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Modelling and Temperature regulation using a new material FeNiCr alloy in induction cooking device

The interest of induction cooking is direct temperature obtained on pan without thermal inertia. However to prevent overheating of the pan, it is necessary to obtain a well regulated temperature. For this aim, we propose to use a new material, FeNiCr alloy, placed outside in the bottom of the pan. In this paper, we model the magneto thermal phenomena of system by a finite element method (FEM) for the mean to determine the temperature evolution in the bottom of the pan taking into account the nonlinearity of system. This study shows, that a temperature value exceed the desired value of cooking (200 - 300 ° C) ,when using a conventional pan (stainless steel). In the aim to have a regulated temperature, a layer of new material, FeNiCr alloy, witch have a low Curie point (300 ° C), is placed in the bottom of the pan. This technique assures a natural regulation of temperature.

Keywords: Finite element method, Magneto-thermal devices, Curie point.

1. INTRODUCTION

Over the last ten year, the use electromagnetic induction principle in cooking systems presents some advantages [1,2,3] comparing to classical process such as direct heating, homogeneous temperature, important energy economy.

The induction system (Fig.1), comprises the inductor itself and a heated plate. The inductor is supplied by a medium-frequency power source (20 kHz) producing an alternating magnetic field, which causes eddy currents in the bottom of plate and therefore, Joule dissipation.

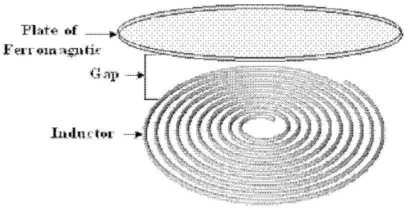

Figure 1: the modelled system

Numerical approach of the self regulation of the temperature of heating (Fig.1) is undertaken with the use of both heating power and Curie transition considered as plate working temperature.

Our work is based on the experimental study concerning an induction heating furnace using new low Curie transition materials [2].

In this paper, firstly we determine the temperature evolution on pan bottom constituted with conventional ferromagnetic material, using magneto-thermal calculation method. Secondly, in the aim to have a regulated temperature, we propose a technique using a layer of new material, FeNiCr alloy [2], which has a low Curie point (300°C), who's placed in bottom of pan. The obtained results are compared.

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2. COUPLED 2D MAGNETODYNAMIC EQUATION

2.1 Maxwell Equations

$$\nabla \bullet D = \rho \qquad (1)$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (2)$$

$$\nabla \times H = J_c + \frac{\partial D}{\partial t} \qquad (3)$$

$$\nabla \bullet B = 0 \qquad (4)$$

Since $\nabla \bullet B = 0$, we can define a vector potential, A, such that:

$$B = \nabla \times A \qquad (5)$$

E and H are the electrical and magnetic fields, B flux density, D displacement current , $\frac{\partial D}{\partial t}$ displacement current density which is neglected, J_c current density, ρ volume electric charges density.

2.2 Medium Constitutive Law

Mediums constitutive law considered with the association of Maxwell equations are as following:

$$B = \mu H \qquad (6)$$

$$J_c = \sigma E + J_s \qquad (7)$$

B : Magnetic induction [T]; H : Magnetic field (A/m); σ : electrical conductivity $[\Omega/m]^{-1}$; J_s :source current density $[A/m^2]$; μ is permeability.

The use of equations (2), (3), (4), (5), (6) and (7) yields to electromagnetic equation in terms of magnetic vector potential A :

$$\nabla \times (\nu \nabla \times A) + j\sigma\omega A = J_S \qquad (8)$$

ν is the magnetic reluctivity ($\nu = 1/\mu$). ω is the angular velocity ($\omega = 2\pi f$, f is the frequency [Hz]).

The studied problem is considered with axisymmetric and harmonic hypothesis.

The development of equation (8) in [r,z] plan permits to deduce the 2D partial differential equation [3]:

$$j\omega \frac{\sigma A}{r} - \frac{\partial}{\partial r}\left(\frac{\nu}{r}\frac{\partial A}{\partial r}\right) - \frac{\partial}{\partial z}\left(\frac{\nu}{r}\frac{\partial A}{\partial z}\right) = J_S \qquad (9)$$

3. COUPLED MAGNETO-THERMAL MODEL

3.1 Descriptive Equations

In order to know temperature evolution in the bottom of pan, which is the image of distribution of induced currents, it is necessary to solve the coupled Maxwell's and thermal equations. For the reason of axisymetric structure of the inductor, an axisymetric 2D solution is possible.

Using the magnetic potential A, electromagnetic phenomena are modelled by the well known magneto-thermal equation [4, 5]:

$$\nabla\times(\nu\,\nabla\times A)+j\sigma\omega A=J_S \tag{10}$$

$$\lambda\nabla^2 T+P=\rho_m C_p\frac{\partial T}{\partial t} \tag{11}$$

The Coupling between electromagnetic and thermal equation is realized trough power density P expressed by:

$$P=j\,\omega^2\,\sigma\,\overline{A}\,\overline{A}^* \tag{12}$$

$\overline{A}^*$ represent the complex conjugate of unknown $\overline{A}$.

T : temperature (°K), ρ_m : Mass density (Kg/m^3),

λ : thermal conductivity (W/m°C); P: power density (W/m^3) ; C_P : specific heat (J/Kg°C) and t is the time.

3.2 Boundary Conditions

The magneto-thermal analysis is performed by FEM (finite element method) using the governing equations (10) and (11) and the following boundary conditions (13) and (14):

$$\text{Dirichlet } (A=0) \tag{13}$$

$$-\lambda\frac{\partial T}{\partial n}=h(T-T_a) \tag{14}$$

h: is convection coefficient and T_a is ambient temperature.

The heat transfer coefficient in (14) has a role in determining the temperature distribution on the pan bottom of the device. Because of axisymetric structure of inductor, this makes h nonlinear due to the convection effect of the air nearby [5].

Thus we assume that h has a constant value (Table.1) along the radial direction of the axisymetric structure in studied system.

Table.1 Parameters of the simulated system

Symbole	Magnitude	Qantity
R	Radius of container	140 mm
e_i	Inductor thickness	3.8mm
e_g	Gap thickness	2mm
e_P	Pan thickness	1mm
d	Throat length	16.25 mm
e_q	throats thickness	2mm
μ_f	ferrite relative permeability	2500
f	Frequency	20*10^3 Hz
J	Current density	2.5*10^6 A/m^2
λ	Thermal Conductivity	26 W/m*°K
h	Convection coefficient	20W/m^2°C
ρ_m	Masse density	7700 kg/m^3
Cp	Specific heat	460 J/°C

4. TEMPERATURE EVOLUTION IN PAN WITH CONVENTIONAL FERROMAGNETIC MATERIALS

The pan is made by a ferromagnetic stainless-steel. The curves σ(T) and μ (T), of the material, are shown respectively in Fig.2 and Fig.3 [6].

For heat the pan, we use an inductor with four throats containing coils (Fig.4). The other parameters shown in (Table1), except the conductivity σ(T) and permeability μ (T), can be assumed constant during the procedure of calculation for temperature.

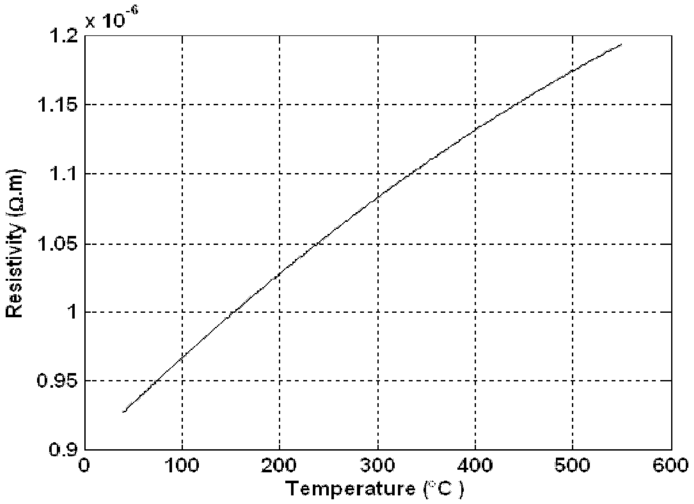


Figure 2. Curve of resistivity

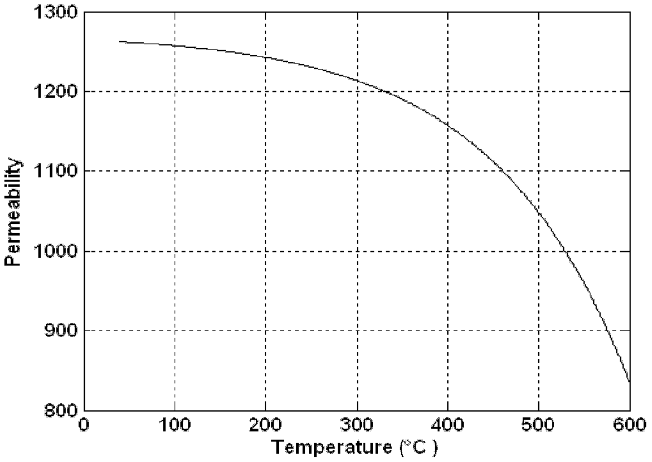


Fig.3. Curve of permeability

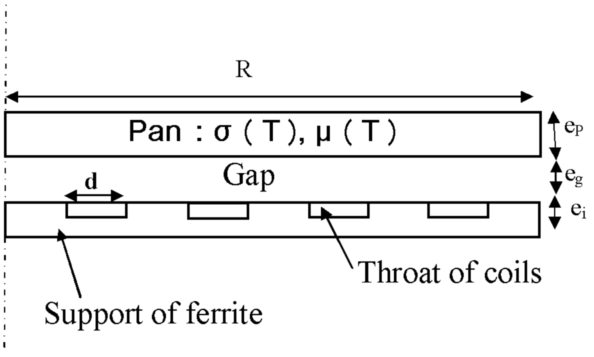


Figure 4. Geometry of the model used in the program

Coupled problem represented by equation (10) and (11) is solved using finite elements program performed under MATLAB package for each time step. The electromagnetic equation is solved with harmonic hypotheses. The update of the electrical conductivity is realized at each time step of solved thermal problem.

The flow chart of magneto-thermal calculation of our system is illustrated in Fig.5.

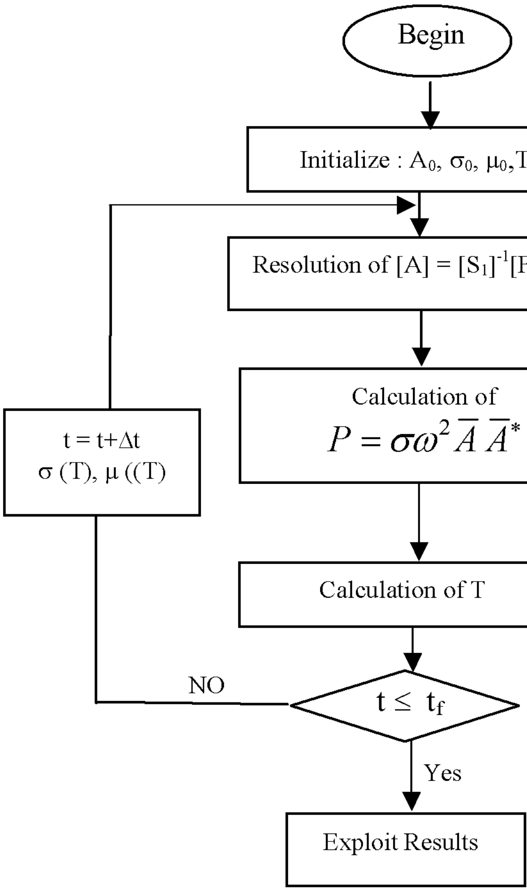


Figure 5. Flow chart of magneto thermal program

The thermal problem is solved step by step in the time using a step of 5 seconds.

The temperature evolution versus time in a point situated at the middle of the pan is indicated in (Fig.6). The desired temperature (200-300) °C is obtained after a time of 70s, but we note that the temperature can achieve 455°C in permanent regime.

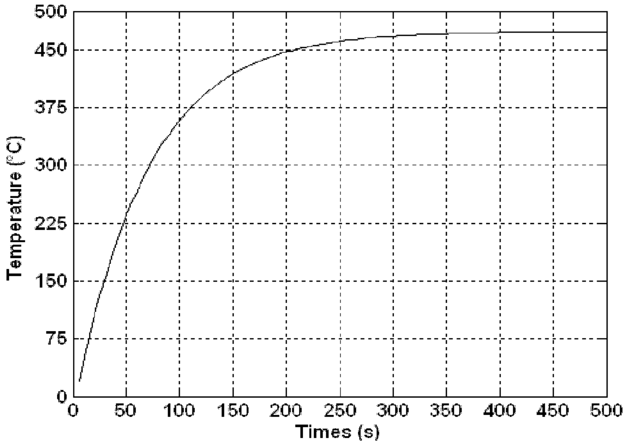


Figure 6: Temperature evolution of conventional material

5. REGULATION TEMPERATURE IN PAN WITH A LAYER OF F_EN_IC_R ALLOY

Experience shows that the Curie temperature may increase or decrease depending on the percentage of Ni and Cr alloy in the FeNiCr [2].

The main aim of this work is to suggest a technique, using a layer of new material, FeNiCr alloy which have low Curie point (300 °C), for natural limitation of temperature in bottom of the pan.

In order to obtain such solution, we consider a pan with a non magnetic material (Aluminium: $\sigma = 37.106(\Omega.\text{m})^{-1}$, μ_0 and thickness e_P=1mm) whose bottom is covered outside by a layer of FeNiCr alloy with a thickness e_L= 0.3mm (Fig.7). We use the same magneto thermal model as described in the section 3 taking the new magnetic and electric properties (μ (T), σ(T)) and thermal characteristics (λ, ρm and C_P).

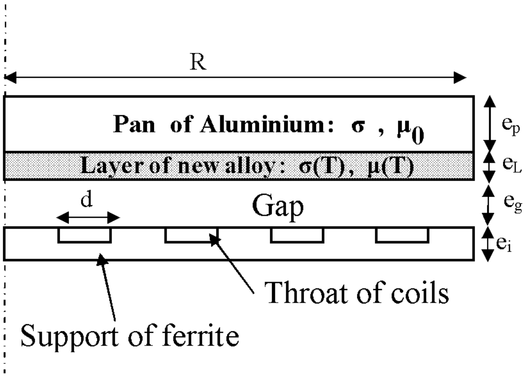


Figure 7: Pan with new alloy

5.1 Electromagnetic characteristics of FeNiCr alloy

We use three types of FeNiCr at different percentages of Ni and Cr with 300°C Curie point [3].

The electrical conductivity σ(T) and the magnetic permeability μ (T) of these materials are expressed as [7]:

$$\sigma(T) = \frac{\sigma_0}{1+\alpha T} \tag{15}$$

$$\nu(T) = \nu\left(1 - e^{\frac{T-300}{150}}\right) \tag{16}$$

$\rho_0 = 1/\sigma_0 = 13.75 \cdot 10^{-8}\ \Omega.\text{m}$;
$\alpha = 0.004$;
$\rho(T) = 1/\sigma(T)$ and $\mu(T) = 1/\nu(T)$.

The curves of σ(T) and μ (T) are shown respectively in Fig.8 and Fig.9.

The values parameters thermal are shown in Table2.

Table.2 : Characteristics of different FeNiCr alloy

Item	*New ferromagnetic material FeNiCr alloy*	*Masse density ρ_m (kg/m^3)*	*Specific heat Cp(J/C°)*	*Thermal Conductivity λ (W/m°K)*	*μ_r (Tc= 300°C)*
1 [7]	Nickel (32-35) % Chromium (20-23) %	8000	450	11.6	1273
2 [7]	Nickel (36-39) % Chromium (26-30) %	8000	500	14.6	1273
3 [8]	Fe-Nickel-Chromium alloy	7849	460	59	1273

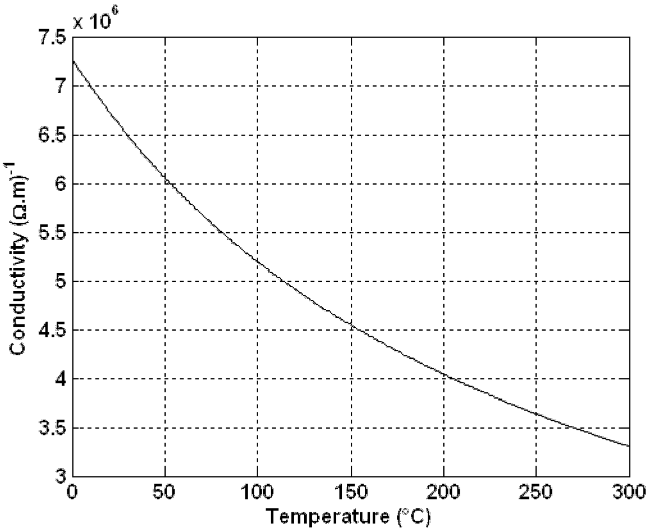


Figure 8: Curve of conductivity

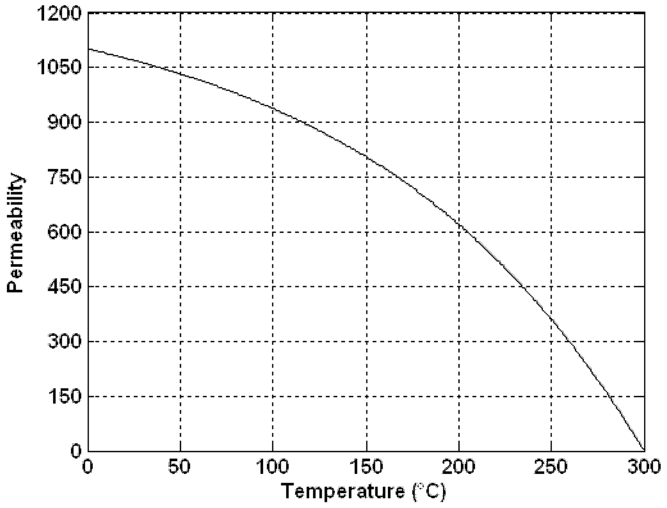


Figure 9: Curve of permeability

6. RESULTS AND DISCUS

The temperature results using the three types of FeNiCr alloy are presented in figures 10, 11, and 12.

At the beginning of the heating, the material (pan) has a considerable value of permeability which concentrates electromagnetic field. However the induced current is considerable and therefore the temperature evolution increases quickly versus time. Once, the temperature approaches the Curie point, the permeability of material decrease until µ0, causing the decrease of the induced current. This last phenomenon guaranties a natural regulation of the temperature.

We can presume that, the use of new material with low value Curie point assures the regulation and limits temperature rise beyond that value.

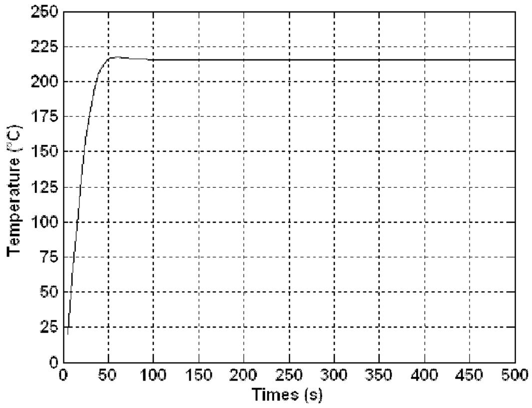
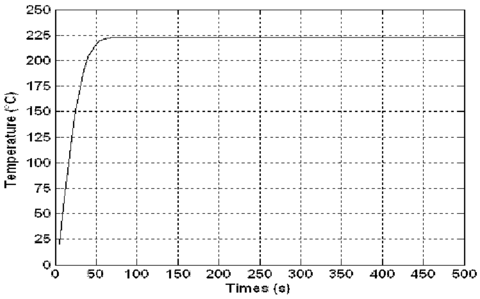


Figure 10: Temperature evolution of material: 1



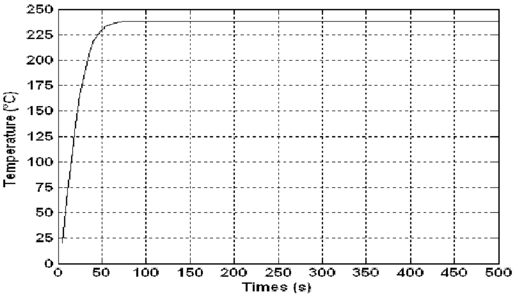


Figure 11: Temperature evolution of material: 2

Figure 12: Temperature evolution of material: 3

7. CONCLUSION

In This paper, a new material FeNiCr alloy has been used, for a regulation of the temperature in induction heating system.

The simulation result shows that the proposed technique gives a well regulation of temperature compared to the use of conventional material. The use of FeNiCr alloy at (300°C) Curie point, assure a natural regulation of temperature between 200°C and 300°C which is suitable for the induction cooking system.

We conclude that the desired final temperature may increase or decrease depending on the percentage of Ni and Cr alloy in the FeNiCr.

REFERENCES

[1] Z.Oudni, A.Kanssab, H. Mohellebi, M.Feliachi « Finite elements modelling of Ferromagnetic plate induction Heating Control Using Curie temperature » *IEEE Conference on Electromagnetic Field Computation CEFC*. 2008 in Athens, Greece, May 11-15, 2008.

[2] T.Waeckerlé, H.Fraise, Nouveau alliages magnétiques FeNi pour la cuisson par induction avec autorégulation de température, *RIGE 2006*, Edition Hermès.

[3] A.Kanssab , M.Feliachi, A.Zaoui, B.Mazari "Optimization by Genetic Algorithms of an Inductor for Induction cooking" *International Conference on Electrical Engineering Design and Technologies ICEEDT'08,* November , 8-10, 2008 Hammamet, Tunisia.

[4] J. Acero, P.J. Hernandez, J.M. Burdio, R. Alonso, and L.A. Barragan "Simple Resistance Calculation in Litz-Wire Planar Windings for Induction Cooking Appliances" , *IEEE Trans. on Magnetics*, vol. 41,no.4,pp.1280-1288, April 2005.

[5] P.Qiugen, Contribution à la modélisation des phénomènes magnétothermiques dans les systèmes électromagnétiques par la méthode des éléments finis, Thèse de doctorat, Université Paris VI, Spécialité : Science Physique (Electrotechnique), 1992.

[6] A.Kanssab, B.Mazari, M.Brahami, F.Bellouazani and B.Belmadani, ''Modélisation et commande par réseaux de neurones d'une table de cuisson à induction'', *Rev. Roum. Sci. Techn.-Electrotechn. et energie 53, 1*, p.109-118, Bucarest, 2008.

[7] M. Féliachi and G. Develey, Magneto-Thermal Behavior Finite Element Analysis for Ferromagnetic Materials in Induction Heating Devices, *IEEE Trans. on Magnetics*. 27, n° 6, p. 5235-5237, nov. 1991.

[8] S.H.Ould Ouali, H.Mohellebi, R.Chaibi, M.Feliachi, Introduction de l'effet de la temperature dans le modele de Preisach pour la generation des cycles d'hysterisis, *Journal de Physique IV*, France 124,pp 315-320, EDP Science, Les Ulis, 2005.