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Title: DYNAMIC MODEL FOR ELECTROMAGNETIC FIELD AND HEATING IN LOADED CYLINDRICAL CAVITIES

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DYNAMIC MODEL FOR ELECTROMAGNETIC FIELD AND HEATING PATTERNS IN LOADED CYLINDRICAL CAVITIES

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ABSTRACT

An analytical solution for the electromagnetic fields in a cylindrical cavity, partially filled with a cylindrical dielectric has been recently reported [1]. A program based on this solution has been developed and combined with the authors' previous program for heat transfer analysis. The new software has been used to simulate the dynamic temperature profiles of microwave heating and to investigate the role of electromagnetic field in heating uniformity and stability. The effects of cavity mode, cavity dimension, the dielectric properties of loads on electromagnetic field and heating patterns can be predicted using this software.

INTRODUCTION

Nonuniform heating and thermal runaway are two main problems frequently encountered in microwave processing of materials. They are caused by a number of factors related to both electromagnetic energy and thermal physical process [2]. A computer simulation was previously reported to study the effects of the thermal physical aspects on dynamic temperature profiles of microwave heating such as thermal conductivity, temperature dependence of dielectric loss factor, heating rate and insulation [3]. However no attempts were made in the previous study to investigate the effect of electromagnetic aspects on the microwave heating pattern. The electromagnetic field was simply assumed as a uniform distribution due to the lack of the knowledge of the real distribution of the electromagnetic filed at that time. Obviously, such a simplification might cause error and underestimate the problems.

An analytical solution for the electromagnetic fields in a cylindrical cavity coaxially loaded with a cylindrical dielectric has been recently reported by Manring [1]. This progress motivated us to extend our computer simulation into electromagnetic fields. Based on Manring's approach a program has been developed to find solutions for resonant frequency, quality factor, electric field pattern and energy distribution for various types of cavity mode, cavity size, sample size and dielectric material. This program was combined with the authors' previous program for thermal analysis. The new software was then applied to simulate the dynamic temperature profiles during microwave heating and to investigate the effects of the electromagnetic field on the heating patterns. Some preliminary results of our modelling will be presented in this paper.

CONFIGURATION OF THE LOADED CYLINDRICAL CAVITY

The configuration of a coaxially loaded cylindrical cavity used in this study is shown in Figure 1. This configuration is referred to as cavity-short type where the load length is equal to the cavity length. The origin, 0, of a cylindrical coordinate system (ρ,ϕ,z) is located at the center of the bottom plate of the cavity. The dimension of the cavity is selected as close to that of the commercial cylindrical cavity, Wavemat model CMPR 250. The cavity length can vary from 6 to 16 cm, which allows eight resonant modes to be excited at 2.45 GHz. In this study, only two types of low index mode, namely, TE_{011} and TM_{011} modes, will be discussed. The TE_{011} mode is especially interesting because it exhibits an electric field pattern which may lead to a high energy density at the surface of the dielectric load and a low energy density in the center. This type of energy distribution may be beneficial in compensating for the heat loss at the surface and improving the temperature uniformity during microwave heating. Alumina (92%) is selected as the dielectric load in the cavity. The data for the dielectric and thermal properties of this material is collected from references [4,5].

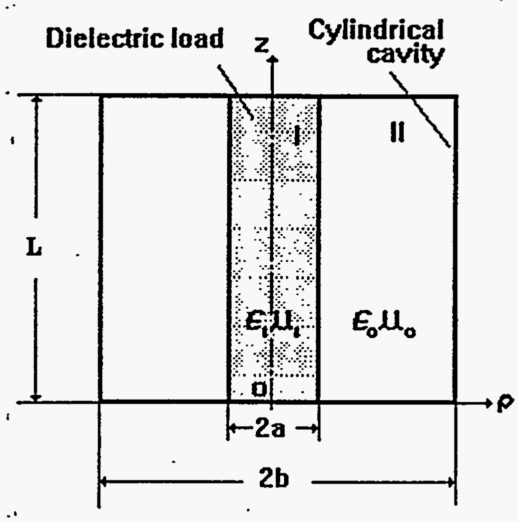


Fig. 1 Configuration of a dielectric loaded cylindrical cavity.

RESONANT FREQUENCY

Following Manring's approach, the complex radian resonant frequency ω and the wave numbers of $k_{\rho 1}$ in region I and $k_{\rho 2}$ in region II for the TE_{npq} or TM_{npq} modes are the roots of the following three simultaneous equations:[1]

$$V_n W_n - U_n^{\,2} = 0 \qquad (1)$$

$$\omega^2 \mu_0 \epsilon_1 = k_{\rho 1}^2 + (q\pi/L)^2 \qquad (2)$$

$$\omega^2 \mu_0 \epsilon_0 = k_{\rho 2}^2 + (q\pi/L)^2 \qquad (3)$$

where, $V_n = k_{\rho 1} k_{\rho 2}\, \mu_0\, (k_{\rho 2} F_2' F_4 - k_{\rho 1} F_2 F_4')$ $\quad (V_n = 0$ for TE_{0pq} mode)

$W_n = k_{\rho 1} k_{\rho 2}\, (\epsilon_1 k_{\rho 2} F_1' F_3 - \epsilon_1 k_{\rho 1} F_1 F_3')$ $\quad (W_n = 0$ for TM_{0pq} mode)

$U_n^{\,2} = [nq\pi/\omega a L]^2 F_1 F_2 F_3 F_4 (k_{\rho 1}^2 - k_{\rho 2}^2)^2$

and ϵ_1 is the complex dielectric constant of the load in region I, which can be expressed as $\epsilon_1 = \epsilon_1' - j\,\epsilon_1''$. ϵ_0 and μ_0 are the electric permittivity and magnetic permeability of free space in region II, respectively. F's are combinations of Bessel's functions of the first and second kind using Harrington's notation [6]. The detailed information for F's can be found in Reference [1].

Equation (1) is an implicit expression containing complex terms of Bessel function for ω, $k_{\rho 1}$ and $k_{\rho 2}$. A complex root finding subroutine, called ROOT , developed by Tijhuis [1] was adopted in the computer program to solve for the complex ω, $k_{\rho 1}$ and $k_{\rho 2}$. Variation of the resonant frequency f_0 with sample size and cavity geometry for Al_2O_3 (92%) loaded TE_{011} and TM_{011} modes is shown in Figure 2. The resonant frequency f_0 decreases with the increase of filling ratio (a/b) and decrease of the aspect ratio of the cavity (2b/L).

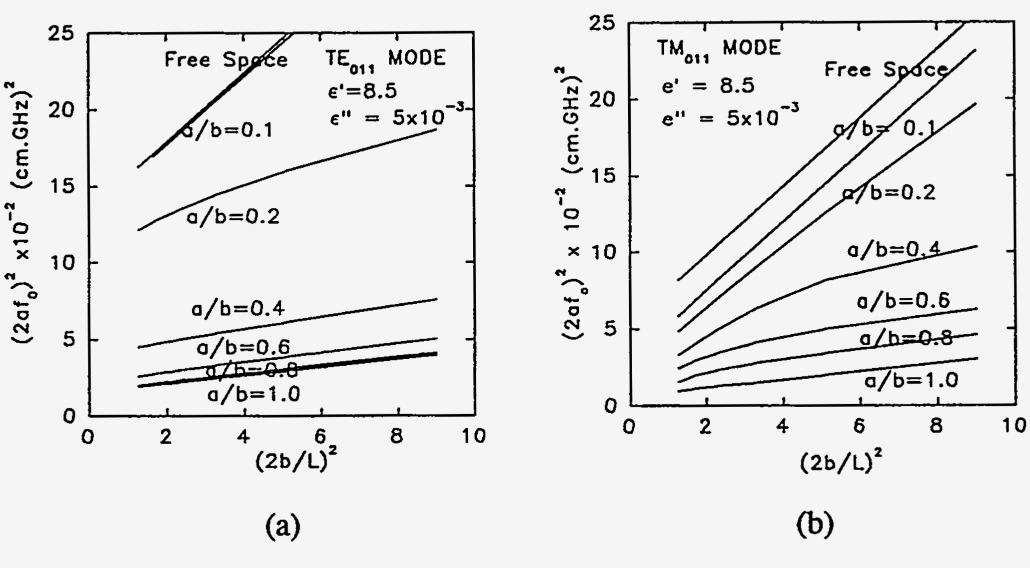


Fig.2 Resonant frequency f_0 vs. cavity aspect ratio (2b/L) for various sample filling ratio (a/b). (a) TE_{011} mode. (b) TM_{011} mode.

ELECTROMAGNETIC FIELD PATTERNS

If the complex roots of ω, $k_{\rho 1}$ and $k_{\rho 2}$ are known, the three components of the electric fields for n=0 case can be solved using the following equations :[1]

For TE_{0pq} mode: $E_{\rho 1} = 0;$ $E_{z1} = 0;$ $E_{\rho 2} = 0;$ $E_{z2} = 0;$

$$E_{\phi 1} = B\, k_{\rho 1}\, F'_2\,(k_{\rho 1}\,\rho)\,\sin(q\pi z/L) \tag{4}$$

$$E_{\phi 2} = D k_{\rho 2}\, F'_4\,(k_{\rho 2}\,\rho)\,\sin(q\pi z/L) \tag{5}$$

For TM_{0pq} mode: $E_{\phi 1}=0;$ $E_{\phi 2}=0;$

$$E_{\rho 1} = -\,(A\, q\, \pi\, k_{\rho 1} / \acute{\omega}\, \epsilon_1 L)\, F'_2\,(k_{\rho 1}\rho)\,\sin(q\pi z/L) \tag{6}$$

$$E_{z1} = (A k_{\rho 1}^2 / \acute{\omega}\, \epsilon_1)\; F_1\,(k_{\rho 1}\rho)\,\cos(q\pi z/L) \tag{7}$$

$$E_{\rho 2} = -\,(C q\, \pi\, k_{\rho 2} / \acute{\omega}\, \epsilon_0 L)\, F'_2\,(k_{\rho 2}\rho)\;\sin(q\pi z/L) \tag{8}$$

$$E_{z2} = (C k_{\rho 2}^2 / \acute{\omega}\, \epsilon_0)\; F_1\,(k_{\rho 2}\rho)\,\cos(q\pi z/L) \tag{9}$$

where A,B,C,D are constants representing the amplitude of each field.

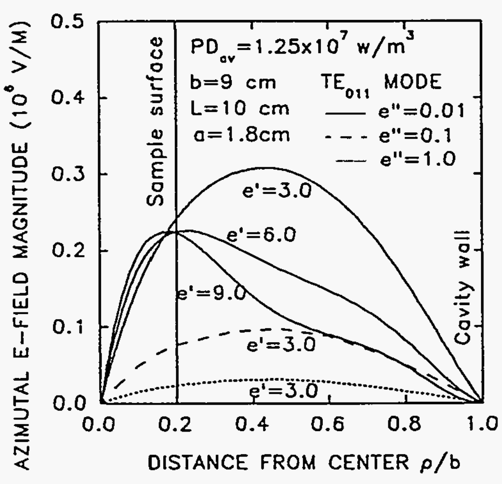


Fig.3 Variation of electric field E_ϕ distribution at z=L/2 with dielectric properties for TE_{011} mode.

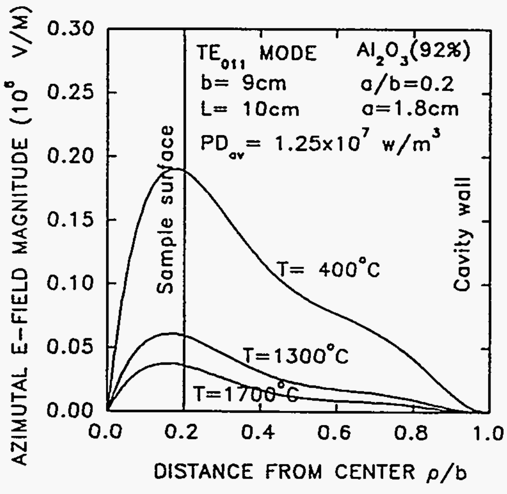


Fig.4 Variation of electric field E_ϕ distribution at z=L/2 with temperature for TE_{011} mode.

Typical examples of the computed electromagnetic field patterns for TE_{011} mode are shown in Figure 3 and Figure 4. The average power density, PD_{av}, defined as the total absorbed power divided by the volume of the sample, is assumed to be constant during the microwave process. It is seen from these figures that the electric field in the load is always higher in near surface area than that in the center. Figure 3 plots the variation of the E_ϕ with the dielectric properties of the materials along the radial direction. As dielectric constant ϵ_1' increases, the peak of the electric field shifts from the center of the empty region II to the center of the load region I. Increase of the dielectric loss factor ϵ_1'' reduces the magnitude of the electromagnetic field. Since both ϵ_1' and ϵ_1'' increase with the increase of the temperature, it can be seen from Figure 4 that the E_ϕ peaks shift to the center of region I and the magnitudes of the fields reduce as the temperature rises. Therefore, there is less chance of arcing in air (region II) when temperature is high or the material has a high dielectric constant or a high loss factor.

ENERGY DISTRIBUTIONS IN THE DIELECTRIC LOAD

The dissipated power density, PD, in a load can be calculated from:

$$PD = 2\,\pi\, f_0\, \epsilon_0\, \epsilon_1''\, E\, E^* \qquad (10)$$

where E is the sum of three components of the electric field E_ρ, E_ϕ and E_z calculated from Eq.(4) to Eq.(9). Figure 5(a) and (b) show the variation of

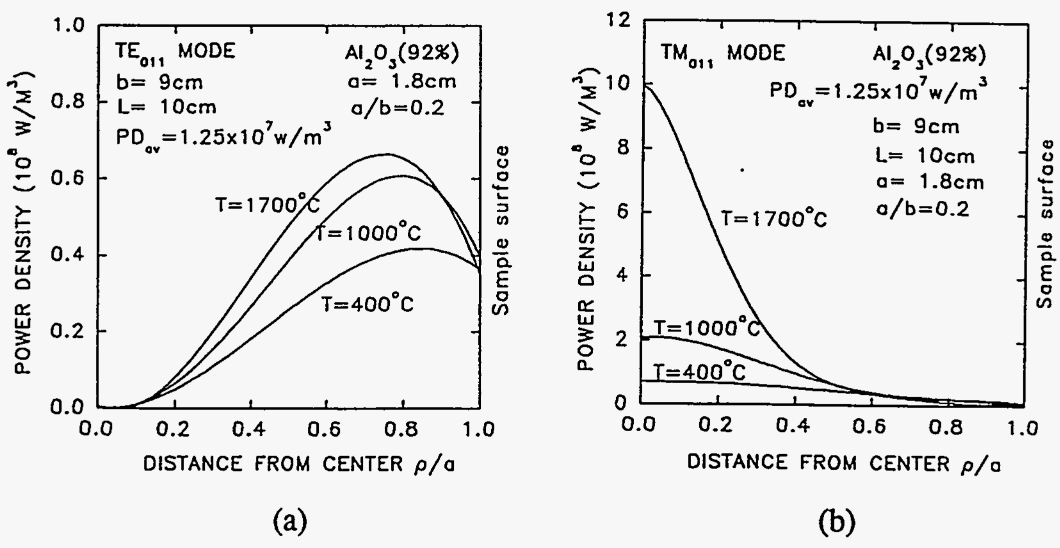


Fig.5 Variation of energy density distribution at z=L/2 with temperature. (a) TE_{011} mode. (b) TM_{011} mode.

energy distribution patterns with temperature for TE_{011} and TM_{011} modes, respectively. The power density patterns of the two modes are just opposite. For the TM_{011} mode, the peak density position is in the center, whereas that of the TE_{011} mode is close to the surface. Although the magnitude of the energy density of both modes increases with the increase of temperature, the change of the peak density in TM_{011} mode is considerably higher than that of TE_{011} mode at temperatures over 1000 °C. This may have a negative impact on the thermal runaway problem as will be discussed in the following section.

DYNAMIC TEMPERATURE PROFILES

The temperature distribution inside the sample is governed by the following general heat transfer equation [3]:

$$d_n C_p(\partial T/\partial t)=(1/\rho)\{\partial[\ k\rho(\partial T/\partial \rho)\ ]/\partial \rho\} + \partial[\ k(\partial T/\partial z)\ ]/\partial z + PD \quad (11)$$

where d_n, C_p and k are the density, specific heat and thermal conductivity. The power density dissipated in the sample, PD, is given by Eq(10). For a given time step, the temperature rise in the load is computed using a finite difference algorithm. The resonant frequency, f_0, electric field E, dielectric properties ϵ_1' and ϵ_1'', and thermal properties of k and C_p are recalculated at next time step to accommodate the effects of the temperature increment on these parameters. This process is repeated until a steady state reached or a thermal instability happens. The details of our numerical approach can be found in References [2,3].

Figure 6 plots the radial temperature profiles for heating of an alumina sample in a TE_{011} mode with a low PD_{av}. A steady state of temperature distribution was reached after 1200 seconds because of the slow heating rate. The temperature distribution is relatively uniform in the center part of the sample but shows high gradient near the surface area due to the large radiation loss at high temperatures. Figure 7 shows the temperature profiles of TM_{011} mode under the identical conditions. Thermal runaway occurs at the center within about 120 seconds which can be attributed to the rapid rising of energy density in the center for $T>1000$°C as shown in Figure 5 . Obviously the energy density pattern of TE_{011} mode are in favor of improving the temperature uniformity and stability of microwave heating. Nevertheless, thermal runaway may still occur for TE_{011} mode as illustrated in Figure 8 where all the conditions are almost the same as Figure 6 except for a doubled average energy density PD_{av} in Figure 8(a), and a doubled sample diameter in Figure 8(b).

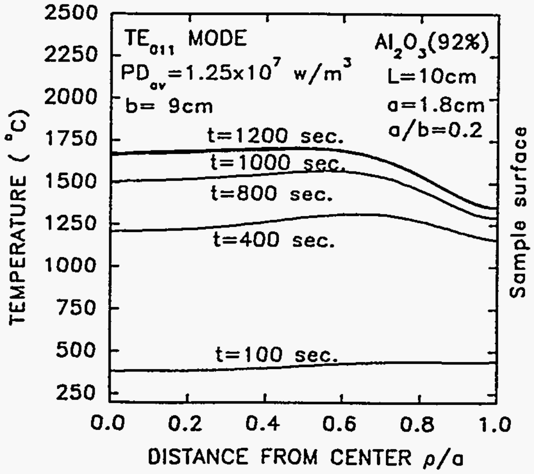


Fig.6 Dynamic temperature profile of Al_2O_3 sample in TE_{011} mode.

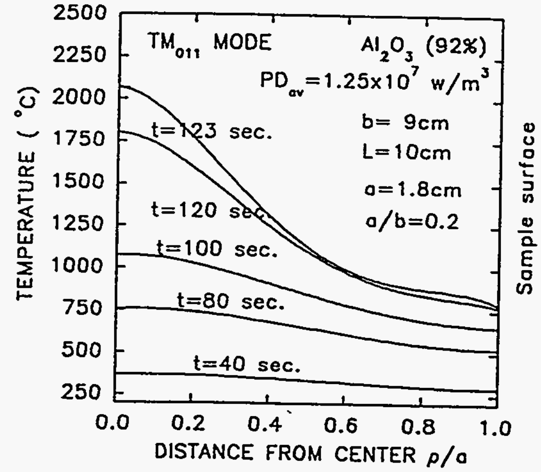
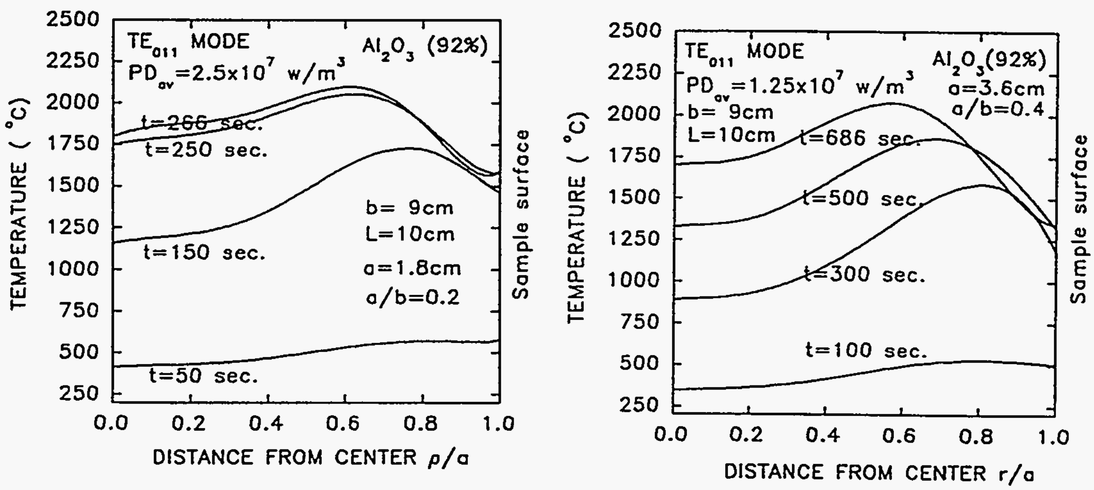


Fig.7 Dynamic temperature profile of Al_2O_3 sample in TM_{011} mode.



(a) (b)

Fig.8 Thermal runaway of Al_2O_3 samples in TE_{011} mode caused by (a) high heating rate and (b) large sample diameter.

CONCLUSIONS

The electromagnetic field pattern plays an important role in determining the temperature distribution during microwave heating. The TE_{011} mode improves heating uniformity and stability, but limited to a certain extent.

The resonant frequency, f_0, decreases with the increases of dielectric constant, ϵ_1', and sample filling ratio, a/b, or cavity aspect ratio L/2b.

High heating rate and large sample size will enhance thermal instability and nonuniformity.

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