Design of microwave applicator for processing biomass waste

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Abstract. Activated carbon is produced by microwave heating method. We designed microwave applicator for processing biomass waste into activated carbon. To obtain the optimal design, CST Microwave studio was selected to simulate microwave radiation inside the applicator. In this work, simulation process has been done to find out microwave radiation with the change a waveguide port position and microwave cavity shape. In the measurement of microwave radiation, we used electrical field (E-field) monitor at frequency 2.45GHz. The result shows that applicator with hexagonal shape has the best performance in power accepted and power outgoing, most uniform E-field radiation in the sample. Microwave applicator for heating process biomass waste into activated carbon can be optimized with adding some stirrer mode.

1. Introduction

The amounts of industrial liquid waste increase year by year. Liquid waste contains heavy metals which are very dangerous for environment. It can reduce the water quality and harm the ecosystem. Beside their toxicity, heavy metals are not-biodegradable, accumulate in food chain, and human tissues that may result in serious health and environmental problems [1]. Several studies of water treatment technology have been done to reduce metals content in liquid waste such as ion exchange [2], electrochemical treatment [3], chemical precipitation [4], and forward osmosis [5]. One of the methods for water treatment is using activated carbon (AC) that has higher surface area and removal efficiency. AC is one of adsorbents used to remove heavy metals from water and waste water [6]. Biomass waste can be used to produce activated carbon that has higher carbon content. Recent studies have applied biomass waste to produce activated carbon like rice straw [7], nutshell [8], mushroom root [9], dan pomegranate skin [10].

To process biomass waste into activated carbon, the biomass waste is heated by conventional heating method, i.e. furnace or using microwave heating method. During heating processes using furnace, the heat source is outside carbon and energy transferred from surface area into interior of carbon, i.e. convection, conduction, and radiation. The method inflicts gradient of hot temperature from surface to inside of carbon. As the result, it needs more energy and the pore size is not uniform, so that function as molecular sieve is not fulfilled [11]. Microwave heating method can be affected by several materials which have dielectric properties. During microwave heating method, activated carbon is heated evenly and homogeneous. The process produces activated carbon with uniform pore

size which have a high selective range and bigger capacity of adsorption to heavy metals in liquid waste.

To design microwave applicator effectively, this work uses software Computer Simulation Technology (CST) Studio Suite. We design a 3D geometry of cavity and simulate microwave applicator. Design of microwave applicator is optimized with the size, materials, and layout of components. Therefore, simulation of microwave applicator is conducted to find out electric field radiation, power flow and temperature distribution. Based on the result of simulation, the most optimal and efficient design microwave applicator is decided and implemented.

The simulation of electromagnetic radiation can be determined by Maxwell equation expressed by [12].

$$\nabla x E = -\frac{\partial B}{\partial t} \tag{1}$$

$$\nabla x H = j + \frac{\partial D}{\partial t} \tag{2}$$

$$\nabla . D = q \tag{3}$$

$$\nabla . B = 0 \tag{4}$$

With,

$$J = \sigma(\omega)E(t) \tag{5}$$

$$D = \varepsilon(\omega)E(t) \tag{6}$$

$$B = \mu_m(\omega)H(t) \tag{7}$$

Where B is the magnetic induction (T), D is the electric displacement (N/Vm), E is the electric field intensity (V/m), H corresponds to the magnetic field intensity (A/m), J is the current flux (A/m2), ρ is the density (kg/m3), ω is the angular frequency (radians/s), σ is the electric conductivity (S/m), ε is the permittivity (F/m), and μ is the permeability (H/m). Equation 1 is called Faraday's law, indicating that circulation of electric field strength surrounded by a closed contour is determined by the rate of change of the magnetic flux density. Equation 2 is referred as Ampere's law, indicating the circulations of magnetic field strength enclosed by a closed contour is equal to the net current through the surface. Equation 3 presents Gauss's electric law, which requires net electric flux equal to the charges contained within the region. Equation presents Gauss's magnetic law, which requires net magnetic flux out of region to be zero. The current flux, electric displacement and magnetic induction depends on the electric conductivity, permittivity and permeability of the material, respectively (equation 5, 6 and 7).

To simulate microwave heating, the heating process has been mathematically modelled using analytical and numerical techniques [12]. Studies related to the modelling of the microwave process started with [13] that used the finite difference time domain (FDTD) techniques to model microwave heating in infinite slabs of salted ham and beef. In 2000, Zhang and Datta studies microwave applicator using different numerical methods such finite element (FEM) method [14]. The proposed study simulated design of microwave applicator for processing biomass waste in order to produce activated carbon using CST.

2. Materials and Methods

2.1. Configuration of Software and Hardware

This study Computer Simulation Technology (CST) Studio Suite version 2019 with supported by laptop hardware (Asus Vivobook K401) which has 2.6 GHz to 3.1 GHz processing speed, 8GB of Random Access Memory (RAM), and Virtual Graphic Adapter (VGA) Nvidia Geforce 940M. this

software and hardware used to simulate cavity of microwave oven for processing biomass waste into activated carbon.

2.2. Design of Microwave Applicator (Cavity, Waveguide, and Reactor Tube)

2.2.1. Cavity Design. Design of cavity influences to microwave radiation in microwave applicator. We designed several cavities based on the different shape which are symmetric rectangular cube and symmetric octagonal tube. Figure 1 shows the design of microwave oven cavity with symmetric rectangular cube and figure 2 shows design of microwave oven cavity with symmetric octagonal tube, respectively.

Figure 1. Symmetrical rectangular cube cavity design.

Figure 2. Symmetrical octagonal tube cavity design.
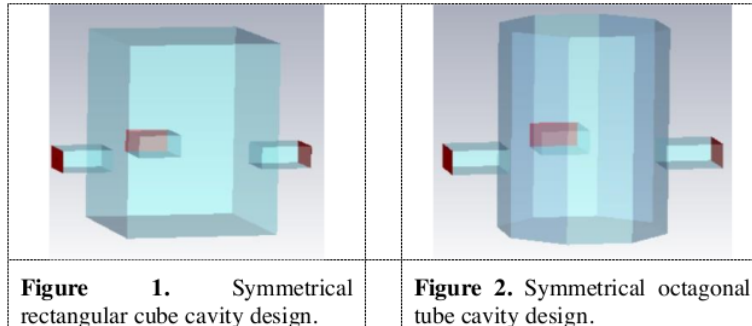
2.2.2. Reactor Tube Design. Reactor tube is designed as reaction container for biomass waste materials. The reactor is designed with the size of outer radius of 8.5 cm, inner radius of 7.5 cm, and height of 19 cm. The design of reactor is cylindrical tube shape so that can be easily applied in experiment. The reactor is equipped with two hoses as input and output of nitrogen gasses. Nitrogen gasses is needed to help the processing of activated carbon in reactor tube. The hoses made with outer and inner size of 0.8cm and 0.6 cm, respectively. The hose is designed to be easily connected with nitrogen hoses. Figure 3 shows the design of reactor tube for reacting activated carbon.

Figure 3. Design of reactor tube.
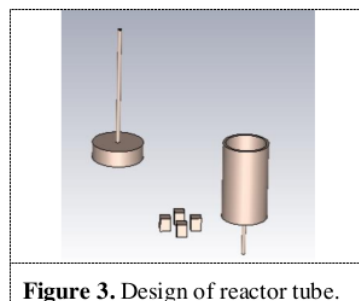
2.2.3. Waveguide Design. Waveguide design is referenced by WR340 waveguide type. It has frequency range of 2.2 GHz to 3.3 GHz with dimension width of 8,631 cm, height of 4.318 cm, and length of 10 cm. Figure 4 shows the design of WR340 waveguide.
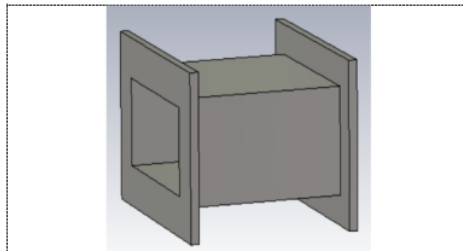
Figure 4. Design of WR340 waveguide

2.3. Meshing Element and Dielectric Properties Configuration

Meshing element is method to divide element in cavity geometries into mesh. In this study, amount of mesh is determined by CST software. The higher meshing element will increase accuracy of variable result in simulation processes but will increase the simulation time. The value of dielectric properties is determined from recent studies about dielectric constant and dielectric loss factor biomass waste. Material biomass waste in this study is coconut shell powder. It has dielectric constant of 3.769 at 1 GHz, 3.641 at 2 GHz, 3.598 at 3 GHz, 3.558 at 4 GHz, 3.511 at 5 GHz, 3.462 GHz at 6 GHz, 3.403 at 7 GHz, 3.341 at 8 GHz, and dielectric loss factor is 0.180 at 1 GHz, 0.181 at 2 GHz, 0.199 at 3 GHz, 0.230 at 4 GHz, 0.263 at 5 GHz, 0.273 GHz at 6 GHz, 0.282 at 7 GHz, 0.289 at 8 GHz [15]. The dielectric constant and dielectric loss factor inputted in CST with choosing material library.

2.4. Simulation Microwave Applicators

Before validating the microwave applicator design, simulation of microwave applicator needs to be optimized for electromagnetics and computational parameters. Frequency range of simulation is configured to 2 GHz and 3GHz with the interest frequency of 2.45 GHZ (Magnetron frequency) 2.45GHz. Field monitor for electric field is selected to find out electromagnetic radiation. Figure 5 shows simulation processes in CST Studio Suite.
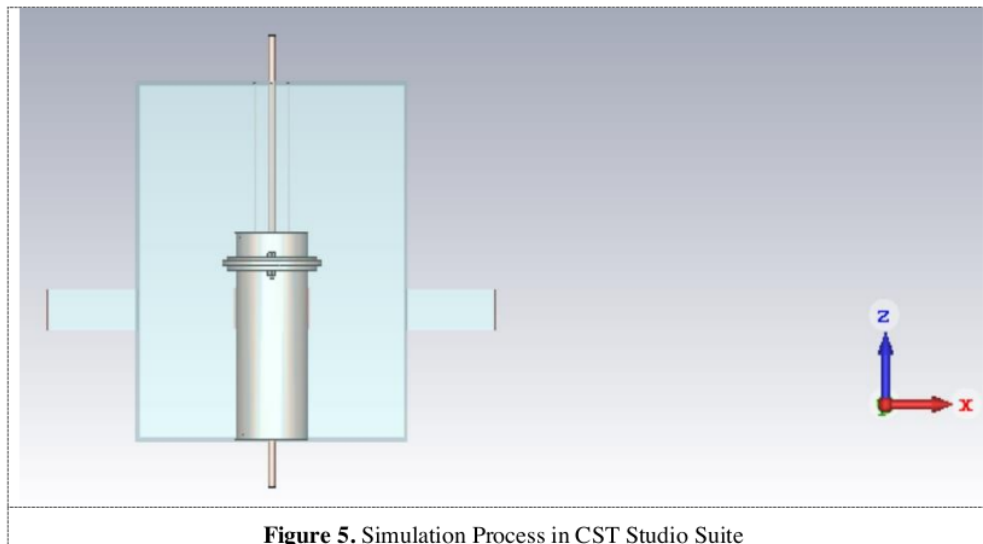

Figure 5. Simulation Process in CST Studio Suite

Electric field monitor is selected to find out uniformity microwave radiation because E-field interact with dielectric properties of material. Uniformity of microwave radiation in the sample can be known with figures in simulation result.

2.5. Analysis and Comparison of Several Design
After the simulation processes, data is analysed to find out which design has optimal microwave radiation. Comparison of several design is studied based on each design that had different radiation form, power excitation and power loss in dielectric material. Design with optimal result will be chosen to apply a design into microwave oven product.

3. Result
Waveguide port position is changed to find out how the position of waveguide (cartesian coordinate) influences microwave radiation and power excitation. This study using three port waveguide simulation which two port selected for optimizing the applicator. Two port waveguides are selected, in order to take efficiently power consumption of microwave oven.

3.1. Symmetric Rectangular Cube Design

3.1.1. Coordinate of Waveguide. In every design of this study, the position of waveguide is selected differently along the x-axis, y-axis, and z-axis of cartesian coordinate. Table 1 shows selected cartesian coordinate of the waveguide position in x, y, and z for symmetrical rectangular cube design.

Table 1. Selected coordinate for symmetric rectangular cube design

No	Waveguide	Coordinate Cartesian		
		X	**Y**	**Z**
1.	Port 1	15	0	25
	Port 2	0	15	25
	Port 3	-15	0	25
2.	Port 1	15	0	10.5
	Port 2	0	15	10.5
	Port 3	-15	0	10.5
3	Port 1	15	0	5
	Port 2	0	15	5
	Port 3	-15	0	5

Three port of waveguide was simulated with different position as shown in table 1. The reactor is placed centrally in the cavity with the 0 value of the x-axis and y-axis is in the central of the cavity. The position of port 1, 2 and port 3 (port on the left, behind and right side of the cavity) is shifted in the direction of z axis with value of 25, 10.5 and 5. All of the port are also centrally placed in the x-axis and y-axis considering that reactor also centrally placed in the both x-axis and y-axis. The simulation can be done using single port, dual ports or three ports depends on the excitation mode that are applied. In this study only single and dual port mode are simulated because the consideration of the volume of sample and the power that is needed for the heating.

3.1.2. Power Excitation

Table 2. Power excitation of every port in rectangular cavity simulation at 2.45 GHz

No	Experiment -n	Power Stimulated	Power Excitation					
			Power Accepted			Power Loss in Dielectric		
			Port 1	Port 2	Port 3	Port 1	Port 2	Port 3
1	Exp. 1	1350 W (450 W /port)	259 W	272 W	259 W	255 W	262 W	255 W
2	Exp. 2	1350 W (450 W /port)	206 W	227 W	206 W	202 W	223 W	202 W
3	Exp. 3	1350 W (450 W /port)	218 W	232 W	218 W	214 W	228 W	214 W

Tabel 2. shows that the second experiment has the biggest accepted power in the port. However, the efficiency is still low since the outgoing power are big.

3.1.3. E-field of one port simulation

Table 3. E-field of single port in simulation of rectangular cavity at 2.45 GHz

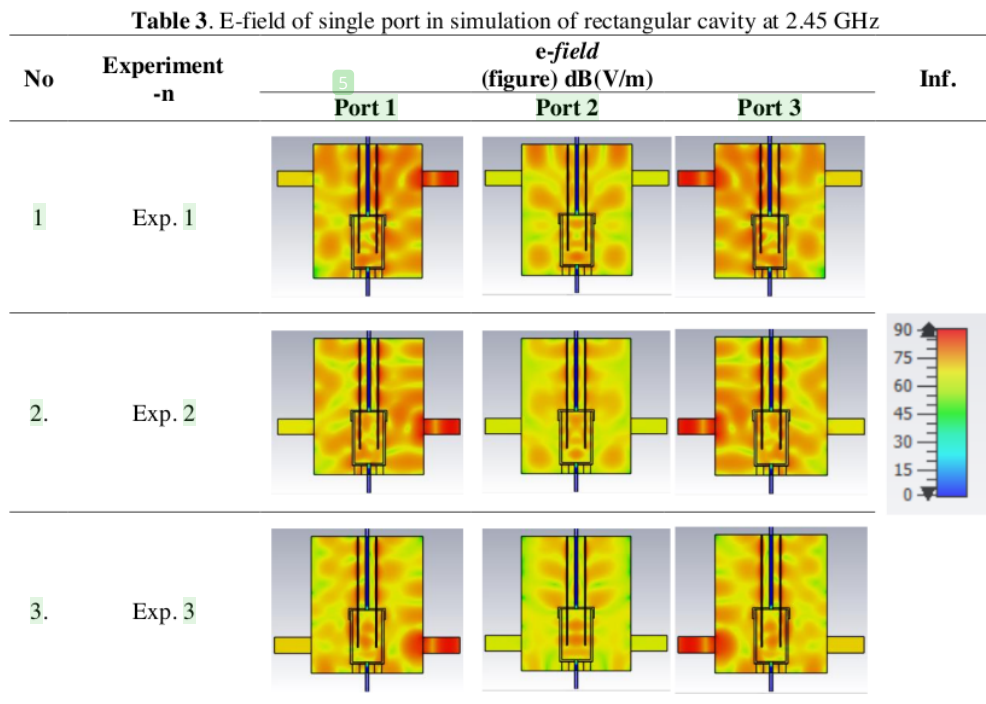| No	Experiment -n	e-field (figure) dB(V/m)			Inf.
		Port 1	Port 2	Port 3	
1	Exp. 1				
2.	Exp. 2				
3.	Exp. 3				

Tabel 3 shows the pattern of E-field within the reactor and the rectangular cavity with one port simulation

3.1.4. E-field in Two Port Waveguide

Table 4. E-field of dual two port simulation of rectangular cavity at 2.45 GHz

No	Experiment -n	E-*field* (figure) dB(A/m)			Inf.
		Port 1 and 2	**Port 2 and 3**	**Port 3 and 1**	
1	Exp. 1				
2.	Exp. 2				
3.	Exp. 3				

3.2. Symmetric Octagonal Tube Design

3.2.1. Coordinate of Waveguide. In this simulation, octagonal applicator is simulated. Table 6 Show selected coordinate cartesian in x, y, and z for symmetrical octagonal tube design.

Table 5. Selected coordinate for symmetric octagonal cavity design

No	Waveguide	Cartesian Coordinate		
		X	**Y**	**Z**
1.	Port 1	15	0	25
	Port 2	0	15	25
	Port 3	-15	0	25
2.	Port 1	15	0	10.5
	Port 2	0	15	10.5
	Port 3	-15	0	10.5
3	Port 1	15	0	5
	Port 2	0	15	5
	Port 3	-15	0	5

3.2.2. Power Excitation

Table 6. Power excitation of every port in octagonal cavity simulation at 2.45 GHz

| No | Experiment -n | Power Stimulated | Power Excitation | | | | | |
| | | | Power Accepted | | | Power Loss in Dielectric | | |
			Port 1	Port 2	Port 3	Port 1	Port 2	Port 3
1	Exp. 1	1350 W (450 W /port)	261 W	269 W	261 W	256 W	266 W	256 W
2	Exp. 2	1350 W (450 W /port)	382 W	420 W	382 W	375 W	415 W	375 W
3	Exp. 3	1350 W (450 W /port)	337 W	344 W	337 W	334 W	343 W	334 W

Table 6 shows that the experiment 2 has biggest accepted power in every port.

3.2.3. E-field of Single Port Simulation in Octagonal Cavity

Table 7. E-field of every port in simulation at 2.45 GHz

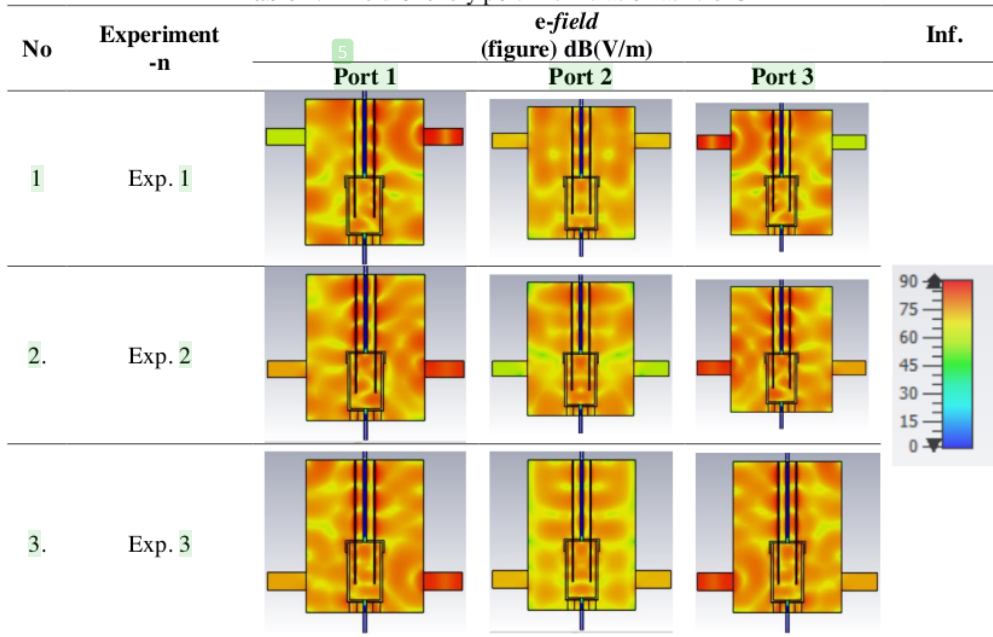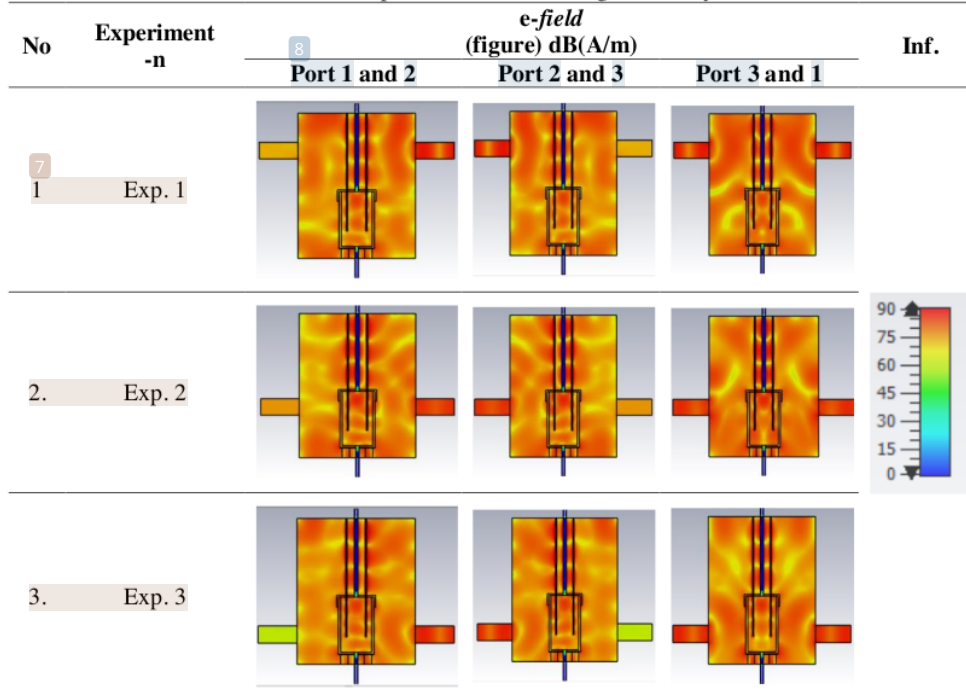| No | Experiment -n | e-field (figure) dB(V/m) | | | Inf. |
		Port 1	Port 2	Port 3	
1	Exp. 1				
2.	Exp. 2				
3.	Exp. 3				

Table 7 confirms the result of power simulation. The Experiment shows selective heating on the sample with higher electric field.

3.2.4. E-field in Two Port Waveguide

Table 8. E-field of two port simulation in octagonal cavity at 2.45 GHz

No	Experiment -n	e-*field* (figure) dB(A/m)			Inf.
		Port 1 and 2	**Port 2 and 3**	**Port 3 and 1**	
1	Exp. 1				
2.	Exp. 2				
3.	Exp. 3				

4. Discussion

4.1. Comparison Symmetric Rectangular Cube and Symmetric Octagonal Tube Design

4.1.1. Power Excitation. Based on table 2 and table 6, octagonal design affected to power radiated (power radiated = power accepted per port) higher than rectangular design. Table 9 Exp. 2 show that microwave radiation (e-field) has higher value (dB) and better uniformity in the sample than other Experiment.

Table 9. Power Efficiency All Port in Exp 2.

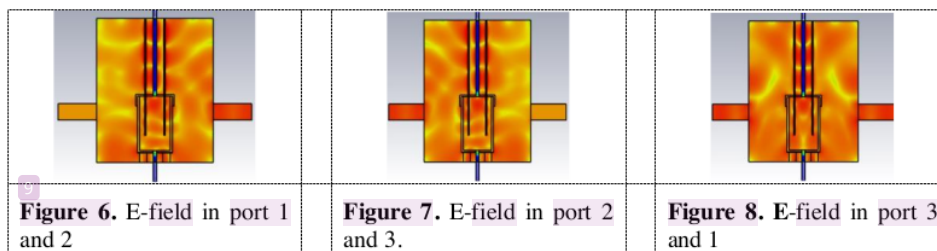| Experiment -n	Power Stimulated	Power Efficiency (%)		
		Port 1	**Port 2**	**Port 3**
Exp. 2	1350 W (450W/port)	84%	92%	84%

Higher microwave power accepted will provide higher power to heat material. Power loss in dielectric material influence the power accepted in simulation. The power loss in material coconut shell powder is equal with accepted power. Outgoing Power is the power that transmitted to other port and can expressed by:

$$Accepted\ Power\ (W) = Stimulated\ Power - Outgoing\ Power\ for\ All\ Port \quad (8)$$
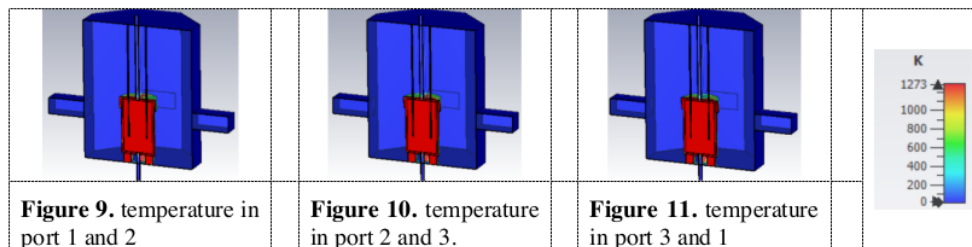
In order to decide the power efficiency, the formula can be expressed by:

$$Efficiency\ of\ Power\ (\%) = \frac{Power\ Accepted\ (W)}{Power\ Simulated\ (W)}\ x\ 100\% \quad (9)$$

4.1.2. Microwave Form Radiation. Based on table 8. Microwave radiation has uniform radiation in Exp. 2, it shown higher value of electric field. Figure 6, 7, and 8 shows electric field radiation for each two port.

| **Figure 6.** E-field in port 1 and 2 | **Figure 7.** E-field in port 2 and 3. | **Figure 8.** E-field in port 3 and 1 |

4.1.3. Microwave Temperature Change on Material. Based on table 8. Microwave temperature change on materials shown in figure 9, figure 10, and figure 11.

| **Figure 9.** temperature in port 1 and 2 | **Figure 10.** temperature in port 2 and 3. | **Figure 11.** temperature in port 3 and 1 |

5. Conclusions

The microwave applicator has been simulated in frequency from 2 GHz to 3 GHz with measurement using field monitor (E-field) at 2.45 GHz. Result from this study indicate that the design of symmetrical octagonal tube with coordinate (Exp 2.) has highest power efficiency and better uniform microwave radiation at the sample. The shape of cavity and position of waveguide has biggest influence in microwave radiation. The maximum Efficiency in this study is 84 % for port 1, 92% for port 2, and 84% for port 3. Port 1 and 3 has equal value efficiency power because position of port 1 and 3 is symmetric. Octagonal symmetric has temperature up to 1000°C is enough to activate carbon into activated carbon. Microwave applicator for heating process biomass waste into activated carbon can be optimized with adds some stirrer mode or other method optimization process heating.

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