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3D Modeling of Electromagnetic-Thermal Phenomena in Induction Heated Rotating Steel Cylinder

1. Introduction

Effective application of induction heating in some high performance industrial processes requires very often careful mathematical modeling because of complexity of physical phenomena and material nonlinearities. The importance of this issue rises when it concerns the heating of moving charges, especially when both the charge and the inductor can move. Such a situation takes place in induction heating of the rotating steel cylinder used among others in paper making industry, where moving inductors are necessary to assure required temperature distribution along cylinder surface. The accuracy of this temperature is one of the most important factors in industrial application concerned. The semi industrial set up of such a heating system has been developed in Computer Engineering Department TUL and research on the precise temperature control system has been carried out.

Since the heating power generated in the cylinder can depend to some extent on the mutual location of the inductors, having an impact on the resulting temperature of the cylinder surface, some preliminary investigation is needed to properly design and apply of the moving inductors system. Because of geometrical limitations of the heating system and various possible modes of an inductors movement the three-dimensional modeling of coupled electromagnetic – thermal fields becomes necessary to analyze mutual influence of inductors during their moves. In the following sections the mathematical background of such a model and their numerical implementation as well as some simulation results have been presented.

2. Description of 3D coupled electromagnetic-thermal numerical model

The heating of rotating cylinder can be realized by induction method. From physical point of view such approach can be considered as electromagnetic and thermal mutually

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coupled fields. The inductor-charge system parameters are usually determined by computer simulation where such coupling is simplified to weak, interactional coupling, as it is presented in Figure 1 [1].

Because of significantly large difference between a period of electromagnetic field and time of heating the coupled transient electromagnetic and thermal field the induction heating process can be described as AC quasi steady state. Such an approach enables to reduce the simulation cost but unfortunately leads to some simplification. The most important one is assumption of the linearity of field, although this simplification can be reduced by different technique, as magnetic curve modification [2].

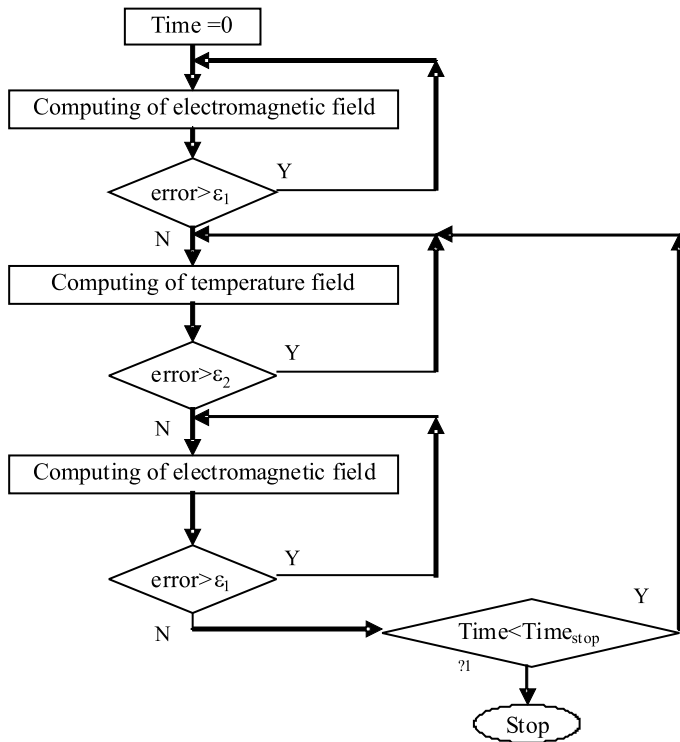


Fig. 1. The simulation algorithm of coupled electromagnetic and temperature fields

The mathematical analysis of AC steady state electromagnetic field in induction heating devices can be carried out by solving Maxwell equations neglecting displacement currents [2]:

$$\text{rot } H = J \quad (1)$$

$$\text{rot } E = -j\omega B \quad (2)$$

$$\text{div } B = 0 \quad (3)$$

where:

- $\mathbf{E}$ – electric field strength,
- $\mathbf{H}$ – magnetic field strength,
- $\mathbf{B}$ – magnetic flux density,
- $\mathbf{J}$ – current density,
- ω – angular frequency.

With these equations constitutive relationships are associated:

$$\mathbf{B} = [\mu] \mathbf{H} \quad (4)$$

$$\mathbf{J} = [\sigma] \mathbf{E} \quad (5)$$

where:

- μ – magnetic permeability of material of region,
- σ – conductivity tensor of material of region.

The magnetic field density $\mathbf{B}$ or field strength $\mathbf{H}$ distribution is very seldom directly calculated. Based on the magnetic flux conservation law (3) the magnetic vector potential $\mathbf{A}$ is defined:

$$\mathbf{B} = \text{rot } \mathbf{A} \quad (6)$$

Using magnetic vector potential $\mathbf{A}$ in equation (2) implies the existence of an electric scalar potential V , such as:

$$\mathbf{E} = -j\omega \mathbf{A} - \text{grad } V \quad (7)$$

In conducting regions the current density $\mathbf{J}$ can be written in terms of the magnetic vector potential $\mathbf{A}$ and of the electric scalar potential V as:

$$\mathbf{J} = -[\sigma](j\omega \mathbf{A} - \text{grad } V) \quad (8)$$

In 2D domain (where $\text{grad } V = \text{const}$) the complex magnetic vector potential $\mathbf{A}$ is usually used and the analysis of electromagnetic field is reduced to solving equation:

$$j\omega[\gamma]\mathbf{A} + \text{rot}[[1/[\mu]]\text{rot } \mathbf{A}] = \mathbf{J}_s \quad (9)$$

where:

- $[\gamma]$ – tensor of electrical conductivity,
- $\mathbf{J}_s$ – excitation current density.

It is important that in 2D domain the magnetic vector potential $\mathbf{A}$ has only one component (as current density (8)) while the magnetic field density $\mathbf{B}$ vector has two spatial components. In 3D domain where magnetic vector potential $\mathbf{A}$ has all three spatial components the magnetic field calculations based on $\mathbf{A}$ description in non-conduction region and $\mathbf{A}$ - V

description in conducting one is very expensive in terms of computational time and memory requirement (three complex unknowns in non-conducting regions and four in conducting regions). In such a situation in 3D domain other than A - V description are used too.

Equation (1) allows you to write that the current density has a conservative flux:

$$\operatorname{div} J = 0 \quad (10)$$

Based on that conservation law (9) the electric vector potential T is defined:

$$J = \operatorname{rot} T \quad (11)$$

Similar as magnetic vector potential A , the electric vector potential T is determined definitionally with the accuracy to the gradient of the scalar potential, so scalar potential should be defined for electric vector potential T too.

For regions in which the eddy currents are neglected the function of the total scalar potential Φ can be used

$$H = -\operatorname{grad} \Phi \quad (12)$$

For regions in which the eddy currents are neglected but however exist magnetic field, with strange H_0 , (generated by imposed current density) the reduced scalar potential Φ_{red} can be used:

$$H = H_0 - \operatorname{grad} \Phi_{red} \quad (13)$$

where H_0 – field generated by current be placed in vacuum.

In simulation of electromagnetic field, based on Finite Element Method (FEM), such formulation (13) allows you to take into account the “non-meshed coils”; current in vacuum regions.

In the region with the eddy currents, the magnetic field strange can be describe by electric vector potential T and total scalar potential Φ :

$$H = T - \operatorname{grad} \Phi \quad (14)$$

This formulation (similar as A - V description) is quite expensive, since four unknowns are necessary in the conducting regions (three components for the electric vector potential T and one component for the magnetic scalar potential Φ).

Taking into account that description based on electric vector potential T (in non-conducting regions) is less expensive than that based on magnetic vector potential A , the first one was used in the paper for describing the electromagnetic model of rotating cylinders.

The analysis of coupled electromagnetic and temperature fields was carried out (Fig. 1) by coupling electromagnetic analysis with thermal described by Fourier-Kirchhoff equation:

$$\operatorname{div}[(-\lambda)\operatorname{grad}\vartheta] + \rho c \frac{\partial \vartheta}{\partial t} = p_v \quad (15)$$

where:

- λ – thermal conductivity,
- ρ – density,
- c – specific heat,
- p_v – volumetric heat source power density.

with the existing boundary conditions taken into consideration.

The discrete 3D model of considered example is presented in Figure 2.

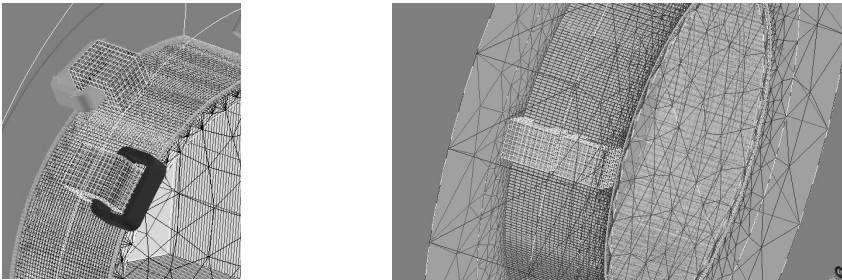


Fig. 2. The discrete model of rotating cylinder

3. Simulation of induction heating of the rotating cylinder with moving inductors

Using the proposed 3D numerical model the process of induction heating of the rotating cylinder has been simulated. Especially, mutual interaction of inductors during their movement over the cylinder surface has been considered. Such an analysis is necessary taking into account the development of the semi-industrial experimental setup [4].

Since the proposed 3D numerical model includes nonlinearities of material properties of the cylinder, like relative magnetic permeability, the model is very accurate and can be used to obtain 3D distribution of magnetic and thermal phenomena. But it is not convenient because of time consuming calculations (ever dozen hours). However such a model may become the basis for creating simpler specialized models for many aspects of induction heating [4]. Exemplary temperature distribution of the cylinder surface from induction heating process of the rotating cylinder is shown in Figure 3.

The first application of full 3D model is determining total real power induced in the surface of the cylinder.

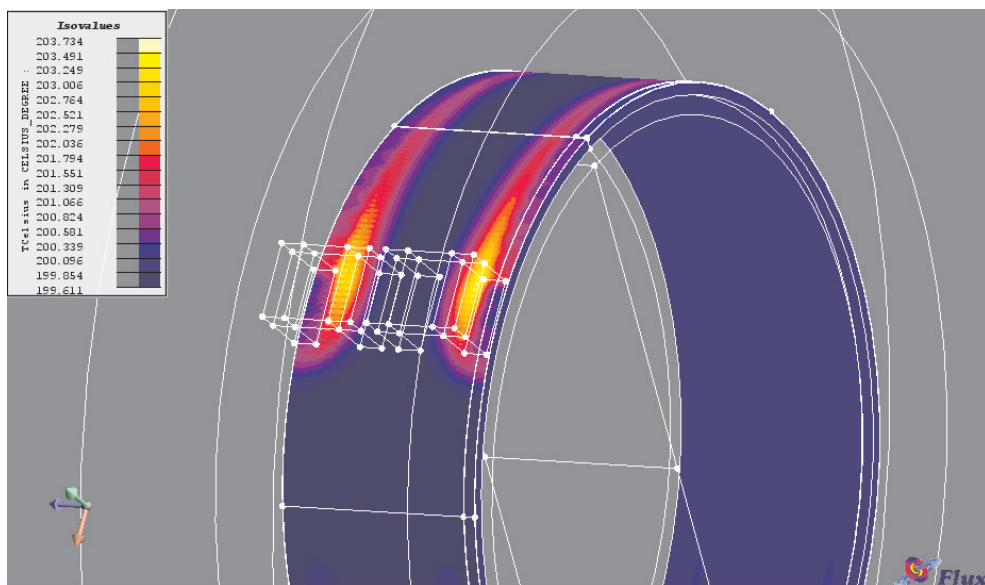


Fig. 3. Temperature distribution on the induction heated rotating cylinder

4. The effect of distance between inductors on total power induced in the rotating cylinder

Essential from efficiency of induction heating system is the issue of mutual influence of electromagnetic fields generated by neighboring inductors. It depends of the relative distance between inductors and the phase current flowing in the coil.

Two kind of relative positions have been examined – distance between inductors in one plane and distance in two planes shown in Figures 4 and 5.

4.1. Inductors located in one plane

Inductors under the cylinder surface are usually located in a one plane. Several values of distance between inductors have been examined – from 0 mm till 60 mm. In each case two border options have been took into consideration: case with current phase 0 and 180. The numerical model and exemplary results of magnetic field distribution are shown in Figures 4a and 4b.

The dependence the real power induced in the cylinders' surface of distance between inductors have been checked and presented in Figure 5.

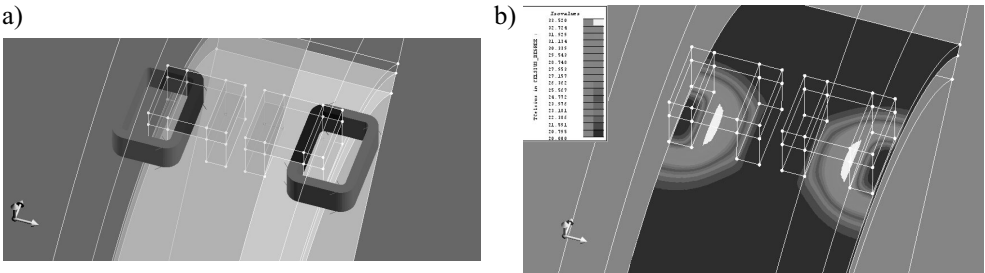


Fig. 4. Numerical model of induction heated rotating cylinder located in one plane (4a) and results of magnetic flux distribution on the cylinder surface (4b)

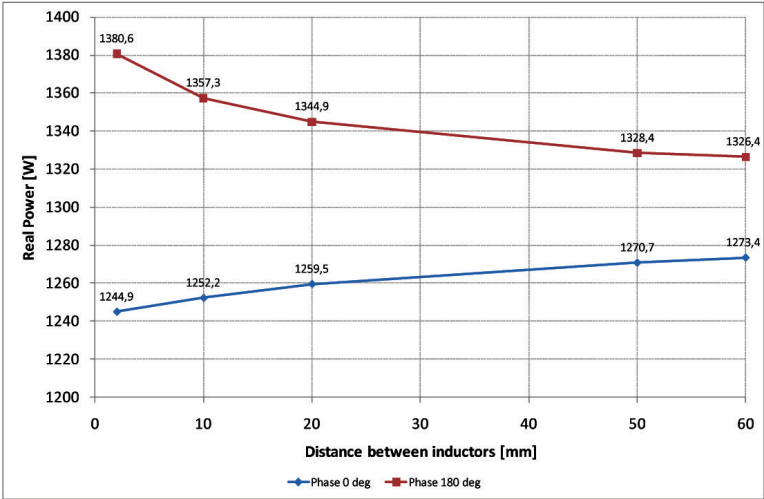


Fig. 5. The dependence of real power P of distance between inductors

It can be seen that if current phase in coils in the neighboring inductors is 0 (currents generating magnetic field vector pointing in the same direction) the power is rising-up with bigger distance between inductors. Differences between smallest and the biggest value of power is about 2.3%.

When phases of coils' currents are 180 deg total power decreases for about 4%. Of course investigated covers are only border lines between which there are real momentary phase between currents which can change stochastically.

4.2. Inductors located in two planes

Another possibility of inductors' location under the cylinders; surface is to put them in two planes as is shown in Figure 6.

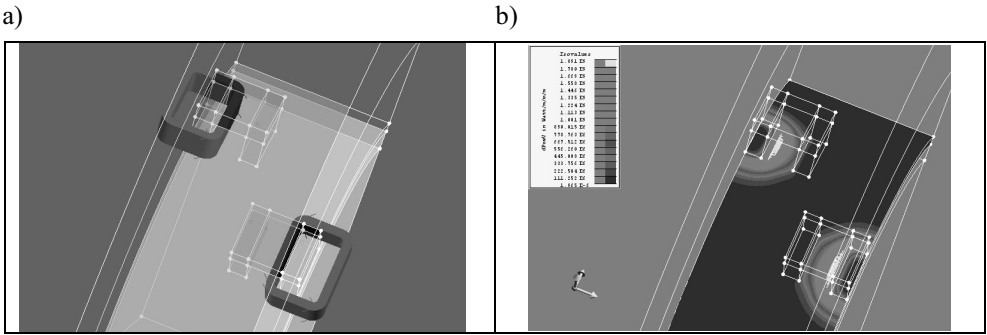


Fig. 6. Numerical model of induction heated rotating cylinder located in two planes (6a) and results of magnetic flux distribution on the cylinder surface (6b)

Results of calculations are shown in Figure 7.

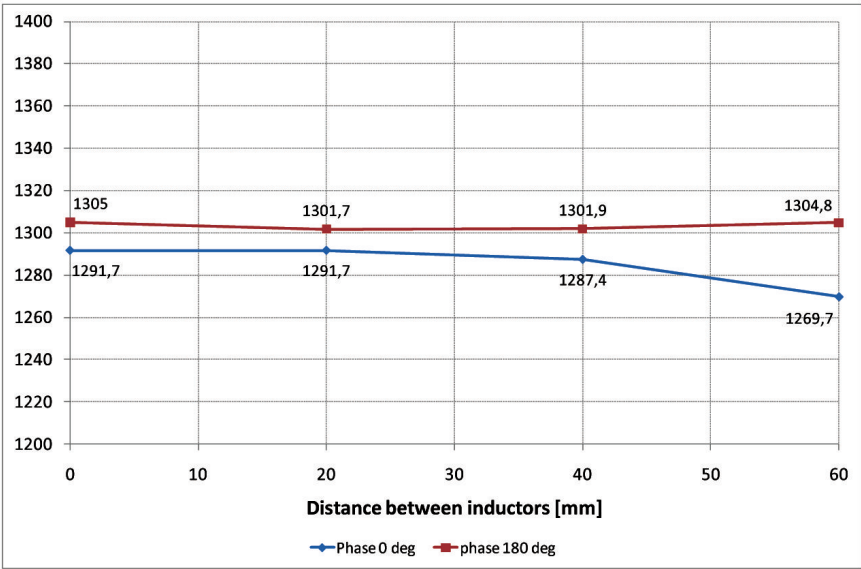


Fig. 7. The dependence of real power P of distance between put in two planes inductors

In such a placement of inductors it can be observed minimal (below 2%) influence of changing phase and distance between inductors for total real power induced in the cylinders' surface.

5. Conclusions

Using the built 3D model the analysis of electromagnetic interaction between inductors located in one and two planes under the surface of the cylinder. Results of those investiga-

tion confirm phenomena of changing induced heating power in the cylinders 'mantle due to relative distance between inductors.

3D numerical model of induction heated rotating steel cylinder could be good basis for detailed analysis of coupled electromagnetic and thermal phenomenon. However, due to long calculation time it couldn't be use to determine static and dynamic characteristic if induction heated rotating cylinder. But analysis of distribution coupled electromagnetic and thermal field in the cylinder's mantle provides possibility of develop few simpler (eg. 2D) and more usefulness models.

Acknowledgements

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