EXPERIENCE AND PERSPECTIVES OF USING ELTA PROGRAMS FOR TEACHING INDUCTION HEATING

A. Zenkov(1), A. Ivanov(1), V. Bukanin(1), V. Nemkov(2), M. Pervukhin(3) and V. Timofeev(3)

(1)St. Petersburg Electrotechnical University, 5, Prof. Popov str., 197376, Saint-Petersburg, Russia,
(2)Fluxtrol, Inc., 1399 Atlantic Blvd, Auburn Hills, 48326, Michigan, USA,
(3)Siberian Federal University, 26a, Kirenskogo str., 660074, Krasnoyarsk, Russia

ABSTRACT. The paper describes experience of authors in teaching induction heating using subject-oriented programs ELTA and 2DELTA. A guide-book for research and practical exercises in the field of induction heating has been developed for graduate and postgraduate students, young specialists and engineers. A set of practical tasks in induction heating, based on computer modeling using the ELTA and 2DELTA programs, is included in a course book, prepared by the authors. Several examples for teaching, training or self-education are presented in this paper to demonstrate the basic electromagnetic and thermal phenomena of induction heating, such as skin, edge and end electromagnetic effects. Use of ELTA and 2DELTA programs for design of induction processes for heating billets in line and slabs in multi-stage heater is also included in the paper.

INTRODUCTION

Induction heating and technologies are very difficult for inexperienced people and at the same time very interesting for obtaining the knowledge. History of induction heating and melting is the best example of this affirmation [1]. During all lifetime and development of induction heating since early 1900th special attention was paid to the study of its basics. Experience was the main teacher for the first investigators of new method of heating. New technologies of education process include both studying theoretical approaches and investigation of induction heating by use experimental and computer simulation methods.

Role of computer simulation in induction heating technique is very important [2, 3, 4]. Computer simulation becomes more and more popular in study, development, setup and maintenance of induction heating technologies and installations. It is very beneficial for education of all levels: teaching, training and self-education. Many programs, created on the base of Maxwell and Fourier equations by different groups of developers, may be used for induction heating simulation. Several of them are the general purpose software and can calculate very complex and complicated cases of electrical and induction system. They require powerful computers, knowledge and much time and usually may be used in education process by experienced developers to study particular phenomena of induction heating.

The preliminary study, teaching and training of the basics of induction heating process may be performed using subject-oriented and easy-to-use programs, such software as ELTA (ELectro Thermal Analysis) [5, 6] and 2DELTA (Two Dimensional variant of ELTA for cylindrical systems). ELTA and 2DELTA programs have been designed taking into account the possibility to use them to the education and self-education process. For example with ELTA 6 the values of penetration depth, threshold electrical efficiency may be obtained for the whole process, and such phenomenon as “edge” effect in the workpiece with rectangular or square cross-section, studied. 2D electrothermal program 2DELTA can give information about “end” effects of the load and inductor in cylindrical systems. ELTA and 2DELTA can also obtain the curves of temperature dynamics during the quenching process and predict the steel structure after heat treatment using CCT diagrams. This basic information is very valuable for explaining special features of induction heat treatment process for students.

In Russian Federation bachelors of universities study induction heating in direction "Electro-energetic and electrical engineering" and profile "Electrotechnological installations and systems". Main object of study is the equipment of metallurgical and machine-building industries, in particular induction electrothermal equipment for heat treatment of steel products and through heating of metallic billets before hot working. Development and servicing of this equipment demands for a well trained personnel in order with deep understanding of fundamental phenomena occurring in electrothermal equipment and methods of optimal design.

ELTA and 2DELTA programs are being used in several universities in Russia (Krasnoyarsk, Saint-Petersburg), Italy and Bulgaria (Gabrovo Technical University) for study and research, as well as in multiple industrial centers and companies, allowing developers to design optimal processes and induction coils.

NEW FEATURES OF ELTA PROGRAMS

ELTA 6 program

Several important improvements had been made in ELTA after the latest presentation about using it for learning and teaching induction heating [5, 6, 7, 8]. New features allow people to observe the "hidden inside" processes of heating in dynamic graph forms. Several examples are presented below:

1) 2D graph of ***reference depth***, which characterizes ***skin-effect.***

Reference depth δ plays a fundamental role in induction heating theory. It allows us to evaluate easily skin effect in the induction system, select proper frequency for heat treating and other processes, and to predict power distribution inside the workpiece cross section and power variation in the process of heating. If characteristic dimensions (cylinder diameter or plate thickness) are smaller than the reference depth, it is a case of low frequency. If these dimensions are larger than 4δ, it is the case of high frequency. For tubes there might be a case when the tube diameter is much larger than δ and the wall thickness is much less. In this case, more complicated criterion must be used. If the product of wall thickness and diameter is less than δ^2, the frequency is low; if the product is greater than $4\delta^2$, the frequency is high from the point of effectiveness of the power absorption.

A commonly used formula in the industry for the absorbed power calculation at high frequency is the same as the formula for power generated by current flowing uniformly in a layer δ. This simple formula is convenient for analytical calculations and some computer simulation. However in reality, the current and power are not distributed uniformly in the layer δ. Some examples of study are shown below.

2) 2D graph of ***threshold electrical efficiency,*** which gives information about maximal possible value of electrical efficiency. It helps to choose optimal geometrical parameters of induction heating system and power source from economical point of view.

ELTA calculates the threshold value of electrical efficiency assuming that the system is infinitely long. Elta calculates maximum electrical efficiency for given dimensions of the system and electromagnetic properties of the workpiece that during the heating process

$$\eta_{\lim} = \frac{1}{1 + \Delta R_i / (R_w N_i^2)}, \tag{1}$$

where ΔR_i – *minimal resistance* of induction coil, R_w – real resistance of workpiece, transferred to the coil, N_i – turn number of inductor.

Choice of frequency is one of the most important stages of engineering design. Both a consumption of electric energy and quality of heating depends on it. For example, for through heating it is essential that electrical efficiency should be close to the maximum value and time of heating should be minimal.

If you see that actual efficiency is much less than the threshold value, you should:

a) check whether the frequency is optimal or not,
b) check the coil winding space factor g (ideal variant for multi turn coil is g = 1),
c) check the wall thickness *d* of inductor tubing *d* (ideal variant is $d = 1.6\ \delta$),
d) increase the system length and/or use the magnetic concentrator (controller).

3) 2D and color map graphs of ***edge effect of slab***.

Edge effects describe distortion of the electromagnetic field, current and power distributions caused by abrupt change in geometry or material properties in the eddy current flow path, e.g. near the edges of a slab or strip. Edge effects are especially important in transverse heating of plates and strips [6].

Surface power density p' is very convenient for description of end and edge effects. Value of p' is an integral of volumetric power density p_V along the slab thickness *d*.

$$p'(x) = \int_d p_V(x, y)dy\,,\ \ p'_c = \int_d p_V(x = 0, y)dy\,. \qquad (2)$$

ELTA 6.0 calculates the surface power density for different conditions and allows the user to select optimal frequency for uniform heating

2DELTA program

2DELTA program provides a two dimensional simulation of coupled electromagnetic and thermal fields in cylindrical induction system using a combination of integral and differential numerical methods. Many typical technological heating lines for simultaneous, non-stationary semi-continuous and continuous processes can be simulated from the start to stationary conditions. 2DELTA is very convenient for study of the end electromagnetic effects of inductor and load. Program has a special block for calculation of electrodynamic forces acting on the workpieces, induction coils and magnetic concentrators.

EXAMPLES OF INDUCTION HEATING

Heating of long ferromagnetic cylinder

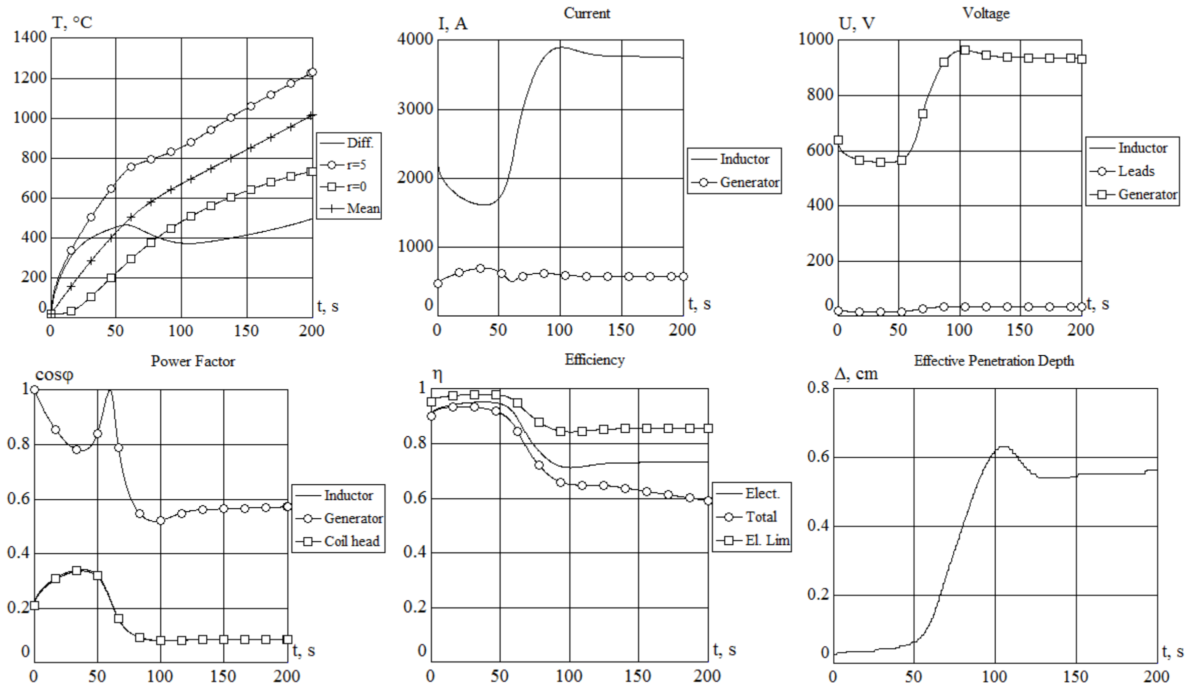
Workpiece: external radius $R_{2e} = 5$ cm, length $l_2 = 100$ cm, material – ferromagnetic steel, initial temperature $T = 20$ °C.

Inductor: ID = 15 cm, length $l_1 = 120$ cm, turn number 70. Resistivity of copper tube with dimensions 1.42×1.42×0.5 cm is $2\cdot10^{-6}$ Ohm·cm). *Thermal insulation*: Portland cement concrete 1 cm thickness.

Processing: frequency 10 kHz, constant coil power 320 kW, heating time 150 sec.

The main goal of this example is to show dynamics of parameters variation during the process of heating. Results of simulation are shown in Figure 1.

ELTA gives all parameters of the coil and other components of installation. For example, electric efficiency varies from 0.95 to 0.71 (corresponding values of the threshold electric efficiency are 0.98 – 0.84). At the beginning of heating, steel is magnetic and effective penetration depth is small (0.3 mm). As temperature rises, power penetrates deeper into the material. When surface temperature reaches the Curie point, the outer layer of steel becomes nonmagnetic. Effective penetration depth increases up to 6.3 mm. In ferromagnetic stage power density drops quickly with the distance from the surface (Figure 2, left). In intermediate stage power distribution changes dramatically due to the electromagnetic field reflection from the magnetic core (Figure 2, right).


Current

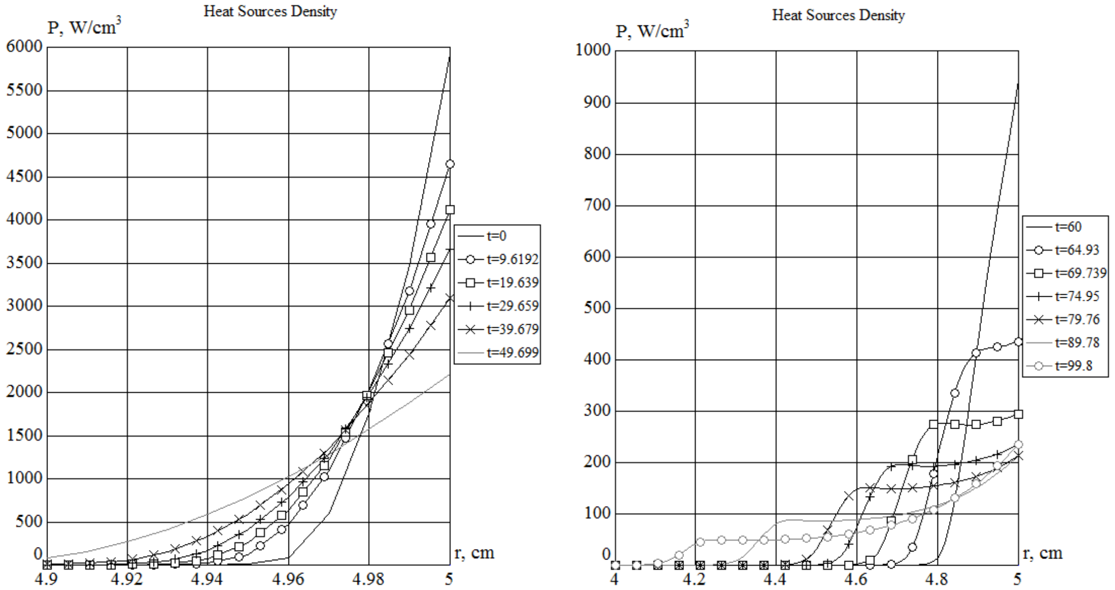
Voltage

Power Factor

Efficiency

Effective Penetration Depth

Figure 1. Dynamics of main induction heating process parameters.


Heat Sources Density

Heat Sources Density

Figure 2. Power density distribution in the workpiece radius during heating in ferromagnetic stage (left) and in intermediate stage (right).

The power slightly drops in the nonmagnetic layer, then reaches small local maximum in the area of magnetic core border, and then drops quickly inside the magnetic material.

Line for accelerated multi stage and multi frequency induction heating

ELTA is very effective for design of mass heating systems providing multiple options: batch heating of round and rectangular bodies, continuous heating in line, duplex process (induction method plus heating in flame or resistance furnace), etc. When heating in several inductors, their design as well as frequency and applied power, voltage or current may be different.

This example demonstrates continuous induction heating of steel bar with 60 cm length and 6.5 cm diameter to 1230±50 °C with production rate 1.50 t/hr. After several iterations it was proposed to use a line containing 9 inductors with two frequencies: 1 and 2.4 kHz (Figure 3).

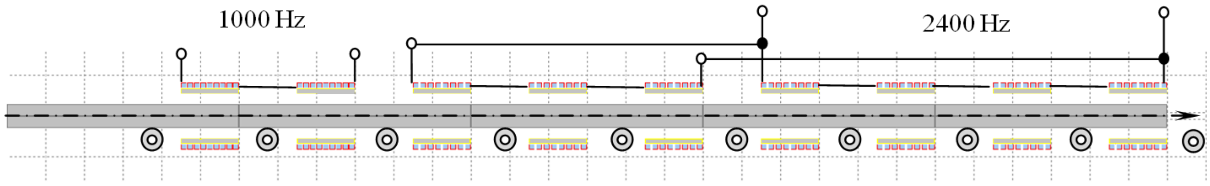


Figure 3. Proposed induction system.

Inductor: ID 15 cm, length 15 cm, turns number 9 for first 2 inductors and 8 for next 7 inductors. Rectangular copper tube 1.5×1.5×0.15 cm. *Thermal insulation*: Portland cement concrete, thickness 1.5 cm.

Processing: continuous heating of steel bar with production rate 1.50 t/hr (calculations in ELTA are made in time, which is related to position of the test point on the part surface in a real process of heating and cooling as $t = v/x$, with v – speed of the part transportation and x – position of the point at time t starting from the beginning of its treatment heating, i.e. time in each coil is 9.38 sec and with a space between the coils of 15 cm the “cooling” stage time in the gap on the air outside the inductor is 9.38 sec). The first 2 coils are connected in series with the same current 6590 A, frequency of power source is 1000 Hz. For the next 3 coils frequency of power source is 2400 Hz, constant coil current 2534 A, and for the last 4 coils frequency is 2400 Hz, constant coil current 1900 A.

Results of calculation are shown in Figure 4.

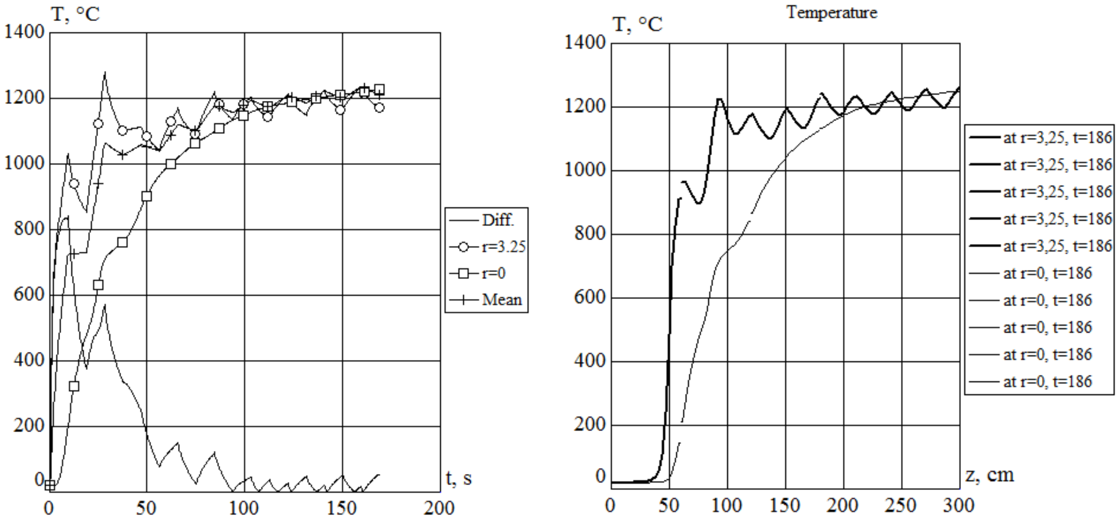


Figure 4. Temperature distributions during the continuous process
as simulated by ELTA (left) and in 2DELTA (right).

2DELTA gives more precise distribution of temperature, taking into account the length of each workpiece and he end electromagnetic effect of inductor and load, but at the same time the integral results of simulation in both programs are very close to each other.

Figure 5 shows 2D temperature distribution in the volume of last workpiece.

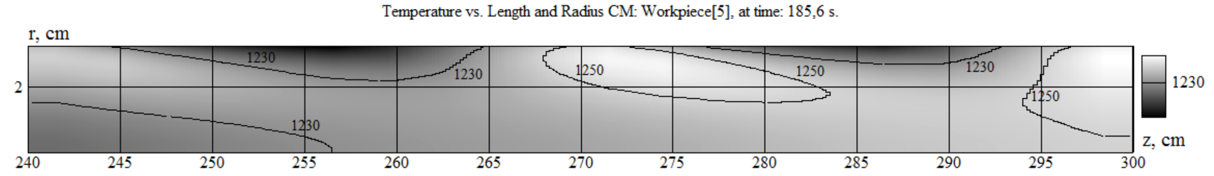


Figure 5. Color map of temperature during the continuous process (2DELTA).

Heating of slab

ELTA 6.0 can simulate slab heating with 1D and 2D approaches. In both cases the system has two planes of symmetry OX and OY and simulation is being performed for a quarter of the cross-section.

When using 2D option, the user can calculate and visualize the following additional items:

- Color maps of temperature, heat sources (power density) and magnetic field strength in the whole slab cross-section for any instant of heating – T, w, H = f(x, y @ any t).
- Color maps of temperature variation – T = f(x, t @ any y) and T = f(y, t @ any x).
- Curves of temperature, heat sources and field strength along horizontal or vertical centerlines for any time instant T, w, H = f(x @ $y = 0$ or y @ $x = 0$).
- Curves of temperature along the perimeter of one quarter of the slab (Figure 6).

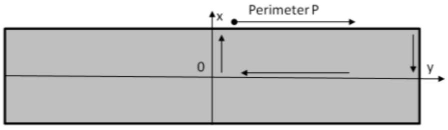


Figure 6. Cross-section of slab with explanation of 1/4 perimeter path.

There is an additional option for calculation of density p' versus the slab width. In the program p' is referred to as Total Specific Power. It may be effectively used for research, practical design of the induction systems and for education (learning and teaching).

Example of study

Slab: thickness d = 16 cm, width 80 cm, length 200 cm, material – carbon steel 1040.

Inductor dimensions: the inductor “window” is 34×98 cm, length 200 cm, turn number 35. There is no special thermal insulation.

Processing parameters: frequency 50 Hz, coil power 1200 kW, heating time 1500 sec with subsequent soaking time of 100 sec. Heating is assumed to be adiabatic, e.g. there are no thermal losses from the slab surface.

This case was specifically designed to study transient edge effects during heating of steel slab. Below Curie point the skin-effect is very high and edge effect is positive, i.e. the edge zone will be overheated. Above Curie temperature a ratio $d/\delta = 2.25$ and there must be underheating of edges. At the same time electrical efficiency of the inductor should be reasonably high because the power absorption coefficient is G = 0.75 [4].

Simulation showed that the transition from magnetic to completely non-magnetic state of slab happens during a rather long period of time from 400 sec to 1050 sec. At t = 400 sec temperature in the corner area reaches 740 °C with the surface temperature in the central zone being only 480 °C (Figure 7, left).

Distribution of p' corresponds to magnetic state with its value on the edge seven times higher than in the central zone. During the following 500 sec the corner temperature grows up to 780 °C, while T_c reaches 817 °C, i.e. increases eight times faster than in the corner.

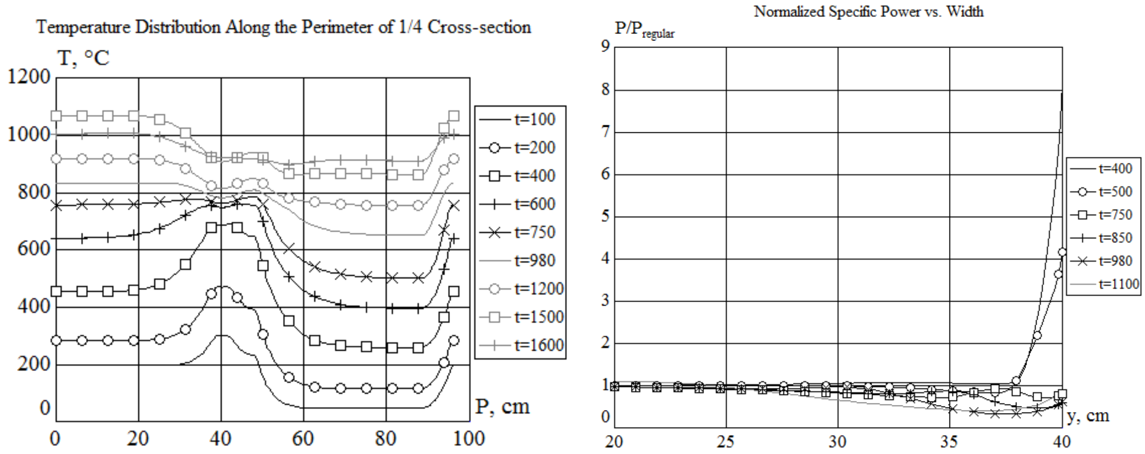


Figure 7. Temperature along the perimeter P of one quarter of the slab cross-section (left). Distribution of normalized total specific power density in the slab width for different instances of heating (right).

After 100 sec of heating all the temperatures grow approximately “in concert” as it should be for a quasi-stationary process. This behavior may be explained by dynamics of variation of p'. Transition of p' from magnetic state (curve t = 400 sec) to non-magnetic (curve 1100 sec) happens unevenly with strong intermittent variation both in time and distance from the edge. Minimum power in the edge zone corresponds to t = 980 sec when p' becomes almost three times lower that p'_{c}. At t>980 curve of p' evenly approaches the threshold curve for hot steel.

ELTA can create animation of color maps. It is very convenient to see dynamics of temperature and power sources from educational point of view (Figure 8).

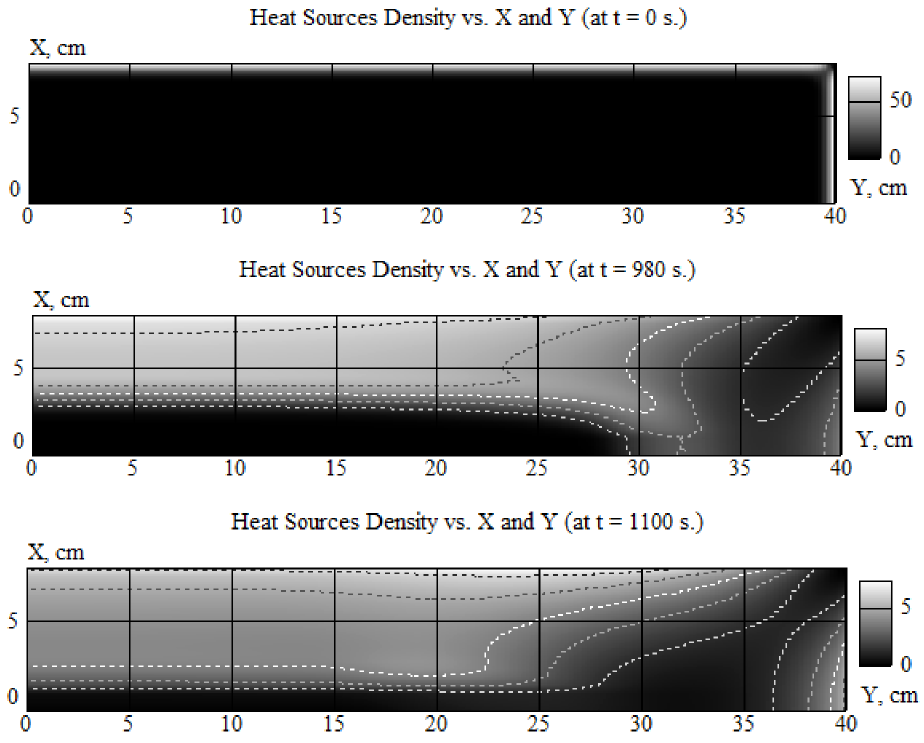


Figure 8. Power density distributions at t = 0 (top), 980 (middle) and 1100 sec (bottom).

Volumetric power density distribution during the transient period is very odd, especially for a period 800-1000 sec (Figure 8, top). It is important to know a width of the edge-effect zone. In magnetic state it is about 2 cm, in hot state – around 10 cm, i.e. it equals to 0.625*d* or approximately 1.5δ. However at t = 980 sec this zone is around 16 cm. Good understanding of edge effects is important for design of the slab heating process simplifying complete simulation of the heating process and the inductor design with account for thermal losses.

CONCLUSIONS

ELTA and 2DELTA programs can be used for lectures, laboratory tasks, home exercises and remote education. They offer the user an opportunity to study induction heating in the way that suits the best to their needs and provide as much practice as necessary to ensure that each point is learnt and can be used in design of induction heaters and technology. Students are encouraged to develop their skills by doing focused exercises. Process of education starts from formulating the problem and creating the “task” and finishes with analysis of the results of calculations. Main teaching topics are the skin effect and effective penetration depth, the threshold electrical efficiency for solid and hollow cylinder workpieces, internal induction heating of hollow cylinder with account for a return leg of the winding, edge effect of slab, end effects of load and cylindrical induction heaters, electrodynamic forces, induction heat treatment, combined induction and furnace heating in different combinations and temperature variation during transportation time, etc. ELTA and 2DELTA have their own report generator that allows to organize selected data according to preinstalled or newly created formats (templates). It is very convenient feature for both education and practical use for system design.

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