Design of induction heating lines using ELTA program

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Abstract

Long induction heating lines are widely used in metallurgical, forging and tube industries. Big length and large number of inductors in one line, make optimal design of these systems rather complicated especially when the heating inductors are connected in series and parallel groups supplied from different power sources. Typically solid or tubular products with square or round cross-sections are being heated in lines. In some installations individual inductors or groups of inductors are supplied from the sources with different frequencies.

This presentation is devoted to design of such systems using program ELTA 6.0. ELTA is a program based on 1D Finite Difference Method (FDM) with semi-analytical account for the lengths of individual inductors and loads. Version 6.0 has an important 2D option for heating of bodies with rectangular cross-sections in the longitudinal magnetic field. All FDM calculations are related to a certain cross-section of the load, which passes through the processing steps in function of time. This algorithm allows the user to simulate multi-step heating processes in one “shot” and is very convenient for simulation of the induction lines with any number of stages describing heating in individual inductors, cooling in the gaps between them and even heating or holding in a flame or electric furnace.

Description of the computer assisted design of induction lines is illustrated by several examples. Due to very fast simulation it is easy to optimize the process of heating, i.e. to find an optimal variation of frequency and specific power versus time and therefore along the heating line.

Key words : induction heating, ELTA program, heating line, computer simulation, forging

Introduction

In metallurgical and tube industries the induction lines are widely used for heating a variety of long products (rods, billets, tubes, slabs, strips) for heat treating or before hot deformation (rolling, forging, pressing). The parts are moving continuously or in small steps along the rails of being supported by driving rolls. These lines can contain many induction coils (several tens). The coils typically have the same length but their diameters, thermal insulation and turn numbers may be different. Induction coils are often connected in series and parallel group supplied from individual power sources with the same or different frequencies. Depending on techno-economical situation gas furnace may be installed before the induction line for energy savings or electrical resistance furnace may be installed at the end of the line for temperature equalization or for holding and flexibility.

Design of such lines is a rather challenging task. It may be divided in two phases. The first phase is determination of the line length, power distribution along the line and optimal frequencies for different parts of the line, which should grand required technological specifications and good techno-economical results. This first stage may be called "the process design". The second phase is a detailed determination of individual coil parameters and their optimization as well as proper selection of the power supply and matching circuitry.

It is obvious that computer simulation must be used at both phases of the project development. There are many programs for simulation of induction systems such as Flux 2D and 3D, Ansys Multiphysics, ThermNet, Magnet, Sysweld, Comsol, and others [1]. These programs are mainly based on Finite Element (FE) method that allows the users describe and simulate 2D and 3D systems of complex geometry. They are expensive and require well-trained operator to run them effectively. The coil and part geometry in multi-stage induction lines is simple but the number of stages and the overall space is very big that creates difficulties in using general-purpose FE programs.

The ideology of ELTA program is different. It is an engineering program which does not require special knowledge in computer simulation due to simple self-explanatory interface and preinstalled design options and database. Calculations are designed "in series steps", i.e. power and temperature is being calculated for each heating stage (inside the induction coils) and "cooling" stages (spaces between coils, quenching and holding zones). It make possible to simulate systems with very large number of steps, which is typical for induction lines. ELTA is at its best in optimal design of the multi-stage processes. The second phase (coil design) may be performed by the same program or with more complicate program (2DELTA, FLUX, etc.) if more detailed analysis of the coil parameters is required such as calculation of losses in individual turns, turn spacing variation, electrodynamic forces etc.

Induction heating line is an object which may be relatively easy optimized [2 – 5]. FDM is effectively used for many tasks of optimization of plane-parallel and cylindrical systems for induction heating. Simple guidelines based on 1D calculations give a good initial approach for the process optimization that must take into account the part geometry, its dimensions, required production rate, available equipment, etc.

Main features of ELTA program

ELTA is based on a combination of one-dimensional numerical (Finite Difference) approach and analytical account for finite lengths of the part and induction coil. Because of that simulation is very fast while providing good accuracy for systems of simple geometry typical for induction lines. ELTA 6.0 program has an option for 2D FD simulation of heating bodies with rectangular cross-section.

One-dimensional equations describing electromagnetic field (1) and temperature (2) in cylindrical and flat bodies are:

$$\frac{1}{R}\frac{\partial}{\partial R}\left(\rho R\frac{\partial \dot{H}}{\partial R}\right) = -j\omega\mu\mu_0\dot{H}\,,\quad \frac{\partial}{\partial x}\left(\rho\frac{\partial \dot{H}}{\partial x}\right) = -j\omega\,\mu\mu_0\dot{H}\,, \tag{1}$$

$$C_v\frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) = w\,,\quad C_v\frac{\partial T}{\partial t} - \frac{1}{R}\frac{\partial}{\partial R}\left(\lambda R\frac{\partial T}{\partial R}\right) = w\,, \tag{2}$$

were R – radius, x – coordinate, ρ – electrical resistivity, $\dot{H}$ – magnetic field strength, ω – angular frequency, $\mu\mu_0$ – magnetic permeability, C_v – specific heat, T – temperature, t – time, λ – thermal conductivity, w – volumetric power density.

Two-dimensional non-linear differential equations for magnetic field $\dot{H}$ and temperature T are:

$$\frac{\partial}{\partial x}\left(\rho\frac{\partial \dot{H}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\rho\frac{\partial \dot{H}}{\partial y}\right) = j\omega\mu\mu_0\dot{H}, \tag{3}$$

where x, y – coordinates of workpiece cross-section.

$$C_v\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) + w. \tag{4}$$

Final length of the system is taken into account using analytical procedure, called Total Flux method. It is based on composing the magnetic substitution circuit for a system “inductor – workpiece” [2]. Multiple tests show that it gives good practical results in simulation of 2D systems of simple geometry. In some cases even 3D systems such as heating of slabs in oval or rectangular inductors can be simulated with good accuracy [6].

The program can simulate the process of heating using an option "power density on the part surface" without accurate description of the coil design, which is very convenient for the first stage of development (Process Design). In detailed coil design (phase two), the program allows to make simulation of selected coils with different preinstalled power supplying circuits at different regimes (generator or coil power, current or voltage, preinstalled or variable frequency, etc.). Hydraulic calculation of the coil cooling is another useful engineering feature of the program.

Design of induction line for heating square billets

Many induction and combined heating lines have been investigated and designed using ELTA program. All technologies are industrial applications for metallurgical and forging plants. The most interesting variant of real technology is presented bellow.

A plant had a forging line with gas furnace that required deep modernization. The problem was to modify the line for billets made of a special steel, sensitive to cracking in temperature range 20 – 600 °C. Final temperature must be around 1250 °C, which was higher than the gas furnace could provide for a required production rate of 10 t/hr. It was decided to make a heating line containing induction heater to preheat billets up to 500 – 600 °C with controlled temperature gradient and increased rate, gas furnace for further heating up to 800 – 900 °C and again induction heating for the final heating. It was very difficult task in comparison with traditional heating of round billets.

Billet dimensions: square 8.3×8.3 cm, length l_2 = 91 – 112 cm.

Processing parameters: required heating speed is limited to 1 – 1.5 K/sec.

This task has many parameters that don't allow us to use optimization methods or intuitively predict design of the line. Operator-guided design was used with expert's evaluation of the results. The best design was selected after several iterations. After preliminary calculations the most promising variants were selected and more detailed analysis of techno-economical analysis performed.

First variant. It is natural to start from traditional type of induction heater, i.e. a continuous heater with induction coils of square configuration (Fig. 1). Billets are moving through the inductors in longitudinal direction on a rolling system. Post-heating induction line may be of the same type as a pre-heating one.

Inductor dimensions: the “window” is $2X_1 \times b_1$ =13.0×13.0 cm, length l_1 = 29 cm, coils turn number 12 from copper tubing $A\times T\times d$ = 2×1×0.2 cm. Thermal insulation – Portland cement concrete 2 cm thickness.

Calculations showed that heating up to mean volume temperature of 563 °C (see Fig. 3) with speed 1.45 K/sec requires 45 induction coils and total length of line 19.5 m. Total power and energy consumption are 1185 kW and 100.5 kWhr/t respectively. The values of electrical efficiency are 83 – 87 %. Total time of heating in induction line is 374 sec. Main attention was paid to edge effect and temperature distribution in the volume of billet. Using the principle "uniformity in large" we can find temperature differences $\Delta T = (T_{aver@edge} - T_{aver@centre})$. These values after induction and gas heating are 80 K and 15 K respectively (Fig. 4 – 6). In the first variant of longitudinal heating edges of square cross-section are overheated (Fig. 5, 6) but ΔT equalizes quickly during transportation and in gas furnace.

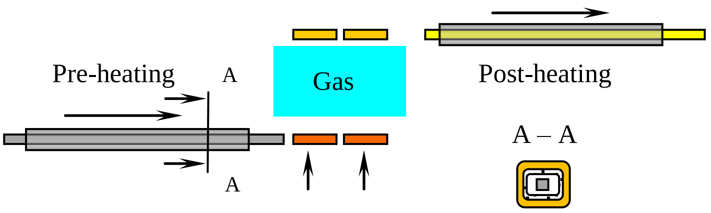

Fig. 1. Sketch of longitudinal pre-heating induction line + gas furnace + post-heating induction line

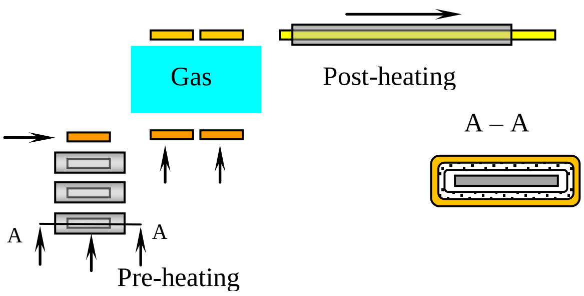

Fig. 2. Sketch of transversal pre-heating induction line + gas furnace + post-heating induction line

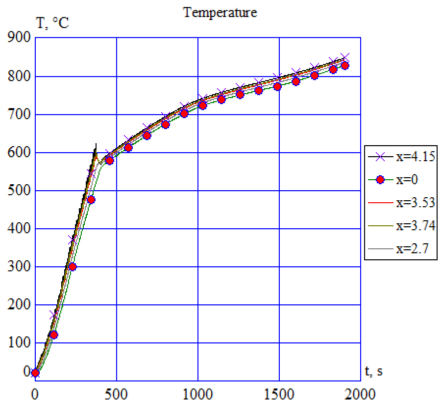

Fig. 3. Temperature variation in the cross-section during time

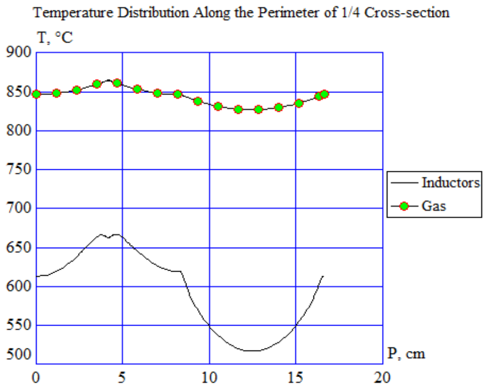

Fig. 4. Distribution of temperature along the perimeter of ¼ cross-section after induction and gas heating

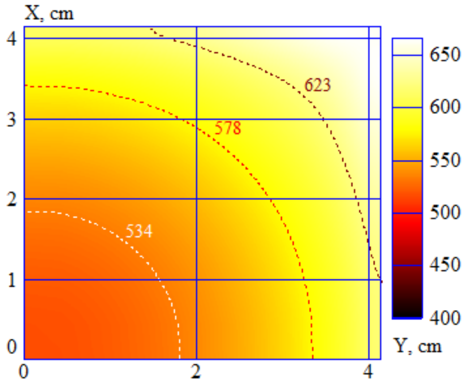

Fig. 5. Color map of temperature in the cross-section after induction heating

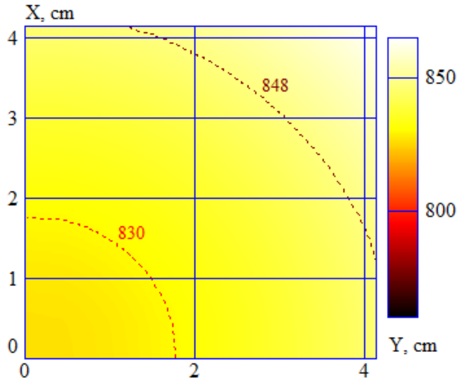

Fig. 6. Color map of temperature in the cross-section after gas furnace

Second variant. In order to reduce the line length, it was decided to use 3 oval inductors for pre-heating line (Fig. 2). All billets are moving through the inductors semi-continuously in transversal direction by using a pusher. It is more convenient than in the first case. There are 14 billets in each inductor, i.e. total length of the load is 14×8.3 = 116 cm.

Inductor dimensions: the “window” is $2X_1 \times b_1$ =13.0×125 cm, length l_1 = 120 cm, coil turn number 26 from tubing $A \times T \times d$ = 4×2×0.2 cm. Thermal insulation – Portland cement concrete 2 cm thickness.

Distributions of temperature in cross-section of the billet during heating in these lines are shown in Fig. 7 – 9.

Mean volume temperature after 860 sec of induction pre-heating is 556 °C. Total power is 1065 kW. Specific energy of induction pre-heating is 99 kWhr/t. The length of line decreases sufficiently from 19 to 4 m.

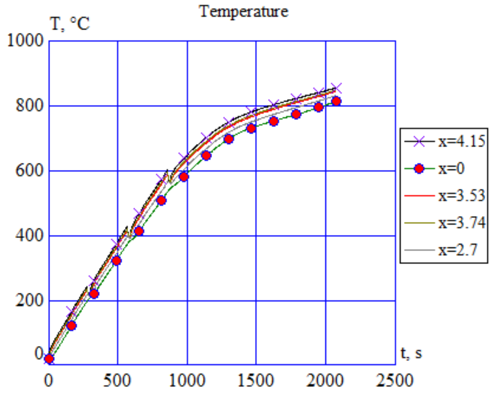

Fig. 7. Temperature variation in the cross-section during the time

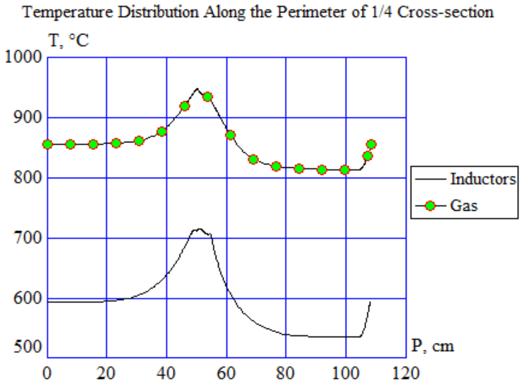

Fig. 8. Distribution of temperature along the perimeter of ¼ cross-section after induction and gas heating

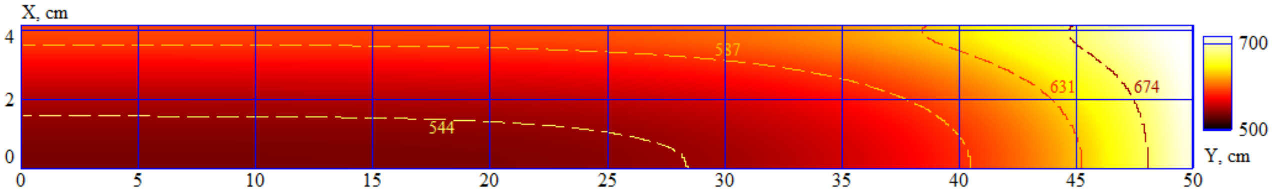

Fig. 9. Color map of temperature in the ¼ of cross-section after induction heating

In transverse heating the ends of the billets are overheated more than for the first variant (Fig. 8) and equalization will requires much longer time due to a big distance. In this case the electromagnetic edge effect of the load plays determining role. Simulation of the whole heating line showed that by means of an optimal design of pre- and post-furnace induction lines it is possible to reach required temperature level of 1250 °C and uniformity of billets at the end of the whole line using both the first and second variants.

All complex induction-gas-induction line, including the second variant of pre-heating induction heater, was successfully designed by V. P. Vologdin Scientific Research Institute of High-Frequency Currents (St. Petersburg) for one of the metallurgical plant. Verification of the calculation results, i.e. integral parameters of inductors and surface temperature, has been performed in laboratory and at the plant. It showed good matching. Distribution of power source and temperature in the cross section of square and rectangular work pieces have been verified also on the base of analytical and numerical methods, as shown for example in [6].

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