Microwave Radiation to Cure Cork Stoppers Using a Conventional Turntable Configuration

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Abstract: Microwave heating has been widely used in industry to synthesize materials, in which conventional procedures are slow, expensive and sometimes inefficient. This work presents an alternative method for curing cork stoppers based on microwave radiation, which is energetically more efficient, where it is possible to accelerate the reaction rate and therefore reduce the cure time comparatively with conventional curing methods. The microwave energy is directly introduced in the volume of the dielectric material and as a consequence, the quality of the process is highly dependent on the uniformity of the electromagnetic field distribution along the material. That is, the non-uniformity of the heating is a potential problem with serious consequences. To understand this phenomenon, a perceptive of how electromagnetic field propagates and interacts with the material is essential. For this purpose, we simulated the heating microwave process using COMSOL Multiphysics® v4.3b software.

Keywords: microwave heating, electromagnetic field, dielectric properties, cork.

1. Introduction

Microwave processing of materials has already been applied to different areas, as ceramics [1], polymers [2], chemistry [3], hazardous waste [4], etc. Nowadays, the application of microwaves to cork has several purposes, as the decontamination and sterilization, the granulated expansion to reduce its specific mass, and the cure method reducing the time and costs related to the heating process.

The material processing in microwave ovens is based in the interactions of the material with the microwave radiation. For this reason, the process is more volumetric and faster when compared with the conventional heating technology, and consequently with less manufacturing costs [5]. This processing is mostly influenced by the electric field distribution, which is related to the material dielectric properties. It is important to study the electric field distributions inside the cavity and to understand the complex phenomenon of the materials dielectric heating, to avoid overheating points that can damage the material. This phenomenon is designated by thermal runway, which depends on the thermal conductivity, the convective heat transfer, the surrounding temperature, the intensity of the electromagnetic field and the geometric form of the sample. Others studies refer some aspects that can influence the heating process, as, the position of the microwave generator relatively to the cavity [6], the variation in the frequency of the microwave radiation, the complex permittivity, $\varepsilon_r^* = \varepsilon_r' - i\varepsilon_r''$ [7], the specific heat, the density [8], the position of the microwave radiating antenna relatively to the waveguide, the effects of the cavity dimensions [9] and the influence of mode stirrers [9, 10]. Some techniques are used to overcome the inhomogeneous heating, like putting some components in the microwave oven as turntables and mode stirrers. Others, much more complex, consist of varying the design of the waveguide or the path through which the microwave energy field is introduced into the oven. A system that can moves the cavity walls, changing the resonant frequency and therefore the position of the electrical field maximums inside the cavity [11] is another possibility already tested. A most complex method, the Travelling Wave Tube (TWT), is able to sweep a range of frequencies aiming uniform heating [12, 13]. Another approach is a multiple generators system with an accurate control of the power supplied to the sample [11].

Numerical methods can be used to model a wide variety of microwave processing systems. The finite-difference time-domain method was used, and it allows simulating the heating process, providing information about the electromagnetic field and the thermal distribution inside the cavity oven.

This paper reports the simulation of the thermal distribution inside a conventional turntable oven. It presents an alternative curing method based on microwave radiation, which is more energy efficient, accelerating the rate of reaction and then decreasing the cure time comparatively with conventional curing methods.

2. Governing Equations

2.1 Heat Transfer Equation

The microwave power generation is calculated either by Maxwell's equations and Lambert's law. Heat transfers are based on the generalized heat equation which depends on the thermophysical properties of the material. Coupling the absorbed electromagnetic energy with the thermal energy generated in the material, considering the time dependence, the heating rate in the material due to the absorption of the microwave radiation, is expressed by

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T + Q \qquad (1)$$

where Q denotes the internal heat generation source term and quantifies the amount of power which is dissipated in the material, and T, ρ, C_p and k are the temperature, density, the specific heat and the thermal conductivity of the material, respectively.

2.2 Lambert's Law Approach

The heat source term calculated from Lambert's law is obtained without solving the electromagnetic field. The volumetric heating rate according to Lambert's law can be express using the exponential drop of microwave power from the surface to bottom [14],

$$U(z) = \frac{F_0}{d_p(z)} exp\left(-\int_0^z \frac{dz}{d_p(z)}\right) \qquad (2)$$

where F_0 corresponds to the microwave power flux at the surface, d_p the penetration depth of the microwaves and z the microwave transmission direction.

The penetration depth, d_p is defined as the distance at which the microwave power is 1/e of the surface power flux, and is given by the following equation,

$$d_p = \frac{c_0}{2\pi f}\left[2\varepsilon_r'\left(\left(1+\left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2\right)^{1/2} - 1\right)\right]^{-1/2} \qquad (3)$$

where ε_r' is the dielectric constant, ε_r'' the dielectric loss , c_0 the velocity of light in vacuum and f the frequency of electromagnetic radiation.

The penetration depth has important consequences when processes are scaled up to manufacture components with large cross-sections or multiple samples, where stacking is required. If d_p is much lower than the thickness of the material, only the surface is heated and the rest of the material heats through conduction from the hottest regions.

For a sinusoidal wave in $TE_{1,0}$ mode, the microwave surface flux is expressed by [15],

$$F_0(x,0) \approx \frac{2P_{surf}}{ab}\sin^2\left(\frac{\pi x}{a}\right) \qquad (4)$$

Where P_{surf} is the surface microwave power, a and b the dimensions of the waveguide.

2.3 Maxwell's Equations Approach

In this approach the electromagnetic field is calculated using the Maxwell's equations. For $TE_{1,0}$ in plane wave propagation mode, the electric field is obtained by the following equation,

$$\nabla \times \mu_r'^{-1}(\nabla \times E) - k_0^2\left(\varepsilon_r' - \frac{i\sigma_{ac}}{\omega\varepsilon_0}\right)E = 0 \qquad (5)$$

where σ_{ac} is the *ac* electrical conductivity, ε_r' the dielectric constant, μ_r' the relative magnetic permeability, ω the frequency of microwave radiation, ε_0 and k_0^2 are the permittivity and wave-vector in free space, respectively.

To heat a material, the microwaves must be able to penetrate it, and that capability is correlated with the complex permittivity of the material, $\varepsilon_r^* = \varepsilon_r' - i\varepsilon_r''$. The dielectric constant, ε_r', quantifies the amount of stored energy, and the dielectric loss, ε_r'', quantifies the energy dissipated in the material.

The absorbed power density of the material can be expressed by,

$$P = \frac{1}{2}[(\sigma_{dc} + \omega\varepsilon_r'')E^2 + \omega\mu_r'' H^2] \qquad (6)$$

where σ_{dc} is the *dc* electrical conductivity, ε_r'' and μ_r'' 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.

As initial condition, the material is assumed to be at uniform temperature, T_0 = 23 °C and respective to the boundary conditions, the walls of the cavity and waveguide are considered perfect conductors. Nevertheless, if there are some losses in the conductive walls, these will be small enough, in order to not affect significantly the distribution of the electromagnetic field.

3. Model

The configuration is shown in Figure 1 and was created from a commercial 1 kW TEKA® microwave oven. The cavity has dimensions 42×39×21 cm and within this, 32 cork granulate composite samples are placed in a rotating PEEK Ketron® mold. The samples are composed by 82% cork granulate, 16.4% polyurethane adhesive and 1.6 % water. A magnetron, labeled P1, with an output power of 1 kW radiate to the interior of the oven at initial temperature of 23 °C, with a frequency of 2.45 GHz over 50 seconds. The feeding port consists of a WR-340 waveguide, which has been excited with the fundamental mode $TE_{1,0}$. The cavity and waveguide are filled with air, where $\mu_r = \varepsilon_r = 1$. The samples have density $\rho = 260$ kg.m^{-3}, specific heat coefficient C_p = 1700 J.Kg^{-1}.K^{-1}, thermal conductivity k = 0.045 W.K^{-1}.m^{-1}, *dc* electrical conductivity σ_{dc} = 1.2×10^{-10} S.m^{-1}, relative permeability μ_r = 1 and complex permittivity $\varepsilon_r^* = 3.8903 - 0.2745i$.

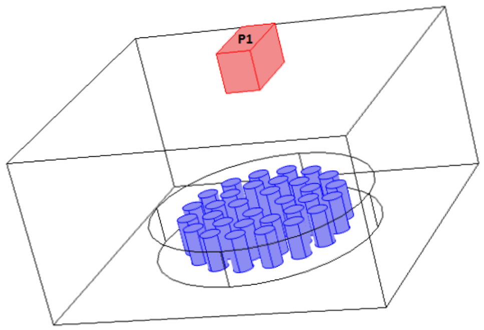


Figure 1. Geometric model.

COMSOL has been able to solve simultaneous electromagnetic and heat transfer equations for a rotating object in a microwave oven. The effect of rotation of the turntable was modeled using 'Translation Motion' available in the Microwave Heating module. The object was rotated according to,

$$vx = -2\pi yN \tag{7a}$$

$$vy = 2\pi xN \tag{7b}$$

where N is the number of turns per second, 0.1 s^{-1} and x and y are the position coordinates of the rotating object.

4. Results and Discussion

Figure 2 shows thermal distribution profiles at the top, bottom and middle sample layers, after 50 seconds of microwave heating.

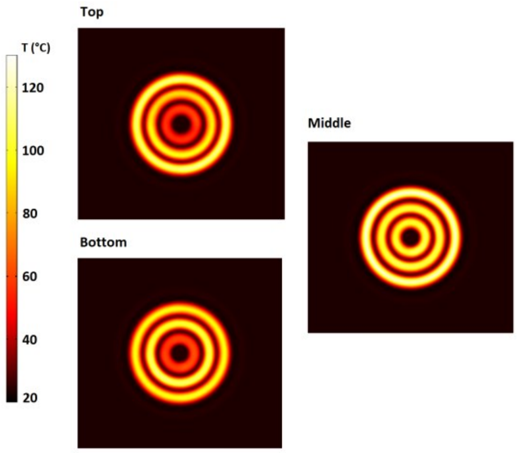
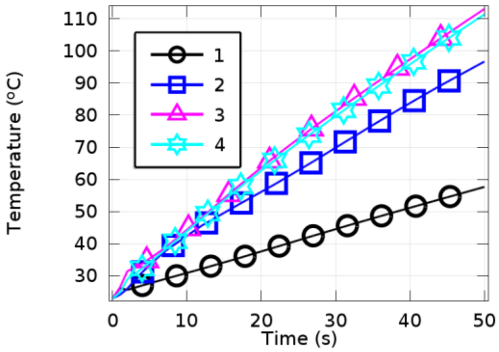


Figure 2. Thermal distribution profiles at the top, bottom and middle sample layers, after 50 seconds of microwave heating.

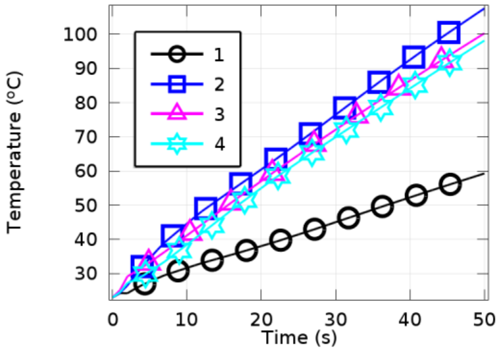
We can observe a reasonably homogeneous heating of the samples. The maximum temperature achieved was 129 °C, which corresponds approximately to the cork stoppers cure temperature. However, at the bottom and at the top, the temperature values for samples nearest to the center are lower.

The samples heating behavior was detailed studied. Figure 3 shows the temperature profiles in different layers for four samples.

Top



Bottom



Middle

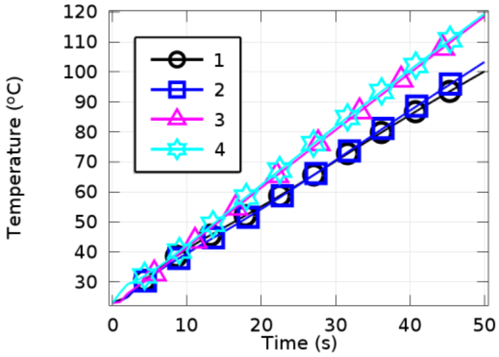
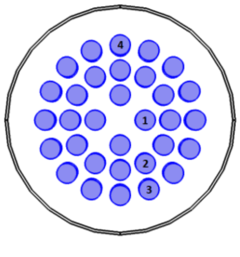
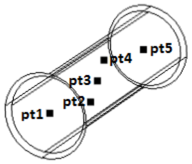


Figure 3. Temperature profiles at the top, bottom and middle layers for 4 different samples during the heating process.



As we can see, the samples achieved almost the same temperature at the middle layer. However, at the bottom and top layers, sample 1 reached lower temperature, presenting a gradient about 50 ºC.

Figure 4 shows the temperature profiles at five random points for the sample 4.



Sample 4

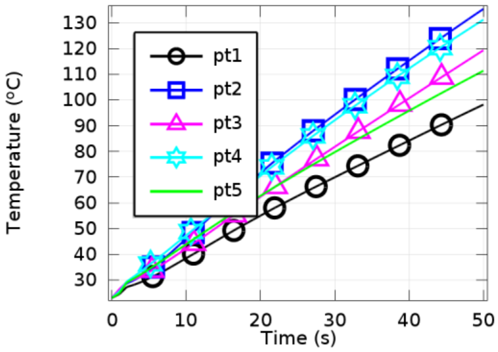


Figure 4. Temperature profiles for pt1, pt2, pt3, pt4 and pt5 points, during the heating process.

The points closer to the center of the sample, as pt2, pt3 and pt4 achieved higher temperatures. The temperature gradients are acceptable for the curing process, as this can be compensated by the heat generation from the cure process.

5. Conclusions

A simulation model was developed to study the possibility to cure cork stoppers through the microwave heating process. With this system, it is possible to cure cork stoppers in a shorter period of time, over 50 seconds comparatively to the 45 minutes required in conventional heating, demonstrating that the microwave radiation is a very good alternative to the conventional technology. However, moveable platforms may not be practical or adequate in many applications, as in tunnel ovens, once they add a complexity on the design. Thus, it is imperative to study others approaches to accomplish our main objective, changing the setup. Also it is necessary to improve the temperature homogeneity.

6. References

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