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APPLICATION OF THE FINITE ELEMENT NETHOD TO COMPUTER SIMULATION OF ELECTROMAGNETIC AND THERMAL PROCESSES IN INDUCTION COOKERS AND HEATED DISHES

In-house computer code EleFAnT2D developed at the Institute for Fundamentals and Theory in Electrical Engineering (IGTE) of the Graz University of Technology, Austria is used to compute by the Finite Element Method distributions of electromagnetic and thermal fields of household induction cookers. The code EleFAnT2D and developed numerical models are used during the Bachelor and Master students training at the Department for Electrical Apparatus, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine. In the paper there are presented the developed mathematical and computer models, solved equations, initial and boundary conditions. Obtained numerical results are described and analyzed in detail. Numerical analysis carried out by students helped them to propose designs of various inductors of induction cookers as well as to develop in their Bachelor and Master Theses conceptual designs of induction cookers in whole. Illustrative examples are presented.

Key words: computer simulation, electromagnetic field, Finite Element Method, heated dishes, induction cooker, thermal field.

1. Introduction

The Department for Electrical Apparatus, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine [1] is the only Department in Ukraine and, probably, in Europe which trains Bachelor and Master students in the field of study "Electrical Household Appliance". Graduates of the Department are Electrical Engineers working in the area of investigation, analysis, design and operation of various household devices for heating, conditioning, cooking, etc.

To increase professional skill of its graduates the Department intensifies teaching in the field of Computational Electromagnetics. In cooperation with the Institute for Fundamentals and Theory in Electrical Engineering (IGTE) of the Graz University of Technology (TU Graz), Austria, the Department uses widely the EleFAnT2D computer code [2] developed at the IGTE to build relatively simple finite element models and simulate electromagnetic and thermal field distributions of induction cookers as examples of modern electrical household appliances. This helps students to understand principles of computational electromagnetics and make initial steps in practical numerical analysis.

2. Problem definition

Induction cookers represent a relatively new class of modern electrical household appliances – electrical kitchen stoves which heat metal dishes by eddy currents generated by electromagnetic field with frequency of 20-100 kHz. The main structural part of the induction cooker is inductor – a one-turn or multi-turn coil, the alternating current flow in which generates an electromagnetic field which in its turn induces eddy currents in heated dishes with meal.

The typical designs of one-ring and two-ring induction cookers as well as their inductor are presented in Fig. 1, 2, respectively. To investigate operation modes of household devices under consideration (power, frequency and their temporal variation, duration of heating, etc.) it is necessary to consider multiphysics phenomena taking place during their operation.

a b

Fig. 1. Design of induction cookers: a – one-ring cooker; b – two-ring cooker.

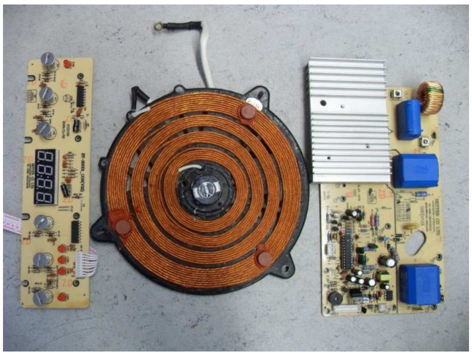


Fig. 2. Inductor of the induction cooker.

Generally, the computer simulation represents a nonlinear multiply coupled problem including electromagnetic and thermal fields. In our cases the electromagnetic field can be solved independently of the temperature distribution without respecting the dependence of electrical conductivity and magnetic permeability on temperature. This simplification is acceptable practically without any negative influence on the results because of rather lower temperature rise – till 240-280 ^{0}C (higher temperatures are unacceptable due to the possible mechanical deformations of dishes as well as loss of nutritional quality of meal).

There are publications [3-6] devoted to induction cookers' electromagnetic and thermal fields computations using various formulations and approaches. The goal of the paper is to present international collaborative academic activities of the Department for Electrical Apparatus, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine and the Institute for Fundamentals and Theory in Electrical Engineering (IGTE) TU Graz, Austria to intensify Ukrainian students training in the field of Computational Electromagnetics using induction cookers as examples of devices under consideration. The paper describes examples of computational models developed by Ukrainian students using in-house computer code EleFAnT2D [2] during their stay at the IGTE under the guidance of their Austrian tutors as well as obtained numerical results and their utilization to develop students' conceptual designs of induction cookers.

3. Computational models of induction cookers

To facilitate students' understanding of the basic principles of Computational Electromagnetics, the finite element analysis of induction cookers' electromagnetic and thermal fields is carried out in 2D formulation. Figures 3, 4 show examples of axisymmetrical computational models built using in-house computer code EleFAnT2D [2] developed at the IGTE. The first (the simplest) model includes (see Fig. 3) a copper two-turn inductor, a pan made from soft ferromagnetic steel, a ferrite core, and dielectric subdomains. In Fig. 4 the improved model of the induction cooker is presented. We consider a modern pan designed specifically for induction cookers: an aluminum pan with a thin bottom ferromagnetic layer which is needed to obtain proper distributions of the electromagnetic field and eddy currents in the bottom of the pan. In addition, a ferrite magnetic core of the induction cooker is designed in such a way that can significantly improve its shielding capacity, thus reducing the scattering of electromagnetic field of the inductor in the surrounding area in order to increase the efficiency of the induction cooker.

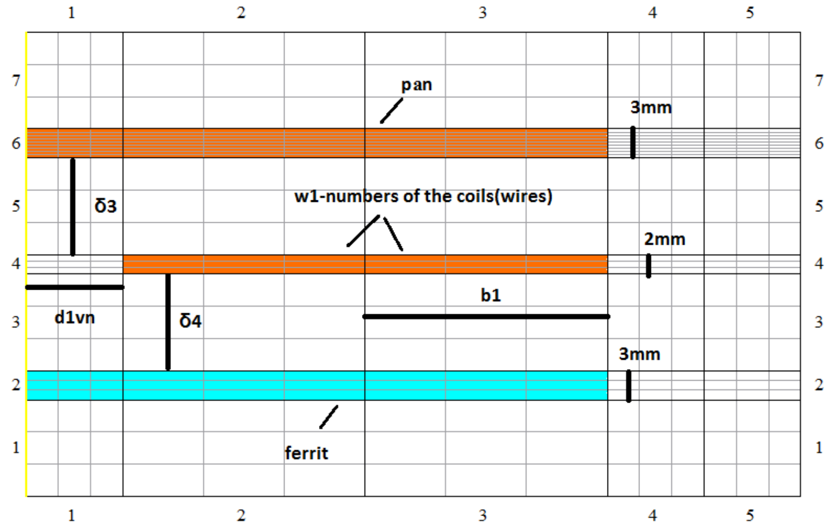


Fig. 3. The first computational model of induction cooker.

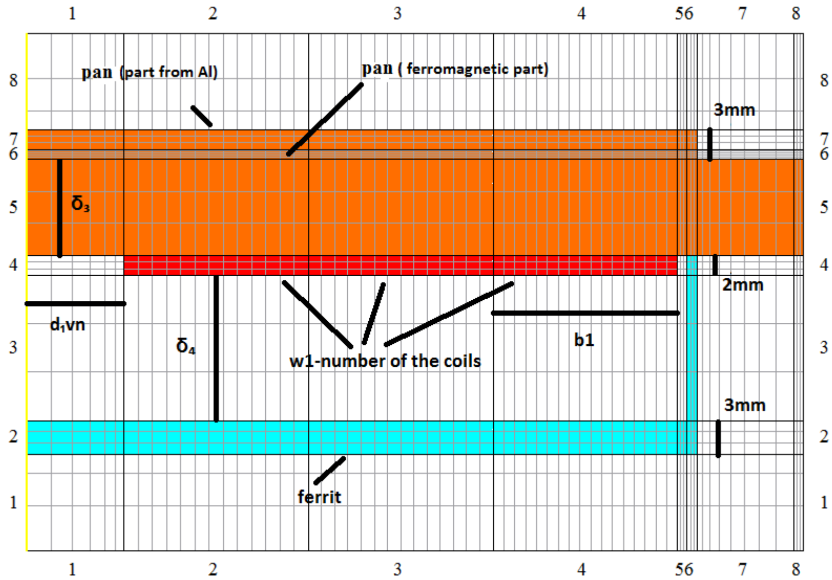


Fig. 4. The second computational model of induction cooker.

So, the second (more complicated) model includes (see Fig. 4) a copper three-turn inductor, heated dishes (an aluminum pan with a ferromagnetic layer), an improved ferrite core, and dielectric subdomains. The goal of students' investigations is to understand the influence of power, frequency, geometrical parameters of the models (see Fig. 3, 4), duration of heating, etc. on the electromagnetic and thermal field distributions.

The time dependent distribution of electromagnetic field is described by [7]:

$$\mathrm{curl}\left(\frac{1}{\mu}\mathrm{curl}\,\mathbf{A}\right)+\gamma\frac{\partial \mathbf{A}}{\partial t}=\mathbf{J}_{\mathrm{ext}}, \quad (1)$$

where $\boldsymbol{A}$ denotes the magnetic vector potential, μ the magnetic permeability, γ the electric conductivity and $\boldsymbol{J}_{ext}$ the harmonic current density applied to the inductor. Parameter γ is generally a function of the temperature T whereas μ is a function of the temperature T and magnetic flux density B. As said above, however, in case of a relatively small temperature rise, the temperature dependencies are disregarded.

The eddy currents produced in electrically conductive bodies given by the second term on the left–hand side in equation (1) give rise to the specific Joule losses w_J:

$$w_J = \gamma \left(\frac{\partial A}{\partial t} \right)^2 \tag{2}$$

whose magnitude decreases roughly exponentially with the distance from the surface of the heated body.

In fact, the complete solution of the parabolic equation (1) is unfeasible due to relatively long time of the heating process. That is why we simplified the model by considering harmonic magnetic field. Now equation (1) can be rewritten in terms of the phasor $\underline{\boldsymbol{A}}$ of the magnetic vector potential $\boldsymbol{A}$ [7]:

$$\mathrm{curl} \frac{1}{\mu} \mathrm{curl}\, \underline{\mathbf{A}} + j\omega\gamma\, \underline{\mathbf{A}} = \underline{\mathbf{J}}_{\mathrm{ext}}. \tag{3}$$

The computations are carried out iteratively, and at each step the permeability μ in each element containing ferromagnetic material is adjusted to the real value of the magnetic flux density. The specific Joule losses are then expressed as:

$$w_J = \gamma\omega^2 \left| \underline{\mathbf{A}} \right|^2. \tag{4}$$

The temperature field is described by [8]:

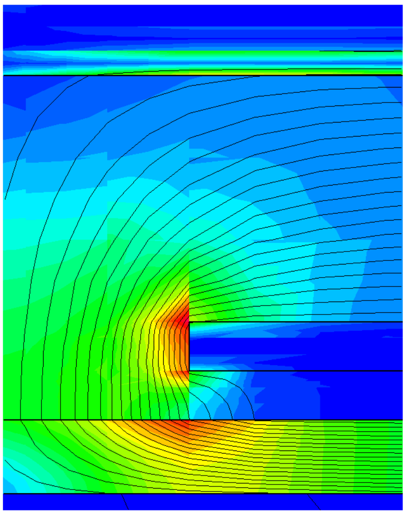
$$\mathrm{div}(\lambda\, \mathrm{grad}\, T) = \rho c \frac{\partial T}{\partial t} - w_J, \tag{5}$$

where λ is the thermal conductivity, ρ the mass density and c the specific heat. All these parameters are generally temperature–dependent functions. The boundary conditions are respected by convection while the thermal radiation is neglected because of the relatively low temperatures.

Equations (3), (5) are solved in the axisymmetrical formulation by the Finite Element Method [9, 10] using in-house computer code EleFAnT2D [2].

4. Obtained numerical results

The distributions of electromagnetic and thermal fields are modelled by students using EleFAnT2D computer code. Examples of obtained distributions are presented in Fig. 5. Figure 5,a shows flux density distribution in the model with geometrical parameters (see Fig. 4) $d_{1\mathrm{vn}}$= 10 mm, b_1= 16 mm, δ_3= 10 mm, δ_4 = 2 mm and frequency of current in the inductor of 20 kHz. In its turn, Fig. 6,b shows steady-state temperature field distribution of the heated aluminum pan with thin ferromagnetic layer.



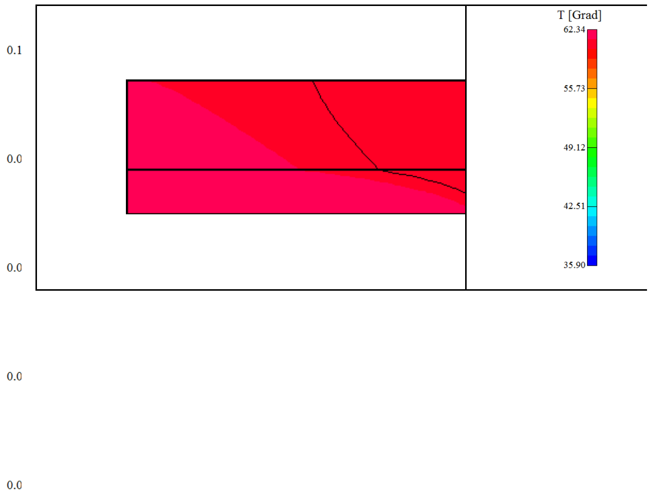


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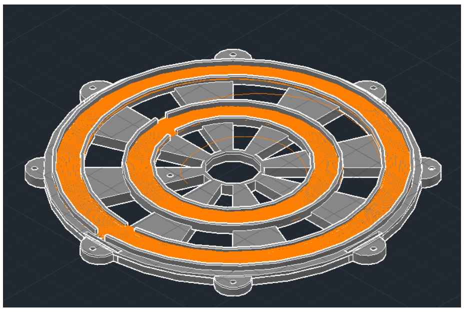
Fig. 5. Examples of obtained numerical results: a – electromagnetic field distribution; b – temperature field of the heated pan.

Numerical analysis carried out by students helps them to propose designs of various inductors of induction cookers as well as to develop in their Bachelor and Master Theses conceptual designs of induction cookers in whole. Illustrative examples are presented in Fig. 6, 7.



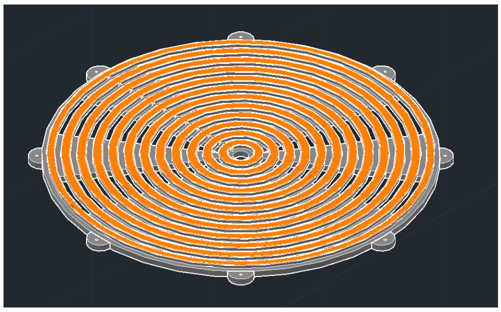


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Fig. 6. Designs of induction cookers' inductors: a – 2-turn inductor; b – 12-turn inductor.

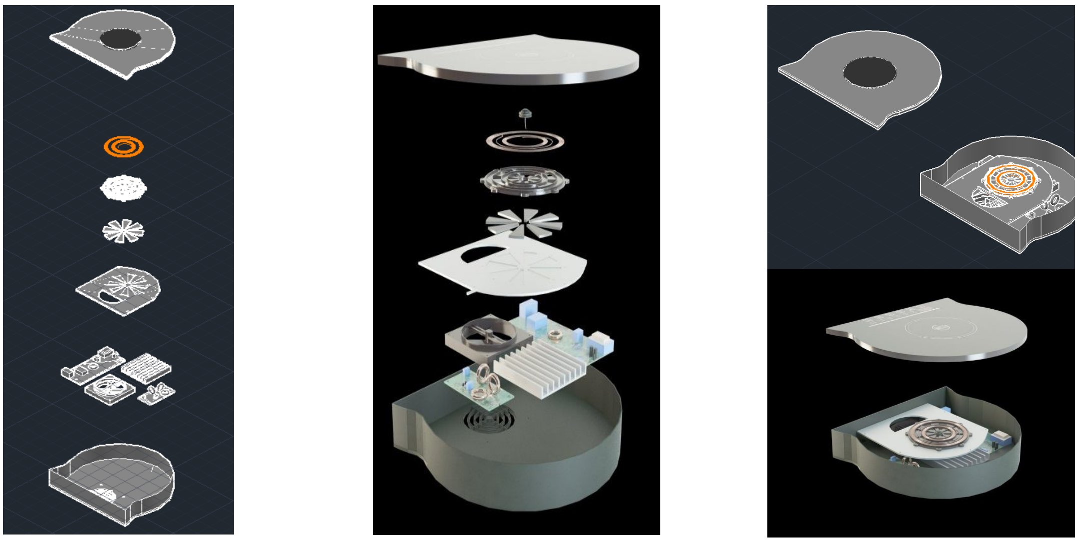

Fig. 7. Conceptual design of induction cooker with 2-turn inductor.

5. Conclusions

The Department of Electrical Apparatus, National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine uses widely the EleFAnT2D computer code developed at the IGTE to intensify teaching in the field of Computational Electromagnetics. The finite element analysis of electromagnetic and thermal fields distributions of modern electrical household appliances – induction cookers is carried out. Training computational models of induction cookers are developed and investigated by Ukrainian students under the guidance of their Austrian tutors. Obtained numerical results and their analysis are used during preparation of Bachelor and Master Theses.

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Анотація. ***Пантелят М. Г. Застосування методу скінчених елементів для комп'ютерного моделювання електромагнітних і теплових процесів у індукційних кухонних плитах і посуді, що нагрівається.*** *Індукційні плити являють собою відносно новий клас сучасної електропобутової техніки – кухонні електричні плити, які розігрівають металевий посуд вихровими струмами, які створюються електромагнітним полем частотою 20-100 кГц. Останнім часом такі плити отримують все більш широке використання. Комп'ютерне моделювання електромагнітних і теплових процесів у індукційних кухонних плитах і посуді, що нагрівається, представляє значний інтерес як з наукової точки зору, так і з метою підвищення рівня підготовки студентів відповідних спеціальностей. Метод скінчених елементів є найбільш поширеним чисельним методом розв'язання задач зазначеного класу. Як приклад його реалізації, для розрахунку методом скінчених елементів розподілу електромагнітного та теплового полів побутових індукційних плит у двовимірній постановці використовується власне програмне забезпечення EleFAnT2D, розроблене в Інституті основ і теорії електротехніки (IGTE) Технічного університету м. Грац, Австрія. Програма EleFAnT2D і розроблені розрахункові моделі використовуються під час підготовки бакалаврів та магістрів на кафедрі «Електричні апарати» Національного технічного університету «Харківський політехнічний інститут», Харків, Україна. У статті наведено розроблені математичні та комп'ютерні моделі, рівняння, що розв'язуються, початкові та граничні умови. Описуються та детально аналізуються отримані чисельні результати. Чисельний аналіз, проведений студентами, допоміг їм запропонувати конструкції різноманітних індукторів індукційних кухонних плит, а також розробити у бакалаврських і магістерських роботах проекти індукційних плит у цілому. Наведено ілюстративні приклади.*

Ключові слова: комп'ютерне моделювання, електромагнітне поле, метод скінчених елементів, нагрітий посуд, індукційна кухонна плита, теплове поле.

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