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Numerical Analysis of Heat Transfer inside Multi-layer Dielectric Materials under Electromagnetic Energy in TE_{10} mode Rectangular Waveguide Cavity

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ABSTRACT

The presented paper investigated the two dimensional numerical analysis coupled of microwave (mode:TE_{10} at the frequency of 2.45 GHz) multi-layered dielectric materials using a rectangular waveguide. This numerical study used to determine heat transport phenomena within multi-layered dielectric materials at which were located in rectangular wave guide to evaluate the variations of temperature and electromagnetic field. The results showed that the effect of different layer of materials were very important roles on overall heating kinetics. These findings were significant to explain phenomena of dielectric materials in microwave heating using a rectangular waveguide.

Key words: Microwave heating, Multi-layer Dielectric Material, Numerical, Rectangular Wave Guide.

INTRODUCTION

From the past to the present, microwave heating is alternative energy which has successfully in many applications. Because the heat transport phenomena inside material from microwave energy has different from conventional heating. Therefore, it is studied by many researchers that have been appeared in the example of recent literatures ([1-7]).

Although a lot of research studies microwave heating application. But most investigations consider on experimental applications. This is because it is easy to apply to find results in their applications. On the other hand, theoretical analysis is difficult to understand and find out accuracy results. However, theoretical and numerical analyses are developed by some researchers from Lambert's law couple with 1 D heat transfer mathematical model to Maxwell's equations couple with 2 D heat transfer mathematical model, respectively. For small or thin sample, the theoretical and numerical analyses of electromagnetic field are obtained by Maxwell's equations. The example of Maxwell's equations which have been used for study numerous heating processes of materials in microwave heating are literatures [8] and [9]. In practice, most of microwave heating applications are used with multi layered dielectric material such as sandwich, steamed stuff bun, concrete, and wood etc. But, in theoretical and numerical analyses, homogeneous dielectric materials are used in most investigations. This problem is the origin of this study.

A recent work investigated the two dimensional numerical analysis coupled of microwave (mode:TE_{10} at the frequency of 2.45 GHz) multi-layered dielectric materials using a rectangular waveguide. This numerical study used to determine heat transport phenomena within multi-layer dielectric materials at which were located in rectangular wave guide to evaluate the variations of temperature and electromagnetic field. The presented results here provide a basis to understand fundamentally of microwave heating of dielectric materials.

2. Mathematical Formulation and Methodlogy:

2.1 Dielectric Properties:

The problem of microwave heating directly relates to dielectric property (ε) within the absorbed material which is an essential primary factor for theoretical prediction. ([10])

$$\varepsilon = \varepsilon' + j\varepsilon'' = \varepsilon_0\left(\varepsilon_r' + j\varepsilon_r''\right) \quad (1)$$

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Where ε_r' is the real part of relative permittivity, ε_r'' is the imaginary part of relative permittivity, and ε_0 is the permittivity of free space which equal to 8.86×10^{-12} F/m, respectively.
Where $\tan\delta$ is the loss tangent coefficient which can be expressed as follow: ([11])

$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{2}$$

2.2 Maxwell's Equation:

For TE_{10} mode microwave, the governing Maxwell's equations can be written in terms of the component notations of electric and magnetic field intensities. ([12])

$$\frac{\partial E_y}{\partial z} = \mu\frac{\partial H_x}{\partial t} \tag{3}$$

$$\frac{\partial E_y}{\partial x} = -\mu\frac{\partial H_z}{\partial t} \tag{4}$$

$$-\left(\frac{\partial H_z}{\partial x} - \frac{\partial H_x}{\partial z}\right) = \sigma E_y + \varepsilon\frac{\partial E_y}{\partial t} \tag{5}$$

Where, dielectric permittivity (ε), magnetic permeability (μ) and electric conductivity (σ) are given by: [12]

$$\varepsilon = \varepsilon_0\varepsilon_r, \qquad \mu = \mu_0\mu_r, \qquad \sigma = 2\pi f\varepsilon\tan\delta \tag{6}$$

Where f is the frequency of microwave, $\tan\delta$ is the dielectric loss tangent, ε_r and μ_r are the relative permittivity and relative magnetic permeability, respectively.

2.3 Heat Transfer Equation:

Form a schematic of the models was shown in Figs. 1. The governing equation of transient heat transfer can be derived as shown in Eq. (7) ([12]). To make the effect of multi-layered materials under microwave heating more clearly, all outside surface of samples are identified to thermal insulation which heat flux is equal to zero. Microwaves in the form of plane wave incident on top surface of sample.

$$\rho C_p\frac{\partial}{\partial t}[T] = k\frac{\partial}{\partial x}\left[\frac{\partial T}{\partial x}\right] + k\frac{\partial}{\partial z}\left[\frac{\partial T}{\partial z}\right] + Q \tag{7}$$

Where ρ is density of material, C_p is constant pressure heat capacitance, and k is thermal conductivity.

The rate of volumetric heat generation due to the absorption of microwave, Q, is represented in the following equation. ([12])

$$Q = \omega\varepsilon_r'' E^2 = 2\pi f\varepsilon_0\varepsilon_r'(\tan\delta)E_y^2. \tag{8}$$

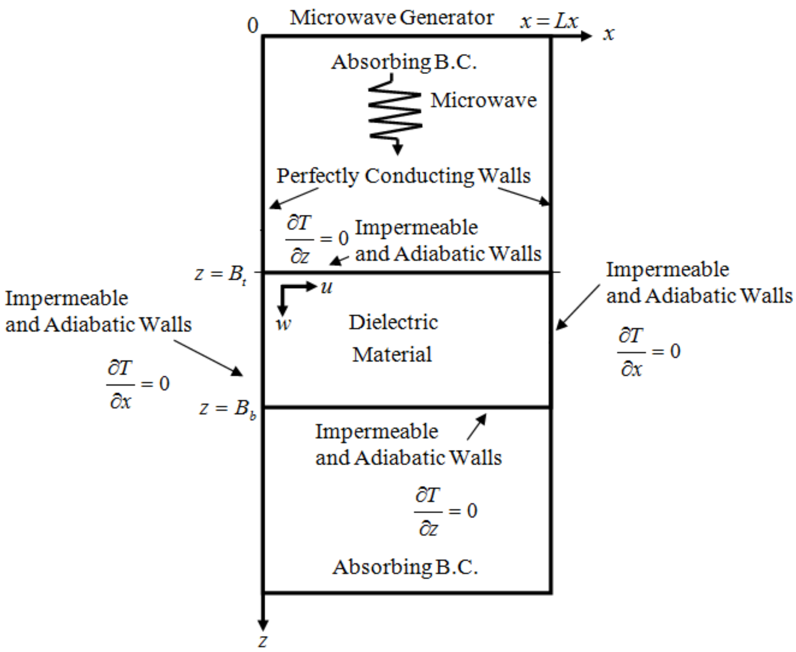


Fig. 1: Physical domain.

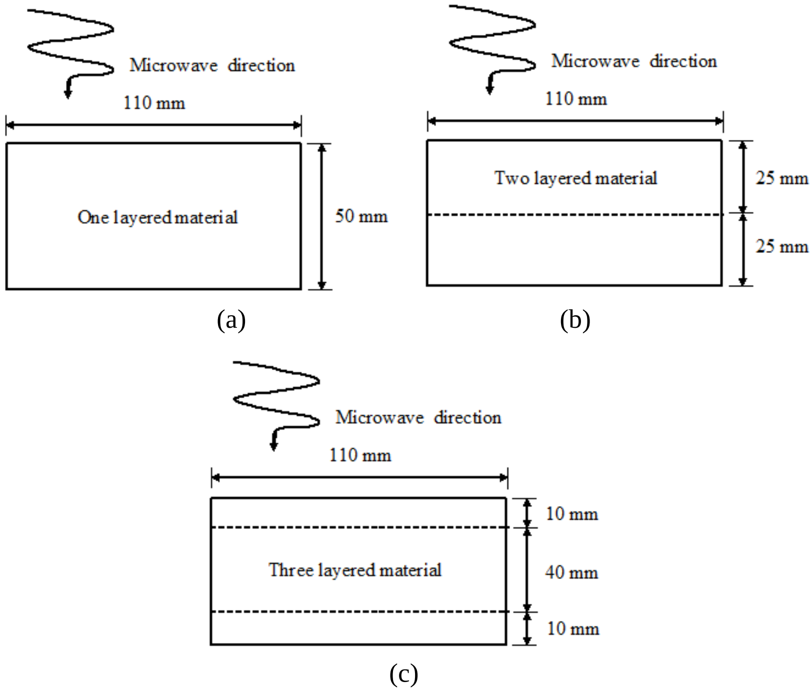


Fig. 2: Sample size.
(a) Single layered or homogeneous material
(b) Double layered or homogeneous material
(c) Triple layered or homogeneous material

2.4 Boundary and Initial Conditions:

Corresponding to Figs. 1-2, boundary conditions for solutions of the thermal governing equations are impermeable surface and interface layered material condition. The detailed analysis of each condition as follows:

Impermeable surface:

The boundary condition at the impermeable are assumed to be zero value of temperature gradient which means no heat flux exchange at the boundary.

$$\frac{\partial T}{\partial x} = \frac{\partial T}{\partial z} = 0 \tag{9}$$

Interface of the layered packed bed:

Temperature and temperature gradient are assumed to be continuous at the interface of layered packed bed.

$$T_{\mathrm{LAYER\,A}} = T_{\mathrm{LAYER\,B}},$$
$$-k\left(\frac{\partial T}{\partial z}\right)_{\mathrm{LAYER\,A}} = -k\left(\frac{\partial T}{\partial z}\right)_{\mathrm{LAYER\,B}} \tag{10}$$

2.5 Numerical Solution:

The heat transfer equation is coupled to the Maxwell's equations to find heat transport phenomena within the sample. Therefore, in order to solve Maxwell's equations to predict the electromagnetic field, a finite difference time domain (FDTD) method was applied. And in order to solve heat transfer to predict thermal distribution, a finite difference was applied. The detailed of computational schemes and strategy were illustrated in Fig. 3.

2.5 Material details:

The domain in this study is heat transfer simulation in dielectric material under TE_{10} mode microwave heating at frequency 2.45 GHz inside rectangular wave guide cavity. This is because the electromagnetic domain can reduce three unknown terms which make the mathematical easier to solve. Additionally, the standard of section area of rectangular wave guide at frequency 2.45 GHz is 4x2 inch^2 or 110x55 mm^2. Therefore, side of sample in x-direction is 110 mm long which show in Fig. 2. The thickness of samples in this study is 50 mm because at this thickness an electromagnetic behavior is still wavy (if sample has high or semi-infinite value of thickness, electromagnetic distribution is appear in exponential decay).

For study the effect of multi-layered sample which has different value of dielectric properties at each layer. Therefore, all of thermal properties in this study at each layer are same value. In this study, two types of dielectric material are used to solve. First one is called high lossy material and second one is called low lossy material. The input data of high lossy and low lossy dielectric properties value was given in Table 1.

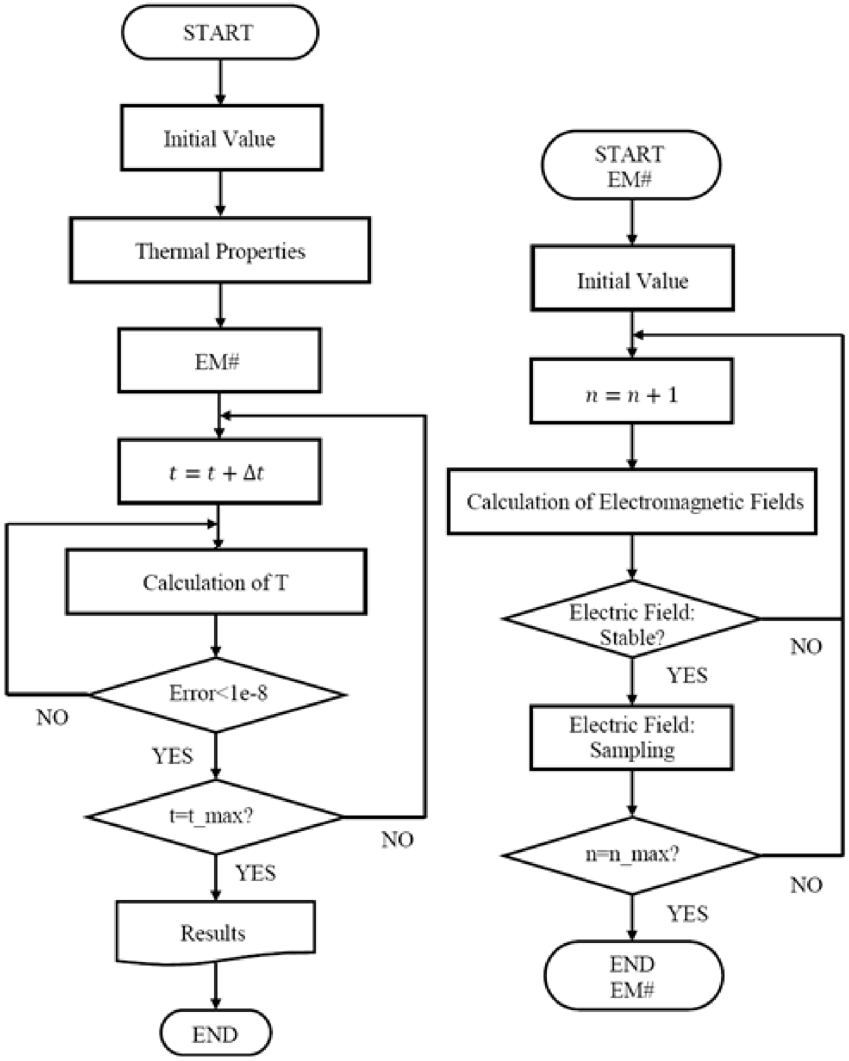


Fig. 3: A computational scheme.

Table 1: Dielectric properties of material.

Dielectric material	Real part of relative permittivity ε_r' (-)	Loss tangent coefficient $\tan\delta$ (-)	Magnetic permeability (μ)	Electric conductivity (σ)
High lossy	75	0.125	1	0
Low lossy	5.1	0.01	1	0

Other values of the input data for electromagnetic properties, thermal properties, and heating conditions were given in Table 2.

The simulated case were solve in transient condition which start from time is equal 0 to time is equal to 60 second. Additionally, the detailed of layered sample conditions for analysis are shown in Fig 4.

Table 2: Electromagnetic (dielectric) and thermo physical properties, and heating conditions used in the computations.

$\varepsilon_0 = 8.85419 \text{ x } 10^{12}$ [F/m]	$\mu_0 = 4.0\pi \text{ x } 10^{-7}$ [H/m]
$\varepsilon_{ra} = 1.0$, $\mu_{ra} = 1.0$	$\tan\delta_a = 0.00$
$\rho_p = 2{,}500[kg/m^3]$	$k_p = 1.0[W/(m \cdot K)]$
$C_{pp} = 0.80[kJ/(kg \cdot K)]$	$T_{\text{int}} = 25°C$
$Power = 350[\text{Watt}]$	$t_0 = 0\,\text{sec}$
$f = 2.45[GHz]$	$t_{end} = 60\,\text{sec}$

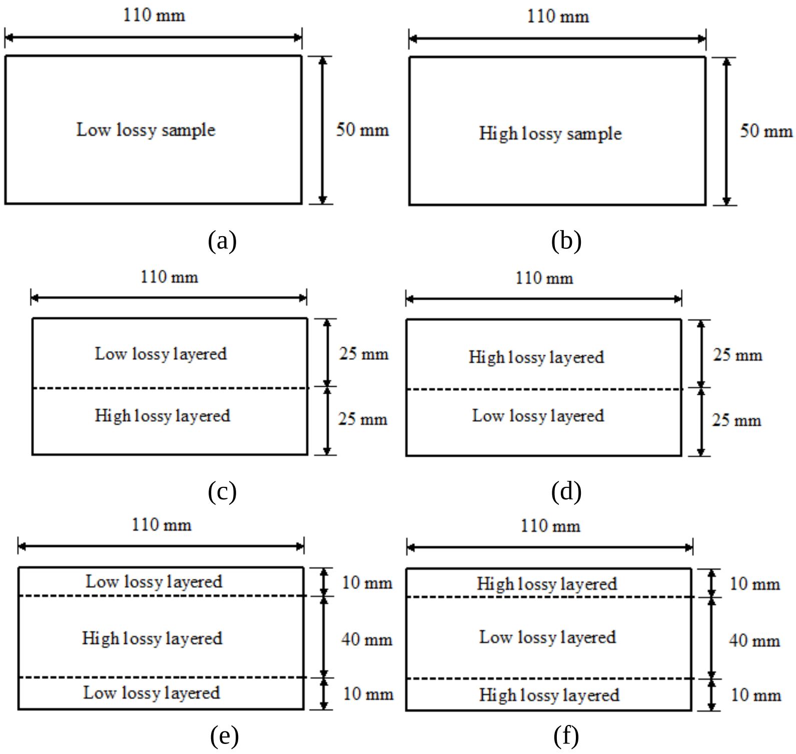
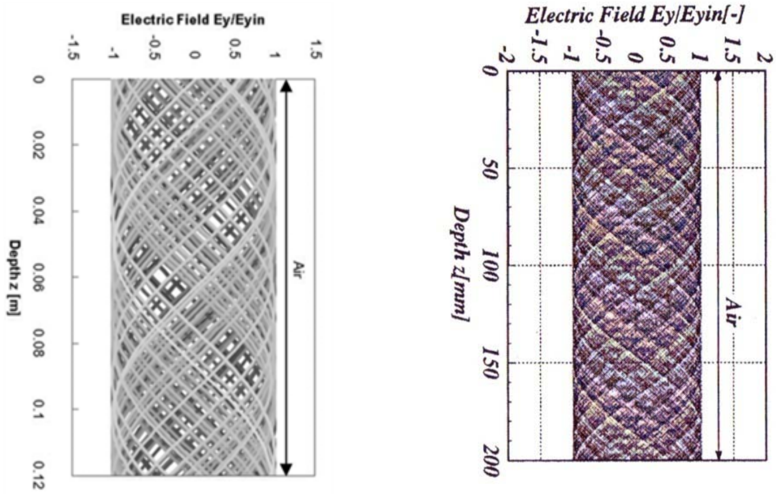


Fig. 4: Sample conditions. (a) Single layered, low lossy sample (b) Single layered, high lossy sample
(c) Double layered, low lossy layered at top (d) Double layered, low lossy layered at bottom
(e) Triple layered, high lossy layered at middle (f) Triple layered, low lossy layered at middle

Results and Discussion

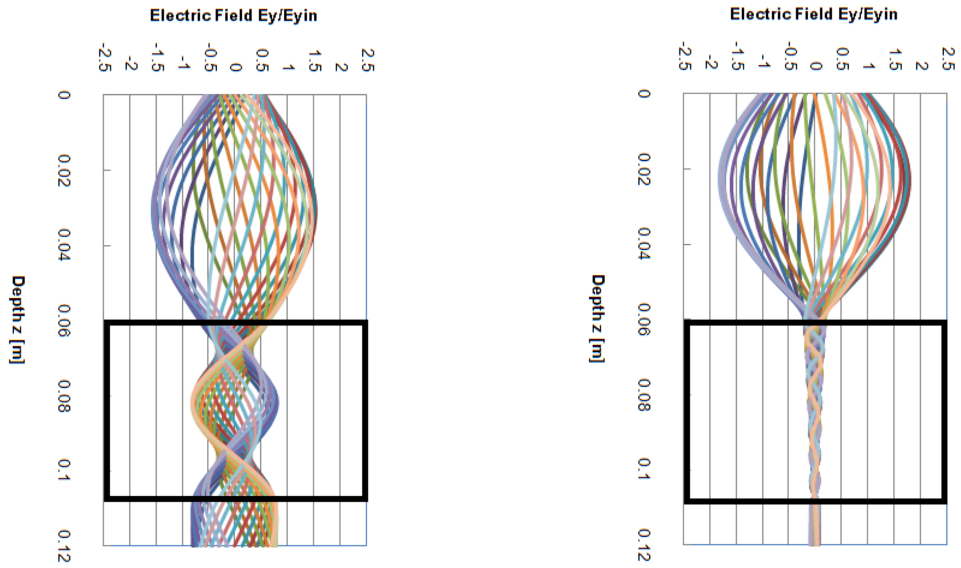
3.1 Electric Field Simulation inside a Rectangular Wave Guide:

Before use mathematical modeling to solve problem, the computational model is validated via compared with the result of Rattanadecho's work [14]. Fig. 5(a) shows the stationary wave inside the empty rectangular wave guide with completely absorbed power at the end of the rectangular wave guide. It is observed that the electric field distribution displays wavy behavior with an almost uniform amplitude along a rectangular wave guide. The resulting data is give a similarly the results obtained by Rattanadecho *et al* [14] (Fig. 4(b)).



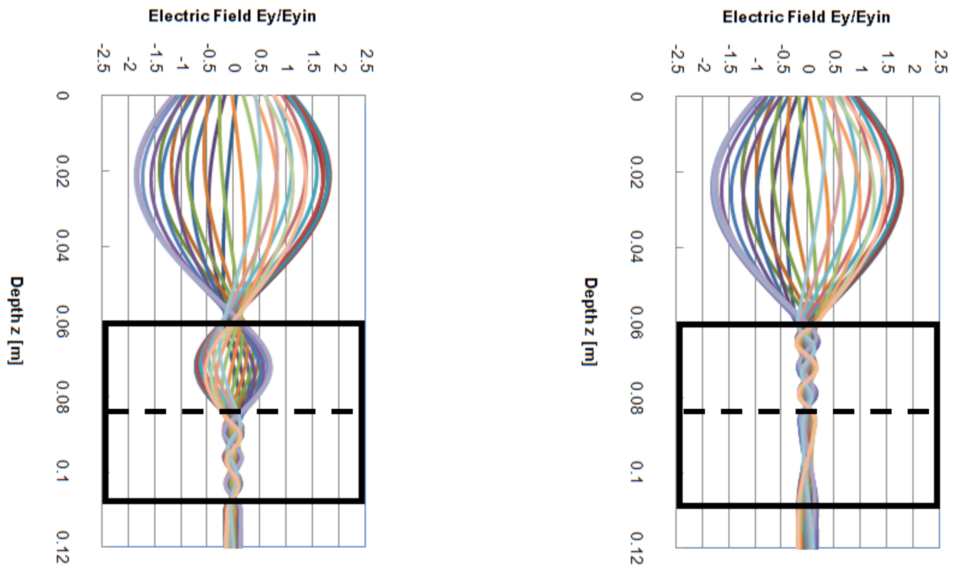
(a) (b)

Fig. 5: Distribution of electric field in case of a rectangular wave guide is empty at time of heating is equal to 60s ($x = 55$ mm).
(a) The result from presented study
(b) The result obtained by Rattandecho *et al*. [14].



(a) (b)

Fig. 6: Distribution of electric field in single layer conditions at time of heating is equal to 60 s ($x = 55$ mm).
(a) Low lossy dielectric sample.
(b) High lossy dielectric sample

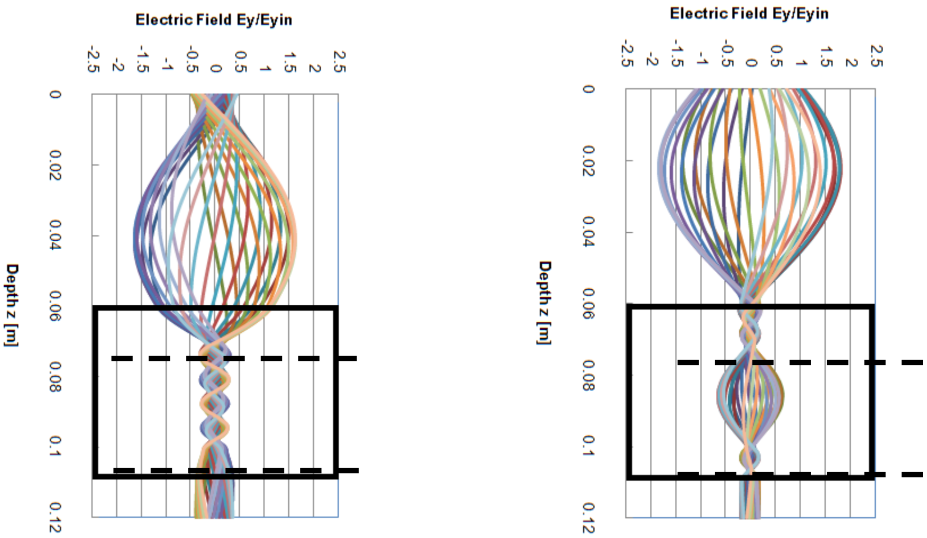


(a) (b)

Fig. 7: Distribution of electric field in double layer conditions at time of heating is equal to 60 s ($x = 55$ mm).
(a) Low lossy dielectric layered at the top of sample.
(b) High lossy dielectric layered at the top of sample

3.1.1 Electric field distribution at single layered conditions:

Figs. 6(a) and 6(b) shows the wave distribution of the electric field when the samples are single layered material. In case of high lossy material, the electric field attenuates owing to energy absorption, and thereafter the absorbed energy is converted to the thermal energy within the sample, which increases the sample temperature. The electric field within the sample is almost extinguished because the sample at this period is very high dielectric properties. From this result, almost microwave energy is transformed into thermal energy at nearly top surface. Therefore an electromagnetic behavior is not wavy inside the sample and is appearing in exponential decay pattern like semi-infinite thickness sample. In contrast, low lossy material, the electric field almost passes through the sample with high standing wave like outside the sample. A few of energy attenuates owing to energy absorption, and is converted to the thermal energy within the sample, which increases temperature. But it is very low while compare with high lossy material. This is because microwave energy is not absorbed by low lossy material which have a few of dipole inside, then high magnitude microwave energy can pass through freely in sample and free space. However, the highest magnitude inside sample is in middle point of sample that lead to hot spot temperature at the center of sample.



(a) (b)

Fig. 8: Distribution of electric field in triple layer conditions at time of heating is equal to 60 s ($x = 55$ mm).
(a) Low lossy dielectric sample.
(b) High lossy dielectric sample

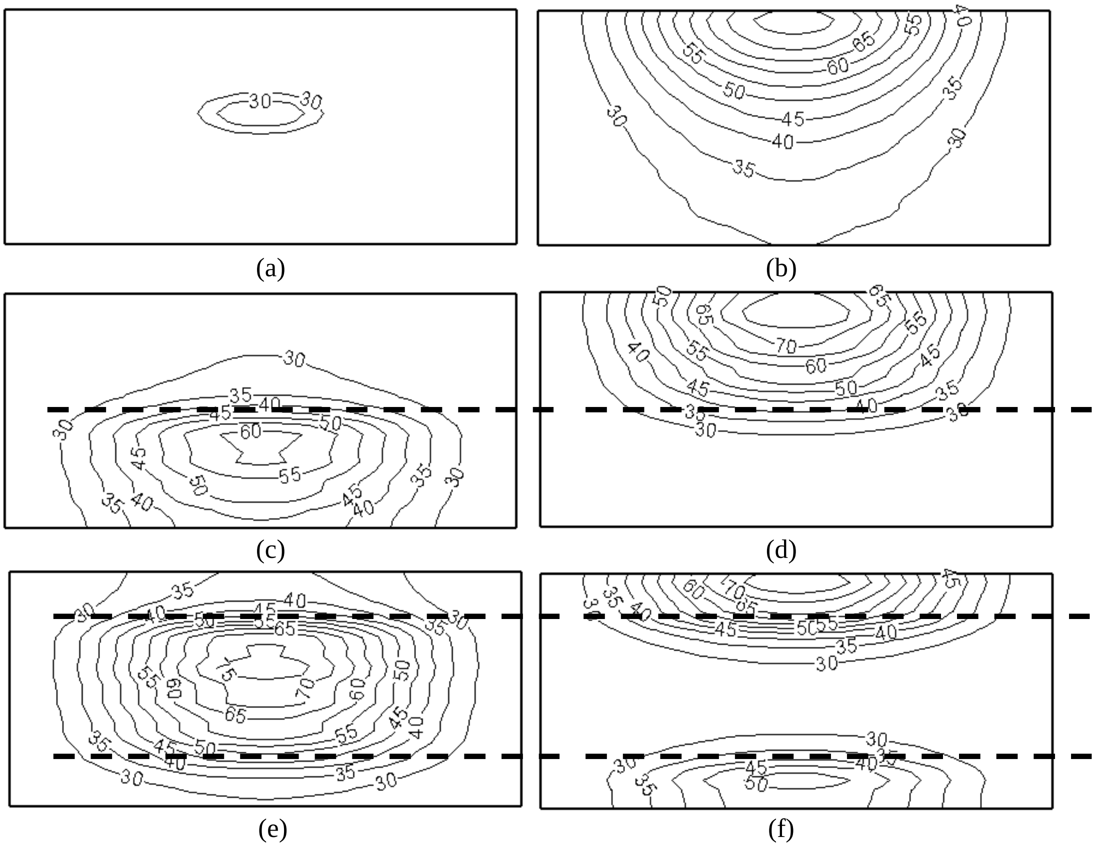


Fig. 9: Temperature distribution (^{o}C) in samples at time of heating is equal to 60 s.
(a) Single layered, low lossy sample (b) Single layered, high lossy sample
(c) Double layered, low lossy layered at top (d) Double layered, low lossy layered at bottom
(e) Triple layered, high lossy layered at middle (f) Triple layered, low lossy layered at middle

3.1.2 Electric field distribution at multi-layered condition:

Figs. 7-8 shows the wave distribution of the electric field in multi-layered samples. In case of double layered sample, the electric field almost attenuates owing to energy absorption, and thereafter the absorbed energy is converted to the thermal energy within high lossy layer, which increases the sample temperature. The electric field behavior in the sample is almost extinguished at this layer while electromagnetic energy almost passes through low lossy layer. From this reason, high magnitude electromagnetic standing wave is occurred at low lossy layer in case of low lossy dielectric layered at the top of sample as shown in Fig. 7(a), while standing wave is not occurred at low lossy layer in case of low lossy dielectric layered at the bottom of sample as shown in Fig. 7(b).

In case of triple layered sample, results are very interesting. Because magnitude and standing wave of electric field inside samples are uniformly strong. This results lead to uniformly distribution of temperature inside sample especially in case of high lossy layer is in the middle part of sample.

The variation of the amplitude and wave length of electromagnetic field results in thermal behavior in the sample which described in Equation (8). This equation is used to transform electromagnetic energy into thermal energy. And for thermal distribution, numerical modeling which discretized from equation (7) is used to simulated results of temperature distribution. Therefore temperature results can be presented as follows

3.2 Thermal Distribution and Dielectric Properties:

Figs. 9(a)-9(f) show temperature distribution inside sample at end of microwave heating time (60 second). The results show that the effect of dielectric properties and sample layer are significant to thermal distribution. In case of single layered condition, temperature profiles have same behavior while compare with electromagnetic field. Temperature have highest value nearly top surface in high lossy material and have highest value nearly center point of sample in low lossy material. However, temperature different between two case is very high. That is because high lossy material has good electromagnetic energy absorption and thermal energy transformation but low lossy material has not good to do. Additionally, it is observed that the temperature distributions within high lossy sample display higher temperature rise but weaker wavy distribution of temperature while compare with low lossy sample.

In case of double layer, low lossy layer at the top of sample result in better temperature distribution when compare with high lossy single layered sample. And low lossy layer at the bottom of sample has better temperature rise up when compare with high lossy single layered sample. This is because of the strongly wavy resonance effect from each layer surface. These results can guide to use lossy material to improve microwave heating process.

In case of triple layer, low lossy layer at the top and bottom of sample lead to best temperature rise up and temperature distribution profile. Therefore, this is very good guide line to improve microwave heating in practice. In contrast, low lossy layer at the center of sample has not well in temperature rise up and temperature distribution. The area nearly to surface is still highest temperature and high lossy layer at bottom surface has low temperature rise up.

4. Conclusion:

The presented numerical analysis describes many important interactions within high lossy and low lossy dielectric material in microwave heating process in case of multi layered sample which using a rectangular wave guide cavity. The following paragraphs summarize the conclusion of this study.

A mathematical model for analysis heat transfer can used successfully to describe the effect of dielectric properties on microwave heating conditions.

A mathematical model for analysis heat transfer can used successfully to describe the effect of multi-layered sample on microwave heating conditions.

The dielectric properties of material significantly to describe heat transfer patterns from microwave heating.

Low lossy material can improve temperature distribution and cause temperature rise up when place on top and bottom surface of high lossy material.

Low lossy material cannot help to improve temperature distribution and cause temperature rise up when place on middle layer of high lossy material.

The results in this work are useful for design heating machine or improve the product quality from microwave heating process.

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