Design and Modeling of an Enhanced Microwave Reactor for Biodiesel Production

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Abstract- A 1 kW, 2.45 GHz multi-mode microwave reactor with continuous power supply was designed in order to conduct the non-catalytic transesterification for biodiesel production. The microwave source used in this reactor is magnetron and it is equipped with a temperature probe and pressure gauge for continuous monitoring purpose. Besides, the electric field and temperature distribution within the reactant medium (mixture of palm oil and dimethyl carbonate) under the microwave irradiation was investigated using a commercial finite element method (FEM) software, COMSOL Multiphysics 5.1. Maxwell's equations and heat transport equation are coupled to describe the microwave heating process. Based on the simulation results, it was verified that the microwave cavity was well-designed as it reflected only 6.6% of microwave power back to the waveguide. Moreover, it has the heating ability to convert 75 % of microwave energy into thermal energy. The percentage difference of 7% between experimental and simulation S11 parameter also shows that simulation result is acceptable. Thus, this proposed model can be served as a good starting point for a more advanced analysis.

Index Terms- Microwave reactor design, Numerical simulation, COMSOL Multiphysics, Microwave heating

I. Introduction

The increasing of liquid fuel demand has eventually brought the research interest towards the alternative fuels. The liquid fuel is mostly contributed by the fossil fuel, which took hundreds of millions years to accumulate. Other than the depletion problem of fossil fuel, the environmental degradation and global climate change, caused by the higher level of greenhouse gas (GHG) emissions, have encouraged research on alternative liquid fuels. Hence, biodiesel should be given more attention as it consists of similar fuel properties with the current petroleum-based diesel and can be used directly in diesel engines without modification to achieve similar performance [1]. Biodiesel also has superior advantages over petroleum-based diesel [2–4]: (a) environmentally friendly, (b) renewable, and (c) biodegradable . In contrast, the major drawback of using biodiesel as an alternative fuel is that it is more expensive due to its higher production cost in term of the feedstock and the oil-to-biodiesel conversion process.

Generally, biodiesel production convert the oil into biodiesel through several refinement techniques, including micro-emulsion, pyrolysis, dilution and transesterification. Among these, transesterification is one of the simplest and economical way in producing biodiesel. In catalytic transesterification, catalysts are used to shorten the reaction time and to produce biodiesel with better quality. However, this method has several drawbacks such as its complicated downstream purification process to remove the catalyst and impurities in order to meet the American Society for Testing and Materials (ASTM) biodiesel standard. Besides, the catalytic transesterification has low adaptability to feedstocks with high water and free fatty acids (FFAs) contents as it will results in negative effect to the transesterification reaction rate [5]. In the other words, this has limited the use of cheaper feedstocks for the biodiesel production using catalytic transesterification method.

To rectify the problems, many alternative methods have been proposed, such as: (a) pre-treatment with an esterification reaction with an acid catalyst to lower FFAs [6], (b) direct reaction with a heterogeneous catalyst for easier separation [7], (c) enzymatic reaction [8], and (d) reaction in supercritical alcohol [9]. Among these proposed alternative methods, supercritical method is very interesting as no catalyst is needed for this reaction and so, it is less sensitive to water and FFAs when compared with the conventional homogenous catalytic transesterification. Nevertheless, the major challenge of this method is that it must occur under very severe conditions (high temperature and pressure), and lead to high energy consumption. One of the research gaps observed is to reduce the operating cost due to high temperature and pressure requirement for non-catalytic supercritical reaction by performing the reactions at milder conditions.

Since last decade, it has been seen that there is an increase in the usage of microwave processing technology, substituting the conventional heating method, for chemical reactions. The potential of the microwave technology to accomplish superior outcomes over the conventional methods in biodiesel production was presented in the recent review paper [10]. Microwave processing is reported to be a better heating method due to its unique thermal and non-thermal effects [10]. Hence, it is proposed to implement the microwave technology to fill in the research gap that mentioned previously. So, a novel microwave reactor with reflux system was developed to carry out non-catalytic sub-critical reaction. Moreover, to further justify the non-catalytic biodiesel production as an economically viable process, a new methyl group donor, dimethyl carbonate (DMC), is introduced as a promising alternative to the conventional methanol. This is because DMC is a green solvent with less toxic and it might improve the overall production process and eliminate the production of waste by-product (crude glycerol).

As the complicated interaction between microwave and the heated materials has not been sufficiently understood, the modeling of electromagnetic problem (eg: microwave heating) has been conducted by trial-and-error method [11]. It was reported that when there is load/food inside the microwave reactor, it is not possible to project the realistic temperature and electromagnetic field distribution [12]. Thus, partial differential equations (PDE) of electromagnetic and heat transfer models are required in the microwave heating modeling and should be solved in a coupled approach in order to maximize the consistency of simulation result. The PDE of electromagnetic problems are more difficult to solve in comparison with the heat transport equation, as the former involves vectors equations while the latter is a scalar equation. There are several numerical methods used to solve PDE, including finite-difference time-domain method (FDTD), finite element method (FEM) and finite volume method (FVM) [13, 14].

In this study, a 1 kW, 2.45 GHz multi-mode microwave reactor with continuous power supply was designed in order to study the non-catalytic biodiesel production under microwave irradiation. Furthermore, numerical simulation was conducted in order to study the electric field distribution and the temperature distribution within the reaction medium (mixture of palm oil and DMC at 1:6 molar ratio) under the microwave irradiation using this microwave reactor. A commercial FEM software, COMSOL Multiphysics 5.1 is used to solve the electromagnetic and heat transport equations in modeling this microwave heating.

II. MATERIALS AND METHODS

A. Microwave Desgin

The design requirements of the microwave reactor was listed in Table 1. Based on the requirements and the cost concern, a design was produced and its 3D model was drawn by using the Solidworks, a computer-aided design (CAD) software.

Table 1. Design features and requirement of the microwave reactor

Design Requirement	
Reactant volume	1-2 Litres
Maximum operating pressure	15 bar
Power supply	Continuous power supply
Control system	Microwave power (0-1000W) and timer
Process monitoring tools	Pressure and temperature
Insulation ability, ΔT	100 ºC
Allowable heat loss (full loaded)	< 3% or 30 W
Other features	3-stub tuner, stirrer, sampling port, and reflux system

B. Numerical Simulation

The aim of conducting numerical simulation is to study the electric field distribution and the temperature distribution within the reactant medium under the microwave irradiation by using the microwave reactor designed. By coupling both non-linear electromagnetic field (microwave) with the Fourier's heat transfer, microwave heating can be modelled, as shown in Figure 1. Table 2 summarizes the simulation settings for the modeling of microwave heating in this study.

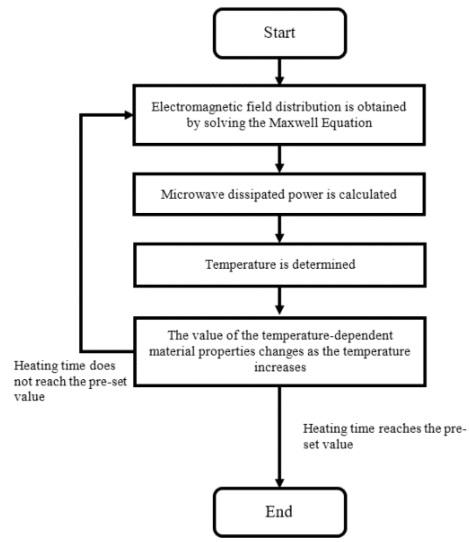


Figure 1. The general simulation procedure in microwave heating modeling

Geometric Model

A 3D geometric model is built for the designed multi-mode microwave heating system with the commercial finite element software, COMSOL Multiphysics 5.1. The microwave cavity is made of stainless steel of Grade 304 with an overall dimension of 450 x 450 x 290 mm (width x depth x height). The waveguide, however, is 112 mm long with a uniform rectangular cross section of 86.36 x 43.18 mm. This waveguide is positioned at the right-hand side and 72 mm from the top of the microwave chamber. On the other hand, the reactant medium takes the shape of the beaker. It is located 30 mm above the bottom of microwave cavity and is surrounded by insulator with 60mm thickness. As the target reactant volume is 1-Litre, so the height of the reactant medium is estimated to be 56 mm.

The numerical simulation is solved for half of the model (see Figure 2) by assuming the electric field distribution and the temperature profile of reactant medium is mirror with another side of the model. By applying the symmetry cut vertically through the microwave cavity, waveguide, insulator and reactant medium, the model size is reduced and hence, minimizing the simulation computational time and memory usage.

Table 2. Summary of the setting for microwave reactor simulation using COMSOL Multiphysics

Materials	**Air**	**Stainless Steel 304[a]**	**Reactant Medium [b]**	**Insulator/ Ceramic Fibre [c]**
Relative permeability, μ_r	1	1	1	1
Relative permittivity, ε_r	1	1	0.0291*T-0.3062 –(4.6818 - 0.0025 *T)*j	0.5
Electrical conductivity, σ [S/m]	0	1.4×10^{6}	1.18×10^{-5}	0
Density [kg/m^3]	101325 /(287*T)	$7945-0.2*T -3.7 \times 10^{-4} *T^2 +2.2 \times 10^{-7} *T^3 -5.1 \times 10^{-11} *T^4$	$1098.28-0.60*T -1.55 \times 10^{-5}*T^2$	160
Heat capacity at constant pressure, C_p [J/(kg·K)]	$1047.6 -0.37*T +9.45 \times 10^{-4}*T^2 -6.02 \times 10^{-7}*T^3 +1.28 \times 10^{-10}*T^4$	$270.2-1.2*T+0.02*T^2 -7.5 \times 10^{-5}*T^3 +8.1 \times 10^{-8}*T^4$	1999.5	1000
Thermal conductivity, k [W/(m·K)]	$-0.0023 +1.15 \times 10^{-4}*T -7.9 \times 10^{-8}*T^2 +4.12 \times 10^{-11}*T^3 -7.44 \times 10^{-15}*T^4$	6.74+0.029*T	$0.188 – 6 \times 10^{-5} *T$	0.06
Microwave power input for half geometry [W]	500			
Operating Frequency [GHz]	2.45			
Time setting	From 0 to 5 min with a time step of 0.1min			

[a] Material properties of stainless steel are adapted from [15, 16]. [b] The relative permittivity of the reactant medium are estimated according to the results reported in paper [17]. [c] Material properties of insulator are obtained from [18].

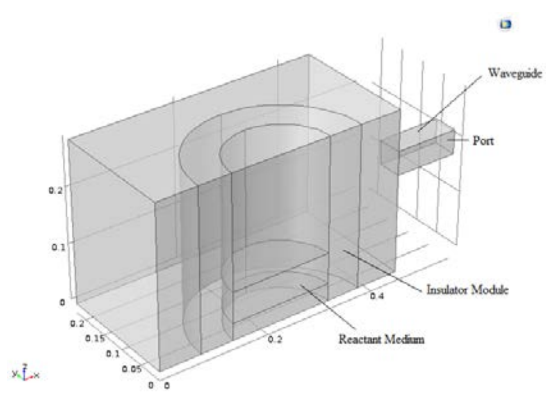


Figure 2. Symmetry model of microwave reactor

Governing Equation

(a) Electromagnetic Field Model

The basic equations for solving the electromagnetic problems are derived from the renowned Maxwell curl relation. By assuming that the electromagnetic fields vary sinusoidally in time at a known angular frequency,ω=2Πf, and that the materials have linear properties with respect to field strength, the electromagnetic field model is described as:

$$\nabla \times (\mu_r{}^{-1}\nabla \times \boldsymbol{E}) - \frac{\omega^2}{c^2}(\varepsilon_r - j\sigma/\omega\varepsilon_0)\boldsymbol{E} = 0 \qquad (1)$$

where μ_r is the relative permeability of a material while **E** is referred to the electric field (V/m). ε_0 and ε_r are the permittivity of free space (8.85 x 10^{-12} F/m) and the relative permittivity correspondingly. σ, however, symbolizes the electric conductivity of a material (S/m), f is the frequency of the electromagnetic wave, and c denotes the speed of light in vacuum, 2.9979 x 10^8 m/s.

(b) Heat Transfer Model

The temperature distribution within a material under the microwave irradiation is obtaining by solving the Fourier's conduction heat transfer equation [19]:

$$\rho C_p(\partial T/\partial t) + \nabla \cdot (-k\nabla T) = Q \qquad (2)$$

where ρ indicates the density of the material (kg/m^3), C_p denotes the heat capacity at constant pressure (J/(kg·K)), T and t are the respective temperature (K) and time (s), k refers the thermal conductivity (W/(m·K)), and lastly Q is the dissipated power per unit volume (W/m^3).

The Poynting's theorem is a statement of energy balance for electromagnetic field. Based on this theorem, the electromagnetic energy that decrease in a certain region per unit time is equal to the total work done by the field forces plus the net outward energy flux per unit time. Hence, the electromagnetic losses are the thermal sources of the reactant medium under microwave heating. This conversion of microwave energy into power dissipation in a material, Q (W/m^3), can be determined by using the equation below:

$$Q_{RMS} = 1/2\{\sigma\boldsymbol{E}\cdot\boldsymbol{E}^* + \omega\varepsilon''\boldsymbol{E}\cdot\boldsymbol{E}^* + \omega\mu_r\boldsymbol{H}\cdot\boldsymbol{H}^*\} \qquad (3)$$

where ε'' is the dielectric loss. The first, second and third terms of the right side of Eq. (3) represent the electromagnetic losses based on the electrical conductivity, dielectric loss and relative permeability of the material. In this study, only the electromagnetic loss due to the dielectric loss is accounted and so, Eq. (3) is reduced to:

$$Q = 2\pi f\varepsilon_0\varepsilon'' E^2 \qquad (4)$$

Boundary Condition

There are 3 types of boundary condition associated with electromagnetic problem:

(a) Port boundary condition is located at the opening of the waveguide (see Figure 2). The magnetron generates microwaves at 2.45 GHz in TE_{10} mode.
(b) Impedance boundary condition is assigned to the metallic surfaces of the microwave cavity and waveguide. This boundary condition is appropriate as the skin depth (metallic surface of microwave cavity and waveguide) is much smaller than the simulation model. It cannot be denied that there are currents flowing within the walls. However, it is believed that the skin effect will bring these currents to the surfaces. Thus, by applying impedance boundary condition, it treats the currents flowing on the surfaces and hence, the meshing of the wall can be avoided and save computational effort dramatically.
(c) Perfect magnetic conductor boundary condition is set to the boundaries along the y-direction, which cut the full 3D geometry into half.

Assumption

The proposed model is depended on the following assumptions:

- The microwave energy absorption by the air is negligible.
- Heat transfer in the air is negligible and thus, only solve the heat equation in the insulator and reactant medium.
- The microwave cavity is perfectly insulated, and thus, no heat is lost through the wall.
- Conduction and convection is the primary mode of heat transfer.
- The microwave reactor system is perfectly symmetry.

III. RESULTS AND DISCUSSIONS

Microwave Design

In this paper, a 1 kW, 2.45 GHz multi-mode microwave reactor with continuous power supply is designed. Magnetron was chosen as the microwave generator, as it is the most frequently used tubes in producing continuous microwave power. Besides, this magnetron was equipped with an air cooling system to support long operating period. Besides, a rectangular waveguide is suggested as it allows the microwaves to be transmitted through successive reflection on its inner walls [20]. WR 340 rectangular waveguide was selected in this project to convey the microwave radiation to the reaction chamber. This is because it has a width of 8.636 cm (> 6.1 cm) and a height of 4.318 cm, which is large enough to fit one complete wavelength of the electromagnetic wave at 2.45 GHz (λ = 12.2 cm). Furthermore, its cut-off frequency of the lowest mode (TE_{10}) is 1.736 GHz. The cut-off frequency indicates the minimum frequency required to allow the electromagnetic wave to propagate. Hence, this WR 340 rectangular waveguide is able to propagate the microwave radiation at 2.45 GHz in this design. In addition, a teflon sheet with 5mm thickness is placed between two waveguides in order to filter any possible dust from the microwave cavity into the magnetron. Teflon is chosen has it is a microwave transparent material with a penetration depth of 90 m.

Stainless steel of Grade 304 (SS304) is used as the main material in building the microwave metallic cavity/ applicator. It is the most versatile and widely used stainless steel due to its outstanding forming and welding features. SS304 has excellent oxidation resistance in alternating service up to 870 °C and up to 925 °C in continuous operating time. Inside the microwave applicator, there is an insulator module which allows a 5 L borosilicate beaker (chemical reactor) to sit on it. The insulator module is made of ceramic fibre, with a function to maintain the thermal energy inside the chemical reactor without losing to the surrounding. Moreover, the door was designed at the top of the microwave reactor and it is fixed with several strews. The distance between the screws was not more than 6.1 cm in order to prevent the microwave leakage.

Furthermore, there is an o-ring in between the door and the microwave applicator to prevent the leakage of the build-up pressure. To monitor the process continuously, the oven was equipped with a pressure gauge, a temperature probe and a sampling port. Besides recording the pressure within the reaction chamber, the pressure gauge also acts as the safety valve. Additionally, magnetic stirrer is utilized to improve the heating homogeneity. Lastly, this microwave system has the ability to connect with a reflux system in order to condense the vaporize dimethyl carbonate (DMC) back to the reactant medium. Figure 3 displays the 3D model of the finalized microwave system, which is created by using Solidworks CAD drawing software. The interior and exterior of the fabricated microwave reactor are also shown in Figure 4 and Figure 5.

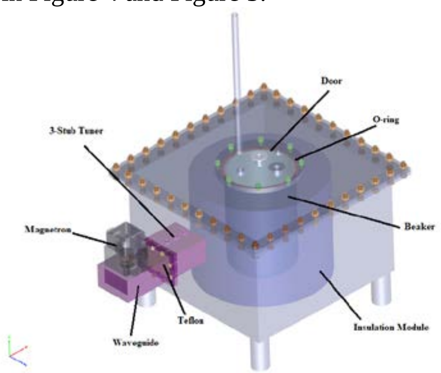


Figure 3. 3D model of final microwave reactor design

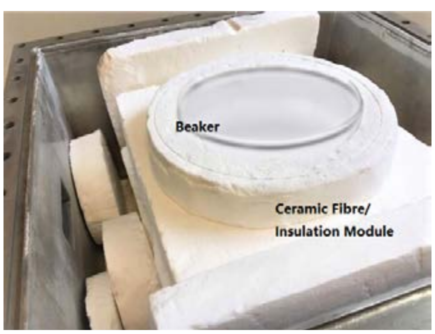


Figure 4. Interior of the fabricated microwave reactor

Figure 5. Exterior of the microwave reactor with its power control panel

Numerical Simulation

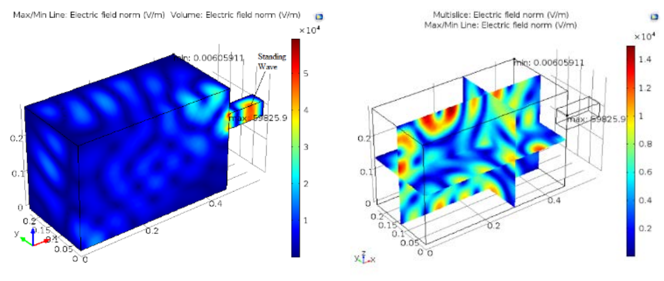
In this simulation, palm oil is chosen as the material of the reactant medium as it is the main ingredient of the transesterification process for biodiesel production. Nevertheless, the presence of the methyl group donor (eg: methanol, dimethyl carbonate and etc.) cannot be ignored as well. Thus, the relative permittivity value of the reactant medium was modified based on the paper reported by Huang et al. [17]. Moreover, five second-order elements per wavelength are applied in this simulation study to resolve the electromagnetic wave propagation [21]. Upon fulfilling this meshing requirement and based on the material properties, the maximum mesh size for the microwave cavity and waveguide is 24.47mm, as both of them are filled with air. Whereas the maximum mesh size for insulator and reactant medium are 17.3 mm and 8.65 mm respectively.

After defining the material for every part of the study model, the electromagnetic heat source will be computed first, and then applied into the time-dependent heat transfer study step. Besides, COMSOL will update with new solution at each time step when the material properties change significantly due to heating until the end time of the thermal simulation is reached. As mentioned previously, in this project, a 2.45 GHz of microwave was generated by the magnetron, travelled along the rectangular waveguide in TE_{10} mode and finally, entered the microwave cavity. Within the cavity, the microwave radiations reflected by the metallic wall, and resulting in an interference phenomenon, which is featured by the alternating high and low electromagnetic field intensity at different positions. In a multi-mode cavity, such as the microwave reactor in this study, there is a need to conduct the numerical simulation in order to get the particular electromagnetic field distribution. Unlike the single-mode cavity, the high and low electromagnetic field regions can be easily determined and calculated in comparison with the multi-mode cavity [11]. Notice that the simulation model used in this section consists of microwave cavity, waveguide, insulator and reactant medium only. For simplicity, the stirring effect is not taken into consideration as it involves only slow stirring (less than 100 rpm). Besides, the effect of thermocouples was also excluded during the simulation to reduce the complicity. Furthermore, the thermocouple used in this studied microwave reactor was shielded and grounded properly and hence, the electric interference will be reduced [22, 23].

By using the COMSOL Multiphysics software to model the microwave heating using the designed microwave reactor, some characteristics of the microwave heating are able to be observed and highlighted in this section. One of them is the electric field distribution within the microwave cavity. Figure 6 and Figure 7 show the electric field distribution in the unloaded and loaded multi-mode microwave oven. Both of the figures showing the presence of alternating higher and lower field strength within the cavity. The maximum and minimum of the electric field strength are also displayed in the figures. Based on Figure 6(b), the minimum and the maximum electric field strength for the unloaded microwave oven are 0.00605911 V/m and 59,825.9 V/m respectively. However, the electric field strength within the loaded microwave cavity (see Figure 7(b)) is within the range of 0.0147569 V/m to 39,589.8 V/m. Notice that there is a decrease of the maximum electric field strength. This suggests that there is microwave absorption by the load, in this case, the reactant medium. In addition, non-homogeneous electric field distributions are observed in both of the conditions, which is one of the main features of multi-mode microwave reactor [11].

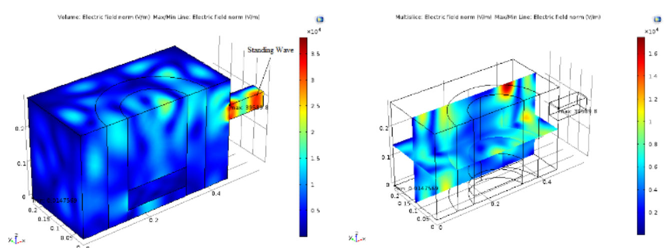
Moreover, standing waves are detected in the waveguide and within the microwave cavity (see Figure 6(a) and Figure 7(a)).

Standing wave is the superposition effect occurred when only two waves travelling in the opposite direction, with same amplitude and frequency, interfere with each other. This phenomenon is usually happened when a wave is reflected back on itself. The standing wave observed in the waveguide indicates that the microwave is reflected by its metallic wall and interfere with the incident microwaves from the magnetron. Besides, the return loss, S11 parameter was determined to express how much of the microwave is reflected by an impedance discontinuity. The simulation results show that the S11 parameter of the studied microwave reactor is 11.783 dB. This value indicates that there is only ~6.6% of microwave power is reflected. To validate this value, a network analyser was used onto the fabricated microwave reactor and the S11 parameter obtained is ~11 dB (~7.94% reflected microwave power), as shown in Table 3. This concludes that the assumptions done previously is valid.



(a) (b)

Figure 6. (a) Volume plot, and (b) Multi-slice plot of the electric field distribution of the unloaded microwave oven



(a) (b)

Figure 7. (a) Volume plot, and (b) Multi-slice plot of the electric field distribution of the loaded microwave oven

Table 3. Validation of simulation result for S11 parameter

	S11 parameter (dB)
Simulation result	11.783
Experimental result	11

Furthermore, the non-homogenous electric field distribution will result in heating inhomogeneity, and thus, hotspots will be observed. The simulation showed that after 5 minute of microwave heating, the maximum achievable temperature is 367 °C at the hotspot location. However, most area of the reactant medium is still remained in red colour (lower temperature). The weighted average temperature of the reactant medium is 140 °C after 5 minute of microwave heating.

As shown in Figure 8, the heating inhomogeneity of the studied microwave system is moderate. With the help of stirrer, it was reported that a more homogenous heating profile will be obtained [24]. Nevertheless, it is not a best solution. Further modification on the microwave reactor design might be done to improve the heating homogeneity by installing an antenna into the microwave chamber [25].

From Figure 8, another fundamental feature of microwave heating is discovered as well, which is the volumetric heating. Microwave heating allows the heat transfer from the inner medium to the outer medium, unlike the conventional heating. This heat transfer style is validated in this simulation by observing the existence of higher temperature spot (white colour) near the centre of the reactant medium while at the same time, the temperature of the outer layer is still remained lower (red colour). Besides that, notice that there is no/little temperature increase of the insulator as it is microwave-transparent.

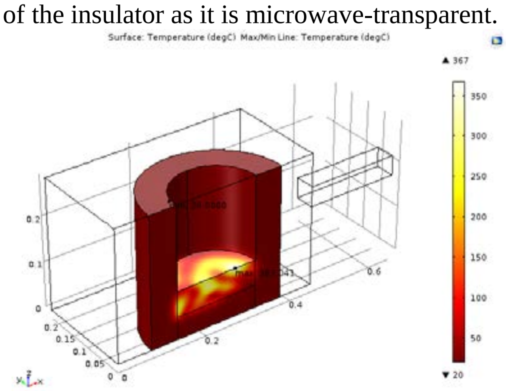


Figure 8. Temperature distribution of the reactant medium and insulator

As highlighted before, the electromagnetic losses are the thermal sources of the reactant medium under microwave heating based on Poynting's theorem. These electromagnetic losses can be now presented by the plotting of the total heat sources. The maximum value of the total heat source are 2.73 x10^6 W/m^3 (refer Figure 9). By performing the volume integration using COMSOL Multiphysics, the total thermal energy within the reactant medium is 377.78 W. Recall that the microwave power setting for this simulation was 500 W, as only half geometry was simulated. Thus, for a full model rated at 1 kW, the total microwave energy converted into thermal energy is doubled up, 755.56 W, which is 75.56 % of the microwave power input. This value shows that the efficiency of the studied microwave reactor is high.

A point within the reactant medium (red colour point in Figure 10(a)) is randomly selected to study its temperature profile over time. The temperature curve (see Figure 10(b)) shows that as the time increases, the temperature of the reactant medium increases from 20 °C to 65 °C parabolically within 5 minutes as the dielectric properties changes with temperature. The reactant medium modelled here is the mixture of palm oil and dimethyl carbonate (DMC). At temperature higher than 90 °C, DMC will be vaporized and built up the internal pressure as time increases. This non-linear effect, however, is not captured by this simulation model as the focus of this simulation is on the reactor itself, not the reaction process. Nevertheless, this model can serve as a good starting point for a more advanced analysis.

Figure 11 compares the simulated and experimental temperature profile. The experimental temperature profile was based on the three experimental replications. Notice that there was mismatch between these two temperature profiles, which might be due to the deviation of the magnetron operating frequency [26].

Generally, the instantaneous magnetron operating frequency emitted in a microwave reactor are affected by the cathode-anode voltage and the high frequency output impedance that depends on the load (target to be heated up) [27] . This load impedance, however, was varied with the material's dielectric properties which changes with temperature. This eventually alters the frequency of the magnetron and affects the heating rate and electric field distribution.

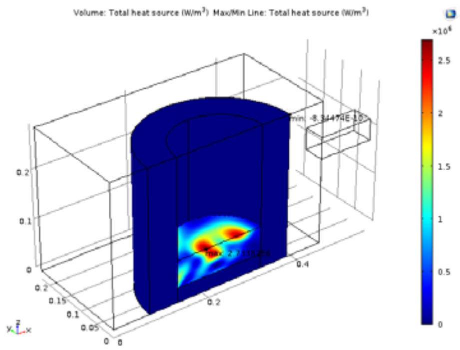
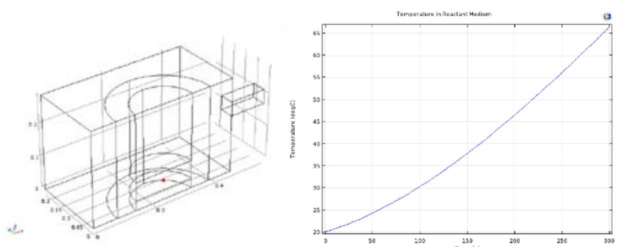


Figure 9. Total heat source within the reactant medium



(a) (b)

Figure 10. (a) A randomly selected point within the reactant medium, and (b) the temperature profile over time at the particular point

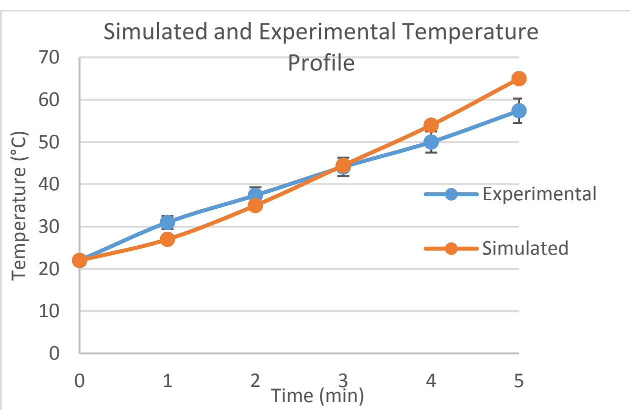


Figure 11. A comparison between the experimental and simulated temperature profile

IV. CONCLUSION

Electromagnetic field and thermal field are successfully coupled to simulate the heating of the mixture of palm oil and dimethyl carbonate, the raw materials for biodiesel production in this study, under microwave irradiation by using COMSOL Multiphysics software. The results showed that the microwave heating under multi-mode microwave reactor is successfully modeled. The main characteristics, such as the presence of hotspot, heat transfer from the inner layer to the outer layer and non-homogeneous temperature and electric distribution profile, are clearly observed. Besides, it was shown that there is a decrease of the maximum electric field strength between the unloaded and loaded microwave reactor. This suggests that there is microwave absorption by the load, in this case, the reactant medium. Moreover, the simulation results was validated by measuring the S11 parameter. There is 7% difference between the real and simulation results. Thus, the simulation result is reasonable and makes it possible to calculate the total microwave energy converted into thermal energy and instruct the design of an efficient microwave-assisted biodiesel reactor. The microwave heating efficiency of 75.56% symbolizes that the enhanced-design of the microwave reactor in this study is good. In a nutshell, most of the non-catalytic transesterification was conducted under supercritical condition. However, this is a microwave reactor that allow subcritical reaction for the non-catalytic biodiesel production. Subsequence modification can also be done based on this design whereby the reaction time can be reduced by optimizing the waveguide position in order to obtain higher heating intensity.

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