Magnetic Flux and Temperature Analysis in Induction Heated Steel Cylinder

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Abstract **- A modern method of solving industry magneto-thermal problems by means of a finite-element algorithm method using FLUX2D software has been proposed. An induction heating system has been simulated. The computational results have been compared with experimental data obtained, from the physical model by means of an infra-red camera. The effect of the supply current frequency on the induction heating efficiency was shown.**

I. NOMENCLATURE

c - specific heat
H - magnetic field strength
E - electric field strength
I - current strength
k - thermal conductivity
r - variable radius of the cylinder
T - variable temperature
T_∞ - ambient temperature
$U(\tau)$- input signal to the induction heating system
$W(\tau)$ - input signal to the controller
$Y(\tau)$- output signal of the close-loop induction heating system
$z(\tau)$ - disturbances of the induction heating system
w - internal heat source
α_c - convection exchange rate
α_r - radiation exchange rate
ρ - electric resistivity
τ - time
ψ - equivalent heat exchange coefficient

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II. INTRODUCTION

There are many practical applications of eddy currents heated steel cylinders in the paper industry. Eddy currents are usually generated by a number of induction coils that are installed parallely to the steel cylinder axis and close to its surface.

In order to design the high efficiency induction heating system it is essential to analyze:

- magnetic flux distribution in the inductors and steel cylinder
- relation between the power applied to the coil and the steel cylinder's temperature.

A reduced scale physical model of the induction heating system [1] has been built and examined trough a numerical simulation.

In this paper we have had intention to:

- determine the flux distribution in the body of inductor and in the steel cylinder,
- determine the temperature distribution in the steel cylinder,
- discuss the problems related to the close-loop temperature control for paper calender induction heating systems.

III. PHYSICAL MODEL

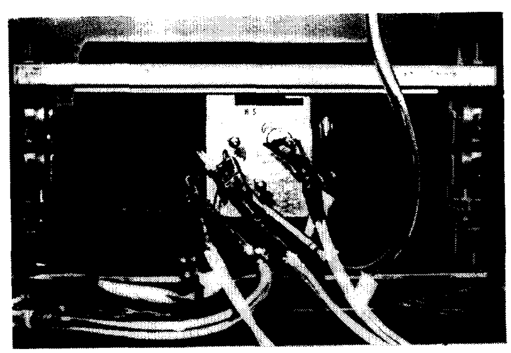

Fig.1. Physical model of the induction heated steel cylinder

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In our laboratory set-up, medium frequency AC/AC power converter (16.6 kHz, 2 kW) energizes the heating inductor [2]. The cylinder of the external radius of 0.6 m and of the internal radius of 0.59 m is driven by an induction motor at a nominal angular velocity of 10 r.p.m. (Fig.1).

IV. Solution of magneto-thermal problems in the induction heated steel cylinder.

In the process of designing an efficient induction heating system of a steel cylinder it is necessary to optimize coupled electromagnetic and thermal fields by applying a numerical methods. In order to determine coupled electromagnetic and thermal fields, we adopted a mathematical model of the induction heating of a long steel cylinder presented in [3]. The electromagnetic field is described by the following equations:

$$curl\,\vec{H} = \frac{\vec{E}}{\rho(T)} \qquad div\left[\mu(H,T)\vec{H}\right] = 0 \tag{1}$$

$$curl\,\vec{E} = -\frac{\partial[\mu(H,T)\vec{H}]}{\partial\tau} \qquad div\,\vec{E} = 0 \tag{2}$$

The thermal field in the cylinder is described by:

$$\mathrm{div}[\,k(T)\,\mathrm{grad}\,T)\,] - \gamma(T)c(T)\frac{\partial T}{\partial\tau} = w \tag{3}$$

The following assumptions were made:

- axial symmetry in the cylinder,
- the intensity of magnetic field $\vec{H}$ has only one z-coordinate-component,
- the heat flux on the steel cylinder surface is constant during a steady-state thermal process,
- in the steady state the heat losses of the steel cylinder due to convection and radiation are constant

The equations (1), (2), (3), can be rewritten in a form where $\vec{H}$ and T are functions of only r and τ:

$$\frac{\partial[\mu(H,T)H(r,\tau)]}{\partial\tau} - \frac{1}{r}\frac{\partial}{\partial r}\left(r\rho(T)\frac{\partial H(r,\tau)}{\partial r}\right) = 0 \tag{4}$$

$$\gamma(T)c(T)\frac{\partial T(r,\tau)}{\partial\tau} - \frac{1}{r}\frac{\partial}{\partial r}\left(r\,k(T)\frac{\partial T(r,\tau)}{\partial r}\right) = w \tag{5}$$

where "w" is an internal heat source obtained from equation:

$$w = \rho(T)\left[\frac{\partial H(r,\tau)}{\partial r}\right]^2 \tag{6}$$

The heat exchange between the surface of the cylinder and the area around it is described by equation:

$$-k\frac{\partial T}{\partial\tau} = (\alpha_C + \alpha_r)(T - T_\infty) \tag{7}$$

To describe all heat exchange between the surface of the steel cylinder and the surrounding area we have introduced an equivalent heat exchange coefficient given by formula:

$$\frac{1}{\psi} = \frac{g_C}{k} + \frac{1}{\alpha_C + \alpha_r} \tag{7}$$

where g_c is the thickness of the steel cylinder.

V. Modeling and simulation

The equations in Section IV have been solved at each node of a meshed geometry using the finite-element method. The main difficulty was to determine the equivalent thermal coefficient ψ in the case of a rotating cylinder.

We have simulated a numerical model of the laboratory induction heating system. It was essential to examine:

- the optimum frequency of supplied current,
- an equivalent thermal coefficient ψ.

The magneto-thermal problem was solved using finite element analysis. Non-linear material properties of the simulated model had to be predetermined to define properly the problem. We assumed that the magnetic permeability of the steel cylinder and inductor depends on both the magnetic field intensity H and the temperature T. Simulations were made for the frequencies of 4, 16.5, and 25 kHz (I=10 A) and a 3 mm inductor-cylinder gap.

VI. Simulation results

The effect of the magnetic flux distribution in the inductor, the gap and in the heated body are shown in the Fig. 2.

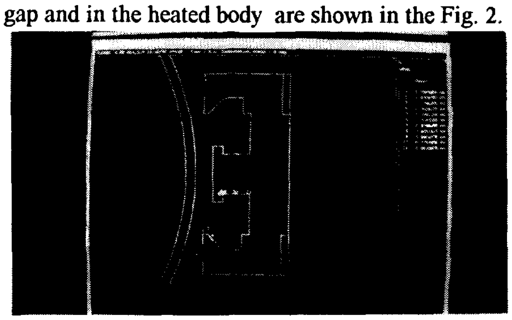

Fig.2. Magnetic flux distribution

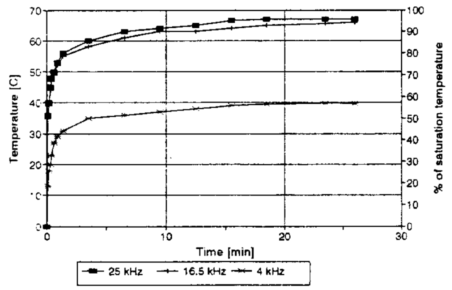

Fig.3. Temperature response of the cylinder to different frequencies of the supply current

The temperature distribution in the steel cylinder depends on the power induced. This power is a frequency-varying quantity. The temperature response of the cylinder to different frequencies of the supply current are shown in Fig.3. Based on the above results we can assume that for optimal gap size (3 mm) the optimal frequency range is 16 to 25 kHz. For this range the magnetic flux and temperature distributions are also optimal. The results of simulation were next compared with the experimental data obtained with the physical model (I = 10 A, frequency = 16.5 kHz). The temperatures on the surface of the heated cylinder were measured using an AGEMA 900 infra-red camera (Fig.4). The results of the numerical simulations are very closed to experimental data. For example the measured temperature on the cylinder's surface is about 66 °C and the calculated temperature on the cylinder surface is 64 °C. Of course this temperature comes from the part of the cylinder that is under the inductor. Differences between calculated and measured temperatures are less then 4 %.

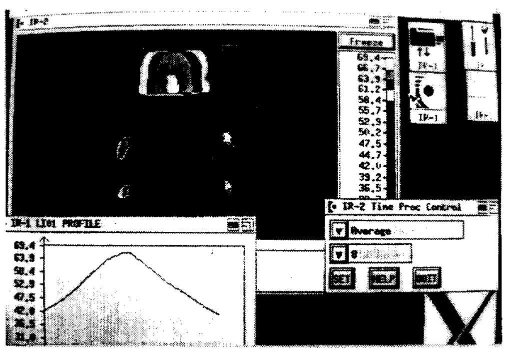

Fig.4. Measured temperature distribution of steel cylinder surface.

VII. Features of Feedback Temperature Control in Induction Heating System.

A general diagram of a temperature control system is shown below:

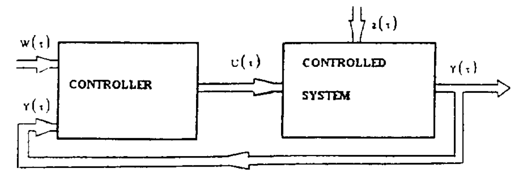

Fig.5 Close-loop temperature control for induction heating system.

The equivalent heat exchange coefficient ψ (7) makes possible to calculate the power supplied to the inductors to obtain desired temperature of the cylinder. The coefficient is proportional to the heat losses from the surface of the steel cylinder and represents disturbance $z(\tau)$. The coefficient depends of the temperature on the cylinder surface on its dimension, and material. Numerical simulation seems to be currently the most cost effective design method to determine $\psi(T)$ curve.

VIII. Conclusions

In this paper we examined the utility of the finite-element-method algorithms in solving complex industrial magneto-thermal problems. The simulation results were compared with experimental data obtained from a physical model of the induction heating system. The results of the numerical simulations are very closed to experimental data. The differences between calculated and measured temperatures are less then 4 %. By applying of function $\psi(T)$ defined in the paper it is possible to design a precise temperature control system for induction heating. The numerical simulation seems to be a very cost effective design tool to determine optimal magnetic flux and temperature distributions in simulated induction heating system and to determine the $\psi(T)$ curve.

Acknowledgment

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