New designs systems for induction cooking devices for heating performances improving

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Abstract: In order to give a temperature distribution at the bottom of the induction cooking, and moderate reduction the temperature outside the useless areas of these systems. This paper is dedicated to the study of the induction heating systems, which involves coupled electromagnetic and thermal phenomena and where new topologies are proposed. The modelling of the problem is based on the Maxwell's equations and the heat diffusion equation. We present a numerical simulation method based on parameterization of thermal electromagnetic coupling phenomena taking into account the changing of the physical characteristics of the body during the induction heating process. The purpose of this new optimum perforation topology is based on improving the thermal performances of the system, which allows improved dissipation by heat exchange. The results are obtained from a two-dimensional calculation code developed and implemented on Matlab software where CVM the finite volume method was adopted as a method of solving partial differential equations with partial derivatives characteristics of physical phenomena.

1. Introduction

Induction heating applied to the domestic cooking has significantly evolved since the first cooking hobs appeared some years ago. Different issues such as maximum power available for heating the pan, dimensional compactness of the hobs, or inverter electronics efficiency have achieved a great development (LIorente et al. 2002). During the last years, the flexible cooking zone concept has been introduced in the hobs in order to cope with the users' demand of flexibility.

The principal objective is to make hobs adaptable to the usage of different pots, with any shape and size. As a result, several possibilities have emerged showing different advantages and drawbacks (Acero et al. 2010). In recent years, due to the inherent benefits of the induction cooker, such as high heating efficiency, quiet, clean and so on, it has been widely used in families and catering instead of ordinary stove plates. Traditional induction cooker basically consists of one metal pan and one magnetic coil. The coil is usually excited by a medium-frequency (20 kHz ~ 100 kHz) power source and producing alternating magnetic field, which causes eddy currents to heat up the pan (LIorente et al. 2002). Recently one of development tendencies for induction cooker is the multicoils design that is adaptive to desire shapes and power capabilities, thus replace the traditional single coil and pregnant pan (Forest et al. 2007). Thermal distribution of an induction cooker is generally determined by its induction coil geometry (Tsopelasand Siakavellas2008).

Traditional single coil system commonly suffers from localized heating distribution which leads to fast aging of the pan. In addition, generally, in the conventional induction heating system (cooking), the temperature distribution provides high points that are located in different regions of the pan, which resulted in a deterioration of the pan. Design of several distributed coils is one effective solution to improve the thermal performance as well as to provide flexible functions. To remedy these problems, there is provided a pierce pan. This paper proposes investigates for new design of heating cooker system. Considering the effects of proximity between the coils (Meng et al. 2011), the eddy currents and power losses distributions are studied using volumes control method analysis (Kurose et al. 2009). The system thermal performances are further evaluated, based on the theoretical analysis. In this work, there is provided an induction heating system with an inductor in several concentric coils below the surface of the cooktop.

With the combination of different strategies of the two pans, the power distribution generated in the work piece can be controlled to ensure uniform heating. This solution is a pierce pan, enables centralized heating , reduces so moderate the temperature outside the areas not usable for the system and to a device dimension to the lower plate and avoid very hot areas in the pan. For the study of such a solution, a theoretical model of the process by induction heating of the two metal pans is provided. In order to get better temperature distribution in the fund uses different calculation strategies. The model is solved numerically using CVM, which gives accurate results; beyond this document provides an extensive model for the heat issue and a theoretical analysis of the performance of our solution of the pan pierce.

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Nomenclature

A	magnetic vector potential, T.m
J_s	source currents density, $A.m^{-2}$
K	thermal conductivity, $W.m^{-1}.K^{-1}$
Q	heat source, $J.m^{-2}$
T	temperature, K
E	Electric Field, V/m

Greek symbols

ν	magnetic Relectivity, $m.H^{-1}$
μ	magnetic permeability, $H.m^{-1}$
σ	electrical conductivity, S/m

The paper is organized as follows: the proposed system with a perforated plate for improved thermal performance in Section I. A theoretical model of the process of induction heating of the full plate and perforated plate with mathematical models is presented in section II. Results and discussion of the thermal model is explained in Section III. The analysis of heating performance of the proposed solution is presented in section IV. Finally, the main conclusion as presented in Section V.

2. Design of heating cooker system

Figure 1 presents the induction heating pan with six coils. The pan is made by a stainless-steel with the magnetic permeability, conductivity and thermal conductivity. These parameters are variable in the process with the exception of the heat transfer coefficient. From the shape of the model, an axisymmetricalmodeling is used.Considering practical pan shapes, two types of pan formats are proposed, including six coils. The coils are connected in series and driven by one current sourceJ_s = 1.10 ^{6} [$A.m^{-2}$], and a various frequency equal to f= [15, 20, 30, 40, 50, 90] kHz.

Due to the proximity effects among the distributed coils represent a crucial role in determining the magnetic flux distribution and eddy currents. Beyond it is proposed to study the systems more inductors; a coil inductors has six hot plate punches (Fig. 1).

The induction cookers implementing the proposed multicoils (six inductors) and pierce pan with Maxwell’s equations modeling to resolve a wide variety of electromagnetic and thermal. The technical parameters of the induction cooker are given in Table 1.

Table 1. SHAPE coils and pan geometrical characteristics.

Characteristics	Dimensions
Inductors	0.10 m
Thickness (Exciting coils)	0.04 m
Thickness (Pan-Exciting coils)	0.06 m
Thickness (coil-coil)	0.40 m
Gap	0.30m
Pan	0.95m
Thickness	0.12m

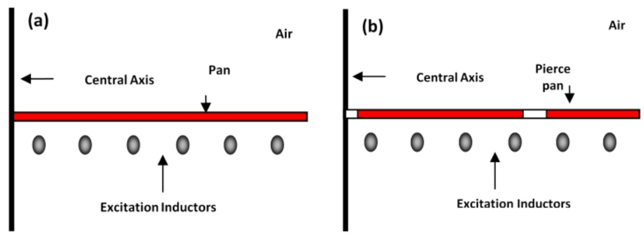

Fig. 1. Induction heating pan with six coils: a) Pregnant pan; b) Pierce pan.

The exciting current is I= 20 [A] at f = [15, 20, 30, 40, 50, 90] kHz for each coil. Electromagnetic phenomena that appear in induction heating devices are governed by the equations of MAXWELL, with the ability to resolve a wide variety of electromagnetic and thermal.

3. Governing equations

The magneto dynamic equation is derived from Maxwell's equations and materials constitutive laws. The heat diffusion equation is governed by the Fourier law. These equations are written in the case of the A formulation related to the magneto dynamic problem (Byun et al. 2000). The mathematical model of induction heating incorporating the mentioned multi-physical couplings must couple the following equations: (i) Maxwell's equations: to access to the currents induced in the specified parts, and (ii) Heat transfer equations: to model the thermal evolution due to the power dissipated by the currents induced in this part (pan).

3.1 Electromagnetic model

The electromagnetic problem is modelled using the four classical Maxwell quasi-permanent states, the relationship between the magnetic field induction B the magnetic field H, and Ohm's law; for an axisymmetrical configuration, a judicious combination of above equations leads, the equation is applied to the magnetic in the case where the load is stationary relative to the inductor. In the case where the work piece is stationary relative to the inductor, U is considered uniformly zero, equation becomes (Byun et al. 1998; Feliachi and Develey1991):

$$\overrightarrow{curl}\,(V\,\overrightarrow{curl}\,\vec{A}) + \sigma\frac{\partial A}{\partial t} = J_{ex} \tag{1}$$

3.2 Thermal model

The temperature is the image of the distribution of induced currents which depends on the following parameters geometric structure of the whole-inducing griddle. The electromagnetic properties (conductivity σ magnetic permeability μ .The temperature evolution is mainly governed by the power dissipated by the induced currents. The heat equation is then written here:

$$k\nabla^2 T + \overline{q} = 0 \tag{2}$$

The term comes from the source of powers dissipated by the Joule effect. (Kurose et al. 2009; Byun et al. 2000) Dirichlet and Neumann boundary condition, Discretization by CVM are applied to all the systems and produces linear system matrices. Note that, the heat conducting system has mixed convection boundary condition (Feliachi and Develey 1991).

3.3 Coupling model

Temperature is the main variable to determine when modeling a system of induction heating, and where the electromagnetic and thermal equations are coupled (Alloui 2003). The coupling term is the density of the average power over a period, which can be written as follows:

$$p = \frac{1}{2}\,\sigma(T)\,\omega^2 A^2 \qquad (3)$$

3.4 Numerical analysis model

The volume control method (CVM) is adopted to solve partial differential equation described coupled electromagnetic and phenomena prevention heating applications induction. The numerical method used in this paper is the CVM recently published (Alloui et al. 2009; Kameni et al. 2014). The CVM can be considered as a special version of the weighted residuals method. It consists, in dividing the domain into a number of non-overlapping sub-domains or control volumes. Each node of spatial discretization is surrounding by a control volume (Fig. 2).

The weighting function is the indicate function whose value is 1 on the sub-domain and zero everywhere else. This variant of the method of weighted residuals is called the sub-domain method or CVM. The classical formulation of CVM deals with differential equations that obey a defined conservation principle by the divergence operator. In this case, we need six nodes around each principle node P to perform the discretization of the algebraic equation: 1) West (W); 2) East (E); 3) South (S); 4) North (N); 5) bottom (B); and 6) Top (T) (Fig.3). This formulation with seven nodes is suitable to study many equations, such as the heat transfer equation or fluid flow ones, but is not well appropriate for the 1D, 2D and 3-D electromagnetic equations, which contain the rotational operator (Khene et al. 2015).In this case, the classical volume control method (CVM) formulation is modeled by adding twelve (12) additional nodes. When the magnetic permeability is constant, the classical CVM formulation may solve the problem (Khene et al. 2015).

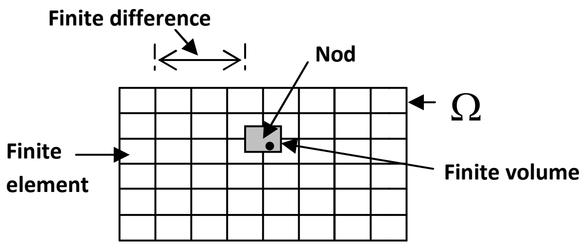

Fig. 2. Studied domain mesh area.

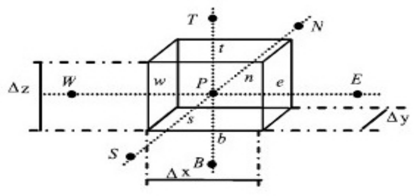

Fig.3. Basic control volume scheme.

The differential system obtained from equations (1) and (3) will be integrated over the control volume D as follows:

Recall the linear equation (1) in harmonic case:

$$\frac{\partial}{\partial z}\left(\frac{\nu}{r}\frac{\partial A^*}{\partial z}\right)+\frac{\partial}{\partial r}\left(\frac{\nu}{r}\frac{\partial A^*}{\partial r}\right)-i\,\omega\,\frac{\sigma}{r}\,A^* = -J_{ex} \qquad (4)$$

The projection of this partial differential equation on the basis of projection functions βi (the projection function equal to 1/r), and its integration on the finite volume, corresponding to the node P, gives:

$$\iint_{z\,r}\beta_i\left(\frac{\partial}{\partial z}\left(\frac{\nu}{r}\frac{\partial A^*}{\partial z}\right)+\frac{\partial}{\partial r}\left(\frac{\nu}{r}\frac{\partial A^*}{\partial r}\right)\right) r\,dr\,dz = \iint_{z\,r}\beta_i\left(i\,\omega\,\frac{\sigma}{r}\,A^*-J_{ex}\right) r\,dr\,dz \qquad (5)$$

The integral of the left side of equation (5) on the finite volume delimited borders (e, w, s, n):

$$\int_s^n\int_w^e \frac{\partial}{\partial z}\left(\frac{\nu}{r}\frac{\partial A^*}{\partial z}\right)dr\,dz+\int_s^n\int_w^e \frac{\partial}{\partial r}\left(\frac{\nu}{r}\frac{\partial A^*}{\partial r}\right)dr\,dz \qquad (6)$$

Thus, the final algebraic equation can then be written in the form:

$$b_P\,A_P^* = b_e\,A_E^* + b_w\,A_W^* + b_n\,A_N^* + b_s\,A_S^* + d_P \qquad (7)$$

With:

$$b_n = \frac{\nu_n\,\Delta r}{r_n\,(\delta z)_n},\; b_s = \frac{\nu_s\,\Delta r}{r_s\,(\delta z)_s},\; b_e = \frac{\nu_e \Delta z}{r_e\,(\delta r)_e},\; b_w = \frac{\nu_w\,\Delta z}{r_w\,(\delta r)_w}$$

$$b_P = b_e + b_w + b_n + b_s + i\,\omega\frac{\sigma_P}{r_P}\,\Delta r\Delta z,\; d_p = J_{ex}\,\Delta r\Delta z \qquad (8)$$

If the discretization of the field has N nodes, it is necessary to study a system of N equations with N unknowns.

3.4.1. Boundary conditions

In the previous study (Alloui 2003), the authors established the equations of internal nodes. For limit the field of study, there are two ways to introduce the boundary conditions figure 4:

a) Condition of Dirichlet imposes the values of A at the edges of the study area. These values are taken null by the consideration of physical infinity;

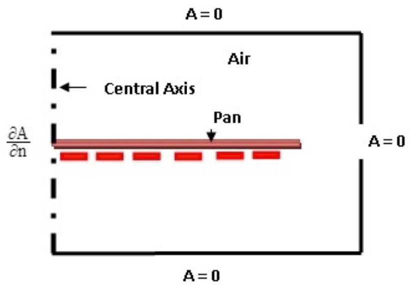

Fig. 4. Geometrical problem description.

b) Mixed Dirichlet and Newman conditions are used in the case where the system to study this symmetry plans. The mixed Dirichlet-Neumann problem imposes the values of A void ofinfinite edges of the study area$\Omega$and those $\partial A / \partial n = 0$ at the symmetry plans (cuts plans) where n is the normal to the cutting plane.

4. Simulation results

In order to conduct a comparison of this Induction Heating Systems with a full pan and another punched, we modeled their magnetic and thermal behavior, one of the challenges of the induction heating process is to choose is the shape of the coil and the choice of frequency. For the iron between the values (plate - inductors) e = 0.0030 m and the properties of electric current to the inductors are connected in series with a current source density J_s = 1.106 A / m with temperature variation test for a range of frequency: f = [10, 15, 20, 30, 40, 50, 90] kHz.

The simulation results obtained by the presentation on the figures 5 (a) and Figure 5 (b). We can say that the magnetic field of the conventional system is located very intensively in some parts of the pan illustrated in Figures 6 (a) and 6 (b), which will lead to local hot spots, and the heating performance degrades with rapid aging of the surface and slower cooling after heating. This can be avoided with the new proposed topology obtained by reinforcing the natural heat exchange between the tank and the surrounding air. On the other hand, the simulation results obtained, we can say that the temperature of conventional induction cooking is located very intensively in some parts of the pan which is 170 ° C (470 K °), which will lead to stains, and the heating performance deteriorates with the rapid aging of the surface and the new pierced plate topology by enhancing the natural heat exchange between the plate and the surrounding air, noting a degradation of the temperature 120 C ° (420 K °) by the effect of the holes these results illustrated in Figs 7 (a,b).

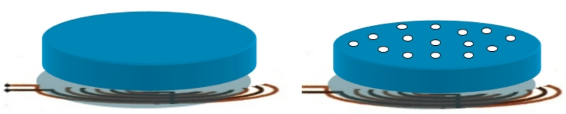

Fig. 5. a) Pregnant Pan; b) Pierce Pan.

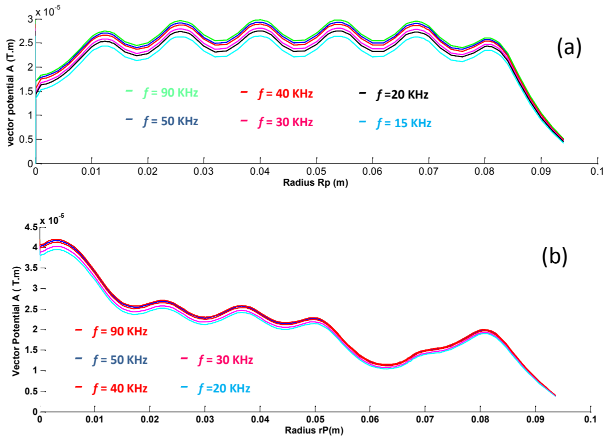

Fig. 6. Space evaluation of the vector potential in a) pregnant plate and b) pierce plate.

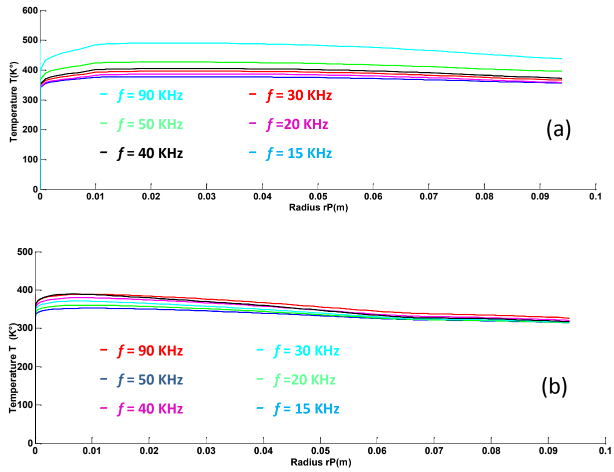

Fig. 7. Space evaluation of the temperature in a) pregnant plate and b) pierce plate.

The results are presented in Figures 8 (a) and 8 (b). We can say that it is the image of the magnetic field of the conventional system and of the new pierced plate topology, which changes shape by the effect of holes in the plate.

To our ongoing study on this novella topology, we will treat their magnetic and thermal behavior by testing different dimensions of the holes d = (0.0008 m,0.0012 m and 0.0020m) in order to achieve a usage limits our pierce pan to of medium and high a frequency range values equal to f = [50, 90] kHz. (a)

On the basis of previous theoretical analysis, it is understood that the induction coil considerably have an indirect impact on the heating process and thermal distribution. The coil format should be well designed for balancing heating efficiency and uniform thermal distribution. In this research, the configuration based on six coils and pierce pan system is adopted by taking advantage of its outstanding uniform thermal distribution performance and acceptable heating efficiency. We obtain uniformed temperature distribution as pursue at pregnant pan.

In Figures 9a,b, we can easily conclude that there is an intense localization of the temperature, beyond we seek the optimal

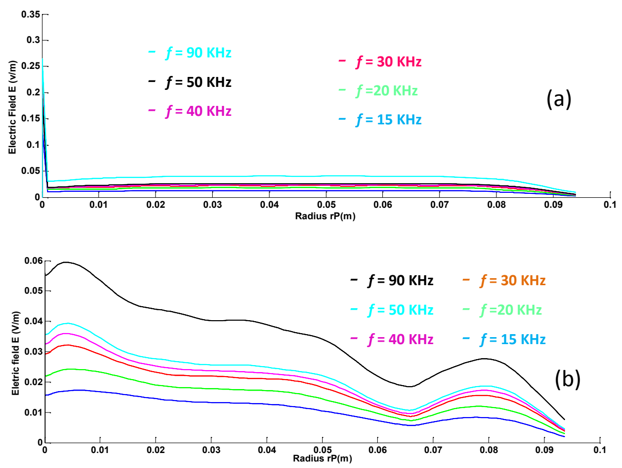

Fig. 8. Space evaluation of the electric field in the a) pregnant pan and b) pierce plate.

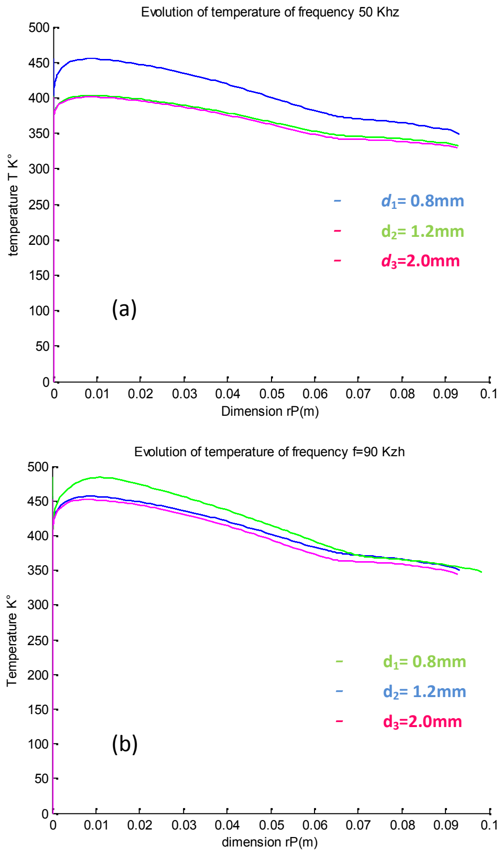

Fig. 9. Repartition of the temperature in load for a frequency a) *f* = 50 KHz and b) *f*=90 KHz.

geometry of the hole of the pan when taking three different dimensions: d_1 = 0.8 mm, d_2 = 1.2 mm and d_3 = 2 mm the illustration indicates that beyond large dimensions, we lose materials and we lose the regulation of the shape of the temperature.

5. Conclusion

In this work, finite volume method is used for solving, respectively, Maxwell's equations and the heat transfer ones. The finite volume mesh is unique for thermal and electromagnetic models that ensure fast and accurate exchange of data.

The different simulations results give the physical behavior of the device for the shape and the position of the inductors adopted. Then, deduce the optimum geometry by changing the dimensions of the perforation of the pan.

It can be confirmed that the lost in material, hence the sizing of the perforation cannot exceed the interval between [0.8 - 2.0] mm to have satisfactory results.

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