3D-SIMULATION OF ELECTROMAGNETIC AND TEMPERATURE FIELDS IN THE CONTINUOUS INDUCTION HEATERS

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Abstract. The quasi-3-D model was developed for continuous induction heating of billets with arbitrary cross section. This computer model is intended for evaluation of electrical and thermal both stationary and non-stationary processes of stage and continuous working regime an induction heater with magnetic and non-magnetic loading with any of cross section shape. The combination of the most effective numerical methods for modeling induction heating process was used in this software: Finite Difference Method (FDM), Finite Element Method (FEM), Boundary Element Method (BEM), Integral Equation Method (IEM) and their combination.

1 INTRODUCTION

One of the basic areas, where the induction heating is widely applied, is the through induction heating of metals before plastic deformation, forging, rolling, pressing, etc. The shape of the cross section of the heating billets can be relatively simple, as for cylindrical or rectangular billets, and more complex, as for example, for flange beams. The purpose of heating is usually achievement of the given temperature with the certain allowable non-uniformity in volume of the product. For the complete description of the temperature field in a heated up body it is necessary to know as temperature distribution in the cross section, as along the length of the billet. Usually continuous in-line induction heaters are used for heating of metal with high production rate. The power of these installations can reach 10-15 MW and accurate predictions of the temperature field's distributions in the billets are very important at the design stage of installation as well for the control of the induction heaters.

The development of the theory of induction heating is indissolubly connected to development and application of modern methods of mathematical modeling. Obtaining results with sufficient accuracy, describing parameters of induction system - one of the important ways to increase productivity, improvement of constructional and working parameters of the equipment of induction systems. The sharp growth of productivity of computer facilities gives an opportunity to use in mathematical models the most effective numerical methods, such as Finite Difference Method (FDM), Finite Element Method (FEM), Boundary Element Method

(BEM), Integral Equation Method (IEM) and their combination. Now these methods are widely used at modeling electromagnetic and thermal processes.

Analysis has shown that the greatest dissemination has received so-called electrothermal models, which mirrored most essential features of the induction heating - coupling of electromagnetic and thermal fields. 2-D electrothermal models for calculation of the induction heating of cylindrical and plane bodies have designed at the end of 70th. Because of considerable time costs on preparing and input initial data, computation time and verification of the results, total cost of the design work was very high.

Essentially the situation has changed with appearance of PCs. Their availability has reduced in necessity of development models with the "friendly" interface, which would allow the user, unfamiliar with the numerical methods, only on the basis of physical phenomena of the task easy to input data and receive appropriate results of computations. The work in this direction was carried out in the St.Petersburg Electrotechnical University (LETI). As the result of such work the complex of the programs has been designed [1,2], which are widely used by leading worldwide organizations, which design and manufacture induction equipment.

Increasing of the production capacities, requirements to production rate of the induction equipment and quality of the heated body has give rise to increasing of the requirements to the designing software. Especially it has a major value at designing of whole technological line, which can consist of several in-line inductors. One of the major factors in software designing is dimension of the solving task. In most cases it is enough to use 2-D setting of the task. For a fast estimation of thermal processes and deriving of integral parameters of the induction system it is possible to use even one-dimensional model, especially when the influence of the “temporal factor”, which usually very short, has vital importance. In this case one-dimensional model is predictable. For deriving the complete information about electromagnetic and thermal processes in induction system user should use 2-D or 3-D model. The most commercial packages, which inclusive the latest reaching in the field of mathematical simulation, are calculated for wide application in different areas of a science and engineering. Usage of non-highly tailored software encounters on serial of difficulties, concerned with complexity of the calculating model. User should has additional knowledge of the methodology of usage such software: defining geometry of the system, boundary conditions, applied sources, solvers, viewing results of computation. Chances of errors appearance at data input, which can be invisible for the user, in this case are relatively high. Total time of computation may be very form several hours to several days, even using modern high-end computers. Software should include different Databases of the material properties, which usually nonlinear, especially depending magnetic permeability on both temperature and intensity of the magnetic field. Computation should inform user about computation process and main characteristics of the induction system, give the possibility to have an influence on computation process.

The advantages of using this software in comparison with some commercial packages:

- Software is designed especially for induction heating applications and it realizes essential coupling of electromagnetic and temperature fields during computations that provides great accuracy
- Most important features of the induction heating installations are taken into account, including characteristics of power sources and possibility to change power, voltage,

current and frequency during the process as well as possibility to simulate stages of holding billets in the inductor and its transport.

- Developer's knowledge of the induction heating theory is included in the software that allows, for example, to eliminate the problem of meshing and essentially to ease preparation of input data and to decrease time for it.
- User has possibility on the base of the visual information to interrupt a computation, to change data and to continue computations.
- Software can be used in the control systems in the real time.
- It is easy to implement procedures of optimal design and optimal control of the induction heating installations.
- Special database of materials and refractories that used in the induction heating installations is developed.

2 DESCRIPTION OF THE SOFTWARE

A high-efficient quasi-3D model was developed for induction heating of billets with arbitrary cross sections. Special algorithm was developed that comprises two 2D models. The first one allows receiving distribution of electromagnetic and temperature fields in the each cross-section of the billet along the length. This model is based on the FEM in the Ritz approach. The second model allows predicting distribution of the electromagnetic field along the length of the billets. Each model can be used separately. At the same time the method of boundary impedance conditions is used for coupling these two models into one quasi-3D model.

This software is intended for electrical and thermal computation both stationary and non-stationary processes of periodic and continuous working regime an induction heater with magnetic and not magnetic loading with any of cross section shape. The calculation of induction heaters with multisectional and polyphase coils, with usual and autotransformer closing is provided. The program includes solution of the exterior electrical and internal electrothermal task. As a result of exterior electrical calculation at a given supply voltage the total true and reactive power, true power in load, electrical losses in coils, current of the coils, electrical efficiency of the coils and distribution of the intensity of magnetic field on surface of the load are defined. The internal electrothermal calculation gives distribution of the temperature in load at particular boundary conditions on a surface of a load, which are set, either from condition of free heat exchange with an environment, or in view of a refractory. Common thermal losses and temperature distribution on internal surface of the refractory simultaneously calculated. The external task is based on the basis of a boundary integral method and the computation of the distribution of an electromagnetic and temperature field in the workpiece (internal task) is made on the basis of a finite elements method. Pasting of external and internal electromagnetic tasks is carried out on elements of a surface of the workpiece by statement of impedance boundary conditions:

$$z_{0i} = \dot{E}_i / \dot{H}_{ti} = \frac{\rho_i}{\delta_{ei}} \left(VR_i + jVX_i \right), i \in G \tag{1}$$

where ρ_i - is specific resistance, δ_{ei} - penetration depth, G - surface perimeter of the workpiece.

The values of impedances z_0 or factors VX_i and VR_i can be found directly from the solving of an internal task.

The process of induction heating of conductive bodies in two-dimensional setting is reduced to solution of a quasi-stationary nonlinear differential partial equation concerning a magnetic intensity

$$\frac{\partial}{\partial x}\left(\rho\frac{\partial \dot{H}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\rho\frac{\partial \dot{H}}{\partial y}\right)=j\omega\mu\mu_0\dot{H} \tag{2}$$

And non-stationary heat conduction equation:

$$C_v\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+w \tag{3}$$

Due to symmetry of distribution of an electromagnetic and temperature field in cross section, only a quarter of the load is considered. The boundary conditions then record as follows:

$$\left.\begin{aligned}
&\left.\frac{\partial \dot{H}}{\partial y}\right|_{y=0}=\left.\frac{\partial \dot{H}}{\partial x}\right|_{x=0}=0;\\
&\left.\dot{H}\right|_{surface}=\left.\dot{H}\right|_{surface}=\dot{H}_m(x,y);\\
&\left.\frac{\partial T}{\partial y}\right|_{y=0}=\left.\frac{\partial T}{\partial x}\right|_{x=0}=0;\\
&-\lambda\left.\frac{\partial t}{\partial x}\right|_{surface}=-\lambda\left.\frac{\partial T}{\partial y}\right|_{surface}=\Delta p_0(T).
\end{aligned}\right\} \tag{4}$$

The specific power of thermal losses is defined as follows:

$$\Delta p_0=\varepsilon\sigma\left(T^4-T_e^4\right)+\alpha(T-T_e), \tag{5}$$

where ε - emissivity, σ - Stefan-Bolzman constant, α - heat transfer coefficient, T_e - temperature of an environment; here T and T_e - in degrees of Kelvin.

The internal electrothermal task is solved by a method of finite element method. Usage this method gives a possibility to define fields distribution in arbitrary cross section. For solution of the thermal task with the help of FEM, it is necessary to use a functional, bound with the equation (3):

$$f = \int_V \frac{1}{2}\left[\lambda\left(\frac{\partial T}{\partial x}\right)^2 + \lambda\left(\frac{\partial T}{\partial y}\right)^2 - 2\left(w - C_v \frac{\partial T}{\partial t}\right)T\right]dV + \int_S \Delta p_0 T dS \qquad (6)$$

For solution of the electrical task the functional for (2) was obtained:

$$f = \frac{1}{2}\int_V \left[\rho\left(\frac{\partial H}{\partial x}\right)^2 + \rho\left(\frac{\partial H}{\partial y}\right)^2 - 2 j\omega\mu H^2\right]dV \qquad (7)$$

Analysis of electromagnetic and temperature distributions in the billets with complicated cross-sections are given in the paper.

3 CASE STUDY. CONTINUOUS INDUCTION HEATING OF THE SLABS WITH ROUNDING CORNERS

The following example illustrates features and abilities of the software UNIVERSAL3D.

Titanium slabs with rounding corners go through line of three inductors (Figure1). Speed of the movement is 4 cm/sec. Length of each inductor is 50 cm with distance of 30 cm between them. The inductors have chamotte refractory with thickness 1 cm. Frequency of the current is 8000 Hz. Coils are connected in parallel and the output voltage of power source is constant during heating - 800 V. The initial temperature of the load is 20 °C.

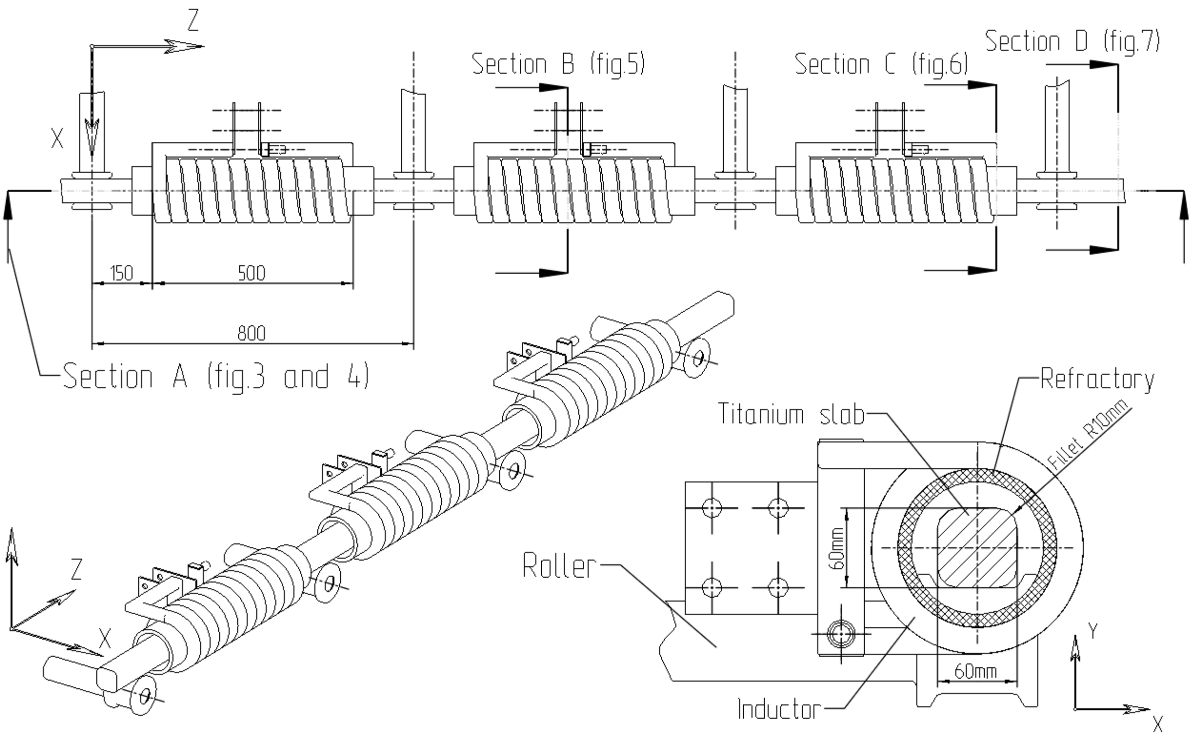

Figure 1. Sketch of the induction heating system

Figure 2. Window UNIVERSAL3D

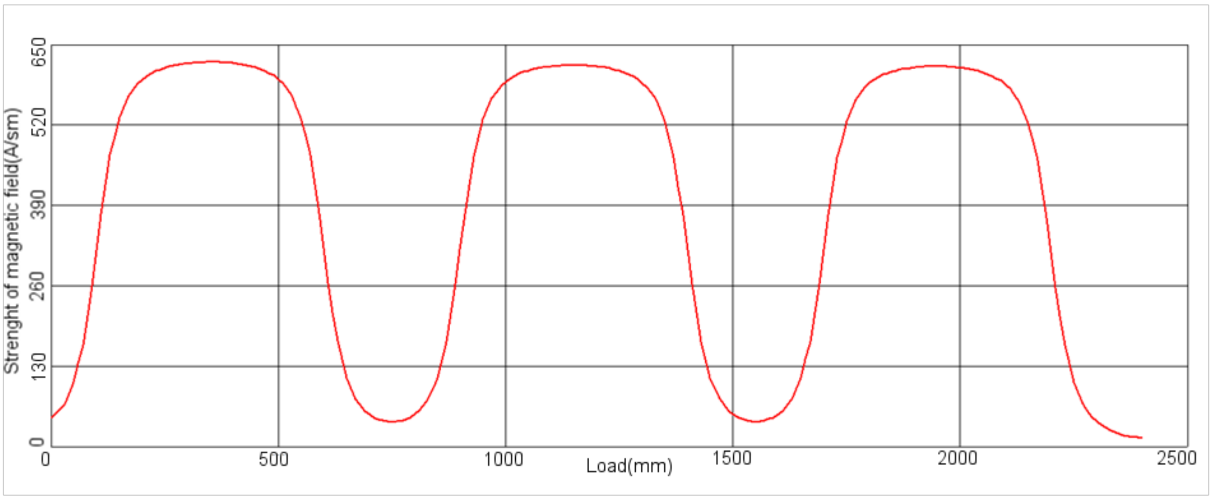

Figure 3. Strength of magnetic field at the surface of the load

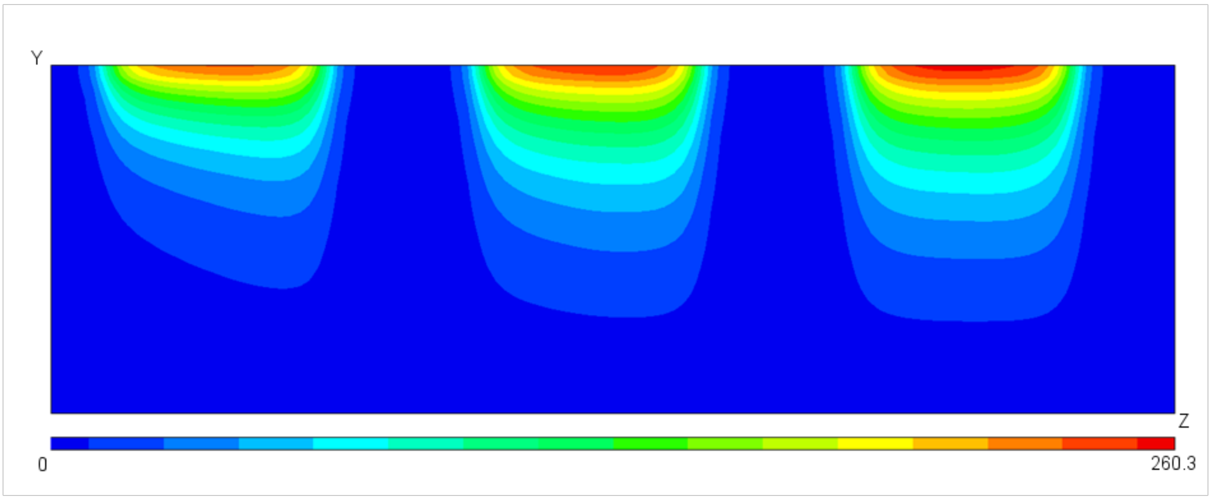

Figure 4. Distribution of the heat sources in the 1/2 section A of the load

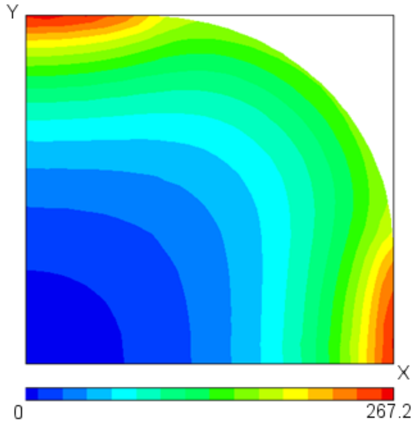

Figure 5. Distribution of the heat sources in the 1/4 section B of the load

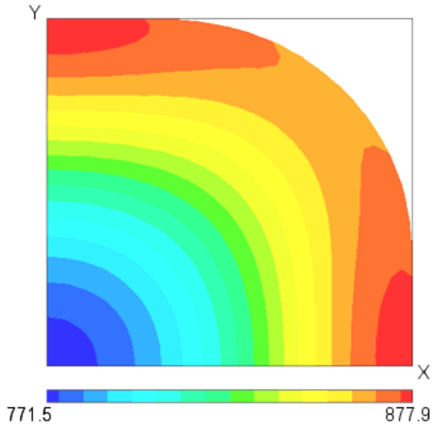

Figure 6. Distribution of the temperature field in the 1/4 section C of the load

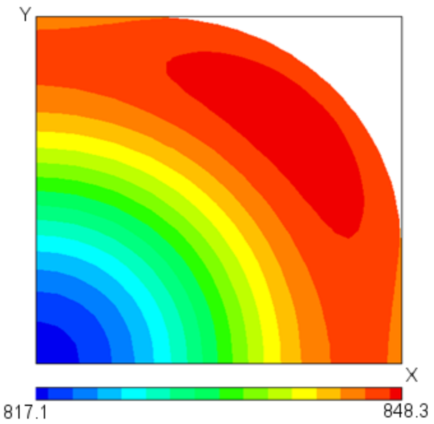

Figure 7. Distribution of the temperature field in the 1/4 section D of the load

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