1.56	3.43
Induction-resistive heating	3.89	2.12	4.43

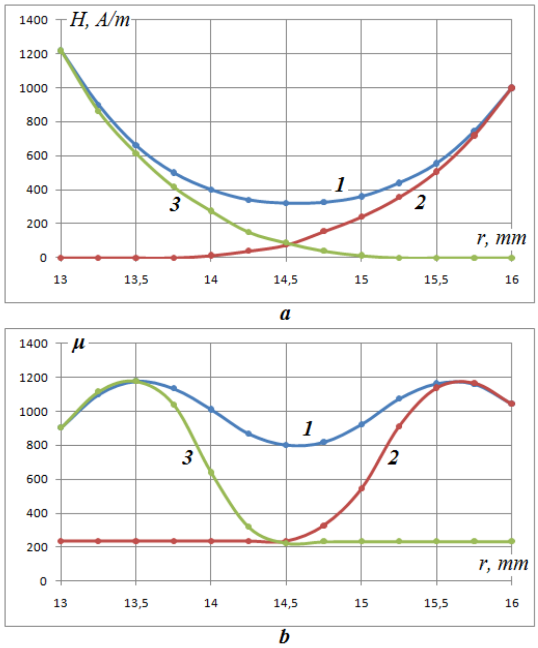

Figure 4. Distributions of the magnetic field strength (a) and relative magnetic permeability (b) in the tube's wall for induction (1), resistive (2) and induction-resistive (3) heating units.

Calculations performed using the developed methods made it possible to determine contribution of the hysteresis loss to total active power in ferromagnetic tube. For induction, resistive and induction-resistive heating system of a pipe made of structural steel this contribution amounts to more than 24% at magnetic field strength on the surface H_0 up to 2500 A/m and to more than 15% at H_0 up to 3800 A/m.

IV. CONCLUSION

1. The method proposed for calculation of heating units of induction, resistive and induction-resistive type using equivalent circuits enables one to take into account the hysteresis losses. At that the difference of the electrical calculation of the unit consists only in the very equivalent circuit.

2. Differential and integral electrical parameters of the system vary depending on the scheme include.

3. In the units considered, at heating with low levels of the magnetic field (up to 4000 A/m), it is required to take into account the influence of the hysteresis on the calculation results; in particular, the contribution of the hysteresis loss to the total active power in ferromagnetic load amounts to more than 24% at magnetic field strength on the surface H_0 up to 2500 A/m and to more than 15% at H_0 up to 3800 A/m.

4. The developed calculation method can be used at designing the units of considered types for ferromagnetic steel heating.

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