A simulation study of parameters influencing microwave heating of seaweed (*Eucheuma cottonii*)

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Abstract. Currently, the process of drying seaweed has been using conventional technology, utilizing sunlight directly. It depends on weather conditions when the rainy season arrives, the drying process will take longer time even 3-4 days. The longer duration of drying causes seaweed's quality degenerate. Previous studies have proved that drying materials use microwave energy can reduce processing time significantly. Heat transfer and electromagnetic field effect on seaweed drying in a microwave oven were studied using a three-dimensional simulation. The parameters observed included variations of power microwave (400, 500, and 600 W), seaweed thickness (3, 5, 7 cm), and waveguides position (top and side). Variation of magnetron energy in microwave heating is affecting the electromagnetic field's value and changing seaweed temperature. As increasing received energy from the magnetron, seaweed temperature and electromagnetic field are ascending. Seaweed that is heated in 3 cm thickness results rising temperature higher than 5 cm and 7 cm thickness. Waveguide located at the top cavity is generating electromagnetic field value higher than it located at the side cavity. As verification method, heating fresh seaweed use microwave oven was resulting similar pattern both electromagnetic field and temperature. The lowest moisture content of seaweed is achieved at the treatment of 600 watt magnetron energy and 3 cm thickness of seaweed.

1. Introduction

The biggest commodity of fisheries culture in Indonesia is seaweed, especially, species of *Eucheuma cottonii*. According to the Performance Ministry of Marine Affairs and Fisheries Report in 2017 [1], production seaweed reached 10,81 million tons. Nearly 80% of the production is sold in dry form without further processing. It can be understood since technology of drying is simplest, easiest and cheapest technology. Currently, farmers dry out seaweed directly under sunlight. This method is very dependent on weather conditions when it comes in rainy season the drying of seaweed requires a longer time. Consequently seaweed composition changes or reduces the quality of seaweed.

Seaweed drying / heating under microwave exposure is expected become one of the solutions problems. At present, the use of microwaves as an alternative technology for heating process in food industry is rising rapidly. Microwave technology results process faster and more efficient than conventional drying methods due to high coefficient of mass transfer [2]. A heating utilize microwave has several advantages such as high drying rate and minimal heating at area where contain low moisture which can reduce overheating product [3].

The most prominent characteristic of microwave heating is volumetric heating that is very different from conventional heating. In volumetric heating, the material can absorb microwave energy directly from inside and convert into heat [4]. According to [5] volumetric heating depends on the dielectric properties of the drying material. Those properties include dielectric constant and dielectric loss. The dielectric constant is the ability of a material to store energy in electric field and the dielectric loss factor is the ability of a material to dissipate energy into heat [6]. In general, the dielectric properties are influenced by frequency, temperature, moisture content, structure of the food material and also determined by their chemical compositions [7]. Electromagnetic waves generated by microwaves are alike magnets which have 2 polar ions (positive and negative). Materials containing positive and negative ions such as water, fat, and sugar will rotate belong to microwaves spin due to same poles. Frequency of the microwave generally at 2450 times per second causes the water and fat molecules rotate in high, it will produce friction between molecule and cause heat. Characters and principle work of microwave heating are suitable for drying seaweed because its high moisture content [8].

However, it is very difficult to measure temperature distribution of seaweed and electromagnetic wave in microwave cavity. Therefore it impossible to carry out whether seaweed has reached at desired temperature during process. In order to obtain target of temperature and distribution in the microwave cavity, numerical simulations is needed which use software simulation. A simulation methods aim to reduce complexity of microwave effect.

Comsol Multiphysics is simulation software which can solve numerical models of electromagnetic fields and temperature in a microwave device then produce its predictive and distribution. The purpose of this research is to find out parameters that influence process of heating seaweed in the microwave. The parameters including microwave power level, seaweed thickness and waveguide position.

2. Research methods

2.1. Material

The material used in this study includes Comsol Multiphysics 5.4 software and desktop PC Intel Core i5-2320, 3.00 GHz processor with 16 GB RAM memory and 64 bit Windows 7 Ultimate operating device. They are a numerical simulation tool of microwave heating meanwhile the validation of simulation results, commercial microwave oven (Panasonic NN-GD692S 1000 W) is used as a heater. Further fresh seaweed *Eucheuma cottonii* is a material for heating. Moreover, the measuring instruments are used enveloping infrared thermometers (KRISBOW Infrared Thermometer KW0600280), digital scales (ACIS Multi-Function AW Series AW-15X) dan moisture content (Moisture Meter TK100 0 80).

2.2. Methods

The first step of study is simulation using Comsol Multiphysics software. It is consist of geometry making (microwave oven, sample dimension), definitions of material properties, governing equation, boundary conditions, mesh generation and solver. The second step is validation. That is comparing simulation results with the real heating fresh seaweed in the microwave oven. Treatments applied were as equal as simulations step including magnetron power (400, 500, and 600 W). Based on preliminary studies these levels have moderate resulted both in final moisture content of seaweed and energy required. Following treatments are thickness of seaweed (3, 5 and 7 cm) and waveguide position (side and top). Meanwhile, parameters observed in validation experimental heating seaweed are shrinking mass and drying rates.

Several assumptions are suggested to simplify and to avoid difficulty and save time of simulation process:

- The magnetron was assumed to operate at a single frequency of 2.45 GHz
- The wall of waveguide is copper and cavity is aluminum.
- Seaweed shape is flat and regardless of the surface roughness

- Seaweed properties are constant in which involved relative permeability, electrical and thermal conductivity
- The initial temperatures of seaweed and air are uniform

2.2.1. *Geometry*. This model was developed from a domestic microwave oven. The geometry is shown in figure 1.

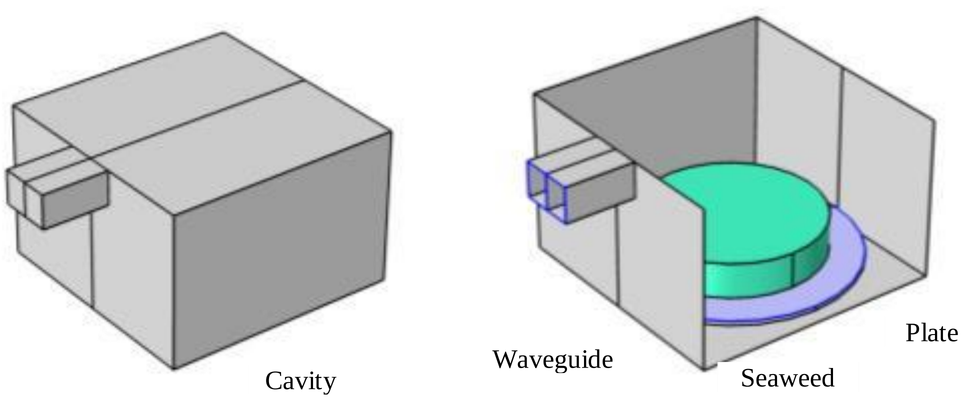

Figure 1. Microwave geometry

The main components in a microwave oven are cavity with aluminum material, waveguide type WR-340, plate glass as fresh seaweed placed. Detailed specifications and sizes of these components are summarized in table 1.

Table 1. Specification of components

No	Components type	Specification	Dimension (mm)
1	Waveguide	Rectangular copper WR-340	P x L X T; 120 x 78 x 50
2	Cavity	Aluminum	P x L x T; 350 x 350 x 270
3	Sample	Seaweed	Radius 160, 124, 105; Height 30, 50, 70; weight 241-245 gram
4	Plate	Glass	Radius170

Definition of material properties. This simulation required properties from materials exposed to microwaves, property details are shown in table 2. Materials in the form of aluminum, air, and glass are obtained from the software library while seaweed is obtained from the literature and laboratory analyses. The material properties include relative permittivity, relative permeability, electrical conductivity (S/m), thermal conductivity (W/m.K), density (kg/m^3) and heat capacity (J/kg.K).

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Tabel 2. Material properties

Properties	Value			
	Aluminum	**Air**	**Glass**	**Seaweed**
Relative permeability	1	1	1	1
Relative permittivity	1	1	2.55	65-17*j
Electrical conductivity (S/m)	3,77E+10	0	0	0
Heat capacity (J/(kg·K)	900	-	-	3.60e3
Density (kg/m^3)	2700	-	-	1053
Thermal conductivity (W/(m·K)	238	0	0	0.304

2.2.2. *Governing equations.* The COMSOL Multiphysics software is used to compute the numerical solutions of coupled electromagnetic and heat transfer equations for microwave heating of seaweed. Maxwell's equations are used to solve the electromagnetic field distribution in the microwave cavity. The governing equation of the electric field wave is as follows:

$$\nabla \times \mu_r^{-1}(\nabla \times \mathrm{E}) - k_0^2(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0} E = 0 \tag{1}$$

where μ_r is the relative permeability of the material; E refers to the electric field intensity in V/m; ε_r represents the relative permittivity; σ denotes the electrical conductivity in S/m; ω is the angular frequency in Hz; ε_0 is the free space permittivity (8.85×10−12 F/m); j is the imaginary number i.

The dielectric permittivity (ε*) of the material is described as a complex quantity which expressed by:

$$\varepsilon * = \varepsilon' - j\varepsilon'' \tag{2}$$

where ε′ is the real permittivity (F/m) known as the dielectric constant and ε″ is the imaginary permittivity (F/m) known as the loss factor.

The heat transfer equations coupled with the microwave field by Fourier's energy balance equation are used to calculate the temperature distribution in the microwave cavity. The governing equations are given by:

$$\rho C_p \frac{\vartheta T}{\vartheta t} = \nabla.(k\nabla T) + Q \tag{3}$$

where ρ represents the density of the material in kg/m3; Cp is to the specific heat capacity of the material in J/(kg·K); k refers the thermal conductivity of the material in W/(m^2·K); T denotes the temperature in K and Q is heat source.

2.2.3. *Boundary conditions.* The perfect electrical conductor boundary condition was used to define the boundaries (3B), which is expressed as:

$$\boldsymbol{n} \times \boldsymbol{E} = 0 \tag{4}$$

The impedance boundary condition shown in figure 2a was considered the surface of microwave cavity and waveguide except for the port which is defined by following equation:

$$\sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r - j\sigma/\omega}}\, n\ \times H + E - (n.E)n = (n.E_s)n - E_s \qquad (5)$$

where μ_r : represented the relative permeability of the material. The boundary condition of port was presented in figure 2c from where the microwave power entered the microwave cavity. Microwave at a frequency of 2450 MHz in the TE10 mode was excited by a rectangular port. The propagation constant (β) of microwave was expressed by

$$\beta = \frac{2\pi}{C_0}\sqrt{v^2 - v_c^2} \qquad (6)$$

where v and v_c are the frequency and cut off frequency of the microwave.

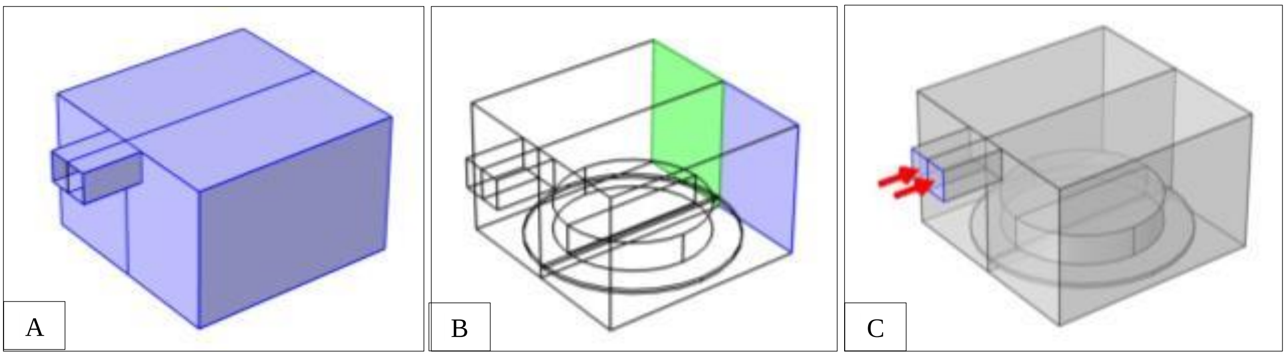


Figure 2. Impedance boundary condition (a), perfect electric conductor (b), port boundary (c)

2.2.4. *Mesh generation*. The size of mesh element was determined by the physical field. Free tetrahedral mesh element was chosen for this model. The subdivision geometry was shown in figure 3.

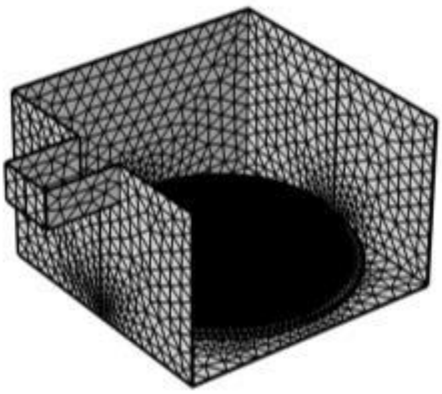


Figure 3. Mesh element

2.2.5. *Solver*. For solving the problem of microwave field in RF module, the solver by using the generalized minimum residual method (GMRES) was used to solve the wave equation in electromagnetic field, and the parallel direct solver (PARDISO) was used to solve the equation of heat conduction and heat radiation. The solution process was transient.

2.2.6. *Experimental validation*. As validate of simulation numerical result, conducted seaweed heating in microwave oven. Applied treatments were thickness of seaweed (3, 5, 7 cm) and microwave power (400, 500, 600 W). Moreover, observed parameters of this experimental are decreasing seaweed weight and drying rates.

3. Results and discussion

3.1. Effect of the heating power

Microwave generates electromagnetic waves which consist of electric field and magnetic field. The waves radiated in to cavity chamber through waveguide. Waves reflected partially by perfect conductor of cavity wall and a part one absorbed by seaweed as solid material heated. Electromagnetic waves are self-propagating waves characterized by electric and magnetic field components oscillating in phase and perpendicular with each other and also perpendicular to the direction of radiation [9]. In this study, level of microwave power highly influences to release intensity of electromagnetic waves. This thing does agree previous research done by [10] and [11].

The result of simulation heating seaweed showed at figure 4. Applied different microwave power produces electric field, magnetic field and average temperatures seaweed diversely. Highest values at power 600 W that are electric field 450,32 (V/m), magnetic field 9,72 (A/m) and temperature 125,39 (^{o}C) then other powers obtain lower values. Microwave with higher power produces as well higher electromagnetic waves. Therefore the power (600 W) leads increasing of seaweed temperature higher than lower power (500, 400 W). Electromagnetic wave escalates oscillating among hydrogen ion inside seaweed, then increasing the temperature.

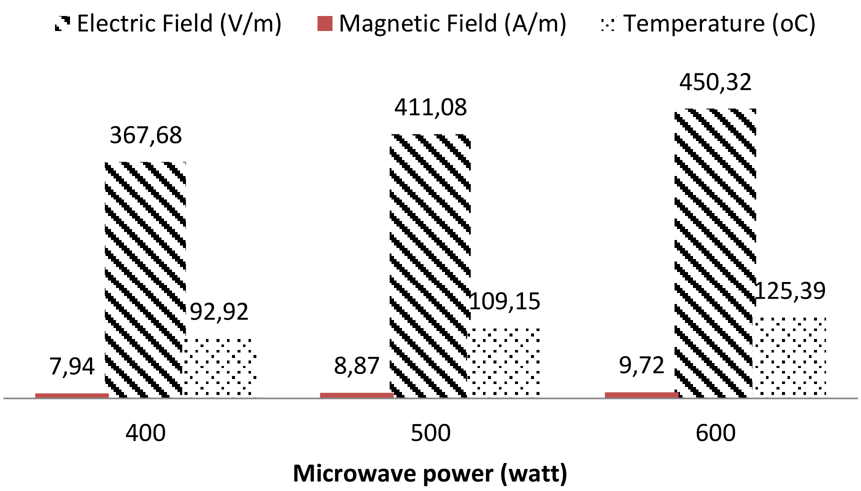
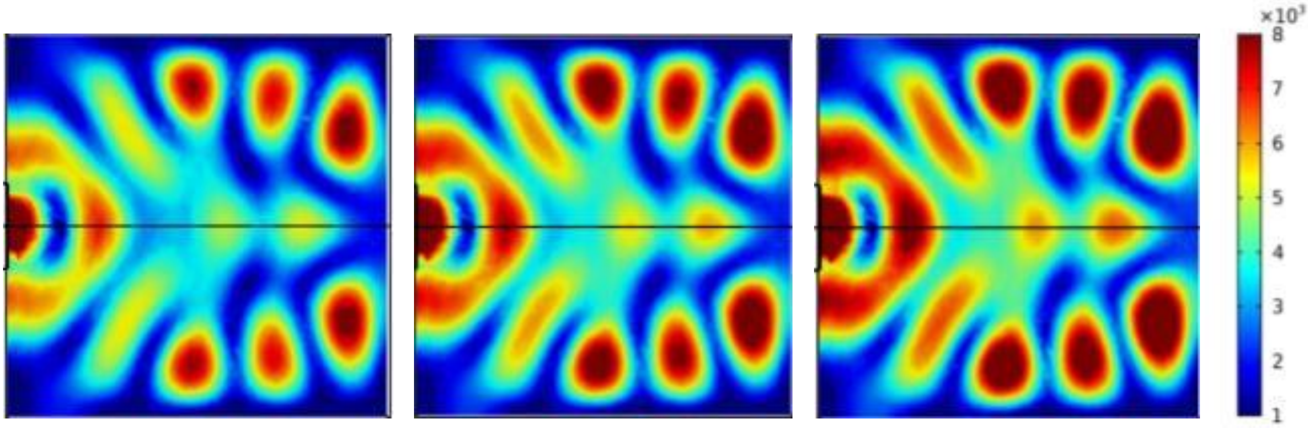


Figure 4. Effect power on average electric, magnetic field and temperature

Figure 5 exhibited pattern of distribution electric field in the cavity. There is no different of electric field among 3 level power microwave. However these levels give different on the intensity. This can be seen by comparing density each of area. For example red areas with high intensity (figure. 5A) appear more concentrated than red area in figure B and figure C.



A **B** **C**

Figure 5. Electric field norm (V/m), (A) 400, (B) 500, (C) 600

Difference of temperature seaweed as result of various power levels showed detail in figure 6. Magnetron as main part of microwave releases electromagnetic wave through waveguide then spreads in to cavity chamber and increasing temperature of seaweed. However it is uneven, low temperature namely cold spot and higher temperature as hot spot. Initially, seaweed temperature is 28 ^oC then, based on result numerical simulation (heating process 30 minute), the temperature seaweed on hot spot raises up to 342,3 ^oC (A), 420,9 ^oC (B) dan 499,5 ^oC (C). While on cold spot, seaweed temperature were reached 78,04 ^oC, 90,55 ^oC, 103,1 ^oC for A, B and C respectively. Similar result concluded by [12], that power of microwave very influences transformation of material temperature. Another report [13] stated heating process utilize microwave oven can reach higher temperature in higher power than in low power at equal time.

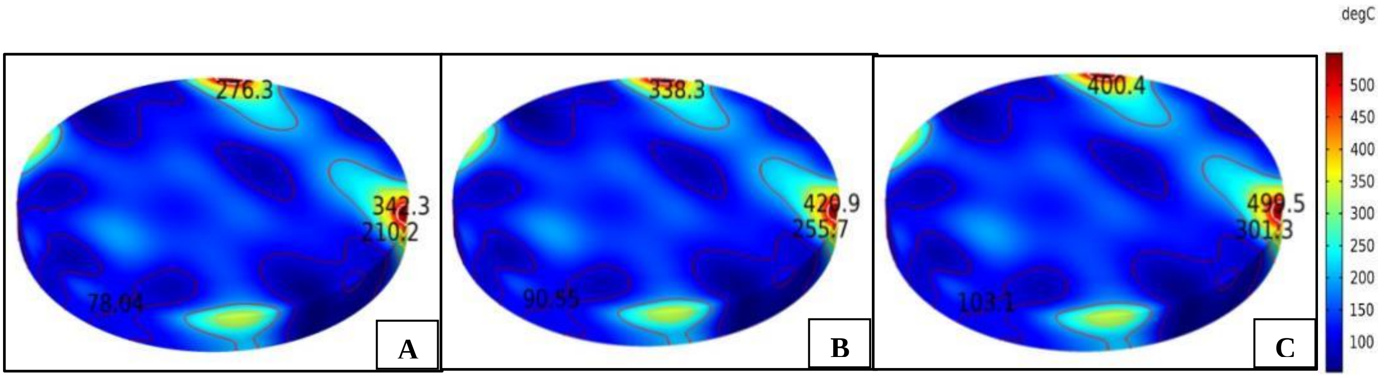


Figure 6. Contour of seaweed temperature for (A) 400W, (B) 500W, (C) 600W.

3.2. *Effect of the thickness seaweed*

Result of simulation showed that thickness of seaweed carry out electromagnetic waves achievement and temperature change (figure. 7). The highest electromagnetic waves among all treatment (3, 5, 7 cm) were 3 cm thickness. It followed by 5 then 7 cm thickness of seaweed. Early study [14] mentioned that thickness of material heated in microwave oven effects absorption electromagnetic wave. Thinner material absorbs this wave more than thicker material.

Another parameter is temperature. Seaweed at 3 cm thickness reaches highest temperature 125,39 (^oC) while 5 cm thickness obtains 94,43 (^oC) and less for 7 cm thickness 92,54 (^oC). This result give information that maximum penetration microwave in fresh seaweed is 3 cm. Entered waves along depth of penetration makes temperature inside seaweed increase. Shallow penetrate would not increase temperature inside seaweed optimally.

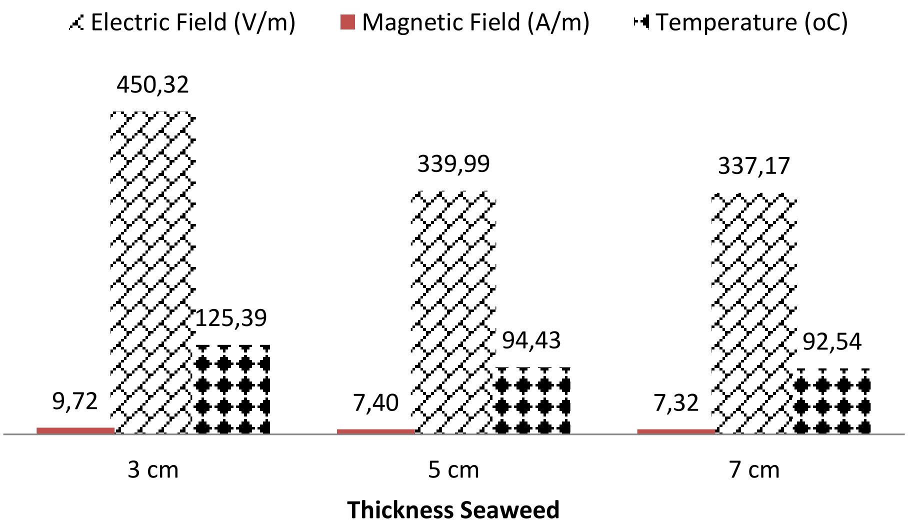


Figure 7. Effect thickness on average electric, magnetic field and temperature seaweed

Distribution of electromagnetic waves in cavity with sample seaweed at several of depth exhibited in figure. 8. Seaweed with 3 cm thickness apparently has higher both distribution and intensity of waves than 5 and 7 cm. At the thin material, emitted electromagnetic wave capable to permeate then it transmitted in to wall cavity and reflected again. But at thick material, wave absorbed fully without permeated. Therefore no more reflection wave in cavity chamber. [15] stated power microwave delivered through a component or material will encounter three process i.e reflected, absorbed and transmitted. Effect thickness on proses heating also conducted [16], the result is in the microwave oven system electromagnetic wave will be returned to the boundary reflection if material heated is slim.

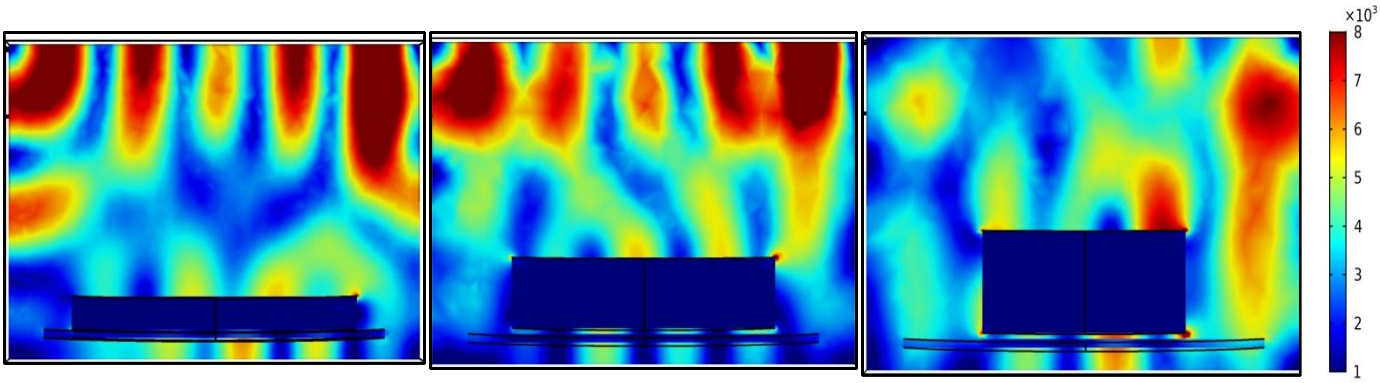


Figure 8. Distribution of electric field norm (V/m) at various thickness of seaweed

Contour model of surface temperature seaweed showed in figure 9. At 3 cm thickness lowest reached temperature was 103,1 (^{o}C) and 87,83 (^{o}C), 80,08 (^{o}C) for 5 cm and 7 cm thickness respectively. Thicker seaweed not only needs more energy to release moisture from inside into surface area but also more time to heat transfer. These phenomena also mentioned by [17], the reason for lower temperature at increased loading height of the sample is because the bigger amount of sample load would require greater energy for the removal of the water content. Therefore 3 cm thickness seaweed could be best treatment for drying in microwave.

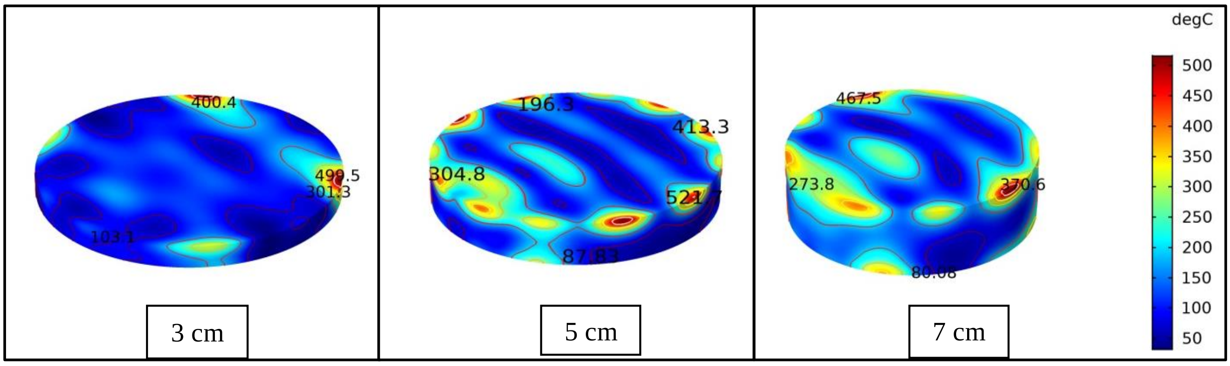


Figure 9. Contour temperature of seaweed in various thicknesses

3.3. *Effect of the waveguide position*

The position of waveguide in cavity affects electric field, magnetic field and temperatures. On top position waveguide resulted those values higher than on side position (figure 10). This result caused by material area tends to widen than height therefore material surface achieved more exposure electromagnetic wave. Based on microwave oven dimension (350 x 350 x 270 mm), when position waveguide exchanged, side to top, it would made space between material and waveguide closer. It is likely to be another reason, rising electromagnetic filed and temperature.

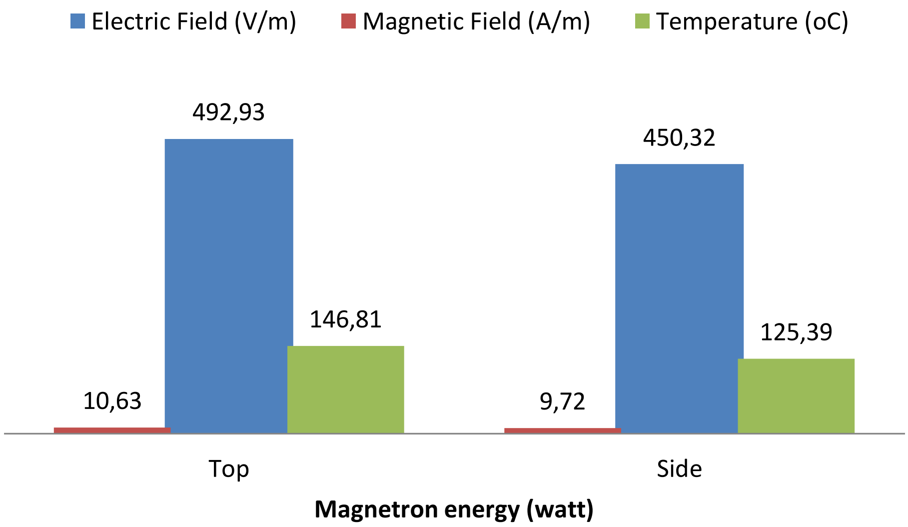
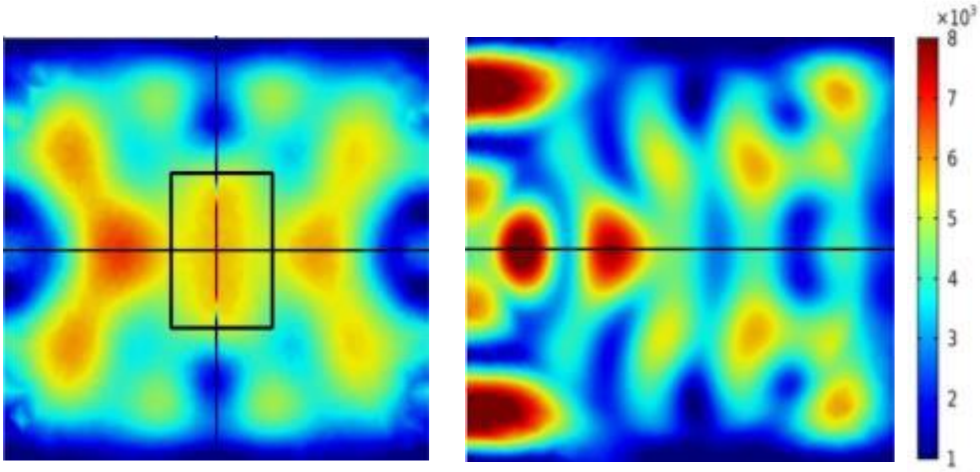


Figure 10. Effect different position waveguide to electromagnetic field and temperature

Distribution electromagnetic wave based different position waveguide exposed in figure 11. On top position waveguide generates wave more uniform distributed than on side do. Figure 11 also showed that on side position hot spot many occur in one side (left).



A B

Figure 11. Distribution of electromagnetic wave based on waveguides position top (A), side (B)

3.4. Experimental Validations

Table 3. Result of experimental validations in various power levels

Power (W)	Time (minute)	Weight (gram)	Drying rate (gram/minute)
	0	1001,25	0,00
	10	940,00	7,33
	20	860,13	9,05
400	30	774,38	9,65
	40	687,75	8,97
	50	602,88	11,03
	60	516,25	10,36
	0	1001,88	0,00
	10	925,75	7,45
	20	828,25	10,44
500	30	726,50	10,16
	40	628,50	9,02
	50	529,00	11,53
	60	434,00	10,34
	0	1000,00	0,00
	10	894,67	10,00
	20	771,33	13,27
600	30	656,67	11,94
	40	533,67	13,19
	50	416,33	11,84
	60	299,83	10,81

Result of heating seaweed use microwave oven showed on table 3 and 4. The various power level microwave treatments indicated that 600 W level resulted shrinkage mass and drying rate highest among other level (500 & 400 W). Seaweed mass at the final heating reach 516,25 g, 434,00 g and 299,83 g for power level 400, 500 dan 600 W respectively. Distinction of decreasing seaweed mass influenced by variation seaweed temperature which is generated power microwave.

Aforementioned at previous section, the simulation numerical obtained highest temperature seaweed was in 600 W power level. Moreover in experimental validation the highest rate reduction seaweed mass was in 600 W. This is demonstrating a suitability condition between real heating and numerical simulation heating of seaweed. It means that increasing level power microwave oven will be followed by increasing temperature of seaweed and resulting maximum drying rate.

Thickness seaweed as material in validation experimental causes various drying rates and declining mass (table 4). Seaweed 3 cm thickness results highest of drying rates and declining mass. While 5 cm and 7 cm thicknesses receive less values. According to data obtained moisture content in thinner seaweed released easily than other one in heating processing. This phenomenon is similar to results of numerical simulations using COMSOL software.

Tabel 4. Effect thickness to decreasing mass and drying rates of seaweed

Thickness (cm)	Time (minutes)	Weight (gram)	Drying rate (gram/minute)
3	0	350,50	0,00
	10	244,67	12,26
	20	128,67	8,90
	30	42,33	4,74
5	0	350,67	0,00
	10	251,17	12,52
	20	147,50	6,38
	30	56,50	3,92
7	0	350,67	0,00
	10	262,00	11,69
	20	172,00	6,54
	30	94,67	4,25

4. Conclusion

Simulation heating seaweed has successfully demonstrated. It involved solution coupled electromagnetic and heat transfer equations. Input values were geometry, determine materials consist of characteristics seaweed which based on analysis laboratory and materials of main component microwave oven commercial. Parameters observed in simulation were level power microwave, thickness seaweed and waveguides position. Result of simulation showed that increasing power microwaves (400-600 W) generate high electromagnetic wave and lead temperature seaweed ascends. Thickness of seaweed causes differences of electromagnetic absorption. Highest electromagnetic wave obtained at 3 cm thickness which effect increasing temperatures and the lowest at 7 cm thickness. Distributions of electromagnetic waves were influenced by waveguide position. Top position given better result than side position either electric field or temperature. Validation experimental proven that phenomena heating has similarity with numerical simulation. Based on these evidences best treatments on drying seaweed in the microwave are using power level 500 W, seaweed thickness 3 cm and waveguide on top position.

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