Modeling of electromagnetic and thermal processes occurring in induction heating cooker

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Induction heating is a famous technology and very usually used for cooking appliances because of its high-energy efficiency. A mathematical model is adopted for a flat inductor-detail system in this paper and it is used for studying the electromagnetic and the temperature field. The analysis is based on the finite element method (FEM). Results of the studied fields distribution and temperature evolution in the detail are presented.

Моделиране на електромагнитните и топлинни процеси възникващи в индукционен нагревателен котлон (Майк Щреблау). *Индукционното нагряване е популярна технология, която все по-често се прилага в бита, поради високия коефициент на полезно действие. Адаптиран е математичен модел на система плосък индуктор – детайл, с който са изследвани разпределението на електромагнитното и температурното поле. Анализът е базиран на метода на крайните елементи. Представени са резултати за разпределението на изследваните полета и изменението на температурата на детайла.*

Introduction

The induction heating is a contactless technique of generating heat energy in a conductive material by producing eddy current losses in the work piece from an external variable high-frequency power source. This principle is enshrined in induction cookers widely entered the household as a substitute for conventional heating systems (electric and gas). Their main advantage is the high efficiency set by the mode of transmission of energy to heat an object [2], [4].

In particular, the induction cooker is a flat inductor, whose electrical parameters are managed in a law that is similar to the classic induction heating. This gives rise to such a system be viewed as a flat inductor – detail system. Such systems are considered in [5], [6].

The aim of this article is to achieve the electromagnetic and temperature field distribution in the flat inductor-detail system. For this purpose is adopted a mathematical model of a flat inductor-detail system, taking into account the specifics of the structure and mode of operation of the induction cookers.

Mathematical model

Specificity in describing the mathematical model is based on the fact that the court, in this case the workpiece, is made of ferromagnetic steel and during the heating process the temperature is lower than the Curie point. Given multi physics model can be represented by a single step, as opposed to surface induction heating of ferromagnetic details, stated in [3].

In designing the multi physics model for analysis of the electromagnetic and temperature fields the following assumptions are made:

- The segment concentrators located under the inductor [1] are modelled through a dense disk of ferromagnetic steel;
- The electromagnetic field is considered as continuous at the boundary between mediums with different values of the magnetic permeability;
- The temperature field is only considered in the detail;
- It is not reported losses of energy from the surrounding surface of the heated detail;
- It is ignored the losses by radiation from the detail to the environment;

- It is assumed that the temperature of the inductor is constant.

Figure 1 shows geometry of the model of axial symmetric flat inductor – detail system.

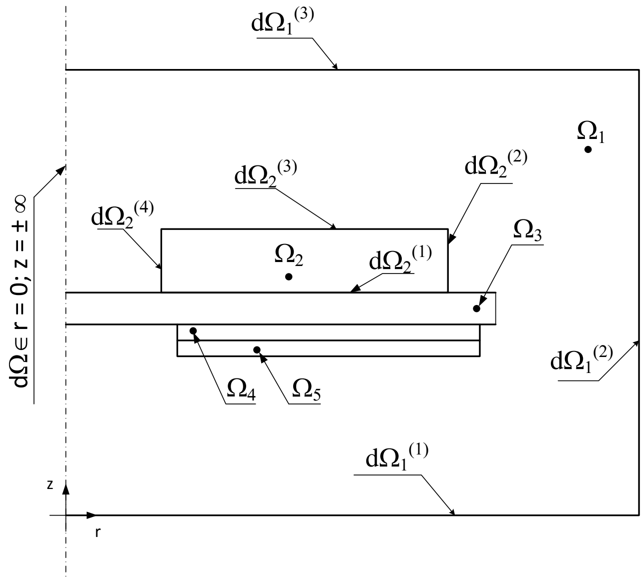

Fig. 1. The geometry of the model. Ω_1 – the air, Ω_2 – the detail; Ω_3 – the pyro ceramic plot; Ω_4 – the inductor; Ω_5 – the magnetic concentrator.

Given the assumptions made and the areas divided in the model in Figure 1, the general form of the multi physics mathematical model of the inductor-detail system in cylindrical coordinates is as follows:

(1)
$$\left|\begin{array}{ll}
\frac{\partial}{\partial r}\left(\frac{1}{r}\cdot\frac{\partial r\cdot\dot{\mathbf{A}}}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{\partial\dot{\mathbf{A}}}{\partial z}\right)=0 & \in\Omega_1\\
\frac{\partial}{\partial r}\left(\frac{1}{\mu(H)}\frac{1}{r}\frac{\partial r\dot{\mathbf{A}}}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{1}{\mu(H)}\frac{\partial\dot{\mathbf{A}}}{\partial z}\right)+j\cdot\omega\cdot\gamma(T)\cdot\dot{\mathbf{A}}=\dot{\mathbf{J}}_c & \in\Omega_2\\
\frac{\partial}{\partial r}\left(\frac{1}{r}\cdot\frac{\partial r\cdot\dot{\mathbf{A}}}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{\partial\dot{\mathbf{A}}}{\partial z}\right)=0 & \in\Omega_3\\
-\frac{1}{\mu}\cdot\frac{\partial}{\partial r}\left(\frac{1}{r}\cdot\frac{\partial r\cdot\dot{\mathbf{A}}}{\partial r}\right)-\frac{1}{\mu}\cdot\frac{\partial}{\partial z}\left(\frac{\partial\dot{\mathbf{A}}}{\partial z}\right)+j\cdot\omega\cdot\gamma\cdot\dot{\mathbf{A}}=\dot{\mathbf{J}}_c & \in\Omega_4\\
\frac{\partial}{\partial r}\left(\frac{1}{\mu(H)}\frac{1}{r}\frac{\partial r\dot{\mathbf{A}}}{\partial r}\right)+\frac{\partial}{\partial z}\left(\frac{1}{\mu(H)}\frac{\partial\dot{\mathbf{A}}}{\partial z}\right)=0 & \in\Omega_5\\
\rho(T)\cdot c(T)\cdot\frac{\partial T}{\partial t}=\frac{1}{r}\cdot\frac{\partial}{\partial r}\cdot\left(\lambda(T)\cdot r\cdot\frac{\partial T}{\partial r}\right)+\lambda(T)\cdot\frac{\partial^2 T}{\partial z^2}+q_v & \in\Omega_2
\end{array}\right.$$

where: A - magnetic vector potential; J_c - current density in the inductor γ - specific electrical conductivity; T - absolute temperature; μ - absolute permeability; ρ - density of the material; c - specific heat capacity; λ - thermal conductivity.

The boundary conditions assigned at the boundaries of the model shown on Figure 1 are as follows [6]:

- **Electromagnetic field:**

Boundaries: $d\Omega\in(r=0, z=\mp\infty); d\Omega_1^{(1)}; d\Omega_1^{(2)}; d\Omega_1^{(3)}$

(2)
$$n\, x\,\dot{\mathbf{A}}=0$$

- **Temperature field:**

Boundaries: $d\Omega_2^{(1)}; d\Omega_2^{(2)}; d\Omega_2^{(4)}$

(3)
$$\frac{\partial T}{\partial n}=0,$$

Boundary: $d\Omega_2^{(3)}$

(4)
$$-\frac{\partial T}{\partial n}=\frac{\alpha}{\lambda}\left(T-T_0\right),$$

The properties of the materials involved in the pattern of model are set according to the current value of temperature [7], [8]. The model is implemented in an environment of Comsol Multiphysics Software.

Results

The obtained results for the magnetic and temperature field distribution are shown in Figure 2, Figure 3.

The temperature evolution on the top of detail is presented in Figure 4.

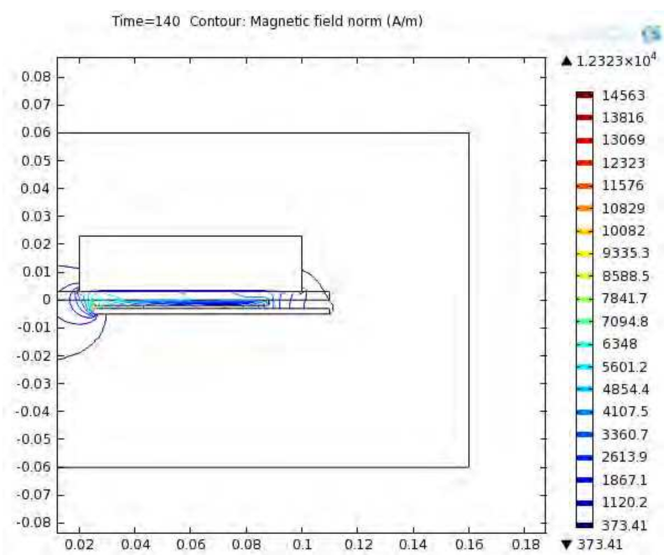

Fig. 2. Magnetic field distribution.

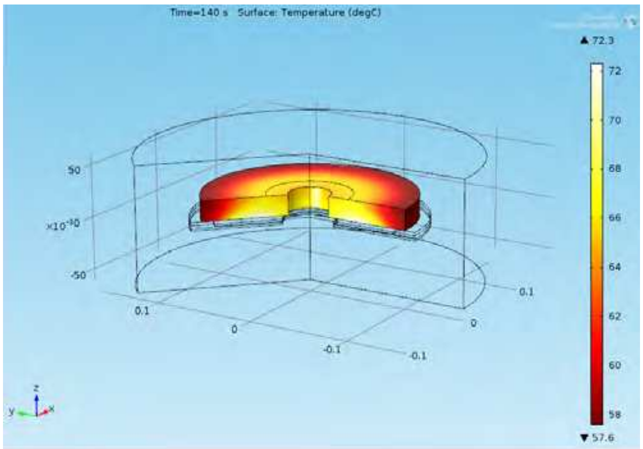

Fig. 3. Distribution of the temperature field in the detail.

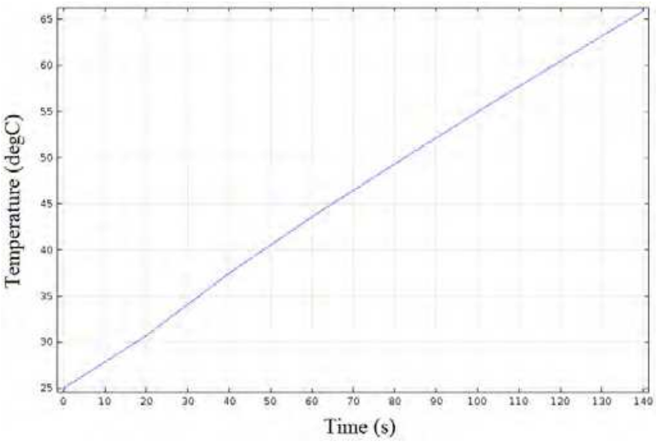

Fig. 4. Temperature evolution on the top of the detail.

Experiment

An experiment was conducted with an induction cooker ALASKA, which consists of a flat inductor with a configuration shown on Figure 5. The inductor is made of copper wire with a diameter d = 2 mm and turns w = 27, shown on Figure 6.

As a load is used a cylindrical detail made of ferromagnetic steel 45, shown on Figure 7.

The inductor is supplied with a sinusoidal current with constant frequency 26 kHz and the input electrical power is 950W. The waveforms of the inductor voltage and the current are shown on Figure 8.

The heating process is monitored with a thermocouple placed on the top of the heated detail. The initial and the final temperature of the detail are according 26°C and 66°C.

Fig. 5. The inductor
1- Concentrator; 2 - Coil

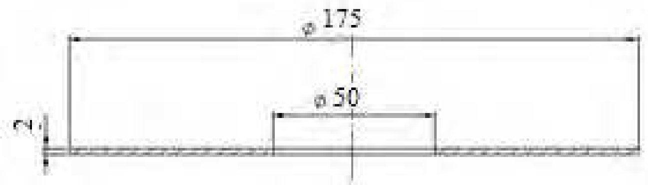

Fig. 6. The Dimensions of the inductor

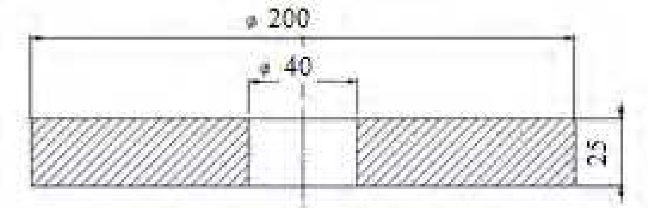

Fig. 7. The detail.

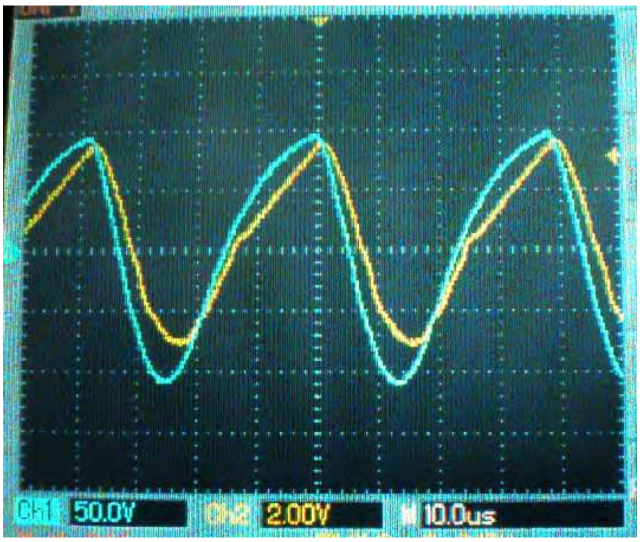

Fig. 8. Inductor voltage (blue) and current throw the coil (yellow).

Conclusions

The model is specifically designed for the researched induction cooker. To assess the adequacy of the model a comparative characteristic for the heating process is presented, shown on Figure 9. The maximum value of the relative error between experiment and model is 7%.

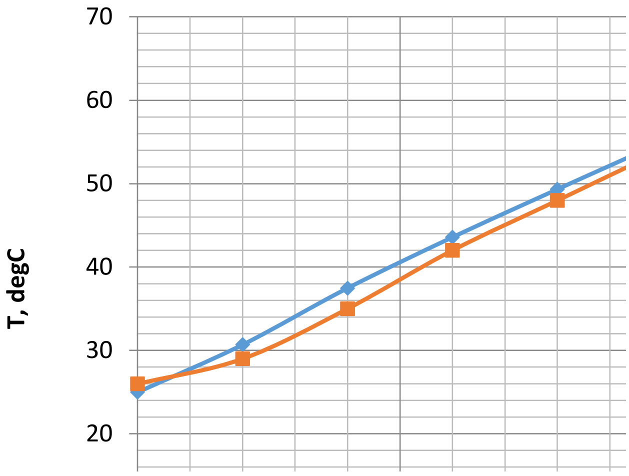

Fig. 9. Comparison between model and experiment.

The distribution of the magnetic field is characterized by a concentration of magnetic field lines between the detail and the inductor due to the screening effect of the ferromagnetic detail and the concentrator located under the inductor.

The temperature field distribution in the detail is rather irregularly. This fact is due to the bigger diameter of the detail then the coil of the inductor. This means that for the regularly heating it is necessary the diameter of the load to be approximately equal to the diameter of the coil.

The proposed admission for the presented configuration of the concentrators in the model does not affect to the final temperature distribution in the detail. This allows the model can be described in 2D dimension instead in 3D.

The adopted mathematical model can be used for more detailed analysis on the processes at work on induction heating cooker in complete with ferromagnetic container with contents in it substance. In future studies need to be presented in detail the peculiarities of the configuration of the containers used at work with induction cookers. It is essential that consideration of the physical parameters of the substance to be heated.

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