FDTD numerical model for heating procedures in microwave multimode cavities

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Abstract: - This work aims to develop a numeric model using FDTD in order relate the microwave spread, with the dielectric material heating on industry applications, standing as a base to future development of a software, which can study the microwave effects on these applications. Initially the basic issues involving the propagation of electromagnetic waves are discussed, as well as the equation that govern it. Then the mathematical treatment is performed, in order to related the known parameters to those obtained on the simulation. Lastly, experiments based in the simulated medium were performed, for the purpose of verify the error presented on the developed model. Those experiments allowed to conclude that the results numerically given, serve as a reference to situations where high precision is not necessary on the final temperature of the dielectric medium.

Key-Words: - Microwave, Microwave Heating, Finite Difference Time Domain, Numerical Method

1 Introduction

The use of microwaves for heating began in World War II [1], a period that the study and research with radars were in evidence. Since then, the use and the scope of heating microwave increased carrying the technology to various sectors of society such as industry and medicine.

The ease and speed of microwave heating as compared to conventional heating, allowed the development of methods for mineral processing, food and tissues [2], increasing the efficiency and quality of the final product.

Microwave heating receive great prominence in the treatment of tumors by hyperthermia process and blood transfusion during the heating procedure [3].

Despite the various applications and advantages, the study of microwave heating still requires the volumetric analysis for heating behavior, due to the high computational requirements of processing and memory, in addition to the variation of intrinsic material properties that vary with the temperature, increasing the computational effort.

The simulations and the experiments that will be made in this work will establish a method of analysis for industrial use, ignoring the variation of permittivity in order to verify the extent of the influence of this variation when comparing the experimental results with the simulations.

2 Microwave Heating

The heating using electromagnetic waves has been widely used in various branches of industry and medicine. The most common applications of this method are dehydration and cooking foods, drying materials, acceleration of chemical reactions, treatment of cancer cells and polymer processing [4].

The rate of heat transfer and the reduced heating time are advantages of microwave heating. Moreover, the control during the process is simpler and faster than the conventional procedure, since it is only necessary to connect or disconnect the generator [5].

The frequency range that established for scientific, medical and industrial applications (ISM) is 6.78 MHz to 245 GHz, covers the two most commonly used frequencies for heating, 915 MHz and 2.45 GHz. The choice of these frequencies does not occur necessarily be the most appropriate, but because there are no power generators suitable for other frequencies [6]. The frequency of 2.45 GHz is used in various applications, including residential microwave ovens, since the frequency of 915 MHz is only for industrial purposes. [7].

In this frequency range, there are two mechanisms for electromagnetic energy into thermal energy conversion: the electrical conductivity and the relaxation of electric dipoles [8].

The electrical conductivity dominates at lower microwave frequencies, lower than 896 MHz. The heat conversion occurs due to the current flowing within the material generating heat by Joule effect. This current is formed due to ions present in the material and the presence of the electric field of the wave. The power density on the conductivity is:

$$\mathrm{P_c} = \frac{1}{2}\sigma|\overline{\mathrm{E}}|^2 \qquad (1)$$

Where:
σ: dielectric electrical conductivity;
|E|: electric field modelu.

The second mechanism occurs at higher frequencies and depending on the interaction of dipoles present in the molecular structure of the material with the electromagnetic field applied. In microwave ovens, water dipoles are absorbing most of the electromagnetic energy. At low frequencies, the dipoles easily guide to the changes in the field, however, at high frequencies, the inertia of dipoles prevents that they align with the field, causing apply vibration and consequent release of heat.

The power density associated with the accommodation of dipoles are:

$$\mathrm{P_{dp}} = \frac{1}{2}\omega\varepsilon''|\overline{\mathrm{E}}|^2 \qquad (2)$$

Where:
ω: angular frequency;
ε'': imaginary complex permittivity.

The conversion of electromagnetic power absorbed heat material is resolved by heat transfer equation, also known as Fourier's Equation [9] as can be seen in Equation 3.

$$\rho_m C_m \frac{\partial \mathrm{T}(x,y,z,t)}{\partial t} \qquad (3)$$

$$= k_t \nabla^2 \mathrm{T}(x,y,z,t) + \mathrm{P_d}(x,y,z,t)$$

Where ρm: material density (kg·m^{-3}), Cm: material specific heat (J·K^{-1}·kg^{-1}), kt: thermal conductivity (W·m^{-1}·K^{-1}) , T(x,y,z,t): temperature (K) and Pd(x,y,z,t) is electromagnetic power density (W·m^{-3}).

The heating rate of the dielectric material irradiated with microwave electromagnetic power is given by the density expressed by Equation 2, Pd represented by (x, y, z, t) in Equation 3.

The temperature change alters the properties of the dielectric, modifying the values of conductivity and permittivity. This change modifies the actual rate of power dissipated in the material, making numerical processes that take into account these changes, complex and numerically expensive.

The complex permittivity effective values calculated considering the temperature variation are defined according to Equation 4, developed by [10], which governs most of the heating processes of dielectric liquids.

$$\varepsilon^*(f,T) = \varepsilon_\infty + \frac{\varepsilon_s(T) - \varepsilon_\infty}{1 + j\left(\frac{f}{f_{rel}(T)}\right)^{1-\beta}} - j\frac{\sigma_{DC}(T)}{2\pi f \varepsilon_0} \qquad (4)$$

Here ε_s(T) is the static dielectric constant versus temperature in Celsius degrees, ε_∞ infinite frequency relative permittivity, f_{rel} is the relaxation frequency versus temperature in Celsius degrees, β is a factor that takes into account the delay in relaxation dipolar, σ_{dc}(T) is the DC conductivity versus temperature.

The variables in Equation 4, which are functions of temperature can be calculated using Equations 5, 6 and 7 developed by [11]; [12]; [13], respectively.

$$\varepsilon_S[T(°C)] = 87.74 - 0.4008T(°C) + 9.398 \cdot 10^{-4}T(°C)^2 - 1.410 \cdot 10^{-6}T(°C)^3 \qquad (5)$$

$$f_{rel}[T(°C)] = (1.1109 \cdot 10^{-10} - 3.824 \cdot 10^{-12}T(°C) + 6.938 \cdot 10^{-14}T(°C)^2 - 5.096 \cdot 10^{-16}T(°C)^3)^{-1} \quad \text{(Hz)} \qquad (6)$$

$$\sigma_{DC}[T(°C)] = \sigma_{DC(25°C)}\exp[-\Delta_T(2.033 \cdot 10^{-2} + 1.266 \cdot 10^{-4}\Delta_T + 2.464 \cdot 10^{-4}\Delta_T^2)] \quad \text{(dS/m)} \qquad (7)$$

Here ΔT = [25 – T(°C)], and σ_{DC}(25°C) DC conductivity at 25 °C.

3 Design Methodology

The methodology adopted in this work is based on the construction of a numerical model using the FDTD numerical method to analyze the heating of dielectric materials in multimode microwave ovens and checking the validity of the method through experimental measures.

The development of the research was carried out in three steps. The first consisted of the literature on the state of the art numerical models dealing with the analysis of electromagnetic fields and heating, and the research in that field.

The second stage was to adjust the numerical model developed by [14] to use the power absorbed in the material amounts to use Equation 3 to verify the heating of water in a cavity referring to a domestic microwave oven, developed in [15]. The water will be disposed in various parts of the cavity cylinder representing plastic cups.

After getting the numerical results, the third step validated the results experimentally. A microwave oven was used, with the net power output of 820 W. The water was disposed in acrylic shelves, inside plastic cups and an infrared thermometer measured the temperature.

3.1 Numerical Analysis of Electromagnetic Fields

The study of the behavior of electromagnetic fields in the cavity was made based on the model developed by [14]. The model analyzes the intensity of the fields in a cavity filled wholly or partly of dielectric materials, allowing you to check the distribution of the fields in the cavity to certain frequencies.

The simulation environment allows inserting dielectric material inside the cavity, this being represented by the limits of the simulation environment, which is also the boundary condition. Fig. 1 shows an example of a cavity with a dielectric cylinder therein.

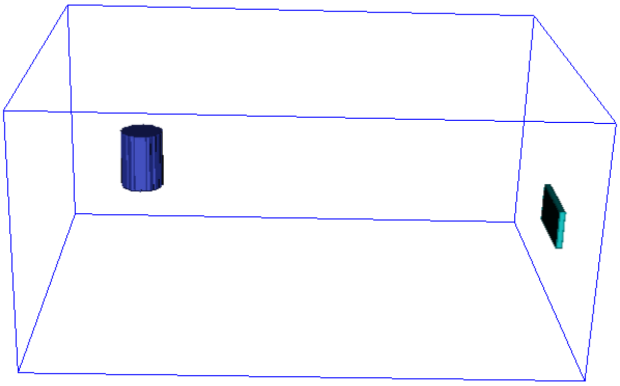

Fig. 1 – Cavity with boundaries defined by the simulation environment

The cavity in Fig. 1 shows the dielectric material at (1) the source at (2) the boundaries of the cavity and the external lines. This model allows you to check the behavior of the electric fields in cavities or separate waveguides.

However, to study the behavior of electromagnetic waves in microwave ovens is necessary to check the coupling between waveguides and cavities. To meet this need has been added to the model a module that allows you to add perfectly conductive materials, which were represented only by the limits of the cavity, as in Fig. 1.

Fig. 2 shows a cavity coupled with a waveguide represented by gray color..

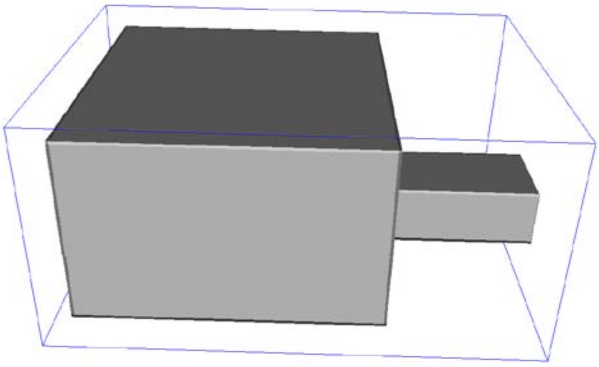

Fig. 2 – Cavity coupled to the waveguide

The behavior of the electromagnetic field inside the cavity depends on the dimensions of the guide and the cavity itself, in addition to volume and the dielectric material properties inside. The microwave oven used was a BMS45ABBNA Brastemp of 30 liters, with internal dimensions of 36 x 22 x 37 cm³. For this work, the turntable, which has the function of providing uniform field, was removed. This withdrawal was due to that in industrial furnaces such mechanism is not used, other means are adopted to achieve uniformity.

As observed by Equation 4, the permittivity varies with temperature and this variation directly influences the behavior of the fields and power density dissipated in the material. To establish a permittivity value in a temperature range, which provides adequate results for this model, was used to Equation 4 for all values between 0 ° C and 60 ° C for water. Fig. 3 shows the change in permittivity at these temperatures.

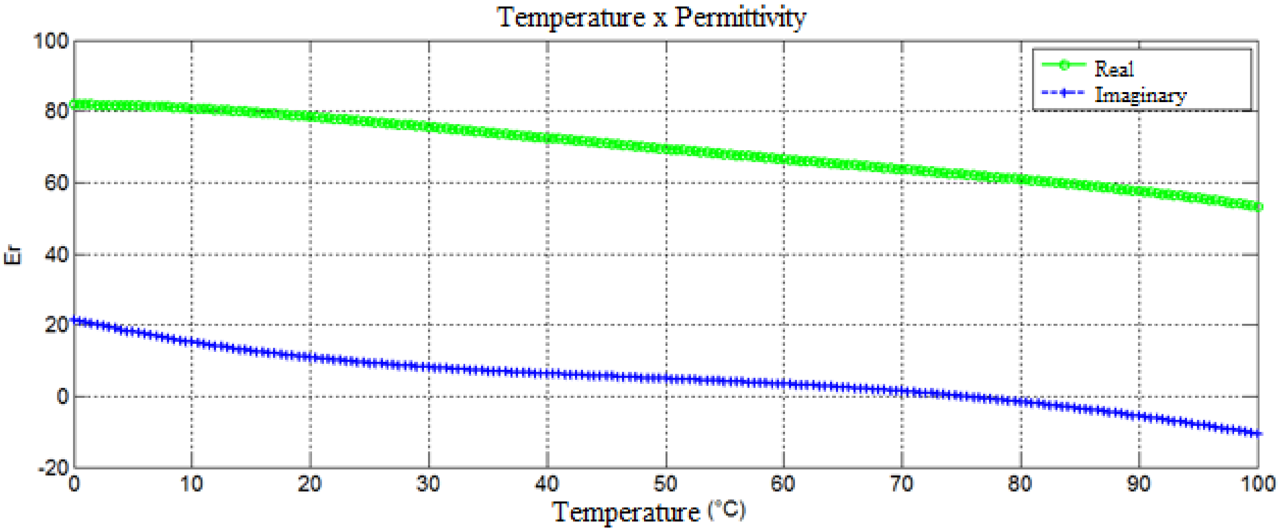

Fig. 3 – Permissividade da água em função da temperatura

The initial temperature of the samples was 28.5 ° C, the average value of this temperature and the maximum temperature analyzed is 47 ° C. For this temperature the relative values of the real and imaginary components of the permittivity are 70.4 and 5.1, respectively.

To meet the numerical model developed by [14], it is necessary to calculate the equivalent conductivity value that represents the losses of the dipole rotation and driving. Equation 8 shows the result

$$\sigma_e = \omega\varepsilon'' \qquad (8)$$

$$\sigma_e = 0{,}7238 \text{ S/m}$$

3.2 Relationship between power dissipation and increasing the dielectric material temperature

To establish the relationship of the values obtained in the simulation with the values of the experiment, was first set the value of the electric field intensity in the waveguide due to the power delivered by the magnetron.

The power carried in a waveguide is a function of the electric field strength and its dimensions, in addition to the frequency of the wave that is transmitted. This power is calculated using Equation 9.

$$P_T = \frac{1}{4\eta}|E_o|^2 ab\sqrt{1 - \frac{f_c^2}{f^2}} \qquad (9)$$

Em que:

PT: power in waveguide, W;
η: intrinsic impedance, Ω;
a, b: waveguide dimensions, m;
fc: waveguide cut frequency, Hz;
f: microwave frequency, Hz.

The microwave oven manufacturer provides the power emitted by the magnetron and from this value, you can find the peak value of the electric field in the guide. This peak value is equivalent to 1.0 in the simulations and thus can calculate the electric field strength across the simulation region.

For the microwave oven used, the output power reported by the manufacturer is 820 W. However, an experiment was conducted to verify the actual power delivered by the magnetron. The measurements gave an average of 650 W.

The electric field from the value obtained was used to calculate the power dissipated across the dielectric material using Equation 2, and then heating the cup check using Equation 3, suitable for the simulation as shown in Equation 10.

$$\begin{aligned} &T^{n+1}(i,j,k) = \\ &T^{n}(i,j,k) + \Delta t\alpha D_t \\ &\times \left[\frac{T^n(i+1,j,k) - 2T^n(i,j,k) + T^n(i-1,j,k)}{\Delta x^2}\right. \\ &+ \frac{T^n(i,j+1,k) - 2T^n(i,j,k) + T^n(i,j-1,k)}{\Delta y^2} \\ &+ \frac{T^n(i,j,k+1) - 2T^n(i,j,k) + T^n(i,j,k-1)}{\Delta z^2} \\ &\left. + \frac{P_d^n(i,j,k)}{k_t}\right] \end{aligned} \qquad (10)$$

Here Δt is the time increment (seconds) and Δx, Δy, Δz are the space increment in the three axis (meters).

The variables α and Dt are presented Equations 11 and 12, respectively.

$$\alpha = \frac{\mathrm{Theating}}{\mathrm{T_{simulation}}} \qquad (11)$$

The constant α is used to relate time simulation of the order of nanoseconds or less and the heating time of the order of seconds or minutes. In this paper, the simulation time is equivalent to a period of oscillation of a wave of 2.45 GHz, approximately 0.41 nanoseconds.

$$\mathrm{D_t} = \frac{\mathrm{k_t}}{\rho_\mathrm{m}\mathrm{C_m}} \qquad (12)$$

Equation 12 gives the value of the thermal diffusivity as a function of density, specific heat and thermal conductivity of the material. The values used in Equation 12 are in Table 1.

Table 1 – Thermal properties of water

Thermal conductivity	0,55 $\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$
Density	1000 $\mathrm{kg{\cdot}m^{-3}}$
Specific heat	4180 $\mathrm{J{\cdot}kg^{-1}{\cdot}K^{-1}}$
Thermal diffusivity	$131{,}58{\cdot}10^{-9}\ \mathrm{m^2{\cdot}s^{-1}}$

4 Simulation Results

The insertion of the electromagnetic field was made using a waveguide with equal measures of a WR-340, excited at 2.45 GHz, $\mathrm{TE_{10}}$ mode.

Fig. 4 and Fig. 5 show a side and front view for the simulation with 16 cups. The final temperature of heating values for a 60 seconds simulation can be seen in Fig. 6 and Fig. 7. In the configuration with 32 cups, Fig. 8 and Fig. 9 shows the distribution of electromagnetic field, since the Fig. 10 and Fig. 11 show the result of heating in the oven for 60 seconds.

In both cases you can check the same behavior of the electromagnetic field in the lower level, with the much higher intensity for the cups aligned with the guide and the adjacent with lower values.

In Fig. 5 shows the upper level, the electric field distribution is similar to the lower level, indicating that the elements aligned with the source absorb more energy because of its location, while those located laterally have very low field intensities.

The simulations were performed on a Intel® Xeon ® Processor E5506 2.13 GHz and RAM of 32 GB. Processing times are shown in Table 2.

Table 2 – Duration of Simulations

Configuration	**Time**
Empty cavity	08h22min
Cavity with 16 cups	04h52min
Cavity with 32 cups	03h50min

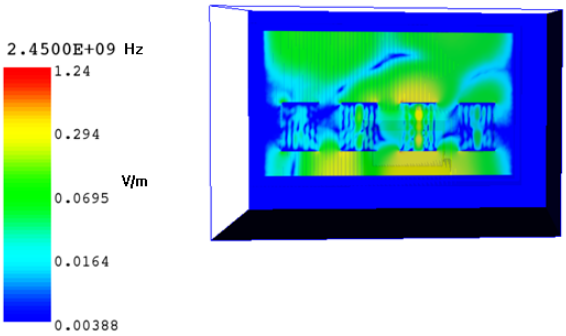

Fig. 4 – 16 cups, side view

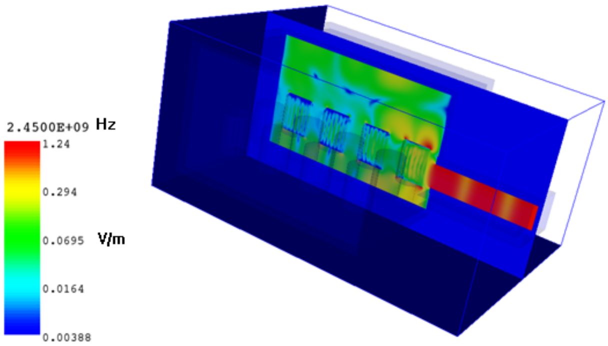

Fig. 5 – 16 cups, front view

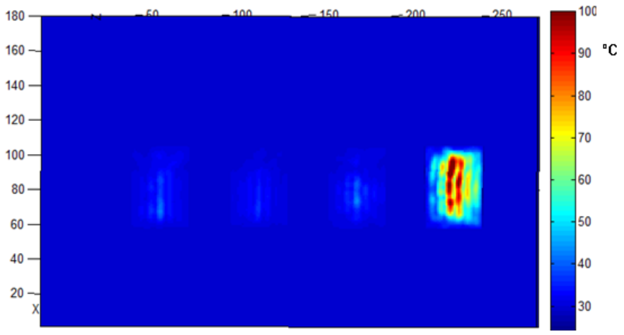

Fig. 6 – Heating 16 cups, front view, t = 60 seg

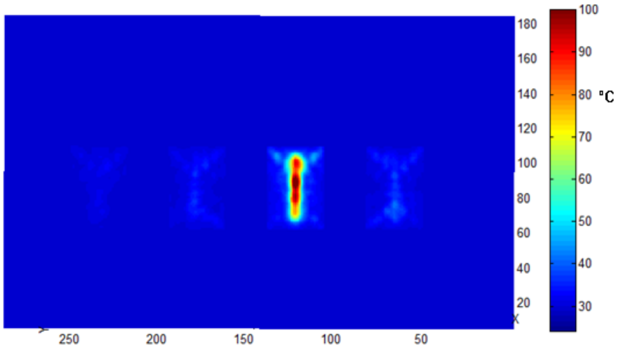

Fig. 7 – Heating 16 cups, side view, t = 60 seg

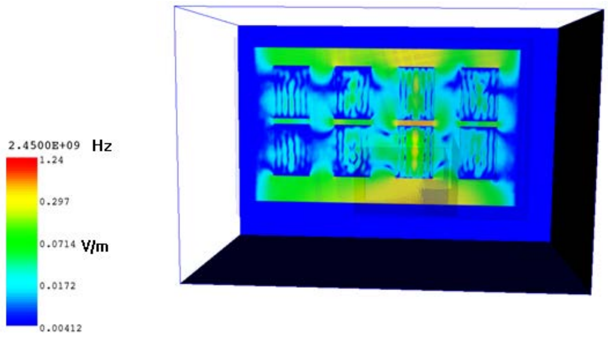

Fig. 8 – 32 cups, side view

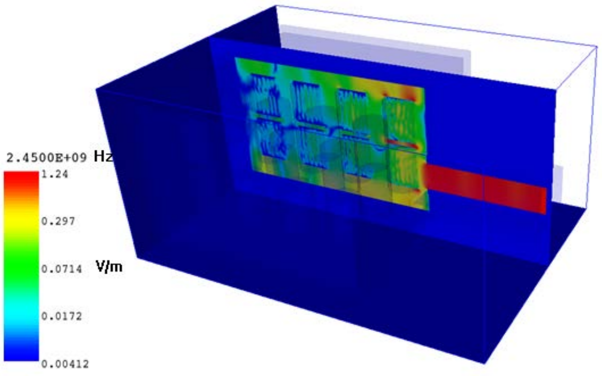

Fig. 9 – 32 cups, front view

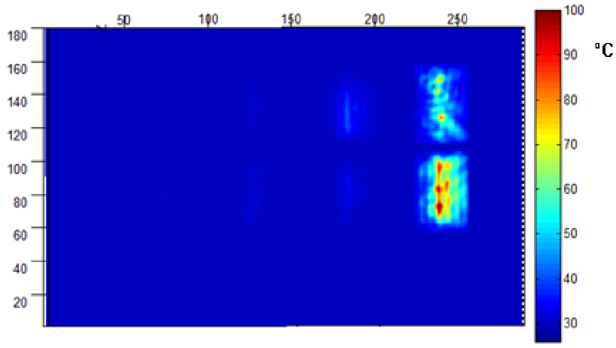

Fig. 10 - – Heating 32 cups, front view, t = 60 seg

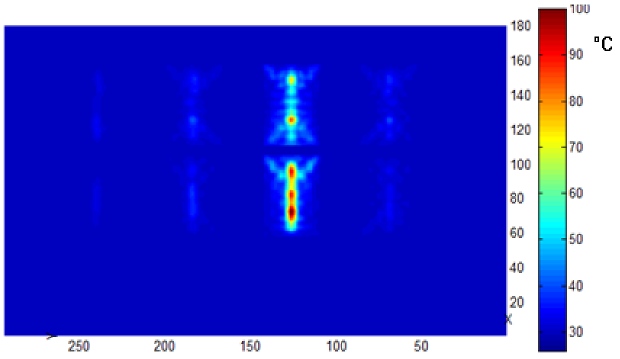

Fig. 11 - – Heating 32 cups, front view, t = 60 seg

5 Experimental Analysis

The validation of the data obtained in the simulation was made based on data collected during the experimental phase of this work. This step consisted in measuring the temperature over time at 32 different points in the cavity.

Measurements were made in the microwave oven indicated in Item 3.1. To represent the physical location of the cups simulations of Item 4, were made two acrylic shelves with holes for engagement of the cups, which can be seen in Fig. 12 and Fig. 13.

The acrylic was chosen for having low relative permittivity (εr = 2.6) compared to water, making its influence on the absorption of the fields is neglected in heating.

Temperature measurement was performed using a digital thermometer with infrared, MT-350 model Minipa.

During the experiment, the temperature of the water was recorded in all the elements according to their position shown in Fig. 14.

Fig. 12 – Microwave oven with 16 cups

Fig. 13 – Microwave oven with 32 cups

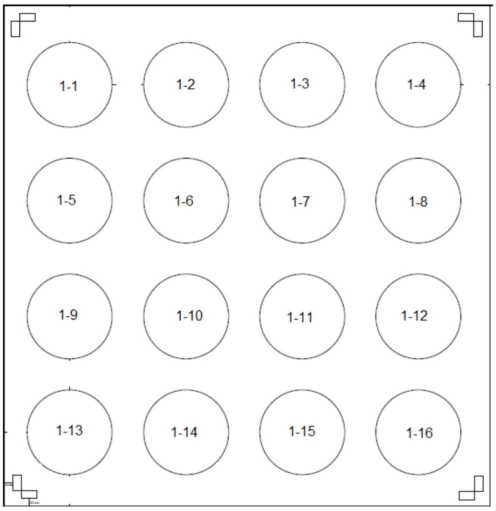

Fig. 14 – Position numeration, below

The measurement was taken until one of the cups reach 60 ° C, as this is the limit value of the study track of this work. After reaching the limit value, we did another measurement to check the corportamento of neighboring elements.

Table 3 and Table 4 show the temperature measured in 60 seconds in the positions shown for the two organizations.

Table 3 – Heating in t = 60 sec

Position	Temperature °C
1-4	40,0
1-5	31,5
1-6	33,0
1-7	38,5
1-8	51,0
1-12	38,5
1-16	33,0

Table 4 – Heating in t = 60 sec

Position	Temperature °C
1-4	38,5
1-5	29,5
1-6	30,5
1-7	33,0
1-8	54,0
1-12	34,5
1-16	30,5
2-4	33,5
2-5	29,5
2-6	30,0
2-7	31,0
2-8	34,0
2-12	31,0
2-16	31,0

6 Relationship between simulated and experimental values

To quantify the accuracy of the developed model was compared to the experimentally measured values, featuring in Table 3 and Table 4, indicated with the simulation results.

Fig. 15 shows the accuracy of the results obtained in the simulation compared with the experimentally obtained for setting up 16 cups, in which it is observed that the percentage error does not exceed 10% for the four elements presented, which showed the greatest difference in measurements. Fig. 16 shows the error for the configuration with cups 32, the same elements shown in Fig. 15.

7 Conclusion

Considering the importance of the study of electromagnetic waves for various applications and the possibility of developing new solutions involving the areas of industry and medicine, the work in question decided to develop a numerical method to serve as the basis of microwave ovens project to reduce development time and costs in the production of prototype.

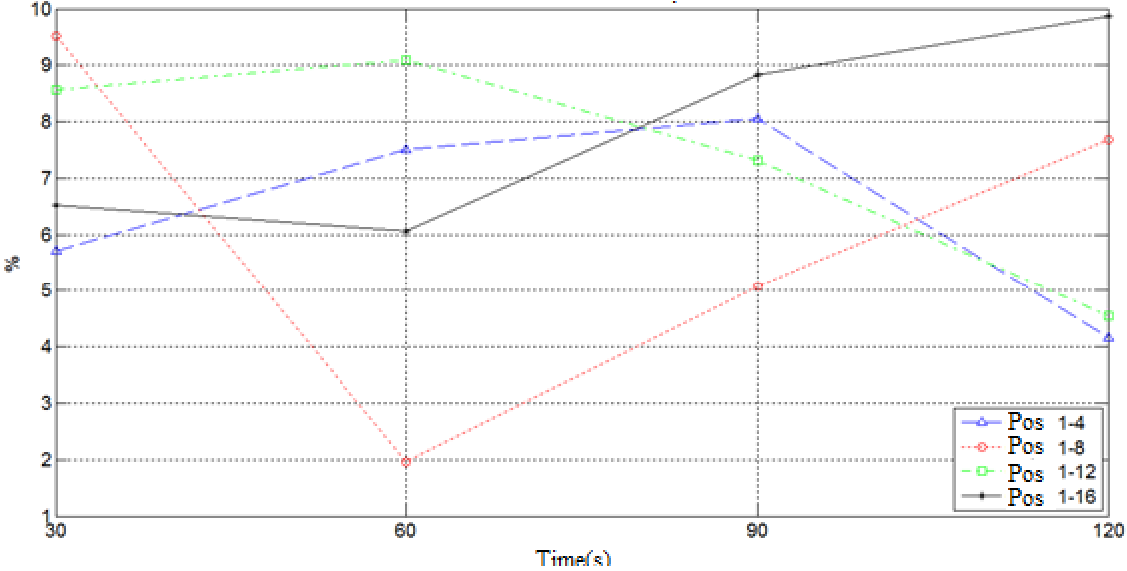

Fig. 15 - Error (%) x Time (s), 16 cups configuration

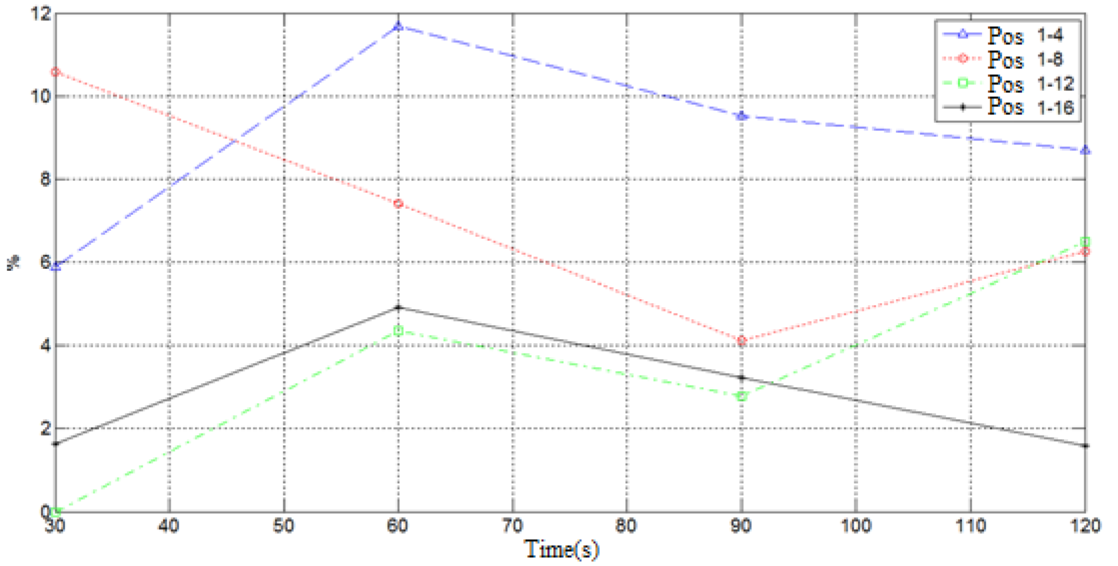

Fig. 16 - Error (%) x Time (s), 32 cups configuration, below

The results obtained in the test with the microwave oven showed that data obtained by simulation are valid until about 70% of the volume of the heated object reaches 60 ° C for adopted permittivity for water..

The simplified simulation of industrial microwave demonstrated the validity of the results to other studies developed in the area, confirming the utility of the method developed for the study and design of cavities used for heating..

Having been developed using Matlab, the algorithm allows the temperature change of materials may be displayed in animated form over time as well as graphs of specific points of heated material.

Also added using perfectly absorbing layers to simulate the propagation of waves in the open. Allowing the representation of industrial cavities with microwave traps [15].

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