International Scientific Colloquium
Modelling for Material Processing
Riga, September 16-17, 2010

Numerical Optimization as an Effective Approach to Modern Design of Induction Heating Installations

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Abstract

Automatic optimization can be applied for modern design of induction heating installations for diverse technological applications. One effective approach to couple numerical models with advanced optimization search codes has been developed. It was successfully applied for design of transverse flux heaters of flat metal products like strip and disks where a proper shape of induction coils could not be found by another way. In the second described example, the required temperature profile over the height of chemical reactor has been reached using the developed tools as well.

Introduction

Electrical heating and melting installations are of great use in the metal-processing industry, automobile manufacturing, forging and casting production lines. The power of the induction units, for example, is up to tens of MW and production rate is up to hundreds of ton per hour. Taking into account hard operating conditions as well, design of the equipment of that scale should provide the best possible combination of technological parameters and robustness of installation. Conventional for today expert way to design the electrothermal systems allows reaching an acceptable level of the developed equipment for limited number of well known in industry processes only. It is mainly based on the empirical knowledge, so improving is done by small quantitative steps from one generation of the designed equipment to another. This state of the art does not allow making qualitative great advance for the technologies used already in industry. Moreover, it stops a lot of new technologies because very often they can be realized under optimal conditions only.

1. Numerical Simulation

The induction heating is extremely effective because of its contactless energy transfer, unlimited power densities and the controlled temperature field in the workpiece. However, high potential of the induction heating can be fully realized on the basis of numerical simulation only.

In general a heating system should be designed so that the required temperature distribution in the workpiece is provided. In induction heaters the temperature field in the workpiece is formed by the distributed Joule heat, the temperature equalization by thermal conduction of the workpiece material, convection and radiation heat losses from the workpiece surface.

The induction heating includes electromagnetic and thermal processes with the heat exchange inside and outside the workpiece. Electromagnetic and thermal regularities are described by differential equations with non-linear coefficients. The non-linear behaviour of the electromagnetic process is mainly conditioned by electro-physical material properties which depend on the temperature and the magnetic field intensity. The non-linear regularities of the thermal process are the result of the temperature dependent thermo-physical material properties and intensity of the heat exchange by convection and radiation. The electromagnetic and thermal non-linearity can have a significant influence on the temperature distribution in the workpiece.

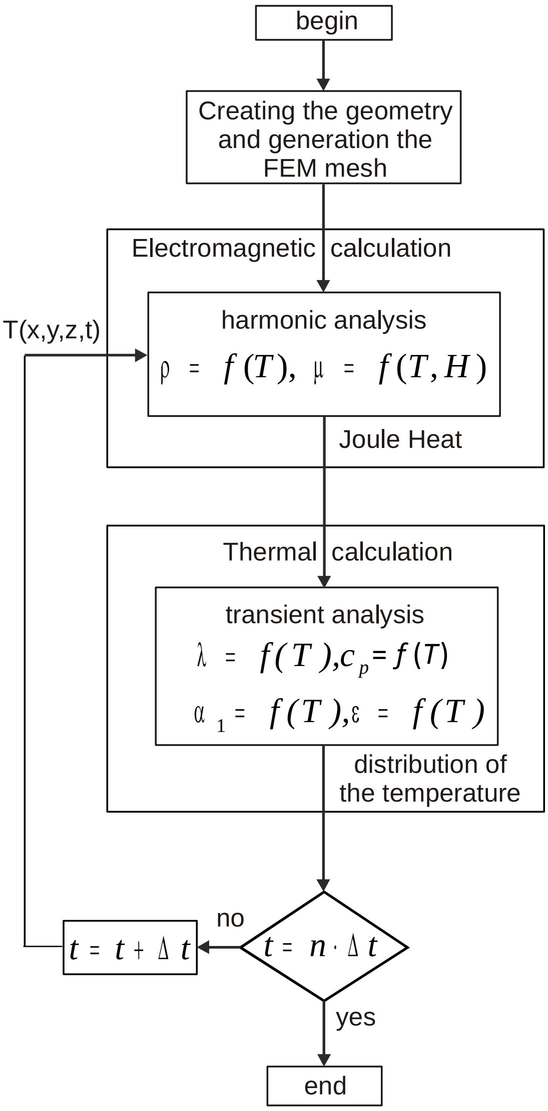

Fig. 1. The algorithm of coupling between electromagnetic and thermal analysis

The temperature distribution in the workpiece is under significant influence of the heat losses from the workpiece surface. This effect is also non-linear because of both convection and radiation heat fluxes strongly depend on the temperature.

Only numerical techniques such as Finite-Different Method (FDM), Boundary-Element Method (BEM) and Finite-Element Method (FEM) allow a user to obtain the coupled solution of electromagnetic and thermal problems taking into account non-linear material properties. Commercial packages based for example on FEM are the tools to simulate the induction systems with different level of skin-effect and non-linear properties of the materials. Iterative or time-step loops are included in numerical models to correct electro- and thermo-physical properties of the heated material according to actual temperature distribution. An example of such model structure is shown in Fig. 1. The commercial package ANSYS based on FEM has been used to develop numerical models. The developed models allow the user to carry out two-dimensional (2D) analysis of electromagnetic and thermal processes in induction systems. If the simulated system is of rotational symmetry for both electromagnetic and thermal processes 2D numerical code describes the behaviour of the system with high accuracy and integral and distributed parameters of the induction system can be obtained at the short computation time. It is important for the automatic optimization procedure because the goal function has to be computed several times during the procedure.

2. Numerical Optimization Techniques

General optimization strategy consists of several steps which are common for all engineering problems. They involve transcribing an engineering description of the problem into well-defined mathematical statement. At the same time the practical realization of the strategy is significantly problem-specified because the number of tasks which are necessary to solve for the particular process is unique. These tasks are to define design variables, to identify and to impose constraints, to formulate the objective function and to limit the design space. From the other hand experience in the optimal design obtained for a certain induction system can be effectively spread for other applications such as induction hardening and the precise heating in chemical reactors.

Different optimization tools have been tested to search the optimum design. Finally, the most robust and effective algorithm have been chosen for further investigation and optimization of the system. The authors experience shows that genetic algorithms (GA) are the most effective tools for optimization of complicated multi-physical systems such as induction heating installations. GA are very robust and stable insearch, independently on complicated shape of the goal function [1]. A universal library of optimization programs with different numbers of independent variables has been created to be used for optimal design of induction heating systems.

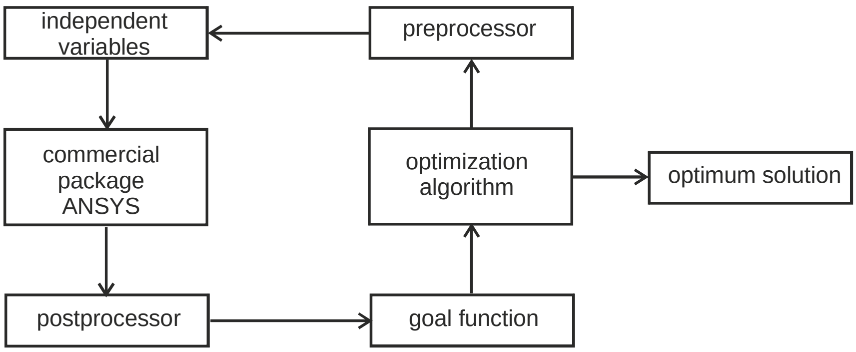

Fig. 2. Structure of the optimization procedure combined with commercial package ANSYS

Another important step is to combine the optimization program with the routine for computation of the goal function. A special approach has been developed to overcome this problem [2]. The optimization search and the goal function computation are running one by one in a loop so that exchange of data is organized via data files (see Fig. 2). The optimization preprocessor transforms the current set of independent variables created by optimization algorithm to the input data file for the process model. After the goal function computation the set of variables and the corresponding value of the goal function are written together into the history file. This history file transformed by special post-processor is available for optimization program that creates a next set of independent variables.

The described approach of optimization and numerical codes of the heating process have been applied for the parametrical optimization of the strip induction heating in the transverse magnetic flux (TFH) and for the precise heating in the chemical reactors.

3. Optimization Search for Transverse Flux Induction Heating of the Strip

One of the main tasks for optimal design is to provide high energetic parameters of the induction system. During the induction heating it is necessary to protect the parts of the equipment, for instances, stainless steel strip centring rollers from the parasitic heating. The sketch of the investigated induction TFH system is shown in Fig. 3. The system consists of TFH coils, stainless steel strip with thickness of 3 mm, copper shield and stainless steel rollers centring the strip. The operating frequency of 1 kHz has been chosen as an optimum value to provide the high electrical efficiency of the heater. It is clearly seen that eddy currents induced in the rollers increase the losses in system and shorten the life time of the rollers.

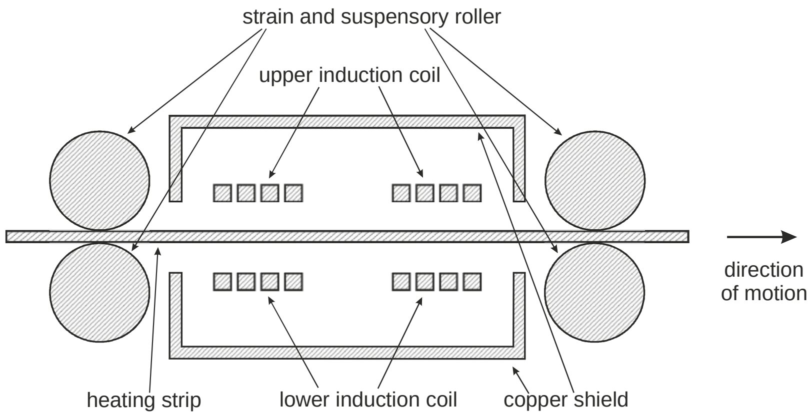

Fig. 3. Configuration of transverse flux induction heater

Symmetry of the system allows solving 2D electromagnetic problem in a quarter of the induction system. Coordinates described the copper shield geometry have been chosen as optimization variables. They are: shift of the shield from the strip (dy), shift of the shield from the rollers (dx) and the shield thickness (d) (see Fig. 4). The range of the optimization search for each parameter is shown in Tab. 1. Electrical efficiency has been chosen as a goal function.

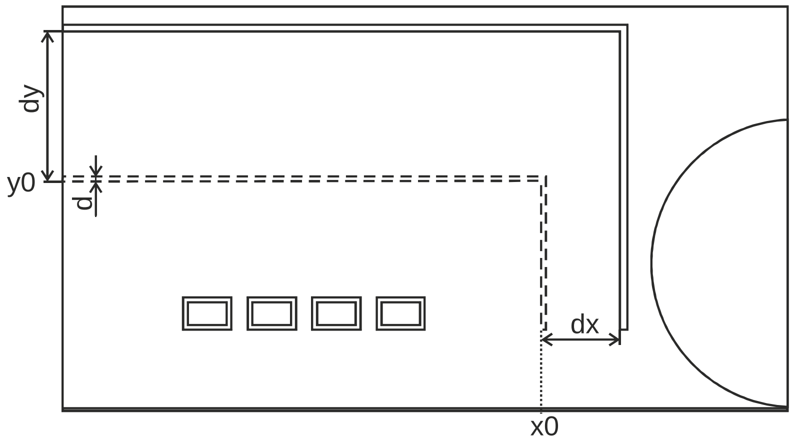

Fig. 4. Numerical system used for optimization

All the variables and corresponding optimum values of the goal function are shown in Tab.1. The maximum electrical efficiency of the heater obtained by the expert solution was 86 %. The best value of electrical efficiency obtained by the optimization search is 92 %. The initial and optimal geometries of the copper shield are shown in Fig. 4 (dashed lines are for the result of expert solution, full lines are for the result of optimization search).

Tab.1. Results of the optimization search

	range	**expert solution**	**GA**
dy, cm	-6.2 … 9.3	0	9.24
dx, cm	-6.2 … 4.9	0	4.89
d, cm	0.1 … 0.5	0.3	0.44
Electrical efficiency		0.86	0.92

4. Optimization Search for Precise Heating in the Chemical Reactors

The induction heating of chemical reactors is one of the modern electrotechnologies and this technique has a number of the essential advantages in comparison with traditional heating methods. The main task of the heating is to obtain the required temperature distribution along the height of the chemical reactor. An example of the required temperature profile along the height is shown in Fig. 5 (full line).

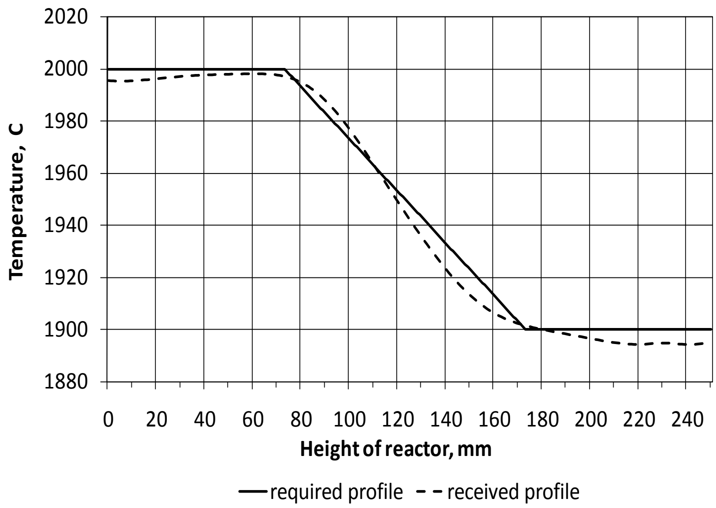

Fig. 5. The required and the received temperature profile along the reactor height

2D coupled electro-thermal numerical model has been developed to investigate the process of the induction heating in the chemical reactor. The model has been connected with GA by the technique described above.

The investigated system consists of the chemical reactor and four solenoid induction coils (see Fig. 6). The reactor is a hollow cylindrical chamber made from iridium. The thickness of the chamber wall is 3 mm, height of the chamber is 250 mm and the internal diameter of the chamber is 55 mm. The internal coil diameter is 110 mm. The operating frequency is 30 kHz. The reactor is covered outside by the thermal insulation. The operating temperature of the chemical reaction is around 2000 ºC.

The length of each coil and the coil currents have been chosen as optimization

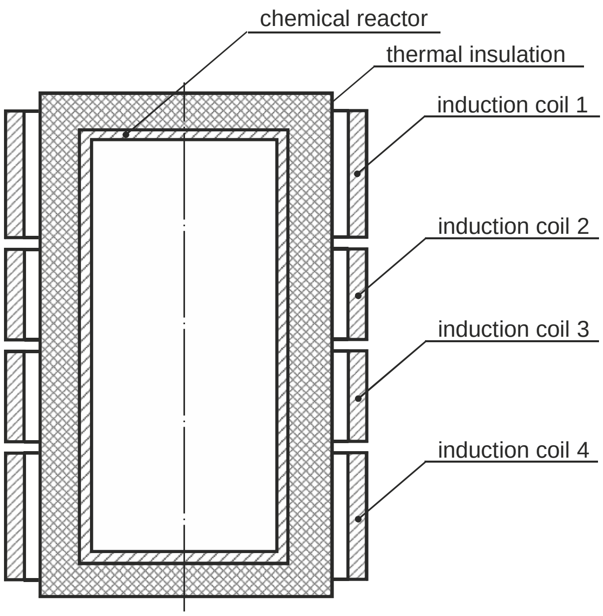

Fig. 6. Sketch of the chemical reactor

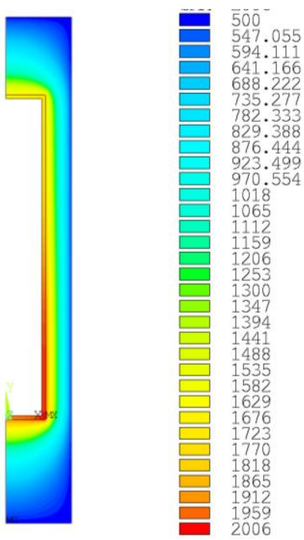

Fig. 7. Optimal temperature distribution in the chemical reactor

variables. The aim of the optimization search is to obtain the required temperature profile as shown in Fig. 5.

During the optimization search the optimum set of independent variables providing the required temperature profile along the chemical reactor height has been found. The temperature profile along the height is shown in Fig. 5 (dashed line). The temperature distributions along the height of the chemical reactor and the thermal insulation are shown in Fig. 7.

Conclusion and Outlook

The concept of the coupled electromagnetic and thermal modelling of the induction heating system is established and can be used for analysis and numerical optimization of the temperature distribution in the workpieces. The developed process model is combined with the optimization search procedure based on Genetic Algorithm. Two examples have demonstrated the results of optimal shape design for different induction systems. The described approach has been successfully used for the optimal design of the industrial induction coils.

Genetic Algorithms together with problem oriented software can be recommended as an effective tool for optimal shape design of inductors. The further prospects of development of methods offered in the present paper are connected first of all to the following problems:

- Use of the developed models and tools of search optimization for automated design of induction strip heating systems;
- Extension of the developed methods and approaches to other electrotechnological processes and installations;
- Development of models for operative optimization and on-line control of industrial technological processes, installations and lines.

Acknowledgment

Financial support from the Ministry of Education and Science of Russian Federation in the frame of the Federal program «Scientific and scientific - pedagogical staff of the innovative Russia» for the years 2009-2013 is gratefully acknowledged.

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