

THERMAL EFFECT OF ELECTROMAGNETIC RADIATION INCIDENCE ON METALLIC SURFACES COATED WITH EPOXY AND FERRITE

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Abstract. *The present paper has the goal of showing the results of a study of the heat transfer mechanisms on metallic structures coated with electromagnetic shields composed by ferrites of $Mn_xZn_{x-1}Fe_3O_4$. These coverings are used as suppressors of electronic noises in embarked electronic systems or to shield antennas. It is made of a rectangular aluminum plate re-covered by a plain film of ferrite that, when being exposed to electromagnetic radiations in the band of 2-20 GHz (microwaves) with a power per unit area of 2,0 mW/cm^2, present distinct mechanisms of energy transformations. The analysis is carried out using a simple discretization procedure through the method of the finite difference having generated a structuralized three-dimensional mesh where different types of boundary conditions are independently applied for each face. A more refined mesh is used for the ferrite coating since this layer is the responsible one for the radiation absorption, besides having a smaller thickness if compared to the aluminum plate. Also the behavior of the interface of the aluminum and ferrite is analyzed through the use of the thermal resistance of contact simulating the temperature jump due the superficial irregularities on the contact area of these materials. The numerical model is validated simulating cases found in the heat transfer literature.*

Keywords*. Heat transfer, microwaves, electromagnetic shields, finite difference, thermal resistance.*

1. Introduction

The search for materials that display characteristics of electromagnetic shields has become a new world concern, because of the increasing use of transmitting/receiving electromagnetic waves equipments. The project aspects of a material that absorbs electromagnetic radiations is mainly focused on merging dielectric and magnetic materials that provide a specified impedance profile for a certain electromagnetic wave incidence. In this way, the development of the technology of manufactured absorbing materials is related directly to the study of the materials as well as the exploration of techniques to obtain shields with good absorption characteristics for a wide spectrum. Shields based on the addition of metal oxide particles to polymers are revised by Weidenfeller (2002). It has been found that they significantly increase both the electric and thermal conductivities, and may substitute metals in applications of interference screening in radio. A widespread used oxide in the radiation absorption and radiation shield industry is the iron oxide (Fe_3O_4), and its used along with thermoplastics is relatively new. Iron oxide is a major constituent of ferrites, which are mixtures of metallic oxides. The physical mechanism associated with absorption of radiation is the internal energy accumulation, which becomes the heat source term in the heat equation. Among many others, Pingkuan (2000) used this concept in the study of heat transfer from a surface exposed to radiation. Actually, the absorption of radiation by ferrite particles embedded in the epoxy causes an increase on the local internal energy and, as temperature rises, heat diffusion occurs to within the coated material and heat convection to surrounding fluid (as well as radiation). Epoxy is transparent to electromagnetic radiation and consequently it does not absorb the radiation that would be transformed into heat. The material to be studied in this work is $Mn_xZn_{x-1}Fe_3O_4$, whose absorbing properties are excellent in the microwave band (Migliano, 1999). One of the reasons for the use and the study of this material is the high electric resistance of the magnesium (10^8-10^{10} Ω), and because of this high resistance, in high frequencies, electromagnetic waves can penetrate into the body of the absorbing giving rise to heat generation. Limitations to the use of these ferrites as electromagnetic shields are due to the temperature of Curie, because it establishes the maximum working temperature before the material loses its characteristic of electromagnetic absorber. The applications of those materials concentrate on industries such as telecommunication and aeronautics, as well as in screenings of cellular and screenings of microwave ovens.

2. Model Description

2.1 *The Lumped Capacitance Method*

The essence of this method is the hypothesis that the temperature inside the solid is spatially uniform at any instant of time during transient processes; in other words, the temperature gradients inside the solid are negligible. For the validity of the simplification of the lumped capacitance method it is necessary to analyze the number of Biot, which is the ratio between the internal resistance to heat diffusion to the external resistance to heat transfer (convection) and is given by Eq. (1)

$$Bi = \frac{hL}{k} \tag{1}$$

where Bi is the dimensionless Biot number, h is the convective heat transfer coefficient, L is the characteristic length, and k is the thermal conductivity. If $Bi << 1$, the resistance to conduction within the solid is much smaller than the resistance to convective heat transfer. An usual threshold to admit that the error associated with the use of the lumped capacitance method is small is $Bi <0.1$, and in solids as plates the error will be less than 5% (Kreith, 1977).

The composite epoxy-ferrite coating layer thickness is of the order of 1 mm, whose small value together with the average thermal conductivity yields to a low Biot number. Therefore, it allows one to carry out a lumped or concentrate analysis for the coating and a simple computational node suffices.

2.2 *Contact Resistance*

Between the coating and the solid substrate, there exists a contact thermal resistance that needs also to be accounted for. Contact resistance phenomenon happens due to superficial imperfections of both materials brought into contact as well as the contact pressure that keeps them together. Fig. (1) depicts a physical model of the interface between any two materials. As illustrated, conductive heat transfer occurs through contacting areas while conduction and radiation through in the areas of flaws.

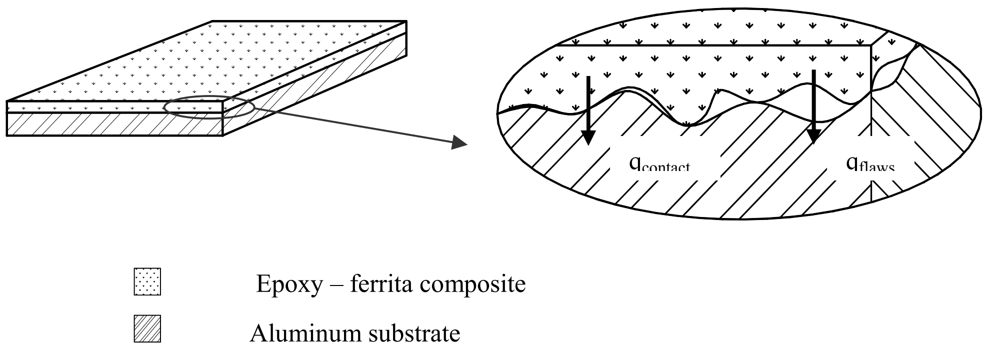


Figure 1. *Interface of materials.*

The thermal resistance of contact is defined by Eq. (2).

$$R''_{t,c} = \frac{T_A - T_B}{q''_x} \tag{2}$$

Where $R''_{t,c}$ is the thermal resistance of contact, T_A is the temperature of the material A in the interface, T_B is the temperature of the material B in the interface and q''_x is the heat flux per area that flows perpendicularly to the average contact location as presented in Fig. (2) taken from the work of Gebhart (1993) .

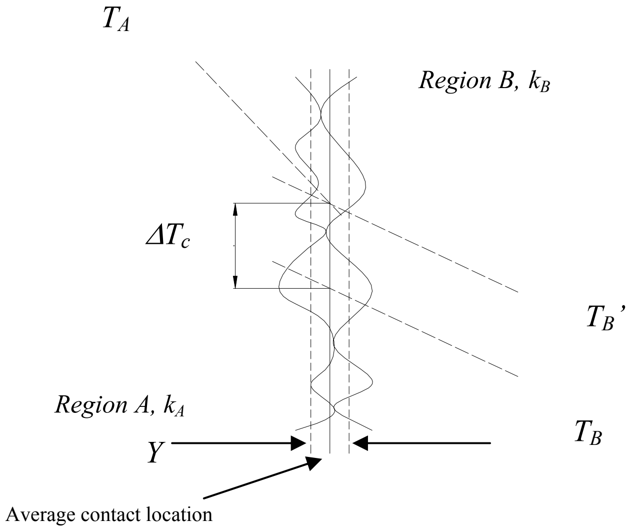


Figure 2. *A contact region between adjacent solid layers of a composite barrier (Gebhart, 1993).*

The physical contact area increases as the contact pressure increases due to the imposed mechanical deformation and this explains why contacting pressure is one of the two important factors to be considered in obtaining the resistance contact. In Fig. (2) dashed lines represent the average contact areas of solid A and solid B, and Y is the distance between these two lines. Temperature distributions for the two solids are T_A and T_B respectively, each side displays a different inclination, since $k_A \neq k_B$. If a perfect contact existed between the two areas, the ideal temperature distribution would be T_A and T_B' and the curves would intersect each other at the medium location as shown in Fig.(2). But due to surface imperfections, a non-negligible temperature gradient exists that results in a temperature jump given by ΔT_c.

Solids whose conductivity is greater than the fluid trapped in the flaws has the thermal resistance of contact reduced as contact points increase, which generally occurs with a better surface polishing (roughness reduction) and higher contact pressure. Several models have been developed for the calculation of this parameter as function of the contact geometry and the thermal properties. Laraqi (2002) presents a simple model where the contact area is modeled as disks of different diameters randomly distributed over the area.

2.3 *Mathematical Model*

For the three-dimensional mathematical modeling of the transient phenomenon of heat transfer, some important considerations have been made to simplify the governing heat equation. The materials are considered to be homogeneous, isotropic and they present constant density and constant specific heat during the heating process. The temperature of the surrounding environment is constant T_∞. In agreement with those considerations the three-dimensional heat equation in Cartesian coordenate system for a plane plate with electromagnetic radiation incidence is given by Eq. (3).

$$\frac{\rho c_p}{k}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \dot{Q} \tag{3}$$

where ρ the density and C_p the specific heat at constant pressure. The heat source term $\dot{Q}$ represents the heat generation that is not null for the ferrite, and vanishes everywhere else.

The boundary conditions are very important to represent the problem realistically. Over the surfaces, one may have convective heat transfer, which must satisfy the following condition (Eq. 4)

$$-k\frac{\partial T}{\partial i}\Big|_{i=x,y,z} = h\left(T - T_{\infty}\right) \tag{4}$$

where the dummy index *i* may receive any one of the directions x, y or z. For the boundary condition at the interface between the composite epoxy-ferrite and the aluminum substrate it has been used the thermal resistance of contact given by Eq. (5).

$$-k\frac{\partial T}{\partial z} = \frac{T_A - T_B}{R_{t,c}} \tag{5}$$

where, T_A is the temperature on the composite side, T_B is the temperature on the aluminum plate side, and $R_{t,c}$ is the thermal resistance of contact.

The heat source term $\dot{Q}$ appearing in Eq. (3) accounts for the absorption of the incident radiation since this material absorbs electromagnetic wave completely (Freitas, 2001) in the range of interest being characterized as a electromagnetic screening.

2.4 *Numeric Model*

2.4.1 Discretization

For the discretization of the domain, the classical Method of the Finite Differences (MFD) is used where the continuous domain is approximate by discreet points (nodes) and by finite approaches among those points. For the numeric solution of the mechanism of heat transfer, the plate is divided into discrete points, where the element will be the temperature of its center and the physical system will be substituted by a fictitious conductive mesh containing the nodes points. Balances of heat are established for each nodal point and, then, obtained as many algebraic equations as are the nodal points. An internal nodal point and its neighboring points are shown in Fig. (3).

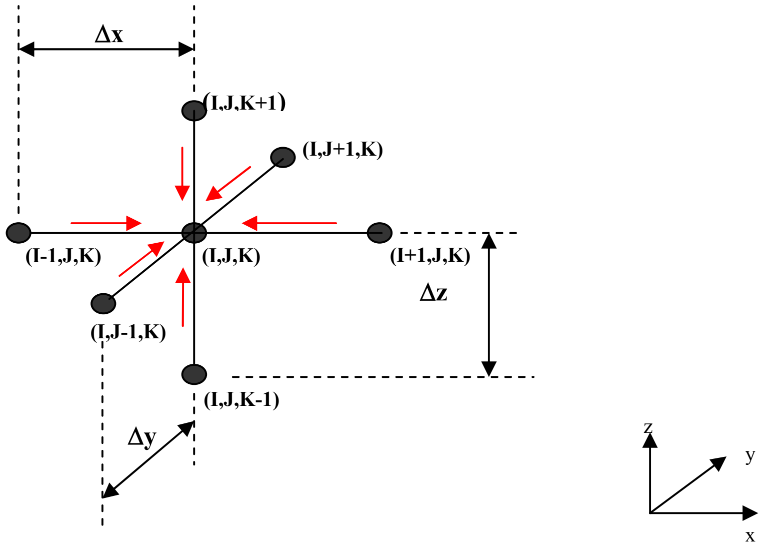


Figure 3. *An internal nodal point and its neighboring points.*

2.4.2 Solution Method

The method employed for the numerical solution to this problem is the explicit method, which is intrinsically stable. It uses an iterative technique of convergence solving the transitory heat equation (Eq. 3) until it reaches steady regime. The equation of the conservation of the thermal energy given by Eq. (3) discretizated explicitily for the internal nodes having $\Delta x = \Delta y \neq \Delta z$ is given by Eq. (6).

$$T_{(I,J,K)}^{P+1} = F_o\left[\frac{\Delta z}{\Delta}\left(\left(T_{(I-1,J,K)}^{P}\right)+\left(T_{(I+1,J,K)}^{P}\right)+\left(T_{(I,J-1,K)}^{P}\right)+\left(T_{(I,J+1,K)}^{P}\right)\right)+\frac{\Delta}{\Delta z}\left(\left(T_{(I,J,K-1)}^{P}\right)+\left(T_{(I,J,K+1)}^{P}\right)\right)+\frac{q(\Delta\Delta z)}{k}\right]+ \left(1-4\frac{\Delta z}{\Delta}F_O-2\frac{\Delta}{\Delta z}F_O\right)T_{(I,J,K)}^{P} \tag{6}$$

where the dimensionless Fourier is given by Eq. (7),

$$Fo = \frac{\alpha \Delta t}{(\Delta z)}, \tag{7}$$

where, α is the thermal diffusivity of the material. For each face, edge, corner and interface of materials a different node equation must be written that represents the appropriate boundary condition stipulated by the problem.

2.4.3 Stability Criterion

With the use of the explicit method for the transient case, the precision of the solution is related to the mesh size and consequently the reduction of the values of Δx, Δy e Δz are not arbitrary. There is a compromise between time steps and mesh size. For smaller mesh sizes a reduction on time steps is also necessary to keep the solution stable. Stable solution of the algebraic system of equations representing the several nodes requires positive matrix coefficients. Back to Eq. (6), this criteria may be satisfied if

$$Fo \le \frac{1}{\left(2Bi+4Bi_z+4\frac{\Delta z}{\Delta x}+2\frac{\Delta x}{\Delta z}\right)} \tag{8}$$

where, Bi_z is given by Eq. (9)

$$Bi = \frac{h\Delta z}{k} \tag{9}$$

Since Bi, Bi_z, Δx, and Δz are positive values, the higher the denominator, the smaller the Fourier number necessary to keep solution stable, which means that smaller time steps are also necessary, considering that is directly related to Fo and other magnitudes, i.e., $\Delta t = (Fo \times \Delta x \times \Delta z)/\alpha$. For internal nodes (no convection), the criteria is

$$Fo \le \frac{1}{\left(4\frac{\Delta z}{\Delta x}+2\frac{\Delta x}{\Delta z}\right)} \tag{10}$$

3. Case Study

The numerical solution was carried out using the structured programming language Fortran, where the user can enter with the desirable boundary conditions, material properties, and geometry. For the problem in study, it was simulated a plate of dimensions 30cm x 30cm x 3 mm, whose upper surface was submitted to a radiation power of 2mW/cm^2, value considered as limit by ANATEL (National Agency of Telecommunications). The properties of the ferrite and the epoxy were supplied by patents developed in CTA (Aerospace Technical Center) and the property of the contact resistance between epoxy and aluminum was found in (Fletcher, 1997). The other boundary conditions applied to the plate are heat convection (h=15 W/m^{2}K) to an environment kept at constant temperature (300 K). The upper surface coated with ferrite is stricken by electromagnetic radiation, which is completely absorbed and heat convection is also allowed. Finally, it can also be verified the real effect of the absorption of the layer of the composite and its mechanism of transmission of heat for the aluminum through the thermal resistance of contact.

3.1 C*omposition and Properties of the Material*

The studied material is a composite made of a mixture in mass of 1/1 of resin adhesive epoxy and ferrite of the type $Mn_xZn_{x-1}Fe_3O_4$, which is very effective radiation absorber in the microwave band (2-20 GHz). The average properties where obtained by mass weight participation are show in Tab(1).

Properties	Epoxy – ferrita composite	Aluminum
Density (kg / m^3)	1565	2702
Thermal Conductivity (W / m K)	3,13	237
Specific Heat (J / kg K)	303,7	903

Table 1. *Some relevant properties of the materials.*

3.2 *Restrictions*

The most relevant restriction to radiation absorption is the Temperature of Curie (Chen, 1986), because it establishes a maximum working temperature in which that material still have the desired magnetic properties that makes it a good radiation absorber. The transformation of Curie does not happen abruptly in a certain temperature. First, the material displays a saturation of polarization and it is gradually reduced within a certain temperature interval. It is resembles to an ordination reaction. It can be determined this variation of the magnetic polarization by the temperature (value that depends strongly on the intensity of the field applied).

Fig.(4) shows that the magnetic permeability raises to a peak before reducing to a very low value. That happens because the energy of magnetic anisotropy is also reduced to practically zero when approximating to the temperature of Curie, making possible the growth of the permeability. One of the criterions to define the temperature of Curie is the temperature of the peak of Hopkinson.

The criteria that will be used here demands that the derived with the temperature of the permeability will be determined and it defines that the temperature of Curie is the temperature of the minimum of these derived (Turtelli, 2000). Exemplifying, in Fig. (4) the temperature of Curie would be approximately 115 °C for curve *a*.

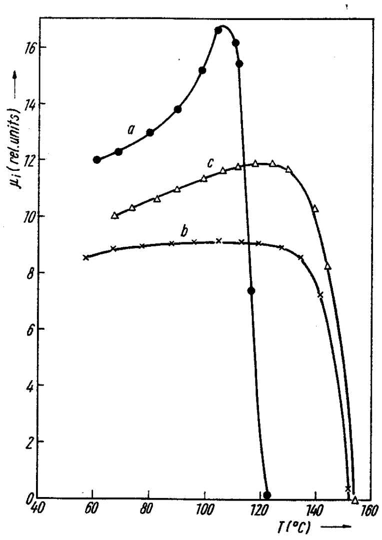


Figure 4. *Variation of the permeability with the temperature, for ferrites Mn0,48Zn0,47Fe2,05 O4 after the following treatments:; (a) 4h a 1320^{0}C, P_{O2} = 2 Torr; (b) 4h a 1320 ^{0}C, P_{O2} = 2x10^{-2} Torr; (c) Same, without the superficial layer (Vogler,1971)*

4. Results and Discussions

By analyzing Fig. (5), it can be verified that for the limiting radiation power (2mW/cm^2), there is heating basically just for the upper layer of the plate coated with the ferrite. The figure also shows that a temperature rise of about 15° C occurs for the ferrite coating, while very little heat diffusion occurs to the inner layers of the aluminum substrate. Other important point is the temperature jump across the contact area between the ferrite coating and the aluminum substrate. Fig. (6) shows a vertical cutting view of the aluminum block where a temperature jump of 14,5° C.

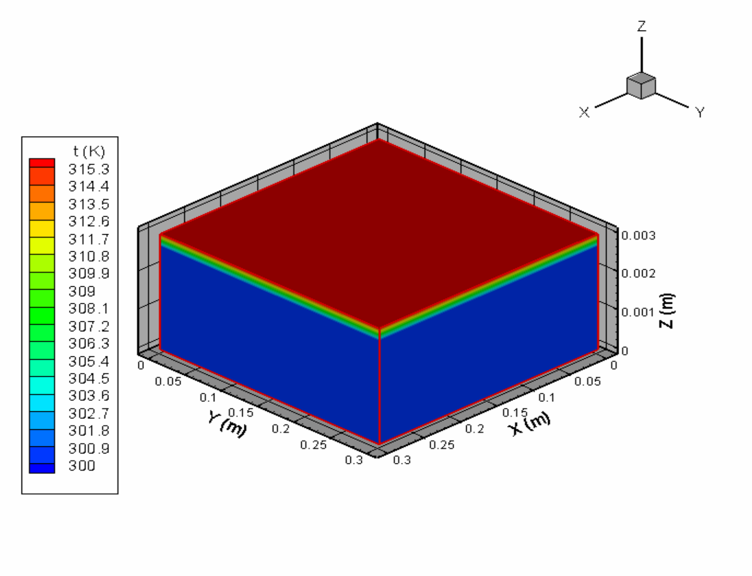


Figure 5. *Field of temperatures of the aluminum coated with epoxy and ferrite.*

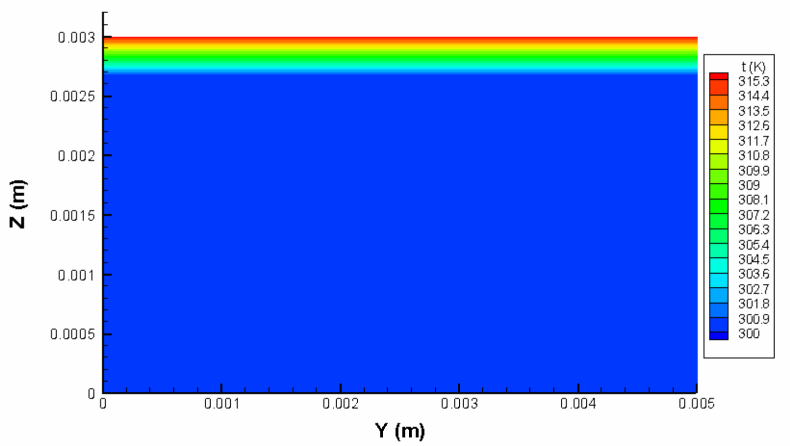
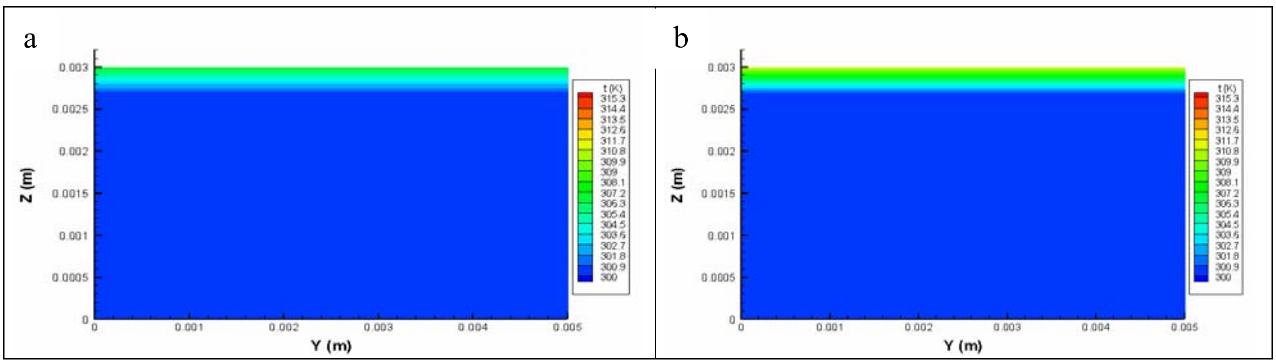


Figure 6. *Middle plane vertical cutting view*

Both Figs. (5) and (6) show the steady solution to the problem For the boundary conditions of this particular study case, the solution everywhere is kept within the limits of the temperature of Curie, because the maximum temperature occurs on the surface whose value is 41° C, which is considerably lower than the limit for this material (115°C). The transitory history of the composite layer may be observed in Figs.(7a), (7b), (7c), (7d) (7e), (7f) (7g) and (7h).



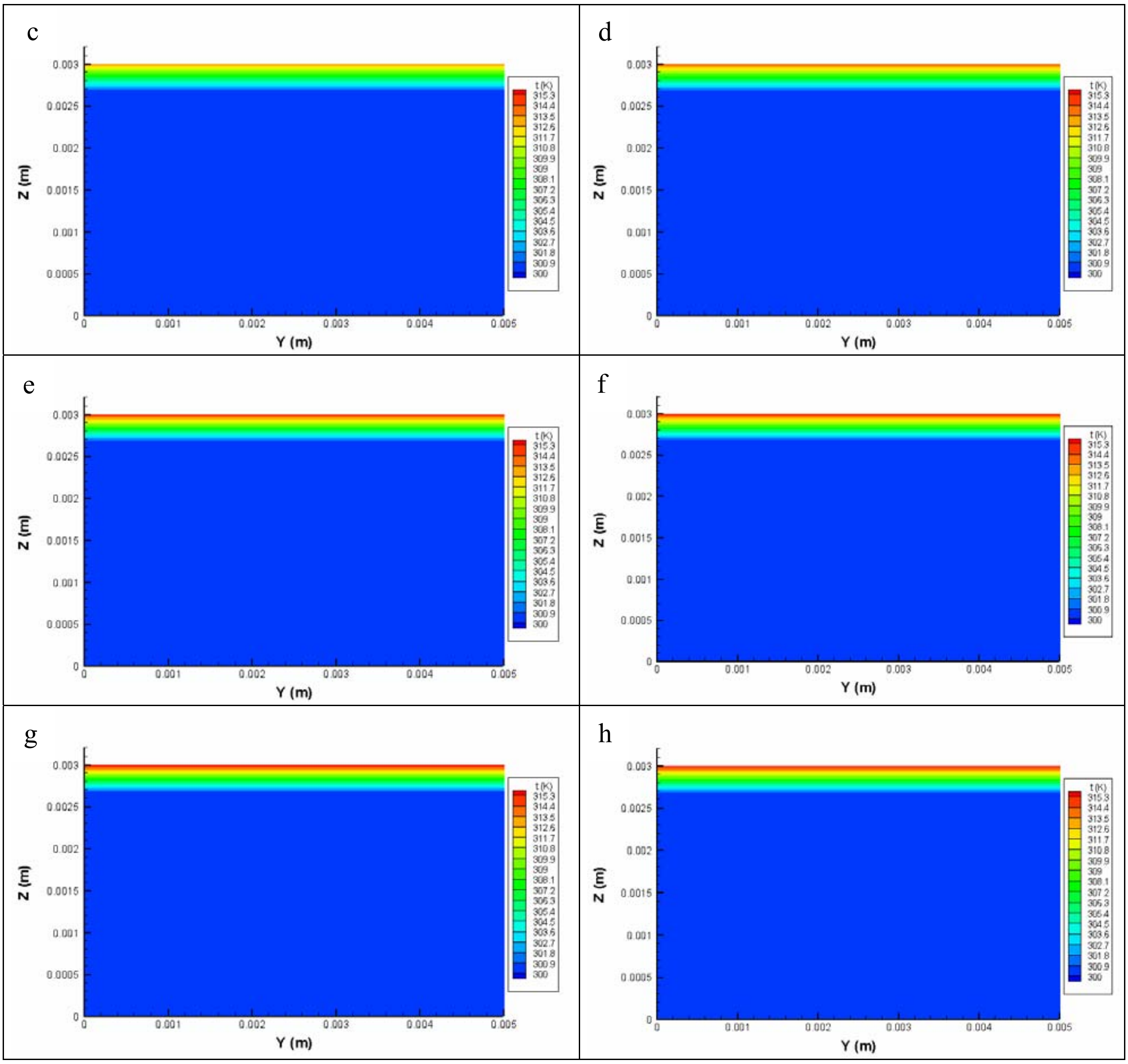


Figure 7. *Transitory sequence*

Fig(7) shows that the responsible to generate heat is the upper layer of the plate coated with the ferrite and the heat that is transfer to the substrate is practically annulled by the effect of the thermal contact resistance.

5. Conclusions

The numerical method presented in this work captures well the main features of the radiation absorption phenomenon by ferrites coated on a substrate, such as aluminum. For the coating layer, a lumped approach suffices which is confirmed by the lower Biot number for this layer alone (0,004). Some of the heating effects are well known to regular mobile phone users, who generally agrees on “mobile phones heat up after a while”. Nowadays people are giving more importance to the effect of the magnetic incidence in the human body, and many government funds have been driven to research on this area.

The high temperature gradient demonstrated by the model of the thermal resistance of contact simulated appropriately the effect of the resistance to the diffusion of heat in the interface of the materials since that the radiation effect in the cavities filled by air can be neglected considering for low temperatures.

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