September 10 - 12, 2003
Pilsen, Czech Republic

ELECTROMAGNETIC AND TEMPERATURE FIELDS IN TRANSVERSE FLUX INDUCTION HEATING SYSTEMS FOR THIN STRIPS

DR HAB. INŻ. JERZY BARGLIK[1]

Abstract: The paper deals with a numerical computation of coupled electromagnetic and temperature fields in transverse flux induction heating systems for moving flat non-ferrous strips. The Opera 3D software was used for calculation of electromagnetic field as well as user codes for calculation of temperature field. To receive uniform distribution within the width of the strip a proper value of frequency of inductor current intensity should be chosen..

Keywords: Electromagnetic field, coupled problem, transverse flux field, induction heating.

1 Introduction

Optimised design of induction heaters for thin moving non-ferrous strips cannot be realised without detailed numerical simulation of their basic parameters. The reason consists in complicated phenomena associated particularly with interaction of several physical fields like quasi-stationary electromagnetic, stationary or non-stationary temperature or in some cases also heat stress fields. The problem was described in details in [1]. One of the more important issues in designing of such devices seem to be finding an optimal value of frequency of inductor current intensity making possible to receive uniform distribution of the temperature within the width of the charge.

[1] The Silesian University of Technology Krasińskiego 8, 40-019 Katowice, Poland, e-mail barglik@polsl.katowice.pl

2 Mathematical model

Let us consider a heating system producing transverse flux magnetic field for continuous heating of brass strips shown in the cross section in fig.1.

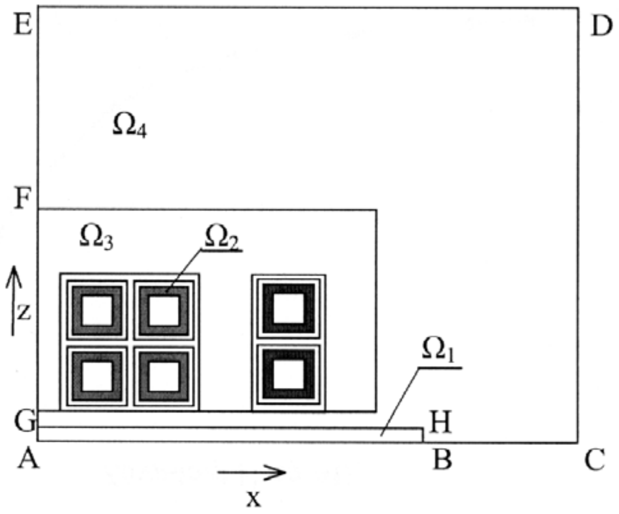

Fig. 1: Basic arrangement of a heating system with transverse flux magnetic field

The brass strip Ω_1 was situated in a narrow air-gap of the inductor consisting of winding Ω_2 replaced in the grooves of the magnetic core Ω_3. The strip moves in the direction of x-axis with a constant velocity v. For concrete value of the thickness of the charge g and for known conditions of the heat transfer a proper value of the air-gap of the inductor was chosen. All coils of the winding were connected in a series, so the transverse flux magnetic was generated in the strip. Borders of surroundings Ω_4 were chosen far enough from the heating system, for instance AE $\approx$8 AF. Three dimensional electromagnetic field was modelled by means of the magnetic vector potential $\boldsymbol{A}$ [2]:

$$\mathrm{rot}\frac{1}{\mu}\mathrm{rot}\,\boldsymbol{A} - \gamma\frac{\partial \boldsymbol{A}}{\partial t} - \gamma(\boldsymbol{v}\times\mathrm{rot}\,\boldsymbol{A}) = \boldsymbol{J}_z \tag{1}$$

where μ denotes magnetic permeability, γ - electric conductivity, $\boldsymbol{J}_z$ - current density within the inductor. In case that permeability of the magnetic core may be considered constant, (1) transforms into the Helmholtz equations for the phasor of magnetic vector potential $\underline{\boldsymbol{A}}$:

$$\mathrm{rot}\,\mathrm{rot}\,\underline{\boldsymbol{A}} - \mathrm{j}\omega\mu\gamma\,\underline{\boldsymbol{A}} - \mu\gamma(\boldsymbol{v}\times\mathrm{rot}\,\underline{\boldsymbol{A}}) = -\mu\underline{\boldsymbol{J}}_z \tag{2}$$

For the sub-regions $\Omega_1 \div \Omega_4$ the equation (2) was modified by using of proper of the each sub-region values of magnetic permeability, electric conductivity, velocity and current density within the inductor. For typical values of the velocity of the strip movement (v $\leq$0,5 m/s) expression $\boldsymbol{v}$ x rot $\underline{\boldsymbol{A}}$ in the equation (2) could be neglected [3].

Equation (2) should be supplemented by the boundary conditions. For planes of external borders represented in fig. 1 by line EDF and for the plane $x = 0$ represented in fig. 1 by line AE (anti-symmetry of current density within inductor):

$$\underline{\boldsymbol{A}} = 0 \tag{3}$$

For plane $z = 0$ represented in fig. 1 by line AC (symmetry of current density within inductors):

$$\underline{\boldsymbol{A}} \times \boldsymbol{n} = 0 \tag{4}$$

Eddy current density induced in the charge $\underline{\boldsymbol{J}}$ and specific Joule losses p_v could expressed by following relations:

$$\underline{\boldsymbol{J}} = \mathrm{j}\omega\gamma\underline{\boldsymbol{A}} \tag{5}$$

where: ω - *pulsation*

$$p_v = \frac{\underline{\boldsymbol{J}} \cdot \underline{\boldsymbol{J}}^*}{\gamma} \tag{6}$$

Based upon known distribution of the specific Jolue losses released in the strip the temperature field was calculated by solving of Kirchhoff- Fourier equation in the subregion Ω_1:

$$\mathrm{div}(\lambda\, \mathrm{grad} T) - \rho c(\boldsymbol{v}\, \mathrm{grad}\, T) = \rho c \frac{\partial T}{\partial t} - p_v \tag{7}$$

where λ denotes specific heat conduction coefficient, ρ - density, c - specific heat. Model for calculation of temperature field was shown in fig. 2.

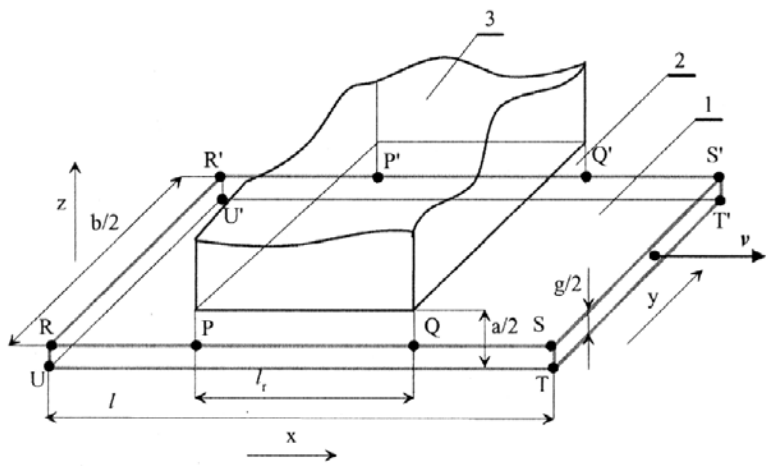

Fig. 2 Model for calculation of temperature field in moving brass strip 1 - strip (Ω_1), 2 - air gap of the inductor and surroundings (Ω_4), 3 - inductor (Ω_2, Ω_3).

The equation (7) was supplemented by following boundary conditions:

- at artificial input plane RR'UU':

$$T(y,z,t) = T_p, \tag{8}$$

where T_p denotes average temperature of the strip before induction heating,
- at artificial output plane SS'T'T:

$$\frac{\partial T}{\partial x} = 0, \tag{9}$$

- at remaining external planes RR'PP', QQ'SS', PP'QQ', R'S'T'U':

$$-\lambda \frac{\partial T}{\partial n} = \alpha (T - T_z), \tag{10}$$

where n denotes normal to the plane, α convection heat transfer coefficient being a function of temperature and having in general different values of the different planes [1], T_z - ambient temperature
- at symmetry planes RSTU, UU'TT':

$$\frac{\partial T}{\partial n} = 0, \tag{11}$$

Due to low temperature type of heating radiation was neglected.

Three-dimensional electromagnetic and temperature fields were analysed as a weak coupled problem by using of a numerical algorithm shown in fig.3.

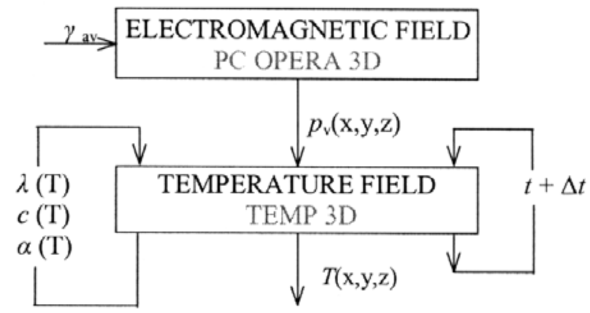

Fig. 3 Model for calculation of weak coupled electromagnetic-temperature fields.

For calculation of electromagnetic field FEM-based professional code OPERA 3D was used [1]. Based upon known specific Joule losses in the strip p_v(x,y,z) distribution of temperature was calculated by means of user code TEMP 3D.

3 Example of calculation results

The computations were carried out for following parameters:
- thickness of the strip $g = 0{,}0032$ m,
- air-gap of the inductor $a = 0{,}01$ m,
- current intensity of the inductor $I = 500$ A,
- frequency $f = 25, 50, 200, 500, 1000, 3000$ Hz.

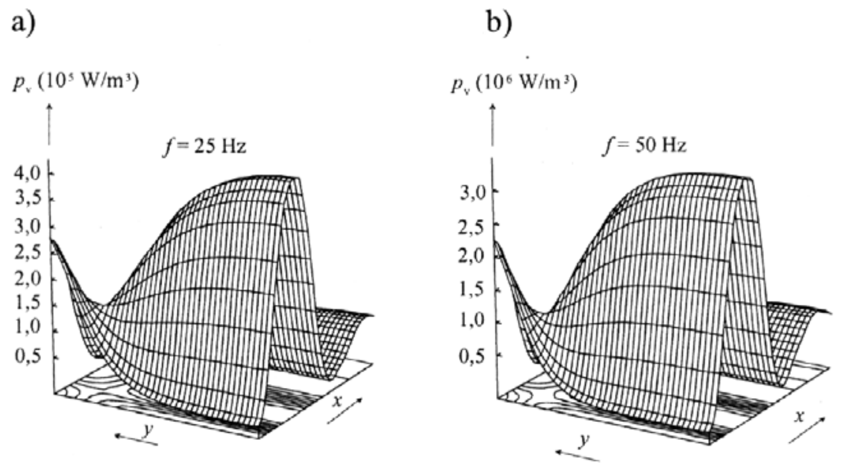

Fig. 4 Distribution of specific Joule losses at internal plane of flat brass strip with frequency f = 25 Hz (a) and f = 50 Hz (b)

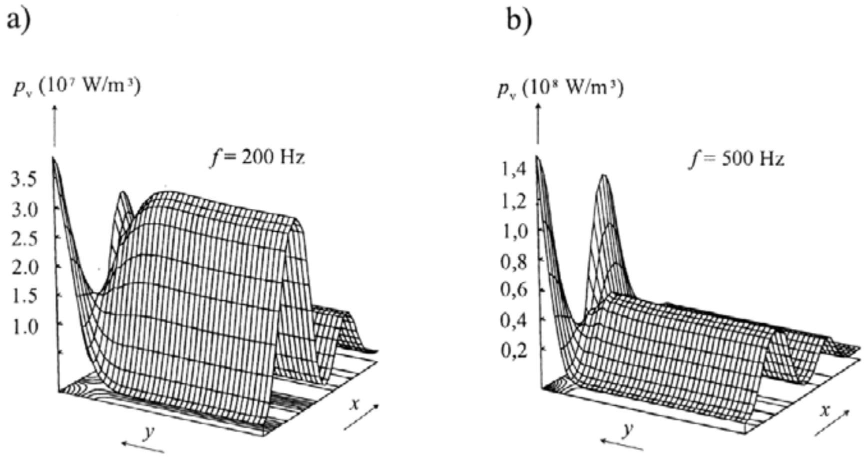

Fig. 5 Distribution of specific Joule losses at internal plane of flat brass strip with frequency f = 200 Hz (a) and f = 500 Hz (b)

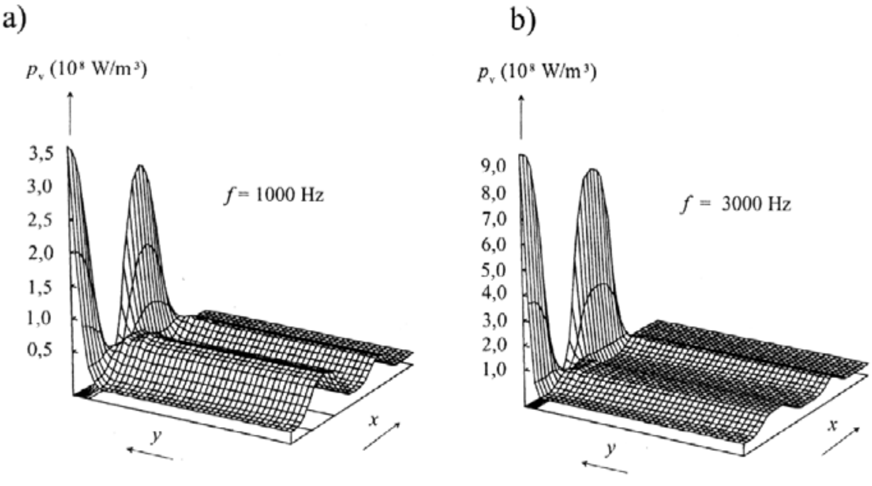

Fig. 6 Distribution of specific Joule losses at internal plane of flat brass strip with frequency f = 1000 Hz (a) and f = 3000 Hz (b)

At lower frequencies (fig.4) distribution of specific Joule losses is non-uniform with a distinct maximum in the axis of the strip. For f = 200 Hz (fig. 5a) distribution of specific Joule losses seems to be more uniform. Average value of the specific Joule losses in this case is about ten times bigger than for f = 50 Hz.

specific Joule losses in this case is about ten times bigger than for f = 50 Hz. When f = 500 Hz distribution of specific Joule losses is again clearly non-uniform with a distinct maximum near the edge of the strip. For bigger frequencies (f = 1000 Hz and f = 3000 Hz) phenomenon are more distinct. Detailed discussion of the results was presented in [1]. Distribution of the specific Joule losses has of course influenced on the uniformity of temperature distribution in the charge (fig.7).

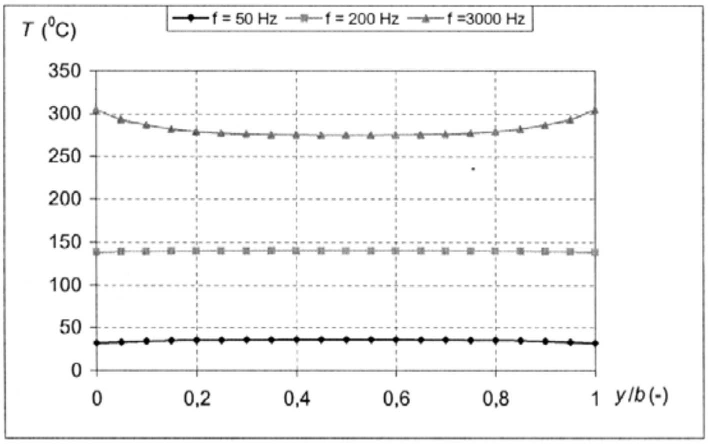

Fig. 7 Temperature distribution in moving brass strip at the outlet of the inductor on relative charge width

4 Conclusion

3D coupled electromagnetic and temperature fields in a typical induction heating system with transverse flux magnetic field for thin brass strips have been analysed. The specific Joule losses and temperature distribution within the moving charge have been computed. A problem of finding an optimal value of frequency of inductor current intensity making possible to receive uniform distribution of the temperature within the width of the charge has been illustrated. Continuation of the work will be aimed at analysis how to find optimal value of frequency of the inductor current intensity with taking into account not only uniformity of temperature distribution but also a total energy efficiency.

References

[1] Barglik J.: Induction Heating of flat Charges in transverse flux Field. Science Issues of the Silesian University of Technology number 65. Gliwice 2002 p. 119 (in Polish)

[2] Zahn M.: Electromagnetic Field PWN Warszawa 1088 p. 782 (in Polish).

[3]. Barglik J., Doležel I., Ulrych B.: . Induction heating of moving bodies. Acta Technica CSAV, Academy of Sciences of the Czech Republic, vol. 43, Prague 1998, pp. 361-373.