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RESEARCH ARTICLE

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Modeling and optimization of induction cooking by the use of magneto-thermal finite element analysis and genetic algorithms

Abstract Induction cooking has several advantages compared to traditional heating system; however, to obtain best efficiency, it is essential to have an inductor giving homogeneous temperature on the pan bottom. For this aim, we propose a structure of inductor with four throats containing coils and optimize their distribution. In this paper, first we model magneto-thermal phenomenon of the system by a finite element method (FEM) for the mean to determine the distribution of temperature on the pan bottom by taking the nonlinearity of system. This study shows that a temperature distribution is not homogeneous. Second, with the aim to have homogeneous temperature distribution on the pan bottom, the optimal determination of throats distribution and their dimensions is obtained by genetic algorithms (GAs). The optimized structure permits to satisfy our aim.

Keywords finite element method, magneto-thermal devices, genetic algorithms

1 Introduction

Induction cooking has several advantages [1] compared to traditional heating system (resistance, gas, etc.), particularly direct heating of pan without thermal inertia. The inductor generates an alternating magnetic field that causes eddy current in the pan; in ferromagnetic pans, it also produces magnetic hysteresis, where both mechanisms heat up the pan [1,2]. The distribution of the temperature on the pan bottom depends on many parameters:

- Geometrical structures of pan to heat and the inductor,
- Characteristics of materials (conductivity σ and permeability μ), and
- Frequency that implies the skin thickness.

Classical inductor, consisted of insulated coils placed on a support (Fig. 1) [3], induces eddy currents in magnetic pan with high efficiency; however, the temperature is non-homogeneous on the pan bottom. We cannot optimize this structure because of the pancake structure of the inductor.

With the aim to have a homogeneous temperature on the pan bottom, we propose a structure of inductor with coils placed in throats (Fig. 2).

In this work, we optimize the structure of throats distribution and their dimension of inductor is proposed.

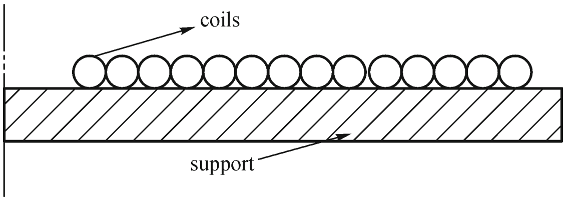

Fig. 1 Inductor with coils winding

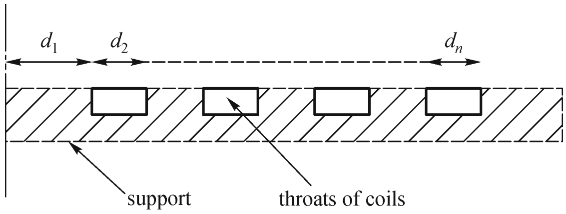

Fig. 2 Inductor with throats

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The method of optimization with genetic algorithms (GAs), which have been widely used mainly in connection with the finite element method (FEM) for optimization of electromagnetic devices [4–6], was restricted to the magnetodynamic phenomena [7]. In this paper, we propose to optimize inductor with magneto-thermal calculation method and to determine the optimal temperature distribution on the pan bottom. This method consists of placing coils in throats upon the support of the inductor and to vary their distances d_i (Fig. 2).

This paper is organized as follows: Magneto-thermal finite element analysis is presented in Section 2. In Section 3, the procedure of calculation without optimization is studied; this section seeks the distribution of the temperature with uniform repartition of the throats in the inductor. In Section 4, the proposed method with GAs is applied to obtain an optimal repartition of the throats in the inductor. Finally, the conclusion is presented in Section 5.

2 Magneto-thermal finite element analysis

2.1 Descriptive equations

To develop an optimal system of induction-heating cooking, it is necessary to know the distribution of temperature on the pan bottom, which is the image of distribution of induced currents. Physical phenomena in studied system can be simulated by solving the coupled Maxwell's and thermal equations. For the reason of axisymetric structure of the inductor, an axisymetric two-dimensional (2D) solution is possible.

Using the magnetic potential A, electromagnetic phenomena is modeled by the well-known magneto-thermal equations [8,9]:

$$\mathrm{j}\omega\frac{\partial \overline{A}}{r}-\frac{\partial}{\partial r}\left(\frac{\upsilon}{r}\frac{\partial \overline{A}}{\partial r}\right)-\frac{\partial}{\partial z}\left(\frac{\upsilon}{r}\frac{\partial \overline{A}}{\partial z}\right)=\overline{J}, \tag{1}$$

$$\lambda\nabla^2 T+q=\rho_{\mathrm{m}}C_{\mathrm{p}}\frac{\partial T}{\partial t}, \tag{2}$$

$$q=\frac{1}{r^2}\sigma\omega^2\overline{A}\,\overline{A}^*, \tag{3}$$

where A is the magnetic vector potential defined such as $\overline{A}=r\overline{A}_\theta$, A_θ is the azimuthal component of the vector potential, υ is the magnetic reluctivity, σ is the electric conductivity, ω is the angular velocity, J is the current density, λ is the thermal conductivity, T is the temperature, q is the heat source density, ρ_{m} is the masse density, C_{p} is the specific heat, and t is the time.

We notice that the constant time of the electromagnetic problem in Eq. (1) is very small compared to the thermal constant time in Eq. (2). In the resolution, we use the harmonic time variation in the first equation and a transit time variation in the second equation.

2.2 Boundary conditions

The magneto-thermal analysis is performed by FEM using the governing Eqs. (1) and (2) and the following boundary conditions (4) and (5):

$$Dirichlet(A=0), \tag{4}$$

$$-\lambda\frac{\partial T}{\partial n}=h(T-T_a), \tag{5}$$

where h is convection coefficient and T is ambient temperature.

For the electromagnetic problem, we use Dirichlet condition ($A=0$) on sufficiently large boundary truncated in the air. On the other hand, the thermal problem is reduced to the container.

The heat transfer coefficient in Eq. (5) has a role in determining the temperature distribution of the pan bottom in the device. Because of axisymetric structure of inductor, this makes h nonlinear due to the convection effect of the air nearby [10]. Thus, we assume that h has a constant value (see Table 1 below) along the radial direction of the axisymetric structure in studied system.

2.3 Electromagnetic characteristics of material

The pan is made of stainless steel. The electrical resistivity $\rho(T)$ and the magnetic permeability $\mu_r(T)$ of the material at temperature T are expressed as [9]

$$\rho(T)=\rho_0(1+\alpha T), \tag{6}$$

$$\mu_r(T)=\mu_{r0}\left(1-e^{\frac{T-750}{150}}\right)^{-1}, \tag{7}$$

where T is measured in degree Celsius (°C), and

$$\rho_0=1/\sigma_0=13.75\times10^{-8}\ \Omega\cdot\mathrm{m},$$
$$\mu_{r0}=1273,\ \alpha=0.004.$$

The curves of $\rho(T)$ and $\mu_r(T)$ are shown in Figs. 3 and 4, respectively.

3 Procedure of calculation without optimization

The proposed system inductor has four throats containing coils (Fig. 5). First, we assume that the distances d_i have a uniform distribution. The other parameters shown in Table 1, except conductivity $\sigma(T)$ and permeability $\mu(T)$, can be assumed constant during the procedure of calculation for temperature.

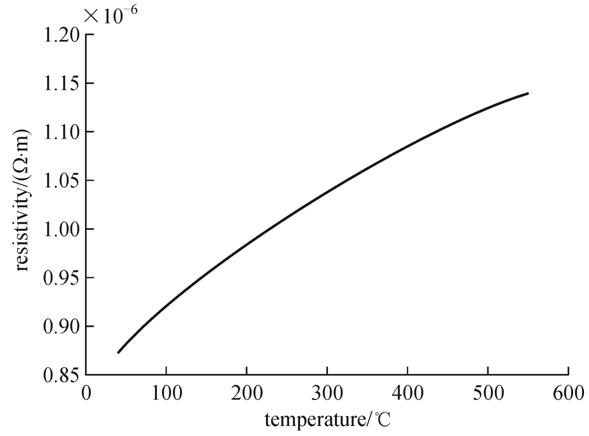

Fig. 3 Curve of resistivity

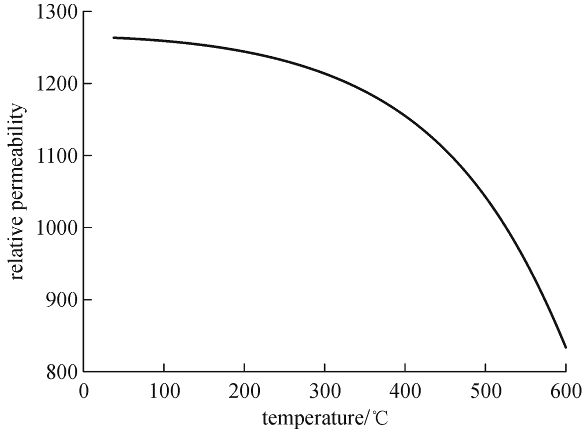

Fig. 4 Curve of relative permeability

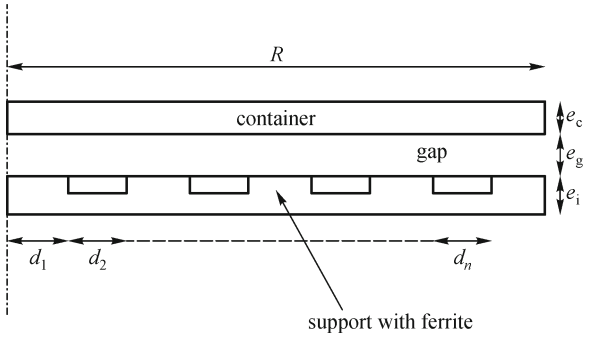

Fig. 5 Geometry of the model used in the program

The magneto-thermal calculation of our system running is illustrated in the flow chart of Fig. 6. The thermal problem is solved step by step in the time using a time step of 5 s until the final temperature is reached.

The curves representing the distribution of the current density and the final temperature on the pan bottom are shown in Figs. 7 and 8. One can note that such a distribution is not homogeneous.

Table 1 Parameters of the simulated system

symbol	description	value
R	radius of container	140 mm
e_i	inductor thickness	3.8 mm
e_g	gap thickness	4 mm
e_c	container thickness	3 mm
$d_1, d_2, ..., d_i$	distances	16.25 mm
e_q	throats thickness	2 mm
μ_f	ferrite relative permeability	2500
f	frequency	20×10^3 Hz
J	current density	1×10^6 A/m^2
l	thermal conductivity	26 W/(m·K)
h	convection coefficient	20 W/(m^2·K)
ρ_m	masse density	7700 kg/m^3
C_p	specific heat	460 J/K

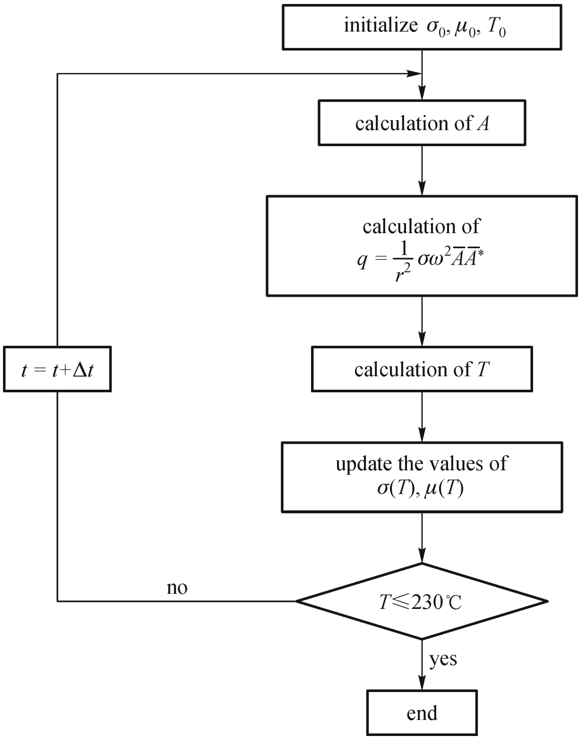

Fig. 6 Flow chart of magneto-thermal program

4 Procedure of calculation with optimization

The aim of the present optimization is to attain a homogeneous temperature distribution on the pan bottom by adjustment of the throats (coils) distribution. For this reason, we define the objective function as

$$f_{\mathrm{obj}}(d_i) = \sum_{i=1}^{n_T} \frac{|T_i - T_f|}{T_f} \leqslant \varepsilon, \tag{8}$$

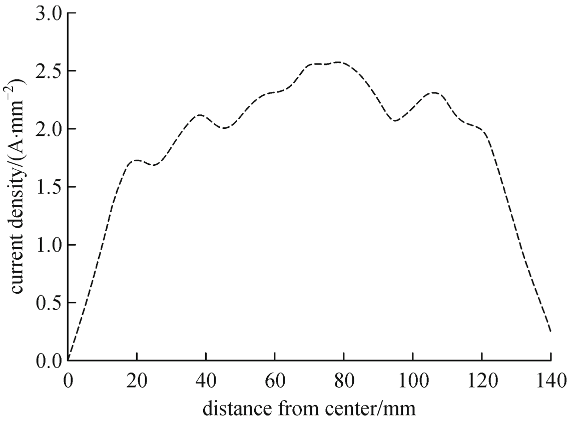

Fig. 7 Curve of current density at the bottom of the pan

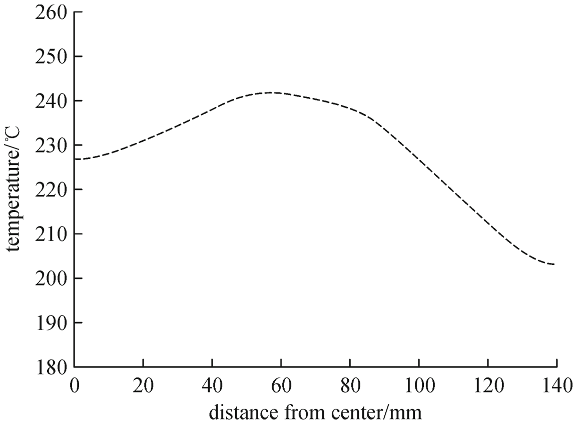

Fig. 8 Curve of temperature at the bottom of the pan

where T_i is the temperature in each point of calculation at the bottom of the pan, n_T is the number of points of statement of temperature along the pan, and T_f is the desired temperature.

The optimization method is used to find the optimal distribution of throats (d_i). For this aim, the objective function (f_{obj}) is minimized. However, as the evaluation of such an objective function is based on the finite element analysis of a nonlinear magneto-thermal problem, the optimization methods based on gradient techniques cannot be applied. On the other hand, we have no constraint about the time optimization. In these circumstances, we have chosen the use of GA as optimization tool. As a matter of fact, such type of optimization has proven its robustness in the case of complex and nonlinear systems [5,6].

• Algorithm optimization

The GAs have been widely used mainly in connection with the FEM for optimization of electromagnetic devices. The main advantages of the GAs are as follows: they can search effectively in multivariable searching space and they are able to pass the optimizing information from one population to the following one. On the other side, GAs are exploration algorithms based on the artificial creatures that represent design configurations. The whole of creatures constitutes a population. Each creature is associated with a value of the objective function, which we want to improve the performances. GA uses only this objective function for optimization, not derivative, which allows a better precision. The creatures are coded in the form of a finite-length string according to one of the coding methods, wherein the binary coding (0,1) is used. From a first population of selected individuals in a random manner, GAs generate new creatures in such a way that new individuals inherit better information from their previous population. GAs use random characters such as reproduction, crossover, and mutation. Reproduction is a process in which creatures associated to high value of objective function have a higher probability to survive. Crossover and mutation allow to introduce new genetic parameters and to test new configuration [11]. The code of GA used is shown in Fig. 9.

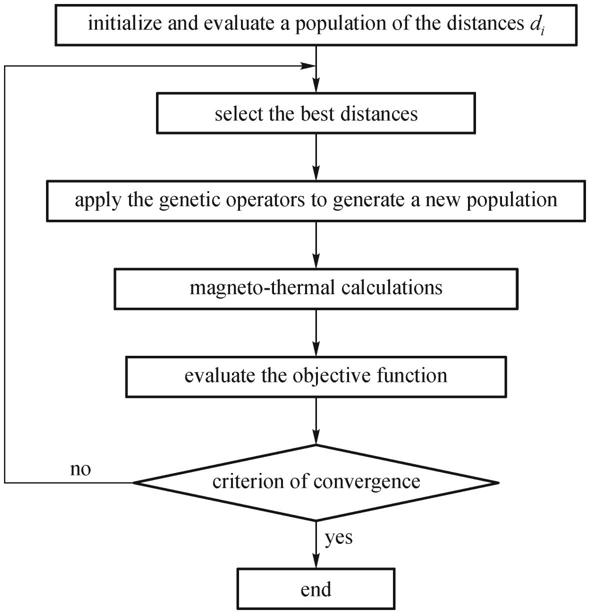

Fig. 9 Flow chart of GA

With the aim to have homogeneous temperature distribution on the pan bottom, we optimize the system to determine throats distribution and their dimensions by GAs. From each step given of the process calculation, the elaborated program reconstitutes the geometry starting from the choice of distances d_i, carries out the new mesh, and solves the magneto-thermal problem.

The computations are carried out using a P4, 3.4 GHz, 2 Go RAM. The result is obtained after 500 iterations corresponding to about 14 h of CPU time. Results of calculations are shown in Figs. 10–13, where Fig. 10 illustrates the optimal distribution of throats and Table 2 exposes their dimensions. In Figs. 11 and 12, respectively, we can observe that a good distribution of the density of current and homogeneous temperature along a ray of the pan is obtained. The temperature evolution versus time in a point situated at the middle of the pan is shown in Fig. 13. Consequently, the optimal distribution of throats and their dimensions are obtained.

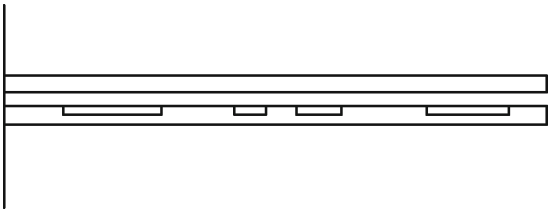

Fig. 10 Geometry of the inductor after optimization

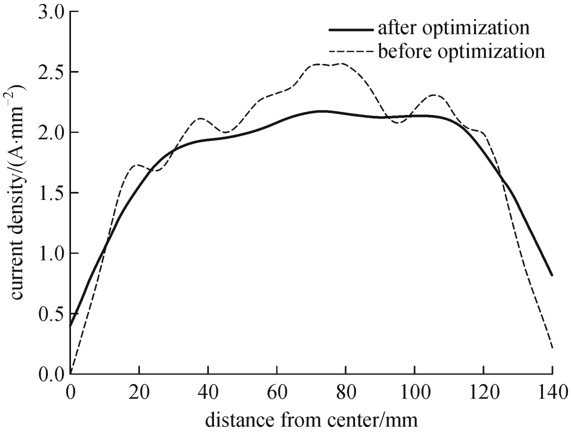

Fig. 11 Distribution of current density at the bottom of the pan

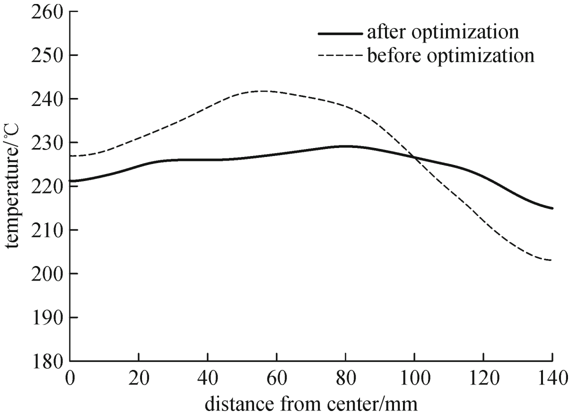

Fig. 12 Distribution of temperature at the bottom of the pan

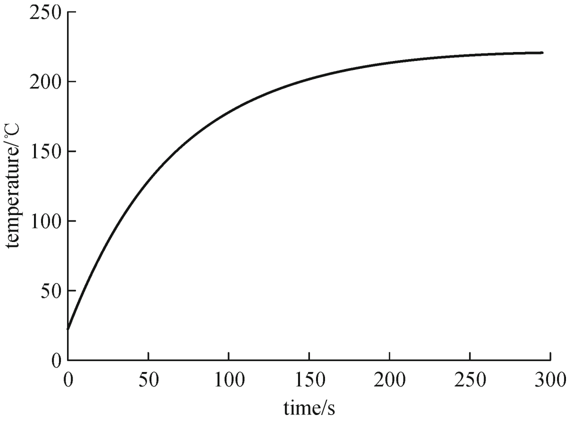

Fig. 13 Temperature evolution versus time

Table 2 New dimensions of the throats

	d_i/mm							
value	16.2	24.0	19.3	7.7	7.9	12.1	21.4	21.4

5 Conclusion

To develop an optimal system of induction-heating cooking,

1) A structure of inductor with coils placed in throats is proposed.

2) A method of optimization using GA searching for an optimal structure of the throats in the inductor is used.

3) A good distribution of the density of current and homogeneous temperature distribution along a ray of the pan is obtained.

4) The optimal distributions of throats and their dimensions are obtained.

References

1. Davies E J, Simpson P G. Induction Heating Handbook. London: McGraw-Hill Book Company Ltd., 1995
2. Su W C. The control design and practical measurement for high frequency induction heating. Dissertation for the Master’s Degree. Chung Li: Chung Yuan Christian University, 1998
3. Acero J, Hernandez P J, Burdio J M, Alonso R, Barragdan L A. Simple resistance calculation in litz-wire planar windings for induction cooking appliances. IEEE Transactions on Magnetics, 2005, 41(4): 1280–1288
4. Holland J H. Adaptation in Natural and Artificial Systems. Cambridge, MA: MIT Press, 1992
5. Yokose Y, Cingoski V, Yamashita H. Genetic algorithms with assistant chromosomes for inverse shape optimization of electromagnetic devices. IEEE Transactions on Magnetics, 2000, 36(4): 1052–1056
6. Yokose Y, Cingoski V, Kaneda K, Yamashita H. Shape optimization of magnetic devices using genetic algorithms with dynamically adjustable parameters. IEEE Transactions on Magnetics, 1999, 35 (3): 1686–1689
7. Burais N, Pertoldi S, Gaspard J Y. Couplage de modèles pour la conception d’inducteur de cuisson par induction. In: Proceedings of NUMELEC’97. 1997
8. Du Terrail Y, Sabonnadiere J C, Masse P, Coulomb J L. Nonlinear

complex finite elements analysis of electromagnetic field in steady-state AC devices. IEEE Transactions on Magnetics, 1984, 20(4): 549–552

9. Féliachi M, Develey G. Magneto-thermal behavior finite element analysis for ferromagnetic materials in induction heating devices. IEEE Transactions on Magnetics, 1991, 27(6): 5235–5237
10. Byun J K, Choi K, Roh H S, Hahn S Y. Optimal design procedure for a practical induction heating cooker. IEEE Transactions on Magnetics, 2000, 36(4): 1390–1393
11. Moreau L. Modélisation, conception et commande de génératrices à réluctance variable basse vitesse. Thèse de Doctorat de l'Université de Nantes. Nantes: Université de Nantes, 2005