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A 전기적인 대구조의 마이크로파 가열의 수치해석 모델링

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A Numerical Algorithm for Modeling Microwave Heating Effects in Electrically Large Structures

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Abstract - In this paper, an iterative method to model the electromagnetic heating of electrically large lossy dielectrics is presented. Frequency domain finite element (FEM) solutions of the wave equation are determined for the lossy inhomogeneous dielectric as the material properties are change with temperature and time. The power absorbed from microwave losses is applied to a finite element time domain (FETD) calculation of the heat diffusion equation. Time steps appropriate for updating the piecewise material properties in the wave equation and the time stepping of the heat equation are presented. The effects of preheating and source frequency are investigated.

I. Introduction

In recent years, electromagnetic heating processes have received a great deal of attention[1]. Efficient modeling of heat absorption has been required for many systems, including industrial processing, drying, dielectric stability, and biological absorption[2][3]. Rapid heat addition demonstrates the capability to produce some novel materials and is much more effective means of achieving sintering. Microwave components require dielectrics with stable properties. Design of a cooling system can be improved by determining the locations of peak power absorption and temperature diffusion. Biological effects of cell phone usage has received a great deal of attention. Additionally, the effects of high power antennae on nearby materials is an important study for determining safe implementation. In this paper, the temperature growth characteristic of industrial processes is studied in detail.

Prior to the development of electromagnetic heating modalities, conventional heating was performed via conduction through the medium and convection at the exposed surfaces. With developing technology, new heating methods became available, such as induction, laser, and microwave methods. Microwave heating is extremely common in today's industrial and commercial environment. For home use, the microwave oven is an inexpensive appliance that is capable of heating food products at a faster rate than the conventional oven. Comparable conventional heating is more limited in application. Ovens designed to heat quickly can generate a temperature gradient with high surface temperatures at contact points. Convection can be applied to offset this phenomena, yet unfavorable material states can still develop.

While the electromagnetic heating process is typically more expensive than conventional heating, a significant advantage is that more control with regard to the heating profile is possible. During heating of low-loss materials, it is possible to achieve nearly uniform radiation when the material dimensions are less than the wavelength. The temperature distribution can then be nearly uniform for heating applications that require such constraints. Alternatively, microwave ovens or furnaces and reflecting surfaces can be designed to increase energy absorption at specific locations with regard to specific sample geometries. Subsurface heating can also be achieved, a significant advantage in electromagnetic drying applications[4]. This procedure is very useful to increase the drying rate. The transition of liquid to vapor may be applied to mechanically force more moisture from the material. While difficulties comparable to conventional heating can occur during microwave heating, the process allows greater flexibility. A significant concern is that subsurface and surface hotspots can occur in objects with dimensions on the order of several wavelengths. The resonant behavior of the material geometry can introduce high field locations. However, it is fairly simple to alter the electromagnetic heating by a frequency shift or changing the orientation and intensity of the radiator. A problem specific to electromagnetic heating, thermal runaway, also needs attention[5]. Since water demonstrates this rapid change in power absorption, particular care must be observed during the warming and thawing of foodstuff and biomedical applications.

II. Defining Equations

Conservation of energy governs the temperature distribution and diffusion inside the dielectric material. The governing equation can be expressed as,

$$W_{ext} = W_{stor} - W_{rad} - W_{conv} - W_{cond} \quad (1)$$

where Wext is the energy delivered from external sources (microwave losses), Wstor is the stored energy and the remaining terms represent thermal losses via radiation, convection and conduction, respectively.

The field distribution inside a lossy dielectric is determined by the wave equation,

$$\nabla \times \nabla \times \vec{E} - \frac{\omega^2}{c^2} \varepsilon(\vec{r}, T | t) \vec{E} = 0 \qquad (2)$$

where the permittivity is a function of both position and time. The temporal variation of the permittivity is due to the changing temperature distribution. The magnitude of the temperature is then used to determine the rate of temperature growth in the material using the equation,

$$c\rho_o \frac{dT}{dt} = \frac{1}{2} \varepsilon_o \varepsilon'' |E|^2 \qquad (3)$$

dependent on the specific heat, density and conduction and polarization losses properties of the dielectric.

Equation 3 represents the external sources in Equation 1 and is applied to the source term, f, in the heat diffusion equation,

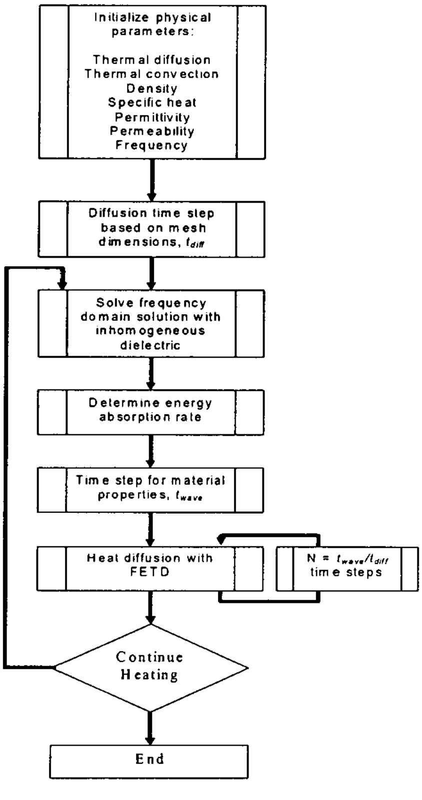
$$c\rho_o \frac{\partial T}{\partial t} = a \nabla \bullet (\nabla T) + f \qquad (4)$$

The gradient of the temperature is the heat flux, q, in Equation 4. The boundary conditions associated with radiation and convection, respectively, are

$$q = h(T - T_{ext})$$

$$q = \sigma(T^4 - T_{ext}^4) \qquad (5)$$

including the heat transfer coefficient and the Stefan-Boltzmann constant.



<Fig. 1> Flowchart of numerical model for microwave heating

Ⅲ. Numerical Model

The flowchart applied to the microwave heating model is shown in Figure 1. Equation 2 is solved using the well known finite element method with piecewise constant dielectric properties. Six-noded triangles are applied with the associated quadratic basis functions, The source is plane wave incidence, permitting the incident field to be modeled via the boundary terms in the FEM formulation. Equation 4 is solved using Voronoi polygons on the same finite element mesh and the scalar temperature distribution inside each element is a compbination of the linear basis functions,

$$T_e = \sum_{i=1}^{3} T_{ei} \phi_i \qquad (6)$$

Heat flow is calculated normal to the polygon boundary, requiring a relatively smooth mesh. The first order time derviative is approximated by a the first order finite difference method.

$$\frac{dT}{dt} \approx \frac{T^{n+1} - T^n}{\Delta t} \qquad (7)$$

The divergence equation can then be applied to the first term on the right side of Equation 4, such that

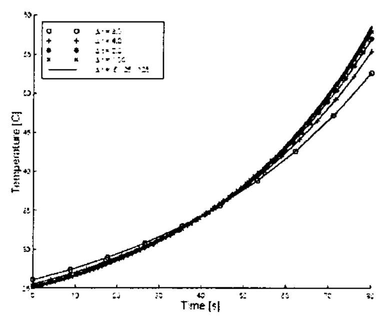
$$\int \nabla \bullet (\nabla T) \rightarrow \oint (\vec{q} \bullet \hat{n}) \, dl \qquad (8)$$

The integration is performed around the polygon bounding the vertex node and represents total heat flux through the polygon to its neighbors. Likewise, the physical boundaries in the geometry can be substituted into the above integral to appropriately model boundary thermal losses.

The time scales associated with each equation are significantly different, where small changes in temperature will correspond to many periods of the incident wave. Therefore, a frequency domain solution with assumed static material properties can be valid for short durations of heating, Additionally, the time step that is required for FETD stability is much smaller than that necessary to increment the dielectric properties. To guarantee stability, the time step is constrained as,

$$\frac{a\Delta t}{c\rho_o \max(area)} \leq 0.2 \qquad (9)$$

The time step for updating material properties was investigated numerically, with the results shown in Figure 2. As can be seen, the curves converge as the time step becomes sufficiently small.



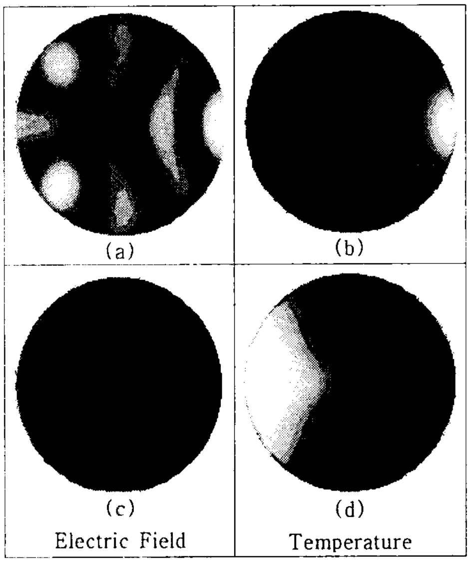
<Fig. 2> Temerature growth sensitivity to time step applied to material properties

Ⅳ. Analysis of the Numerical Model

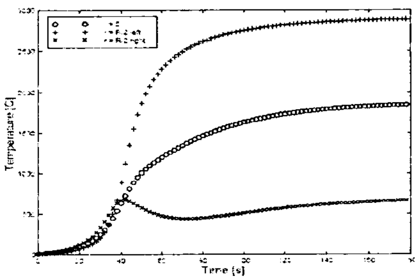
This model was applied to the dielectric heating of a lossy cylinder, with a diameter approximately four wavelengths at room temperature. The dielectric was given the temperature dependency

$$\varepsilon_r = 3.9 + .0001(T-25) + j[0.46 + .001(T-25)]$$

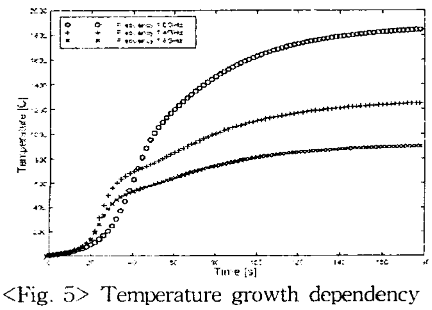
which can be considered an approximate expression for some ceramic sintering processes[6]. For experimental purposes, the heating process was allowed to reach a very high steady state temperature that is possible in some materials.



<Fig. 3> Field (a,c) and Temperature (b,d) distributes at early stages (a,b) and late stages (c,d) of the heating process



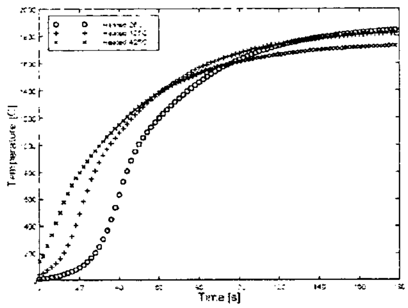
<Fig. 4> Temperature growth at interior points centered along the cylinder axis (r=0, r=± R/2)



<Fig. 5> Temperature growth dependency on frequency

Ⅳ. Conclusion

An algorithm was developed to model microwave heating of lossy inhomogeneous dielectrics. Solutions for both the wave equation and the heat diffusion equation were implemented on the same triangular mesh. Numerical stability was verified for both the FETD solution of the heat equation and the time stepping scheme for updating dielectric properties in the elements. The dimensions of the object were large, allowing peaks and null field locations to occur at multiple locations inside the dielectric material. Initial temperature growth correlated with these peaks, As the material temperature increased, and consequently became more lossy, the field power losses were reduced due to lower electromagnetic penetration and surface heating became apparent. A steady state temperature and field distribution was reached, indicating that the coupled solution was stable. It was noticed that both increasing the frequency and preheating had the effect of reducing the steady state temperature.



<Fig. 6> Temperature growth dependency on initial temperature

[References]

[1] A. C. Metaxus, Foundations of Electroheat, John Wiley and Sons, New York, 1996

[2] G. A. Kriegsmann, "Pattern formation in microwave heated ceramics: cylinders and slabs", IMA Journal of Applied Mathematics, vol. 66, pp1-32, 2001

[3] A. Sekkak, L. Pichon, A. Raz다, "3D FEM magneto-thermal analysis in microwave overns", IEEE Trans. on Mag. vol. 30(5), pp3347-3350, 1994

[4] J. R. Thomas, R. M. Roos, "3D temperature distributions produced by a microwave spot heating applicator", Microwave Proc. of Mat., vol 430, pp 345-350, 1996

[5] G. Roussy, A. Bennani, J. M. Thiebaut, "Temperature runaway in microwave irradiated materials", J. of Appl. Phys., vol. 62(4), pp1167-1170, 1987

[6] G. Sethi, A. Upadhyaya, D. Agrawal, "Microwave and convetional sintering of premixed and prealloyed Cu-12Sn bronze", Science of Sintering, vol. 35, pp49-64, 2003