EDGE EFFECT OF LOAD IN TRANSVERSE FLUX INDUCTION HEATING SYSTEMS

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ABSTRACT. The problem of edge effect in continuous transfers flux inductor heaters (TFIH) is examined using a new problem oriented program based on a structure of ELTA program. This new program is designed to simulate distribution of power sources and temperature along the width and length of the workpiece in continuous TFIH system. In paper methods of calculation are described and the results of several case studies are presented. Main attention was paid to distribution of the power source and temperature along the width of thin strips from copper, aluminum, stainless steel and ferromagnetic steel.

INTRODUCTION

Induction heating in transverse flux can be economically effective for thin workpieces from aluminum, copper, gold, silver and other metals with low resistivity. One thing for sure is that obtaining of temperature uniformity is never easy, because a strong edge effect of the load plays determining role in quality of heating. Multiple studies since the beginning of 1960s showed that it is a very serious problem for this type of heating. Start of theoretical investigation for edge effect is being done in 1960th by V. A. Peysakhovich [1]. The problem remains urgent until now, and many researchers try to find optimal solution taking into account edge effects of load and inductor [2-8]. TFIH is very complicated system, and 3D calculation programs such as FLUX, MAXWELL, ANSYS, etc. are usually used to simulate electromagnetic field and temperature distribution and obtain desired heat quality at high efficiency. At the same time a preliminary estimation of edge effect for the load can be performed with more easy calculation methods and programs.

The new Transverse Flux Heating program can find distribution of power sources and temperature along the width and length of workpiece in continuous transverse flux induction heating system. Both analytical and numerical methods of calculation are used in it to obtain the induced current densities and power in the strip. Maxwell equations for the field are presented in the form of series.

METODS OF CALCULATION

Analytical method

The analytical solution of TFIH system (Figure 1, *a*) can be obtained, assuming that the metallic strip is located between two large and flat poles of electromagnet without poles and slots (Figure 1, *b*). If the dimensions of strip are less than the sizes of poles, it is possible to show that the current distribution in the strip will be almost the same as in the long rectangular workpiece. This circumstance was used by A. Peysakhovich for the evaluation of electromagnetic field, power sources and temperature in the strip, to be heated in the inductor of transverse magnetic flux [1]. Winding was substituted by a number of infinite thin wires, located on the surface of magnetic yoke (Figure 1, *b*).

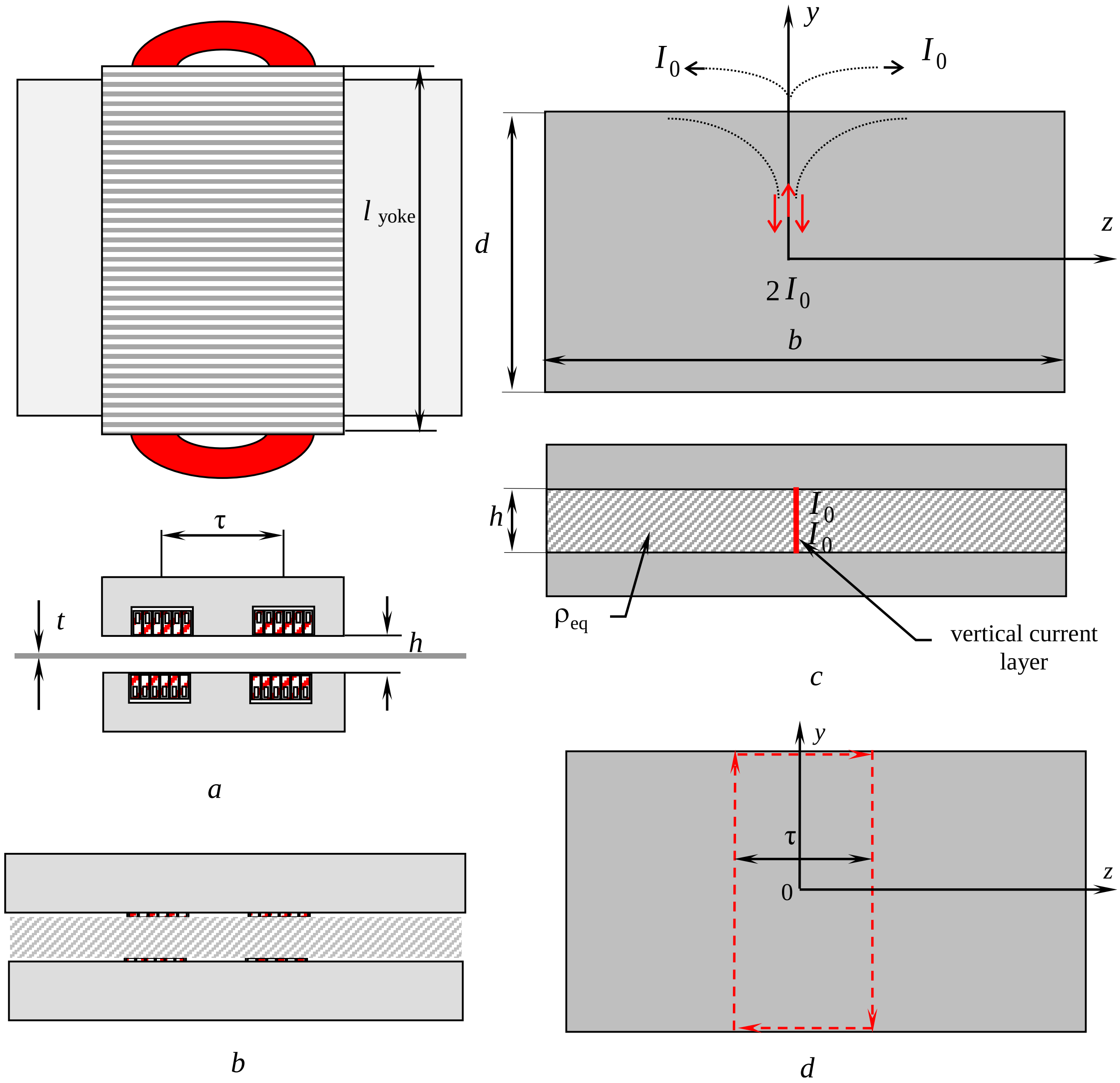

Figure 1. E-type transversal induction heater (*a*), simplified variant of induction system (*b*) lines of induced current in the workpiece from one wire with a current I_0 (*c*) and idealized lines of induced current in the workpiece from two wires of TFIH (*d*).

It is possible to extend the real width of the wires in the form of thin layers without taking into account the influence of slots, using a principle of superposition. We will consider that length of magnet yoke l_{yoke} is greater than or equal to the strip width *d*. Strip fills the entire gap between the top and bottom parts of the magnetic yoke, and its resistivity is raised by a ratio of the gap and the strip thickness (*h/t*).

Since magnet yoke are assumed to be ideal, the magnetic field strength H_x on perimeter of strip will be $H_e = I_0/h$. This is boundary condition in the equations for electromagnetic field.

The following assumptions are admitted:

- magnetic circuit is ideal flat (magnetic permeability $\mu \to \infty$);
- width of strip is less than or equal to the width of the magnetic yoke ($d \le l_{\text{yoke}}$);
- wires of the inductor circuit are vertical current layers in the strip, perpendicular to the strip edge (Figure 1, *d*);
- strip with constant properties “fills” the entire gap;
- equivalent strip resistivity is $\rho_{\text{eq.}} = \rho h/t$;
- the solution is searched for one wire (Figure 1, *c*).

The initial two-dimensional equation of electromagnetic field to find the density of the induced eddy currents can be described in the form, which is used for the calculation if the load has the rectangular cross section

$$\frac{\partial^2 \dot{H}_x}{\partial y^2} + \frac{\partial^2 \dot{H}_x}{\partial z^2} = j\omega\mu\mu_0 \dot{H}_x \cdot \qquad (1)$$

There are two approaches to solve the 2D equation (1): analytical and numerical methods.

The magnetic field density on all perimeter of the strip can be described in the form $H_x = H_e = I_0/h$ according to the total current law.

The boundary conditions in equation (1) for two wires (Figure 1, *d*) can be described as $H = H_e$ at $y = \pm d/2$ and $z = \pm\tau/2$.

The current I_0 creates the induced current densities $\dot{J}_y$ и $\dot{J}_z$

$$\dot{j}_y = \varphi(\frac{d}{\Delta}, \frac{y}{\Delta}, \frac{z}{\Delta}), \;\; \dot{j}_z = \psi(\frac{d}{\Delta}, \frac{y}{\Delta}, \frac{z}{\Delta}), \qquad (2)$$

where y/Δ – relative coordinate, $\Delta = \sqrt{2\rho h/(\omega\mu\mu_0 t)}$ – effective reference depth of the strip material.

For the finite length of strip *b* the induced current densities can be written in the following Fourier series [1, 9]

$$\dot{j}_z = \frac{\dot{E}_z}{\rho_{\text{eq}}} = j\dot{H}_e \frac{8}{\pi\Delta^2} \sum_{n=1,3,\dots}^{\infty} \frac{(-1)^{\frac{n-1}{2}} Sh p_d y}{n p_d Ch(p_d \frac{b}{2})} \cos\frac{n\pi(z-\frac{b}{2})}{d}, \qquad (3)$$

$$\dot{j}_y = \frac{\dot{E}_y}{\rho_{\text{eq}}} = -j\dot{H}_e \frac{8}{\pi\Delta^2} \sum_{n=1,3,\dots}^{\infty} \frac{(-1)^{\frac{n-1}{2}} Sh[p_b(z-\frac{b}{2})]}{n p_b Ch(p_b \frac{d}{2})} \cos\frac{n\pi y}{b}, \qquad (4)$$

where $p_d^2 = (\frac{n\pi}{d})^2 + \frac{2j}{\Delta^2}$, $p_b^2 = (\frac{n\pi}{b})^2 + \frac{2j}{\Delta^2}$.

The goal of calculation is determination of:

- distributions of $\dot{J}_y$ и $\dot{J}_z$ and $\dot{J}_{y,z}$ in material of strip from two layers of the current in the slots of the magnet yoke, taken into account the phase angle (0° for direct conductor and 180° for return conductor) and the condition for summary current $\sum_i \dot{I}_i = 0$, on coordinates $y(-d/2, +d/2)$ and $z(-\tau/2, +\tau/2)$;
- the total distribution of $\dot{J}_{y,z}$ from other slots.

The main properties of $\dot{J}_y$ and $\dot{J}_z$ functions in the case $z \to \pm\, \tau/2$ are: $\dot{J}_y \to 0$; $\dot{J}_z \to$ const, does not depend on z and must correspond to current distribution in the infinitely wide plate along the direction z:

$$\dot{J}_y = \frac{ch(1+j)\dfrac{z}{\Delta}}{ch(1+j)\dfrac{d}{2\Delta}}. \tag{5}$$

The current densities $\dot{J}_{y,z}$ will be the two-dimensional arrays of the complex values with fixed d/Δ. The specific power can be calculated and summarized independently knowing summary current densities $\dot{J}_{y\Sigma} = \sum_i \dot{J}_{yi}$ and $\dot{J}_{z\Sigma} = \sum_i \dot{J}_{zi}$

$$p_{\mathrm{v}}(y,z) = \rho_{\mathrm{eq}}\left[\left|\dot{J}_{y\Sigma}\right|^2 + \left|\dot{J}_{z\Sigma}\right|^2\right]. \tag{6}$$

In this case power distribution on the width of strip and the total power can be easy calculated. Two examples of calculated power distribution on the aluminum strip t = 2.5 mm, d = 1200 mm, l = 1000 mm in the TFIH system with τ = 210 mm, h = 60 mm and power source frequency 50 Hz are shown in Figure 2.

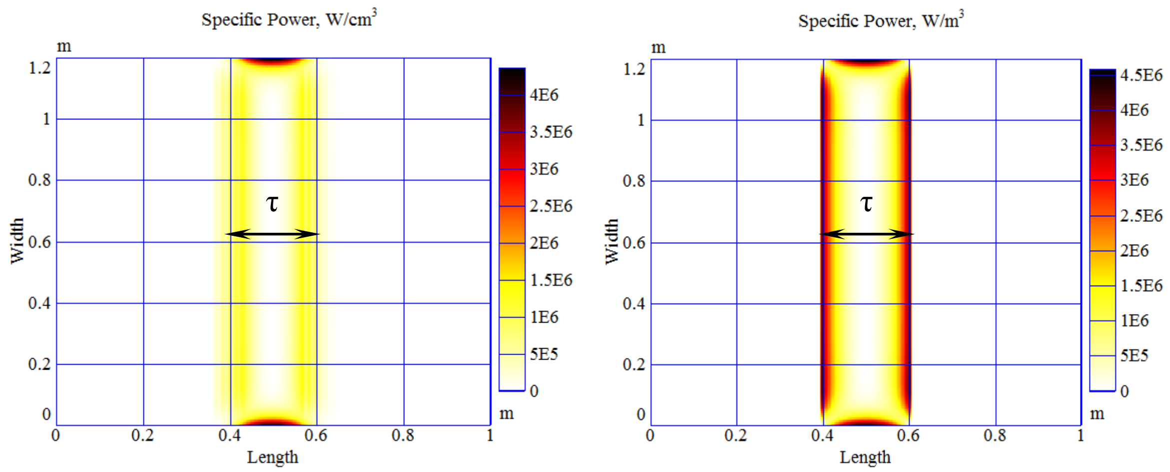

Figure 2. Color map of specific power in the aluminum strip heated in E-type TFIH for 6-wire coil as in Figure 1, *a* with inductor current 1000 A (left) and for one singe-wire coil with total inductor current 6000 A (right).

Real inductor has 6 turns coil (Figure 1, *a*) and distance from direct and return conductor is τ = 290; 263; 233; 203; 173 and 143 mm respectively. Calculation showed that distribution of total power along the strip width both for real 6-wire and for idealized variant of singe-wire coil is the same and investigation of edge effect may be performed taken into account only thin singe-wire coil (direct and return conductor) and the pole pitch τ = 210 mm.

Numerical method

As can be seen in Figure 2, right, distribution of power between two poles is the same as for rectangular cross section of slab. Calculation of 2D equation is realized in ELTA 6.0 using finite difference numerical method and it is used for investigation of longitudinal edge effect taken into account non linear properties of materials [10].

Equation in numerical method of calculation for magnetic field in a rectangle body has the form

$$\frac{\partial}{\partial y}\left(\rho_{eq}\frac{\partial \dot{H}}{\partial y}\right)+\frac{\partial}{\partial z}\left(\rho_{eq}\frac{\partial \dot{H}}{\partial z}\right)=j\omega\mu\mu_0\dot{H}. \tag{7}$$

One quarter of the cross section may be considered due to double mirror symmetry. The boundary conditions are $H = H_e$ at $y = d/2$, $z = \tau/2$, $\partial\dot{H}/\partial y = 0$ at $y = 0$ and $\partial\dot{H}/\partial z = 0$ at $z = 0$.

Value of p' is an integral of volumetric power density p_v along the pole pitch τ, witch can characterize the transversal edge effect in the form p'/p_c':

$$p'(y)=\int_{\tau} p_v(y,z)dz\,,\;\; p_c'=\int_{\tau} p_v(y=0,z)dz\,. \tag{8}$$

Two-dimensional distribution of power sources in workpieces of rectangular cross-section can be obtained using formula:

$$p_v=\rho\left(\frac{\partial\dot{H}}{\partial y}\frac{\partial\overset{*}{H}}{\partial y}+\frac{\partial\dot{H}}{\partial z}\frac{\partial\overset{*}{H}}{\partial z}\right). \tag{9}$$

For real cases parameters of material can vary dramatically in the process of high temperature transversal heating. The edge effects after the first part of inductor (direct conductor) interfere with the edge effect of the second part (back conductor) and have to be taken into account.

INVESTIGATION OF TFIH EDGE EFFECT

New program may be inserted in ELTA 6.0 program to make simulation of Transverse Flux Heating (Figure 3) and predict temperature distribution in the width of thin strips.

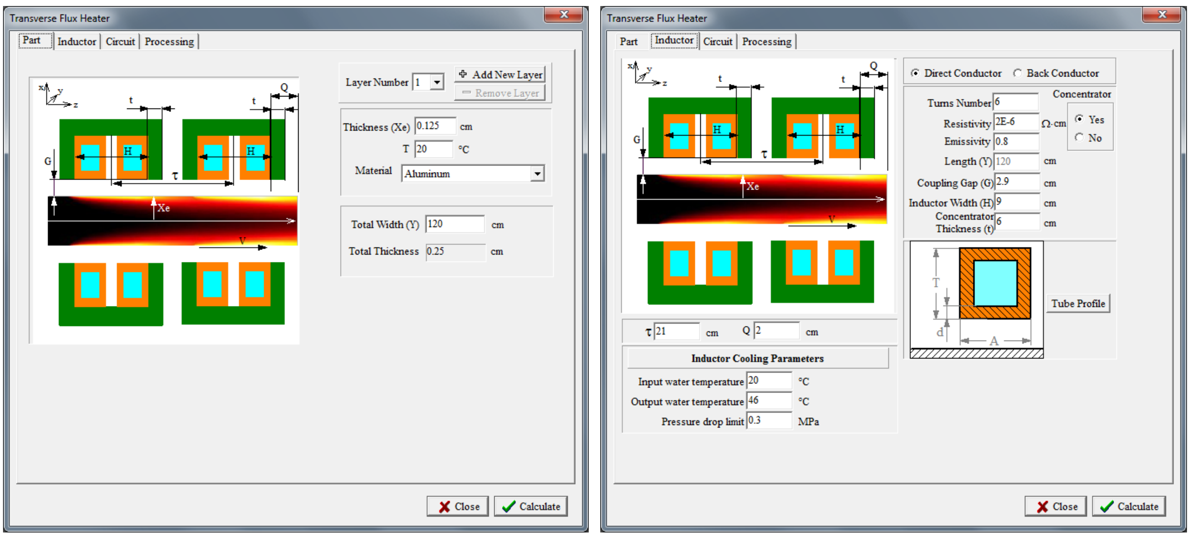

Figure 3. Windows of TFIH program.

The program can simulate integral of volumetric power density along the strip width using both analytical and numerical method of calculation. Multiple tests showed that results of calculations are practically close. Knowing distribution of power after ½ part of TFIH system (direct conductor) and after the whole system (back conductor) distribution of temperature along the width of strip can be predicted.

Results of simulation

There are several technologies of non-magnetic and ferromagnetic materials, when final temperature is relatively low and their properties change not sufficiently. Examples of these investigations are shown below.

Strip parameters: thickness t = 2.5 mm, width d = 1200 mm, materials – copper, aluminum, stainless steel and ferromagnetic steel.

Parameters of E-type TFIH system (Figure 1, *a*): direct and back conductor – inductor width 90 mm, turns number 6 from copper tube, coupling gap 29 mm (total window opening h = 60.5 mm), pole pitch τ = 210 mm.

Processing: continuous heating.

Calculated specific power along the width of strips after heating up to 150 – 200 °C is shown in Figure 4.

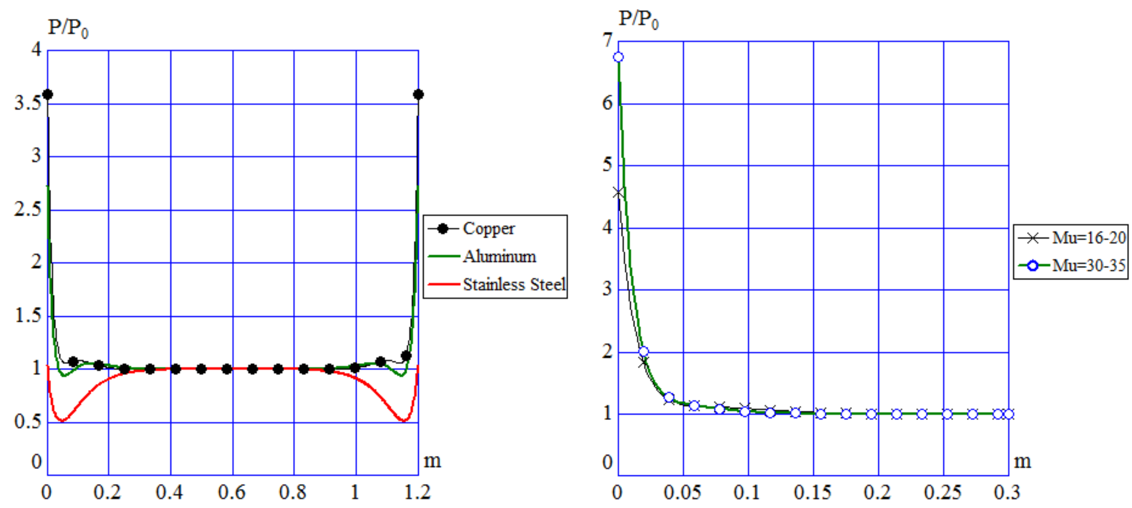

Figure 4. Distribution of power along the strip width for non-magnetic materials (left) and for steel 1040 with different magnetic permeability on the surface of strip (right).

The more conductivity of material (copper and aluminum) the more power on the edge of strip (Figure 4, left). Edge effect is negative for material with low conductivity (Stainless Steel). To increase power in edge zone of strip the frequency of power source must be more than 50 Hz or pole pitch must be more than 210 mm.

The pronounce of edge effect for ferromagnetic steel depends on magnetic permeability μ=f(H, T). For low temperature relative specific power P/P_0 on the edge is equal to 6.8 and 4.3 for magnetic permeability 30 – 35 and 16 – 20 respectively (Figure 4, right). Calculated values of magnetic field strength on the surface of strip in direct and return conductor are 600 and 500 A/cm for the first variant and 1160 and 857 A/cm for the second variant respectively.

In the case of high temperature heating we need to take into account significant variation of material properties in the process of heating for both non-magnetic and ferromagnetic strips.

Example of study is the same as in previous case, but the final temperature is higher. The results of simulation for aluminum and steel 1040 strips 2,5 mm thickness are presented in Figure 5 and 6.

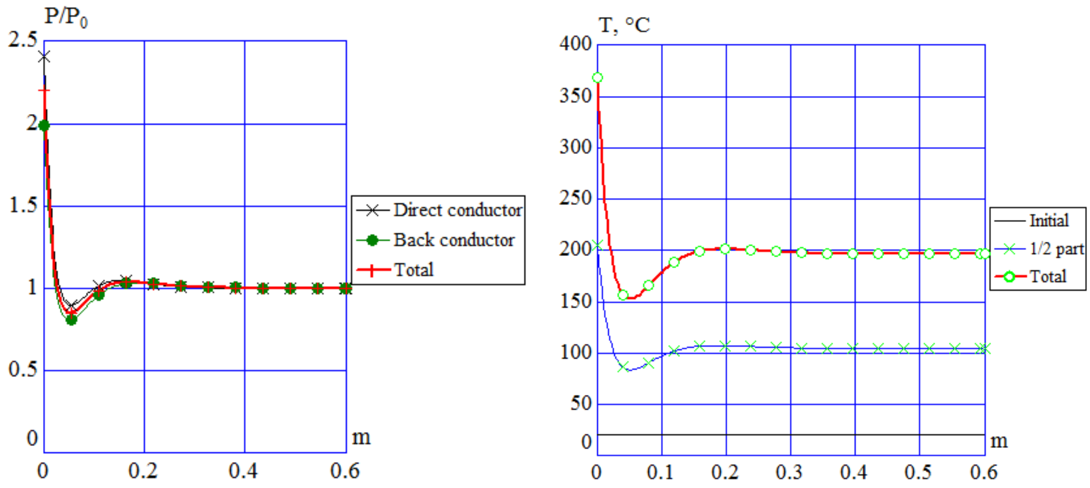

Figure 5. Distribution of power (left) and predicted temperature (right) along the width of aluminum strip 2,5 mm thickness.

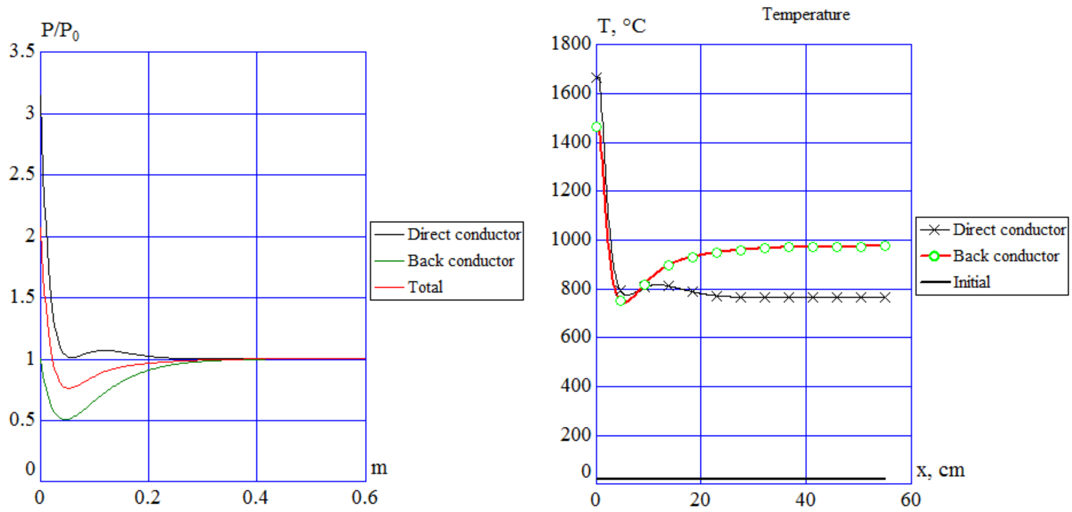

Figure 6. Distribution of power (left) and predicted temperature (right) along the width of steel 1040 strip 2,5 mm thickness.

The practical experience of design and results of multiple simulations and experimental investigations show that problems of uniform heating in TFIH systems are very difficult. The typical problems are overheating of edge zone or deep drop of temperature in zone near the edge. Experimental investigations of heating in TFIH system (Figure 1, *a*) showed that deformation of ferromagnetic strip 5 mm thickness and 1200 mm width did not permit to move it through the inductor with window opening 120 mm.

To provide the required temperature distribution along the strip width the designers have to select rational frequency, to find optimal pole pitch and optimize many other constructive and electrical parameters. If geometrical parameters of strip and technology of heat treating process are known series of user-guided calculations can obtain the useful preliminary results for future improving the uniformity of heating.

To reduce the overheating on the edge of strip several additional constructive decisions may be proposed such as water cooled short-circuited copper rings, magnetic concentrators, metallic screens, decreasing the pole pitch near the strip edge, displacement of inductors, etc. [1, 4]. To increase the temperature in the zone near the edge the addition inductors can be used or more complicated profile of induction coils [1, 4, 5, 6, 8]. These variants of improvement need to use 3D computer simulation and detail investigations.

CONCLUSIONS

This study confirmed existing and provided new information about edge effects of strips in TFIH system. New program Transverse Flux Heater based on a structure of ELTA has been developed to investigate edge effect. This program can simulate distribution of specific power along the strip width. Knowledge of edge effect is very important for understanding behavior, simulation, and optimal design of TFIH systems. Balancing proper selection of frequency and the coil position or length allows the designer to provide the required temperature distribution along the part.

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