

Design optimization using dielectric slab for efficient microwave heating

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Abstract: In this paper, usage of a dielectric slab on the top and bottom sides, on the top side, and on the bottom side of a clay sample was presented as a means of improving heating efficiency in multimode applicator. In order to accomplish the optimization procedure, we used four different dielectric slab types having different thickness values. The simulated results show that by using additional dielectric slab it is possible to increase the electric field intensity inside the applicator and obtain higher power absorption rates within the sample and high-efficiency designs.

Key words: Load location optimization, microwave heating, multimode applicator, dielectric slab

1. Introduction

Currently, microwave heating finds its application in various industrial fields compared to traditional heating due to its high heating rates, reduced processing time, and significant energy savings. However, microwave heating is affected by several factors, which leads to low efficiency and nonuniform heating. Low efficiency is mostly caused by load mismatching between the load and supply power that gives maximum reflection back to the source. Traditionally, heating efficiency is maximized by matching the load with external devices such as tuners, mobile short-circuits, irises, and stubs that may provide an adaptation between the microwave source and the material to be heated, i.e. sample, which reduces reflection coefficient and increases system efficiency [1–6].

Feeding microwave power at more than one location to a multimode applicator can result in improvement of field uniformity and increase in heating power provided coupling is proper and polarization is chosen correctly [7]. Recently, the effects of different geometries, dielectric values, and positions of a dielectric sample, operating frequency and initial temperature on the microwave heating efficiency and electric field distribution during microwave heating have been studied numerically and experimentally to a great extent [8–10]. Load matching is used to achieve high power efficiencies by reducing the reflection coefficient that goes back to the waveguide port. Load matching in microwave heating can be achieved by different methods such as by properly surrounding the sample with dielectric materials [11–13] or by placing the material to be heated at an optimal position [14–16].

In this study, a new approach for achieving high heating efficiency in multimode applicator was proposed. In comparison with other studies [11,13], our study was conducted only with one-layer dielectric slabs of different type and thickness on the top and bottom sides, on the top side, and on the bottom side of the sample material in order to achieve maximum heating efficiency during microwave heating. However, the other studies were conducted by covering the sample material with two different dielectric constant layers on all sides. In addition,

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our study is easy to implement and the materials we used as dielectric slabs are easy to found. The design optimization was done based on the absorbed power by the sample during the heating process and the systems reflection coefficient values. The simulation results are obtained by using COMSOL Multiphysics commercial software.

2. Materials and methods

The schematic diagram used in this study is shown in Figure 1. The microwave applicator is represented by a metallic box of rectangular shape, ($A = 21.5$ cm, $B = 35.4$ cm, and $C = 33.7$ cm), typical of many industrial and microwave multimode applicators. The TE₁₀ mode is excited in the WR-340 waveguide at 2.45 GHz. Clay sample is positioned in the multimode applicator L_2 distance from the bottom of the applicator, the lower slab is placed at L_1 distance from the applicators' bottom, and the upper slab is placed at L_3 distance from the bottom of the applicator. Here L_1 and L_3 distances vary depending on the thickness of the slab, whereas distance L_2 is fixed at 5 cm. The sample is covered on the top and bottom sides, on the top side, and on the bottom side with different dielectric slab materials. For this particular study, glass, rubber, teflon, and kestamid dielectric materials with thickness values of 0.5, 1, and 2 cm were used. The sample inside the applicator is a clay sample with relative permittivity $\epsilon_r = 52.60 - j11.59$. In this study, the electromagnetic problem has been solved in the frequency domain with the aid of the following vector-wave equation;

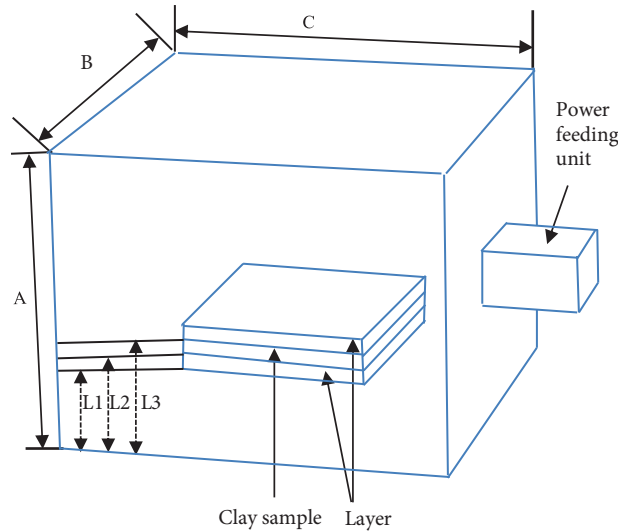


Figure 1. Multimode applicator loaded with dielectric slab.

$$\nabla^2 \vec{E} + \omega^2 \mu \epsilon \vec{E} = 0, \quad (1)$$

where \vec{E} is the vector's electric field, ω is the angular frequency, μ is the magnetic permeability, and ϵ is the dielectric complex permittivity of the medium, given by;

$$\epsilon = \epsilon_0 (\epsilon' - j\epsilon'') = \epsilon_0 \left(\epsilon' - j \frac{\sigma}{\omega} \right), \quad (2)$$

where ϵ_0 is the vacuum permittivity, ϵ' is the dielectric constant, ϵ'' is the loss factor, and σ is the conductivity of the medium. The ability of a dielectric material to absorb microwaves and store energy is given by the complex permittivity of the medium.

The efficiency of the system is calculated as, the ratio of the absorbed power by the material to be heated (P_b) to the microwave input power (P_a);

$$\eta = \frac{P_b}{P_a} \times 100 \quad (3)$$

The reflection coefficient (ρ) also defines the heating efficiency of the multimode applicator. System efficiency is inversely proportional to reflection coefficient. If (ρ) = 0, there is no reflected power back to the source and the input microwave power will all be absorbed by the sample. On the contrary, if (ρ) shows a value near to one, almost all the input microwave power will be reflected, with very small efficiency in this case. Thus, microwave heating efficiency can be defined as a function of the reflection coefficient, expressed as:

$$\eta = 1 - |\rho|^2. \quad (4)$$

The above mentioned equations with the proper boundary conditions of the metallic walls and the waveguide excitation are used to find the electric field distribution and heating efficiency during microwave heating.

3. Results

The sample is heated for 5 min at 2.45 GHz operating frequency inside the multimode microwave applicator. The applicator is fed 900 W for each simulation through the rectangular waveguide. The clay samples' size is 18 x 18 x 1 cm with thickness of 1 cm throughout the study. For this study, the dielectric constant and dielectric loss of clay sample was measured by using a network (Agilent, E5061B) instrument with two parallel 200 mm probes at 2.45 GHz frequency. The clay sample is covered on the top and bottom sides with different dielectric slab materials. Moreover, the effects of the dielectric slabs' thickness on the performance of microwave heating were investigated. Electric field distribution is simulated for 9 scenarios and to optimize the heating efficiency during microwave heating, the efficiency of the system was calculated from the input and absorbed power by the sample. The obtained numerical and simulation results relating to microwave heating are presented and discussed as follows.

The position of sample material in the multimode applicator affects electric field distribution and efficiency of the system during microwave heating. Therefore, the position to place the sample material in multimode applicator was investigated from 2 cm to 11 cm in height with equal distance of 1 cm from the bottom of the applicator to find the position that gives maximum performance before covering the sample by any dielectric slabs. Different optimal places gave optimal efficiency, but for this study, we randomly chose 5 cm from the bottom of the applicator. Therefore, during our simulation studies, sample material was positioned at 5 cm from the bottom of multimode applicator. Figure 2 shows electric field distribution over the sample and inside the applicator before using any dielectric slab at 5 cm distance from the bottom of the applicator. The power absorbed by the sample was 515.81 W and the calculated efficiency and reflection coefficient was 57.31% and 0.653 respectively. In the following simulations and scenarios, the electric field distribution pattern over the sample and inside the multimode applicator is simulated, and the system's efficiency and reflection constant value is calculated to determine the best design optimization method.

Addition of a dielectric slab around the sample forces new electric field distribution and propagation path within multimode applicator. The dielectric slab acts as a matching element between air-sample interface to reduce the reflection field and increase heating efficiency within the multimode applicator. Therefore, the dielectric slab thickness and type related to the dielectric constant value determines the power absorbed by the sample. High dielectric constant value slab with lower thickness; and low dielectric constant value slab with

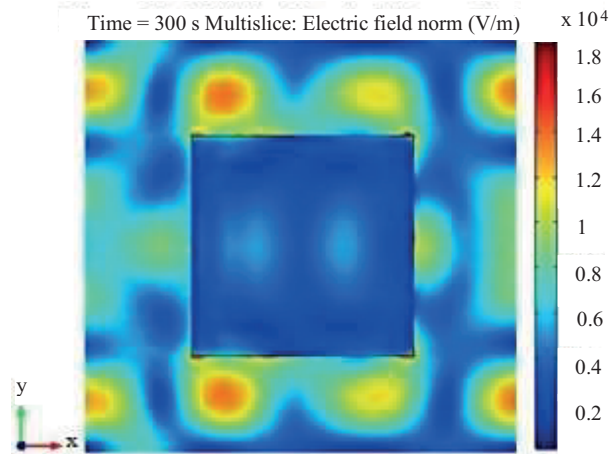


Figure 2. Electric field distribution before using any dielectric slab.

high thickness gives maximum efficiency regardless of the position of the slabs. For scenarios 1–3 the sample material was covered by dielectric slabs on the top and bottom sides. For scenarios 4–6, the dielectric slab is on the top of the sample. Finally, for scenarios 7–9, the dielectric slab is placed on the bottom side of the sample material. The size of clay sample and slabs affect the electric field distribution and heating efficiency. However, in this study for simplicity, the length and width of the slabs are taken to be equal with the samples' length and width, only the slabs' thicknesses vary for different scenarios. The different dielectric slabs used for this study are glass, rubber, teflon, and kestamid with different thickness values (0.5, 1, and 2 cm). Simulation conditions for the study are listed in Table 1.

Table 1. Different testing scenarios.

Scenario no.	Kestamid ($\epsilon_r = 3.7$)	Glass ($\epsilon_r = 7.0$)	Teflon ($\epsilon_r = 2.1 - j0.0003$)	Rubber ($\epsilon_r = 4.0$)
1 (both sides)	0.5 cm	0.5 cm	0.5 cm	0.5 cm
2 (both sides)	1 cm	1 cm	1 cm	1 cm
3 (both sides)	2 cm	2 cm	2 cm	2 cm
4 (top side)	0.5 cm	0.5 cm	0.5 cm	0.5 cm
5 (top side)	1 cm	1 cm	1 cm	1 cm
6 (top side)	2 cm	2 cm	2 cm	2 cm
7 (bottom side)	0.5 cm	0.5 cm	0.5 cm	0.5 cm
8 (bottom side)	1 cm	1 cm	1 cm	1 cm
9 (bottom side)	2 cm	2 cm	2 cm	2 cm

For the first scenario, a dielectric slab with a thickness of 0.5 cm is placed on the top and bottom sides of the sample. From the simulated results we obtained the absorbed power for different dielectric slab types as follows; for glass = 829.83 W, rubber = 779.09 W, teflon = 697.59 W, and kestamid = 770.04 W. The calculated efficiencies are 92.2% (glass), 86.57% (rubber), 77.51% (teflon), and 85.56% (kestamid). The calculated reflection coefficients are 0.28, 0.37, 0.47, and 0.38, respectively. From the calculated results maximum efficiency as well as minimum reflection coefficient is obtained when glass was used as dielectric slab.

For the second scenario, we increased the thickness of the dielectric slab to 1 cm. From the simulated results, the power absorbed by the sample for different slabs are as follows; for glass = 856.32 W, rubber = 854.24 W, teflon = 820.73 W, and kestimid = 701.56 W. Based on this, the calculated efficiencies are 95.15% (glass), 94.92% (rubber), 91.19% (teflon), and 77.95% (kestamid). The respective reflection coefficient values are 0.22, 0.23, 0.30, and 0.47. For this scenario, glass gives better efficiency and minimum reflection coefficient compared to other dielectric slab types.

For scenario 3, as in the two scenarios mentioned above, the sample is covered on the top and bottom sides with different dielectric types of slab, but the dielectric slabs' thicknesses were increased to 2 cm. From the simulated results we obtained the absorbed power for different slab types as follows; for glass = 446.51 W, rubber = 550.91 W, teflon = 876.30 W, and kestimid = 605.92 W. The calculated efficiencies are 49.61% (glass), 61.21% (rubber), 97.36% (teflon), and 67.32% (kestamid). The respective reflection coefficient values are 0.71, 0.62, 0.16, and 0.57. In the third scenario, teflon layer gives better efficiency and minimum reflection than the other dielectric slab types.

From the above simulated and calculated results, the absorbed power by the sample and electric field distribution pattern has been changed after the sample is covered by different types of dielectric slabs. This is because different dielectric constant and thickness values of the different types of dielectric slabs. When the sample was covered on the top and bottom sides, the obtained efficiency results were as follows: for 0.5 cm layer thickness (glass), 92.2% with a reflection coefficient of 0.28; for 1 cm layer thickness (glass), 95.15% with a reflection coefficient of 0.22; and for 2 cm layer thickness (teflon), 97.36% with a reflection coefficient of 0.16. However, among the three different scenarios mentioned above, a 2-cm teflon dielectric slab gives better performance compared to the others. Figure 3 shows the electric field distributions over the sample material and inside the multimode applicator for scenarios 1–3 of dielectric slabs that give maximum efficiency and minimum reflection coefficient for each scenario.

For scenarios 4–6, the sample material is covered only on the top side with different dielectric slabs that have different thickness values such as 0.5 cm for scenario 4, 1 cm for scenario 5, and 2 cm scenario 6. For scenario 4, the power results obtained absorbed from the simulations are as follows; 716.03 W (glass), 684.30 W (rubber), 613.40 W (teflon), and 677.43 W (kestamid). The calculated efficiencies are 79.56% (glass), 76.03% (rubber), 68.16% (teflon), and 75.27% (kestamid). The respective reflection coefficient values are 0.45, 0.49, 0.50, and 0.56. For scenario 4, glass dielectric slab gives maximum efficiency and minimum reflection coefficient compared to the other dielectric types.

For scenario 5, with a 1 cm thickness dielectric slab, the absorbed power values obtained by the sample is 835.94 W (glass), 815.22 (rubber), 735.87 W (teflon), and 808.26 W (kestamid). The calculated efficiencies are 92.88% (glass), 90.58% (rubber), 81.76% (teflon), and 89.81% (kestamid). The respective reflection coefficient values are 0.27, 0.31, 0.43, and 0.32. For senario 5, glass dielectric slab gives better heating efficiency and lower reflection coefficient.

For scenario 6, simulations are done for different dielectric slabs with 2 cm layer thickness. The absorbed power by the sample for different slabs are as follows: 541.14 W (glass), 681.54 W (rubber), 838.59 W (teflon), and 735.00 W (kestamid). The efficiencies are 60.13% (glass), 75.73% (rubber), 93.18% (teflon), and 81.67% (kestamid). The respective reflection coefficient values are 0.63, 0.50, 0.26, and 0.43. Teflon dielectric slab shows better improvement in heating efficiency and lower reflection coefficient.

When the sample material is covered by a single dielectric layer only on the top side, the efficiency varies depending on the different slabs' dielectric constants and thicknesses. For scenarios 4 and 5, we found

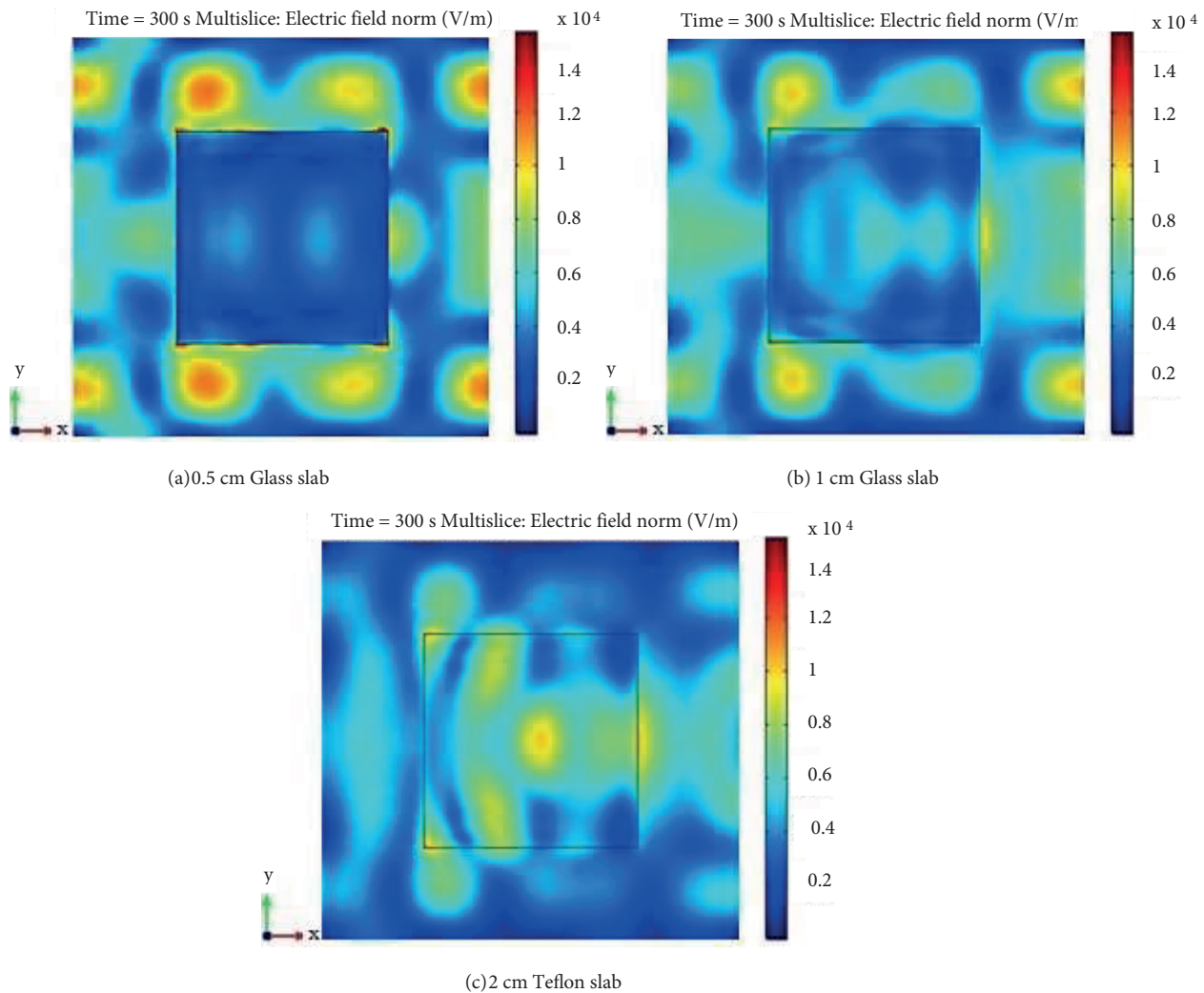


Figure 3. Electric field distribution for scenarios 1–3 of dielectric slab that gives maximum efficiency.

maximum efficiency and minimum reflection coefficient values for glass slabs of 0.5 cm and 1 cm thicknesses. Also from scenario 6, we found maximum efficiency and minimum reflection coefficient values for teflon slab of 2 cm thickness. Figure 4 shows the electric field distribution over the sample material and inside the multimode applicator for scenarios 4–6 of dielectric slabs that give maximum efficiency and minimum reflection coefficient value for each scenario.

For scenarios 7–9, the sample material is covered only on the bottom side with different types and thicknesses of dielectric slabs. For scenario 7, the dielectric slab thickness is 0.5 cm; for scenario 8, it is 1 cm; and for scenario 9, it is 2 cm.

For scenario 7, the dielectric slabs' thicknesses were 0.5 cm for all of the dielectric layer materials. The absorbed power obtained from the simulation results are as follows: 717.40 W (glass), 661.08 W (rubber), 591.12 (teflon), and 653.09 (kestamid). The efficiency is calculated as follows: 79.71% (glass), 73.45% (rubber), 65.68% (teflon), and 72.57 (kestamid). The respected reflection coefficient values are 0.45, 0.52, 0.59, and 0.53. Glass dielectric slab shows better improvement in efficiency and reduces reflection coefficient values compared to the other dielectric slab types.

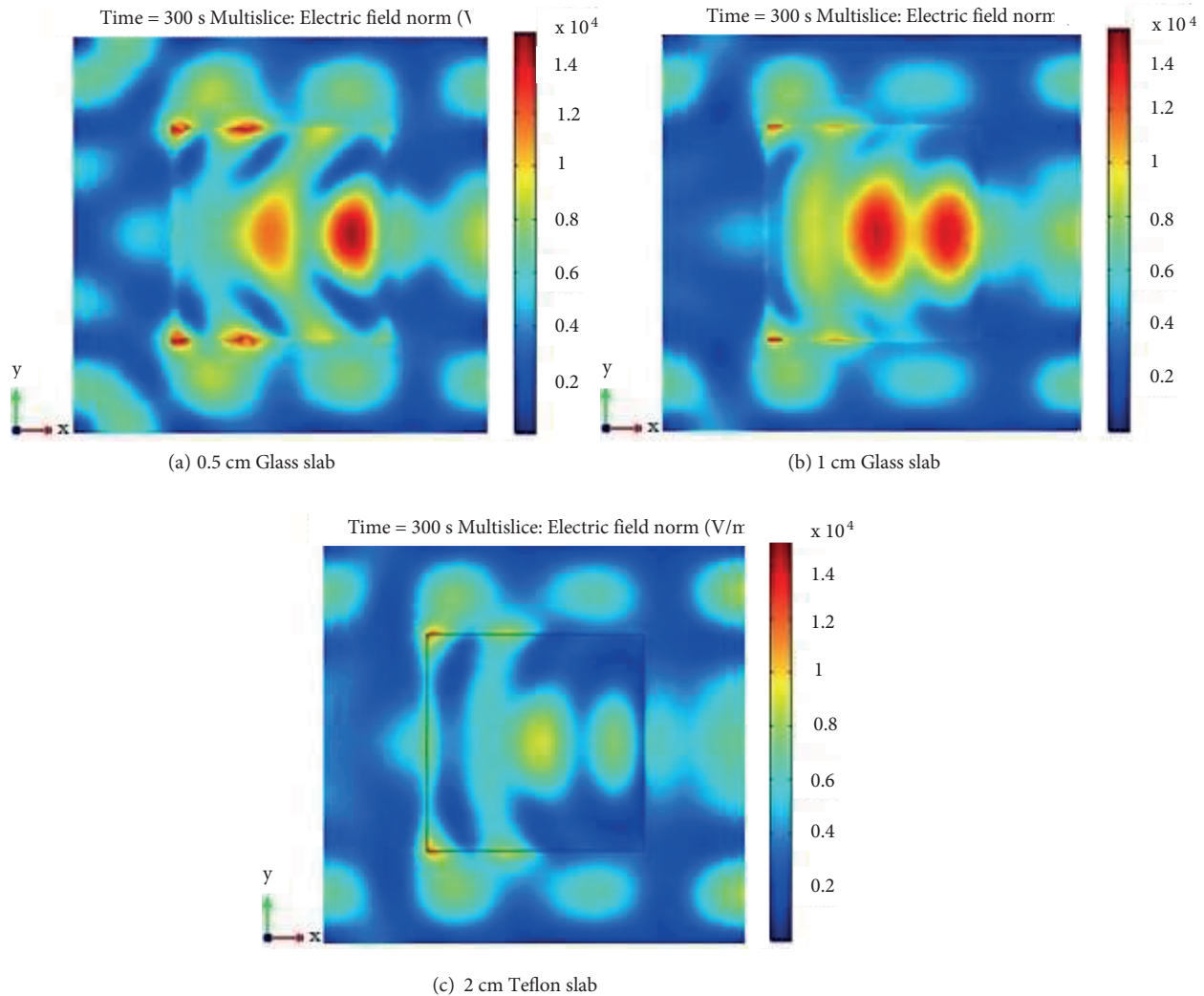


Figure 4. Electric field distribution for scenarios 4–6 of dielectric slab that gives maximum efficiency.

For scenario 8, the different dielectric slabs' covering the sample on the bottom sides had 1 cm layer thickness. The absorbed power by the sample obtained from the simulations are as follows: 843.27 W (glass), 812.42 W (rubber), 689.06 W (teflon), and 800.79 W (kestamid). The calculated efficiencies are 93.7% (glass), 90.27% (rubber), 76.56% (teflon), and 88.79% (kestamid). The respective reflection coefficient values are 0.25, 0.32, 0.49, and 0.33. For this scenario, glass dielectric slab shows better improvement in efficiency and reduces reflection coefficient values.

For scenario 9, the dielectric slabs' thickness used for this scenario was 2 cm. The absorbed power values obtained from the simulation are as follows: 538.85 W (glass), 684.11 W (rubber), 821.60 W (teflon), and 720.76 W (kestamid). The calculated efficiencies are as follows: 59.87% (glass), 76.01% (rubber), 91.29% (teflon), and 80.08% (kestamid). The respective reflection coefficient values are 0.63, 0.49, 0.27, and 0.45. Teflon dielectric slab gives better system efficiency and lower reflection coefficient value.

When the sample material is covered by different dielectric slabs' on the bottom side, the efficiency of the system varies a lot in accordance with slabs' thicknesses and dielectric constants. For scenarios 7 and 8,

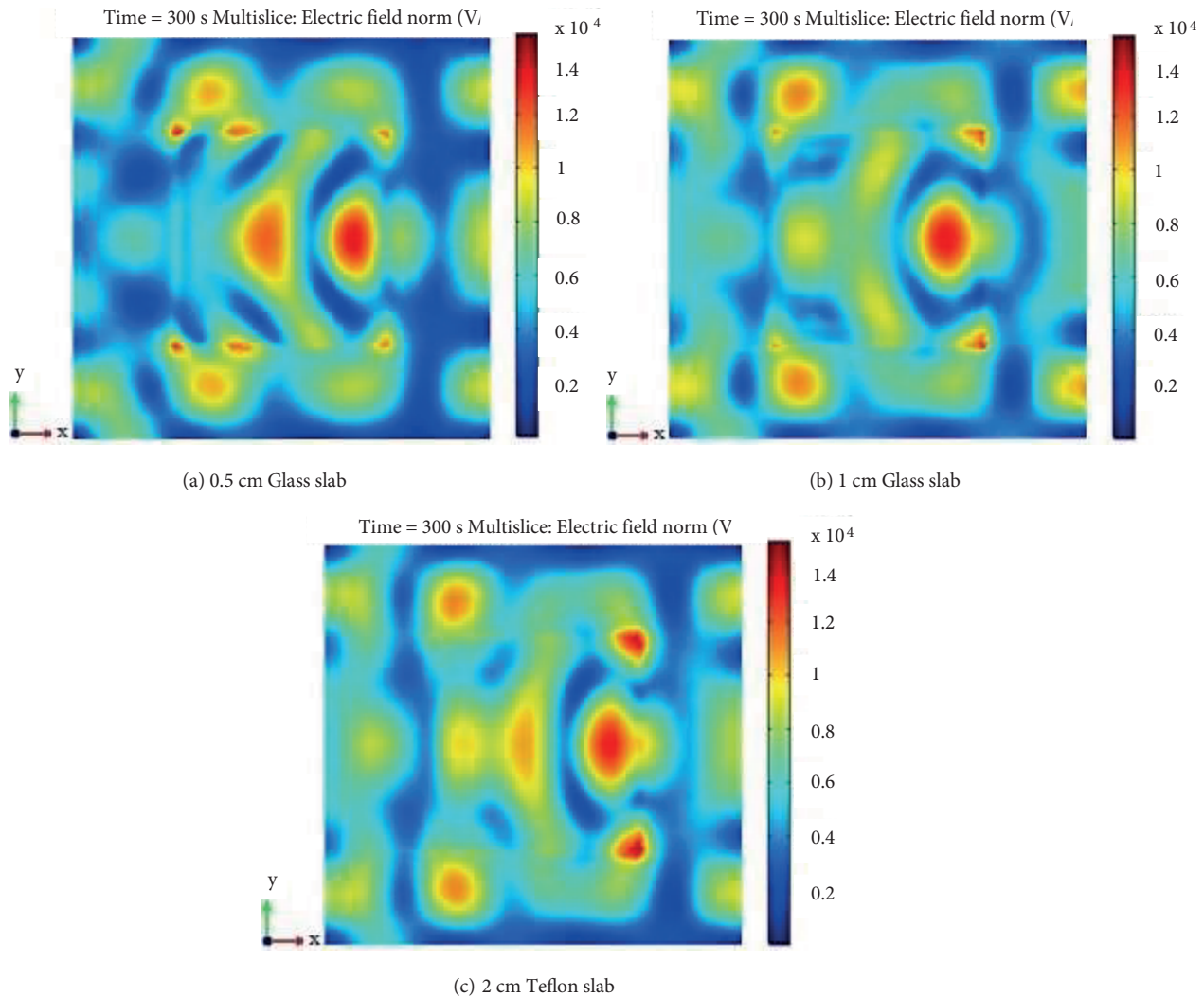


Figure 5. Electric field distribution for scenarios 7–9 of dielectric slab that gives maximum efficiency.

glass slab gives a better efficiency and lower reflection coefficient values. However, for scenario 9 teflon slab gives maximum system efficiency and lower reflection coefficient value. Figure 3 shows the electric field distribution over the sample material and inside the multimode applicator for scenarios 7–9 for dielectric slabs that give maximum efficiency and lower reflection coefficient values for each scenario.

In conclusion, when the sample is covered on top and bottom sides, on the top side, and on the bottom side and the dielectric slabs' thicknesses were 1 cm and 0.5 cm, glass dielectric slab gives better system efficiency and lower reflection coefficient. In addition, for 2 cm thickness, teflon slab gives better system efficiency. Therefore, it can be concluded from these data that the time needed to carry out the design optimization process is very dependent on the following conditions: 1) samples' position; 2) dielectric slabs' type and thickness; 3) placement of the slab/s, since these parameters influence the absorbed power by the sample. Table 2 summarizes our work as shown below.

Table 2. The optimum efficiency obtained from each scenario and their corresponding dielectric slab types and thicknesses.

Scenario no.	Slab thickness (cm)	Best dielectric slab	Efficiency (%)	Reflection coefficient (ρ)
1 (both sides)	0.5	Glass	92.20	0.28
2 (both sides)	1	Glass	95.15	0.22
3 (both sides)	2	Teflon	97.36	0.16
4 (top side)	0.5	Glass	79.56	0.45
5 (top side)	1	Glass	92.88	0.27
6 (top side)	2	Teflon	93.18	0.26
7 (bottom side)	0.5	Glass	79.71	0.45
8 (bottom side)	1	Glass	93.70	0.25
9 (bottom side)	2	Teflon	91.29	0.27

4. Discussion

In this study, we investigated the design optimization of microwave heating by using different dielectric slabs on top and bottom sides, on the top side, and on the bottom side of the clay sample in order to increase the heating efficiency. For this study, we used glass, rubber, teflon, and kestamid dielectric slabs with different thickness slab values (0.5, 1, and 2 cm). The easy availability of the dielectric materials used in this study provides an advantage for practical applications. For this reason, such an optimization can be easily adapted to industrial applications for minimum reflection and maximum efficiency. In this study, optimization was performed using a single dielectric layer. In future studies optimization can be improved by using a combination of different dielectric layers and experimental work can be done in an industrial application. It could also be improved by adding another dielectric slab and/or finding the slab thickness and location that give maximum system efficiency as well as minimum reflection by using an optimization algorithm.

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