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Analysis of Microwave Radiation for Heating

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Abstract: Microwave heating is an important industrial process that is widely used across a range of industries. Through the use of single wave guides for batch ovens and multiple waveguides for continuous processing a wide range of applications can be addressed. The uniformity of the electromagnetic field is governed by the design of the waveguide and the cavity. To achieve optimum distributions of the appropriate electromagnetic field for high quality processing the generation and propagation of microwave radiation has been investigated.

Keywords: Microwave, Electromagnetics, Heat Transfer, Waveguide.

1. Introduction

Microwave heating is an important process for many commercial, industrial and household applications. Industrial microwave ovens are widely used in the chemical processing, agri-food, medical products and consumer products industries. Resonant cavities are often used to speed up chemical reactions and have the advantage of being small and producing efficient distributions of microwave energy. These multimode cavities can be considered as batch ovens where products can be treated, alternatively microwave tunnels with multiple waveguides can be used to provide continuous production.

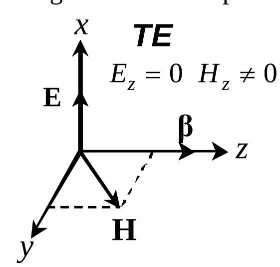
In microwave heating applications, the energy is introduced directly into the volume of the material and as a consequence the quality of the process is highly dependent on the uniformity of the electromagnetic field distribution. Thus, developing a uniform electromagnetic field inside the cavities represents a crucial challenge to avoid localized overheating.

Due to the difficulties associated with measuring electromagnetic fields, optimization of cavity design and selection of appropriate process conditions through experimental iteration is impossible. To better understand the complexity of the problem and enhance the design of microwave processing technology microwave processing has been analyzed using COMSOL Multiphysics.

2. Use of COMSOL Multiphysics

In this work, Maxwell's equations are reduced to a system of simultaneous algebraic equations that model an arbitrarily shaped geometry of heterogeneous and anisotropic materials. The depth to which microwaves penetrate material depends on its electrical properties; it is the interaction of the oscillating electric field of the microwave with a solid that produces dielectric heating thus giving rise to a heat source. Thus a full treatment of the problem should include a multiphysics analysis of both the electromagnetic field behavior, transient heat generation and heat transfer into the body of the material and surroundings.

The general form for the Transverse Electric wave propagating in the $z-$ direction is defined by the following governing equation for the longitudinal magnetic field component H_z :



$$\frac{\partial^2 H_z}{\partial x^2} + \frac{\partial^2 H_z}{\partial y^2} + \underbrace{\left(\gamma^2 + k^2\right)}_{k_c^2} H_z = 0 \qquad (1)$$

and the transverse electric and magnetic field components are given by:

$$\begin{cases} E_x = \dfrac{-j\omega\mu}{\gamma^2 + k^2}\dfrac{\partial H_z}{\partial y} \\ E_y = \dfrac{j\omega\mu}{\gamma^2 + k^2}\dfrac{\partial H_z}{\partial x} \end{cases} \qquad (2)$$

$$\begin{cases} H_x = \dfrac{-\gamma}{\gamma^2 + k^2}\dfrac{\partial H_z}{\partial x} \\ H_y = \dfrac{-\gamma}{\gamma^2 + k^2}\dfrac{\partial H_z}{\partial y} \end{cases} \qquad (3)$$

Where:

$k = \omega\sqrt{\mu\varepsilon}$: TEM wave number

$\gamma^2 = k_c^2 - k^2 = k_c^2 - \omega^2\mu\varepsilon$: propagation constant for TE wave

k_c : cutoff wave number defined by specific boundary conditions.

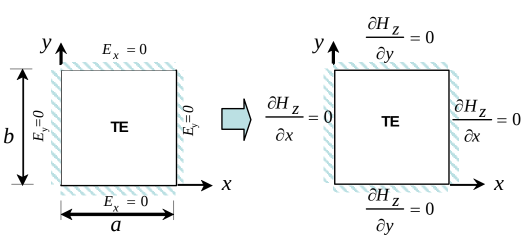


Figure 1. TE rectangular waveguide and boundary conditions (transverse components of electric field are zero at conductor boundaries).

For a rectangular TE waveguide, the boundary conditions for the analysis are shown in Figure 1.

The longitudinal magnetic field is given by:

$$H_z(x,y,z) = H_0 \cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)e^{-j\beta_g z} \quad [A/m]$$

and the transverse electric and magnetic components are given by:

$$\begin{cases} E_x = \dfrac{j\omega\mu}{k_c^2} H_0 \dfrac{n\pi}{b}\cos\left(\dfrac{m\pi x}{a}\right)\sin\left(\dfrac{n\pi y}{b}\right)e^{-j\beta_g z} \\ E_y = \dfrac{-j\omega\mu}{k_c^2} H_0 \dfrac{m\pi}{a}\sin\left(\dfrac{m\pi x}{a}\right)\cos\left(\dfrac{n\pi y}{b}\right)e^{-j\beta_g z} \end{cases} \qquad (4)$$

$$\begin{cases} H_x = -\dfrac{1}{Z_{TE}} E_y \\ H_y = \dfrac{1}{Z_{TE}} E_x \end{cases} \qquad (5)$$

where:

$f_{cmn} = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$ is cutoff frequency

$k_{cmn}^2 = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2$ is cutoff wave number

$\beta_g = \frac{2\pi}{c}\sqrt{f^2 - f_{cmn}^2}$ is guiding mode propagation constant

$Z_{TE} = \frac{E_x}{H_y} = -\frac{E_y}{H_x} = \frac{\omega\mu}{\beta_2}$ is TE wave impedance, $[\Omega]$

$c = 1/\sqrt{\mu\varepsilon}$ is the speed of light

Thus the total power is given by:

$$P = \frac{\omega\mu\beta_g H_0^2 ab}{4k_{cmn}^2} \qquad (6)$$

For the TE_{10} Mode magnetic and electric components are given by:

$$H_z = H_0 \cos\left(\frac{\pi x}{a}\right)e^{-j\beta_g z} \qquad (7)$$

$$\begin{cases} E_x = 0 \\ E_y = \dfrac{-j\omega\mu}{(\pi/a)} H_0 \sin\left(\dfrac{\pi x}{a}\right)e^{-j\beta_g z} \end{cases} \qquad (8)$$

$$\begin{cases} H_x = -\dfrac{1}{Z_{TE}} E_y \\ H_y = 0 \end{cases} \qquad (9)$$

Where:

$$\beta_g = \frac{2\pi}{c}\sqrt{f^2 - f_{c10}^2}, \quad f_{c10} = \frac{c}{2a}$$

These equations provide the opportunity to validate simulations performed using COMSOL Multiphysics with closed form solutions. The longitudinal magnetic field, H_x, is shown in Figure 2.

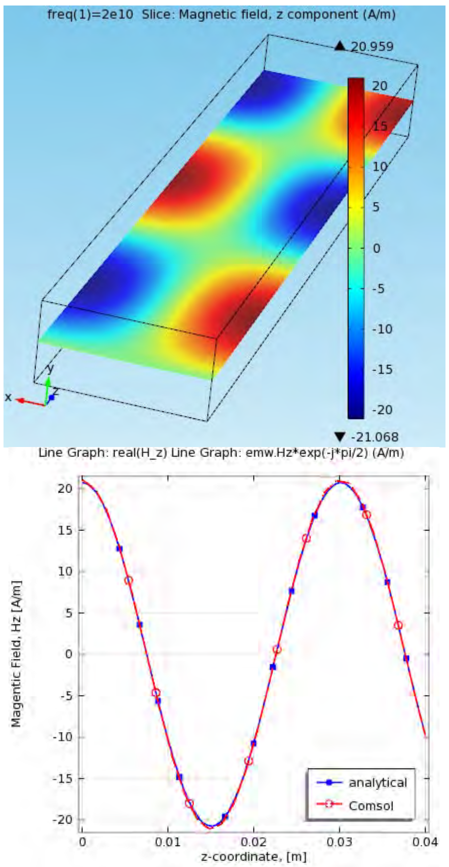


Figure 2. Longitudinal magnetic field H_x

The spatial variation in the transverse electric field, E_y, is given in Figure 3

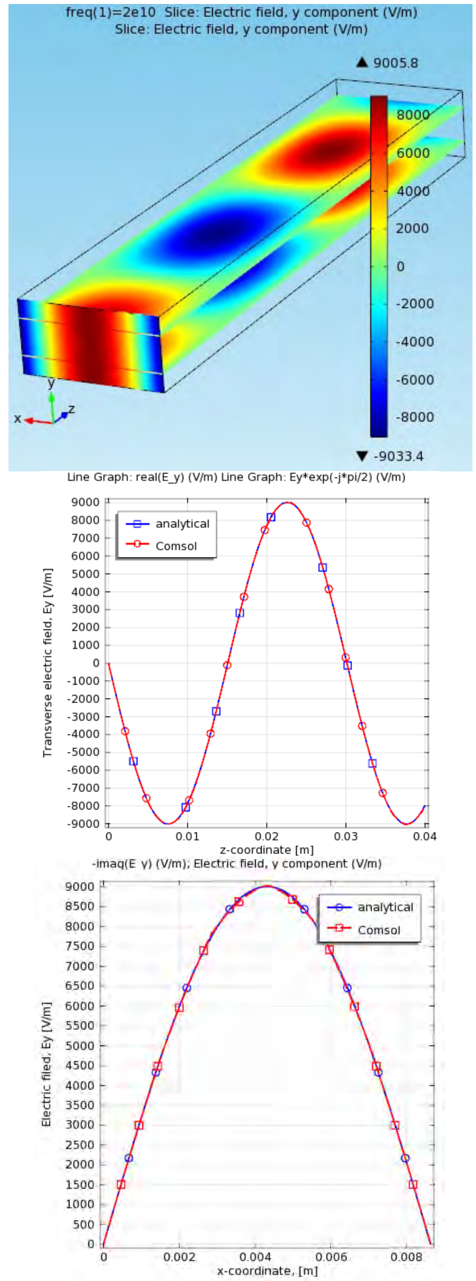


Figure 3. Transverse electric field E_y

The electric field distribution represents the key factor that influences how materials heat in a microwave oven. Therefore, to optimize design and operating parameters it is necessary to calculate how the electric field varies with factors such as cavity shape, microwave power, waveguide design and wave guide location. Examples of the resulting distribution of Electric and Magnetic field produced in a microwave cavity for a polarized source are shown in Figures 4 and 5.

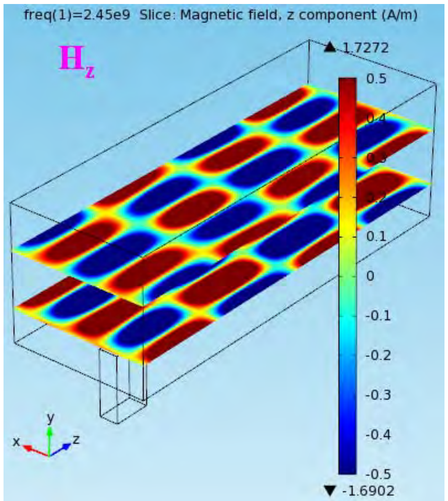


Figure 4: Variation of z component of magnetic field, H_z

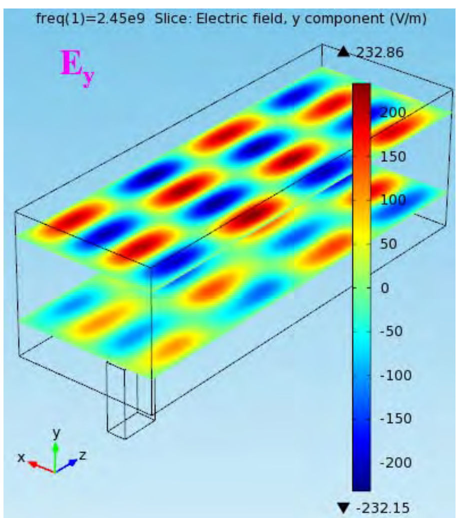


Figure 5: Variation of y component of electric field, E_y

The electric field distribution can be used to calculate the resulting temperature. For some applications, a more accurate analysis of the temperature distribution may require consideration of the heat evolved due to temperature induced phase changes. Consider the effect of the phase change from liquid to vapor. The latent heat of vaporization can be expressed by:

$$C_P = C_P^0 + V_v \lambda \frac{\partial H}{\partial T} \qquad (10)$$

where

C_P^0 : specific heat of solid

λ : latent heat of vaporization

V_f : initial moisture content

$H = flc2hs(T - T_v, \Delta T)$: Heaviside function

T_v : temperature of vapor formation

ΔT : temperature range for vaporization

Integration of this approach with the analysis of the microwave interaction with the solid enables a more accurate prediction of the temperature distribution to be made.

3. Summary

The analyses of the microwave propagation performed here can be used to predict the temperature rise in materials. Descriptions of the field distribution can be used to define cavity shapes, polarization effects and field distributions that will provide improved heating patterns and therefore more robust processing conditions. This work can be easily extended to problems with multiple microwave sources by coupling additional waveguides to the cavity.