

# 3D Electromagnetic Field Simulation in Microwave Ovens: a Tool to Control Thermal Runaway

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**Abstract:** In microwave heating applications, the energy is introduced directly into the volume of the material and as consequence the quality of the process is highly dependent on the uniformity of the electromagnetic field distribution along it. That is, the non uniformity of the heating is a potential problem with serious consequences. Thermal runaway is the most critical, in materials with temperature dependent dielectric properties. As the material absorbs electromagnetic energy, the temperature increases as does its ability to absorb more energy.

To understand this phenomenon, a perceptive of how electromagnetic field propagates and how is absorbed by materials is essential, and then, we carried out the 3D electromagnetic field simulation in a microwave oven loaded with a ceramic sample, changing several parameters, as the dielectric properties of the load and the magnetron frequency, using COMSOL software.

**Keywords:** Microwaves, electromagnetic field, simulation, thermal runaway.

## 1. Introduction

The higher cleaning environment and reduction in manufacturing costs are important requirements in industrial heating. Nowadays, the microwave heating presents interesting performances, such as shorter time of processing, with clear advantages. In order to understand the interaction of microwaves with materials [1-4], and consequently to optimize the oven designs to improve the product quality, many studies were made in the last years. One of the crucial challenges for researchers is the uniformization of the electromagnetic field inside the cavities or ovens, in order to avoid overheating points that can destroy the material at a local level. This phenomenon, known as thermal runaway, has been observed in different materials, including zirconia [5], alumina [6] and nylon [7]. To understand and control that problem, we have to

model mathematically the microwave electromagnetic field inside the cavities, using the Maxwell equations and the boundary conditions. To obtain the field distribution in a complex object or within a multimode cavity in the three dimensional space [8, 9], we must solve the Maxwell equations, usually using the Finite Element Method. The technique competes very favourably with the other numerical methods, as it is based on reducing the Maxwell's equations to a system of simultaneous algebraic linear equations [10], and can model arbitrarily shaped geometries of heterogeneous and anisotropic materials.

The penetration depth of microwaves into materials depends on the electrical properties of them, and gives rise to a heat source. The electromagnetic wave absorption is responsible for the macro and micro structural changes in the materials morphology, and consequently for their electrical properties.

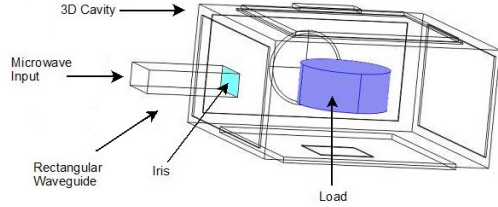
The electric field distribution is a factor that influences how materials undergo processing in a microwave oven. To calculate the different distributions is then crucial to understand the complex phenomenon of the dielectric heating of materials under a microwave radiation.

This paper shows how electromagnetic field propagates inside a material and how is absorbed, simulating the 3D electromagnetic field in a microwave oven loaded with a ceramic sample, changing several parameters, as the dielectric properties of the load and the magnetron frequency, using COMSOL software.

## 2. Methods

A microwave oven cavity, with dimensions 42x39x21 cm was used to simulate the electromagnetic field distribution. The configuration is shown in figure 1, where is also shown a cylindrical sample placed in the centre of the cavity. The magnetron with an output power of 1 kW radiates to the interior of the oven, with a frequency of  $2.45\pm 0.25$  GHz. The

feeding port consists of a WR-340 waveguide, which has been excited with the fundamental mode  $TE_{1,0}$ .



**Figure 1.** Configuration used in the microwave cavity oven, where is shown a load with cylindrical shape placed in the center of the cavity.

The absorbed power density ( $Wm^{-3}$ ) of the material, with a complex permittivity,  $\epsilon^* = \epsilon' - i\epsilon''$ , can be expressed by

$$P = \frac{1}{2} \left[ (\sigma + \omega\epsilon'')E^2 + \omega\mu''H^2 \right] \quad (1)$$

where  $\sigma$  is the electrical conductivity,  $\epsilon''$  and  $\mu''$  the imaginary parts of the permittivity and permeability respectively.  $E$  and  $H$  are the absorbed electric and magnetic fields. In our case, the nonmagnetic material used in this work eliminates the need of using the second term of this equation.

To simulate the electric field, we used the COMSOL software. The introduction of the microwave radiation is made by a rectangular port, as is show in figure 1. The electric field vector is calculated using

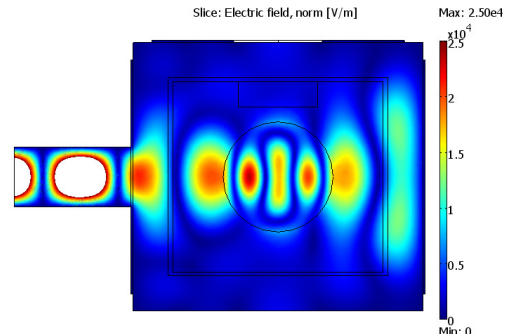
$$\vec{\nabla} \times (\mu_r^{-1} \vec{\nabla} \times \vec{E}) - k_0^2 \left( \epsilon_r - \frac{i\sigma}{\omega\epsilon_0} \right) \vec{E} = 0 \quad (2)$$

### 3. Experimental results

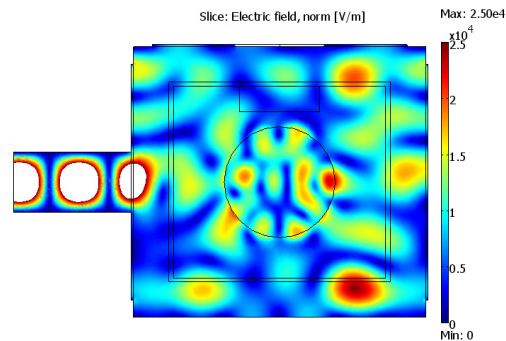
Respective to the boundary conditions, the walls of the cavity are considered as perfect conductors, represented by the boundary condition  $\vec{n} \times \vec{E} = 0$ . That is, the tangential electric field component is zero. To simulate the temperature variation in a ceramic material in the cavity, we used a symmetry cut as a mirror symmetry for the electric field, which is represented by the boundary condition  $\vec{n} \times \vec{H} = 0$ .

The changes in the magnetron frequency are very important in the electric field distribution inside the oven cavity. As we can observe in

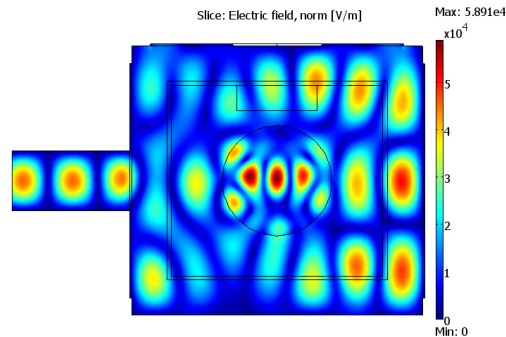
figures 2, 3 and 4, a small variation of 10%, corresponding to 250 MHz, provokes very different electromagnetic fields distribution inside the cavity. For the lowest magnetron frequency, that is 2.20 GHz, we observe lower number of maximums. The inverse behaviour is clearly observed for the highest limit in the magnetron frequency studied, 2.70 GHz. That is, when the frequency increases, the number of oscillations of the electric field increases, mainly due to the decrease of the wavelength.



**Figure 2.** Electric field distribution inside the cavity for 2.20 GHz,  $\epsilon^* = 3.5 - i0.001$ .

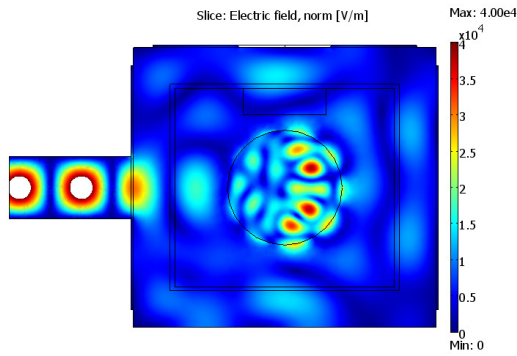


**Figure 3.** Electric field distribution inside the cavity for 2.45 GHz,  $\epsilon^* = 3.5 - i0.001$ .

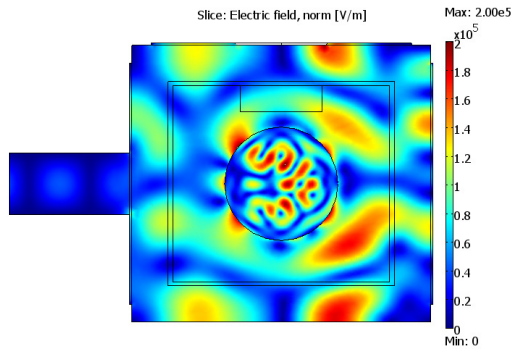


**Figure 4.** Electric field distribution inside the cavity for 2.70 GHz,  $\epsilon^* = 3.5 - i0.001$ .

The effect of the material dielectric constant is shown in figures 5 and 6. The electric field distribution is calculated for cylindrical samples in the centre of the cavity, with complex permittivity  $\epsilon^*=6.25-i0.001$  and  $\epsilon^*=9-i0.001$ . The non uniformity is clearly seen, and it is observed that the lower the permittivity of the material, the lower the values of the field. We also note that the number of oscillations decreases with the effective wavelength increase of the sample,  $\lambda_{\text{eff}}=\lambda/\epsilon^{1/2}$ .

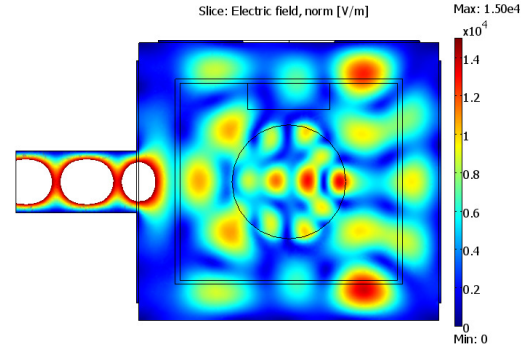


**Figure 5.** Electric field distribution for a sample with  $\epsilon'=6.25$  and frequency of 2.45 GHz.

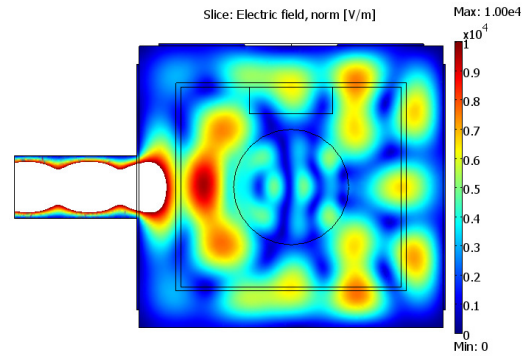


**Figure 6.** Electric field distribution for a sample with  $\epsilon'=9$  and frequency of 2.45 GHz.

In figures 7 and 8 we present the distribution of the electric field for samples with different losses, that is,  $\epsilon''=0.1$  and  $\epsilon''=1$ , with  $\epsilon'=3.5$ . The impact of the imaginary part of the complex permittivity, directly related to the a.c. conductivity, is clearly seen. The non uniformity of the electric field inside the sample is observed, and for high values of  $\epsilon''$ , the electric field penetrates incipiently in the sample, as the penetrating depth is very low.



**Figure 7.** Electric field distribution for a sample with  $\epsilon''=0.1$  and frequency of 2.45 GHz.



**Figure 8.** Electric field distribution for a sample with  $\epsilon''=1$  and frequency of 2.45 GHz.

#### 4. Discussion

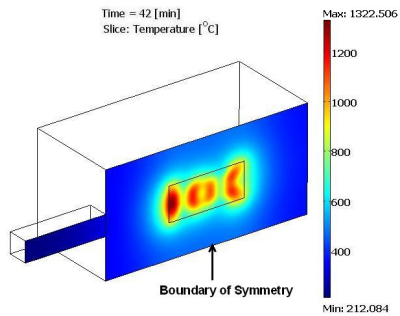
The relation between electromagnetic and thermal behaviour was studied, simulating the temperature variation in a ceramic material in the cavity, for a magnetron power of  $P=1$  kW at 2.45 GHz. Solving the heat transfer equation for the temperature  $T$  as a function of space and time,

$$\rho C \frac{\partial T}{\partial t} = k \nabla^2 T + P \quad (3)$$

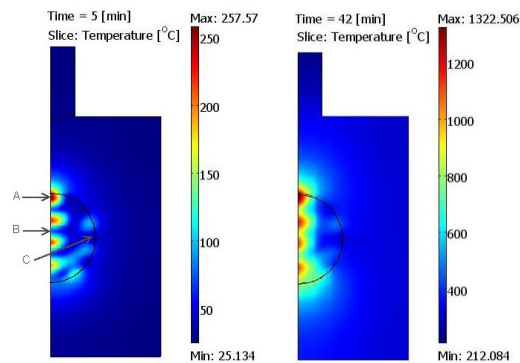
where  $\rho$ ,  $C$  and  $\kappa$  are the density, the specific heat and the thermal conductivity of the material, respectively, we obtained figure 9 and 10, where 4 hot spot's can be observed. For this simulation, we used  $\rho=2.2$ ,  $C=1$  kJkg<sup>-1</sup>K<sup>-1</sup> and  $k=0.24$  Wm<sup>-1</sup>K<sup>-1</sup>, and  $\epsilon^*=9.0-0.25i$ .

The temperature of the ceramic material depends on the electric field strength and on the material dielectric loss.

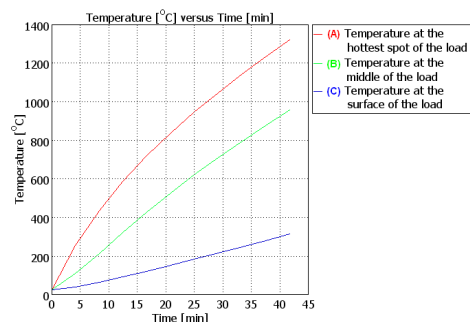
As the material absorbs energy, its temperature increases with a corresponding relatively large increase in the dielectric loss. The higher loss allows the material to absorb more energy resulting in a higher temperature. If the power absorbed is left unchecked, thermal runaway may occur as the material quickly heats until it breaks down.



**Figure 9.** Temperature distribution in the ceramic material, at the plane of symmetry, showing 4 hot spot's.



**Figure 10.** Temperature distribution in the ceramic material, showing 4 hot spot's, after 5 minutes of exposure (left) and 42 minutes (right).



**Figure 11.** Temperature variation in the ceramic material, at 3 different points.

In figure 11, where is showed the variation of the temperature in a load exposed to microwave radiation, we observe that, with the increased absorption of microwave energy by the material, the temperature variation between different points in the load increases, which leads to cracks in the material. In this case the thermal runaway phenomenon is not observed.

## 5. Conclusions

The simulated results, obtained using COMSOL software, showed that, both the complex permittivity (real and imaginary parts) and the frequency of the microwave source have a strong influence on the field spatial distribution. This dependence could have important consequences in efforts to optimize the conditions for processing materials using microwave radiation.

We can obtain the evolution of the thermal profile of the sample using the energy absorption, which can be computed from those electromagnetic simulations.

To illustrate the useful of the used numerical technique, the thermal behaviour in a ceramic material was simulated, where 4 hot spot's was observed. This phenomenon presents a challenge for microwave engineers, since sample cracking are often exhibited, mainly because the formation of hot spot's due an inhomogeneous electromagnetic field distribution.

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## 7. Acknowledgements

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