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Heat Transfer Evaluation on Microwave Sterilization: Case Study of Oil Palm Fruit

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Abstract. Microwave energy can be used for oil palm fruit bunch sterilization. It penetrates onto the core of oil palm fruit bunches and generates heat inside out. This sterilization aims to inactivate lipase that influences palm oil quality. This study evaluates effect of dielectric properties power developed per unit volume and interior temperature distribution on heating rate during heating process. The experiment carried out at various combinations of microwave power and the oil palm bunches portion in microwave oven. This study observed that distribution of interior temperature in a single oil palm fruit was influenced by power density and fruit's diameter. Greater power density provides high microwave energy per kg sample to attain greater temperature of microwave heating and vice versa. Distribution of interior temperature in the fruit with the thickness (r) of 6 mm and above indicated non-uniformity heating. Furthermore, interior temperature of fruitlet with r = 4.5 mm indicated distribution of temperature from endocarp to exocarp, meanwhile simulation temperature on smaller fruit diameter (r = 3 mm) indicated thermal runway effect after 5 min heating duration.

1. Introduction

Every palm fruit bruises during harvesting and transportation to palm oil milling facilitate the release of free fatty acid by lipase with the presence of water. Sterilization is compulsory in the mill to protect palm oil quality through inactivation of 90 % lipase activity at certain time and temperature. Fundamentally, lipase activity can be reduced through heating process at temperature above 50 ^{o}C. One of the heating method for oil palm sterilization is microwave irradiation. This method has several advantages because it can either carried out very fast at high temperature or proceeded slower at lower temperature. Utilization of microwave energy to enhance chemical processes such as sterilization, extraction and demetallization reported by several authors elsewhere [1, 2]. Opportunity to utilize microwave energy for heating palm fruit firstly introduced by Tan (1980) who investigated dielectric properties and moisture loss of fresh oil palm fruit during heating process [3]. Ever since many studies reported utilization of microwave energy for oil palm fruit sterilization with respect to stripping efficiency after sterilization [4], crucial time and temperature for sterilization [5] and quality of extracted oil [6, 7]. Over all studies on heating oil palm fruit with microwave energy can be classified into three parts: (1) the study of the opportunities for the use of microwave energy to heat the oil palm fruit, (2) the study of the quality of palm oil after heating with microwave energy, and (3) the study of the ability of microwave heating to facilitate the release of oil palm fruit from their stems. All those previous studies reported potency of microwave irradiation to sterilize palm fruit at laboratory scale. Sarah (2018) also reported microwave irradiation offered various modification on mode of operation to obtain palm oil with high carotenoids content (Red Palm Oil) or on the contrary produce palm oil without any carotenoids [8]. Conventional palm oil milling produces crude palm oil that refined further to remove as much as carotenoids content in palm oil to satisfy costumer. In facts carotenoids is very important to human health because it contains β-carotene that acts as pro vitamin A in human living. The fact β-carotene destroyed during sterilization or heating process due to high temperature or long period of exposure indicates sterilization time and temperature are very crucial to oil palm sterilization by microwave irradiation. Both indicates significant heat transfer process occurs during sterilization from microwave energy as a source of energy into thermal energy.

This study evaluates mechanism and effect of microwave energy transformation into thermal energy at microscopic level. Heat generation occur prior of heat transfer as electromagnetic waves applied into oil palm fruit sample. Interaction between microwave, polar water molecules and charged ions in oil palm fruit causes water molecules in oil palm fruit to constantly rotate and couple with electromagnetic field. Molecular friction resulting from dipolar rotation of water molecules generates heat and resulting rise on fruit temperature in kernel or endocarp. Furthermore, heat transfer occurs when heat flows from kernel or endocarp into exocarp of oil palm fruit.

Heat generation in the concept of microwave heating is indicated by an increase in temperature of the material per unit of time, and heat transfer from the interior of material into the exterior or surface. This is indicated by the difference in temperature of the interior and exterior of material, where the interior temperature is higher than the temperature of the exterior. At time the microwave energy is absorbed by dielectric material, rate of temperature increases depends upon number of distinct parameters, such as frequency, dielectric loss factor and electric field. The rate of heating of material expressed by power equation [9, 10, 11]. Energy produced per unit volume of the microwave heating of oil palm fruit can be estimated using Eq. (1) where $\boldsymbol{P_v}$ represent the energy developed per unit volume (Wm^{-3}), f is frequency (Hz), ε_o is vacuum permitivity ($F\ m^{-1}$), E is electric field strength inside the load ($V\ m^{-1}$) and $\boldsymbol{\epsilon}''$ is dielectric loss factor.

$$\boldsymbol{P_v = 2\pi f \varepsilon_o E^2 \epsilon''} \quad (1)$$

Energy transfer with respect to Eq. (1) is highly dependent on the dielectric properties of oil palm fruit and frequency of the microwave oven. Meanwhile, heat transfer in material during microwave heating occurs from the interior, where generation of heat took place, into the exterior, by dissipating heat. Heat transfer equation can be used to evaluate distribution of interior temperature during heating process with power absorbed as source term in heat transfer equation [12, 13, 14, 15]. Eq. (2) can be used to estimate the interior temperature distribution within a single oil palm fruit where k is the thermal conductivity ($W\ m^{-1}K^{-1}$), ρ is density ($kg\ m^{-3}$), c_p is specific heat capacity ($J\ kg^{-1}\ K^{-1}$), T is the temperature (K), t is the time (s) and $\boldsymbol{P_v}$ is energy developed per unit volume ($W\ m^{-3}$).

$$\boldsymbol{\rho c_p \frac{\partial T}{\partial t} = k\nabla^2 T + P_v(x, y, z, t)} \quad (2)$$

Eq.(2) solved numerically with respect to boundary as given in Eq.(3) [12, 13, 14, 15] where h_c is convection heat transfer coefficient over a surface and T_a is temperature of air inside the microwave oven (^oC). The initial temperature of air and fruit inside the microwave oven was assumed constant at 25 ^oC.

$$\boldsymbol{-k\nabla T = h_c(T - T_a)} \quad (3)$$

2. Materials and Methods

2.1. Materials

Materials used in this study is oil palm fruitlets *Tenera* variety taken from oil palm tree around the campus. The fruitlets sorted with respect to their size (big, medium and small sizes) and were put in the dry environment. This study utilized domestic microwave oven (Sharp R-958A series) with frequency of 2450 MHz and maximum allowance power of 800 W. Sample of palm fruit at various mass (0.5 kg to 1.5 kg) exposed by microwave energy at various power level (medium, medium high, high respectively). Data logger (Pico Temperature Data Logger PT 104) was installed to measure temperature of fruit during irradiation period. Dielectric properties of sterilized palm fruit were measured utilizing dielectric probe (8710-2038) and computer controlled (ENA Series Network Analyzer Agilent Technologies), at frequency range of 300 kHz to 20 GHz. Dielectric properties obtained was then used to evaluate heat transfer in a fruitlet during irradiation period.

2.2. Methods

This study evaluated heat transfer with respect to Eq (2). Several authors reported their simulation work using similar equation [12, 13, 14, 15]. In this study, Eq (2) was modified into Eq (4). For one dimensional body, partial diffential equation from Eq. (2):

$$\rho c_p \frac{\partial T}{\partial t} = k\nabla^2 T + P(r,y,z) \quad (4)$$

Rearrangement of Eq. (4):

$$\frac{\partial T}{\partial t} = \left(\frac{k}{\rho c_p}\right)\left(\frac{\partial^2 T}{\partial r^2}\right) + \frac{P}{\rho c_p} \quad (5)$$

Finite Difference Method (semi discretization, central different) was used to solve Eq. (5). With respect to Eq. (3) boundary for Eq. (5) is:

$$-k\frac{\partial T}{\partial r} = h_c(T - T_a) \quad (6)$$

Power from microwave that absorbed by dielectric of oil palm fruits per unit volume calculated using Eq. (1). while electric field could be estimated numericaly by using Eq (7) [16].

$$E_z = \frac{1}{2\pi}\frac{1}{\ln(b/a)}\int_a^b\int_0^\pi cos\phi' \frac{\exp(-jkR')}{R'}.\left[\frac{1}{\rho} - \left(jk' + \frac{1}{R'}\right)\frac{(\rho-\rho' cos\phi'}{R'}\right] d\phi' d\rho' \quad (7)$$

Term R' and k' from Eq. (7) are: $R' = [(z-z')^2 + \rho^2 + \rho'^2 - 2\rho\rho' cos\phi']^{\frac{1}{2}}$ and $k' = \frac{2\pi f}{c}\sqrt{(\epsilon_r' - \epsilon_r''}$ respectively.Temperature distribution inside mesocarp was modeled into radial direction at various combination of mass and power. The endocarp was represented by r=0 while exocarp depends on thickness of mesocarp. inner mesocarp. Heat transfer within the fruitlets was evaluated using Matlab software R12a series.

3. Results and Discussions

3.1 Potency of palm fruit properties for heat transfer process during irradiation

Dielectric properties of oil palm fruit figure out the potency of fruit to be heated or irradiated by microwave energy. Dielectric constant shows the ability of palm fruit absorbs the microwave energy while dielectric loss factor informs conversion of microwave energy into thermal energy. Ratio between two properties become an indicator for heat transfer efficiency. Overall, the mean value of dielectric properties of fresh fruit and heated fruit from triplicate measurement is shown in Table 1.

Table 1. Dielectric properties, relative permitivity and loss tangent of various fruit categories

Fruit categories	Power level	Dielectric constant	Dielectric loss factor	Relative permitivity	Loss tangent
Fresh fruit	-	14.155±1.797	4.162±0.376	14.754<-16.385^o	0.294±0.014
Heated fruit	Medium	15.896±1.938	6.030±0.580	17.001<-20.774^o	0.379±0.027
	Medium High	10.523±0.316	3.010±0.216	10.945<-15.963^o	0.369±0.042
	High	14.042±1.222	4.467±0.580	14.095<-4.974^o	0.286±0.011

Dielectric constant always greater compared to dielectric loss factor. This study did not observe significant variability on dielectric properties of fresh ripe fruit and ripe fruit (of heated fruit) while dielectric constant and dielectric loss of heated fruit resulted from this study vary according to degree of ripeness of the fruit. For ripe fruit, the dielectric constants ranged between 10.285 to 17.662, while dielectric loss factors ranged between 2.811 to 7.156.

Dielectric constant and dielectric loss factor of medium high treatment was observed lower as compared to dielectric values of others treatment. Variability of dielectric properties of heated fruit in this study was due to fruit characteristic and did not influence by the power. Dielectric loss factor of the study ranged between $10^{-2}<\varepsilon''<5$. Value of dielectric loss factor meets the theoretical requirements for dielectric heating process. According to Metaxas and Meredith (1988), dielectric loss factor of less than 10^{-2} requires the strength of the very high electric field to ensure a reasonable level of temperature rise in the material. Meanwhile, dielectric loss factor greater than 5 might cause problems on the depth of penetration, because the power of the microwave absorption materials very high. Most of the electromagnetic energy is absorbed within a first few mm, leaving the internal parts slightly affected, thus the cause of non-uniformity of heating [17].

Ratio between dielectric loss factor and dielectric constant was expressed as loss tangent (tanδ), which explained potency of oil palm fruit to generate heat from microwave energy. Based on the loss tangent, only 29.4 % of the electromagnetic energy absorbed by the sample of oil palm fresh fruit has the potential to be converted into thermal energy. Meanwhile for sample ripe oil palm fruit, which has been heated at medium power level, approximately 37.9 % of the amount of electromagnetic energy that is absorbed by the oil palm fruit has been converted into thermal energy. Overall, palm fruits show the potency to be heated by microwave energy with respect to their dielectric properties values. Dielectric properties data obtained were used to estimate interior temperature distribution during heating as describes in the following discussion.

3.2 Effect of microwave power and sample thickness to interior temperature distribution

Heat transfer evaluation in this study carried out with respect to Eq. (5) to Eq. (7) and the effect of microwave power to heating process. Actualy investigation on interior temperature distribution in this study is very complex due to the heating process utilized 0.5 to 1.5 kg sample with irregular shape and not uniform in size. To conduct simulation, it was assumed oil palm fruit is spherical elongated in shaped which has 2 diameters: the equatorial diameter (d_e) and polar diameter (d_p) as shown in Figure 1. There were several fruitlets size in this study with d_e and d_p combination of 2.5 cm and 4 cm (fruit 1); 2.5 cm and 3 cm (fruit 2); 2 cm and 3 cm (fruit 3); and 1.5 cm and 3 cm (fruit 4) respectively. For kernel, the average kernel in this study has d_e ranged from 1 into 1.5 cm, and d_p ranged from 1.5 into 2.5 cm. Total thickness of mesocarp (for both sides of the kernel) ranged from 0.5 to 1 cm (in the equatorial direction) and 1 to 2 cm (in the polar directions). Simulation in this study was carried out in accordance with the thickness of mesocarp. Mesocarp thickness on each side of the mesocarp can be expressed as the radius of the mesocarp, each of 2.5 to 5 mm (equatorial direction) and 5 to 10 mm (polar direction). Based on that, the simulation of temperature distribution in the oil palm fruit is done in a radius of 3, 4.5 and 6 mm each represent fruit size from small, medium and big sizes respectively.

Figure 1. The size of a single oil palm fruit (fruitlet) in palm fruit sample in this study

Eq. (6) is solved numerically by derivative approximation, by using finite differences method with central difference approach at both time and space derivative at various position [18]. Scheme of single oil palm fruit for discretization process is shown in Figure 2.

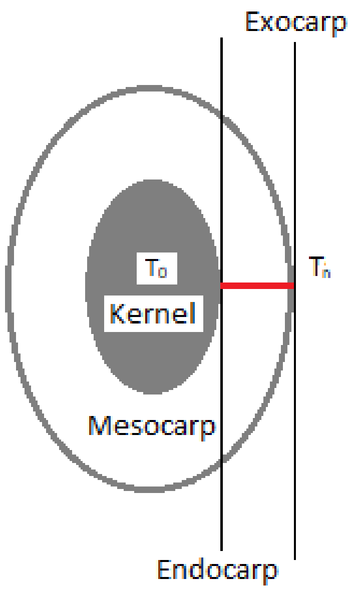

Figure 2. Scheme of single oil palm fruit

Semi discretization of transient heat transfer equation to evaluate interior temperature at endocarp, mesocarp, and exocarp are given in Eq. (8), Eq. (9) and Eq. (10) respectively.

Model for interior temperature distribution at endocarp:

$$\frac{dT_1}{dt} = \frac{2k}{\rho Cp}\left(\frac{T_2 - T_1}{(\Delta r)^2}\right) + \frac{P}{\rho Cp} \qquad (8)$$

Model for interior temperature distribution in the mesocarp if radial distances is divided into n section, thus for i = (n-1):

$$\frac{dT_{n-1}}{dt} = \frac{k}{\rho Cp}\left(\frac{T_n - 2T_{n-1} + T_{n-2}}{(\Delta r)^2}\right) + \frac{P}{\rho Cp} \quad (9)$$

Model for interior temperature distribution at exocarp:

$$\frac{dT_n}{dt} = \frac{2k}{\rho Cp}\left(\frac{T_{(n-1)} - T_n}{(\Delta r)^2}\right) + \frac{P}{\rho Cp} \quad (10)$$

The results in Figure 3 show temperature distribution of the model in mesocarp fits with temperature of mesocarp obtained from experimental data at a radial distance of 4.5 mm.

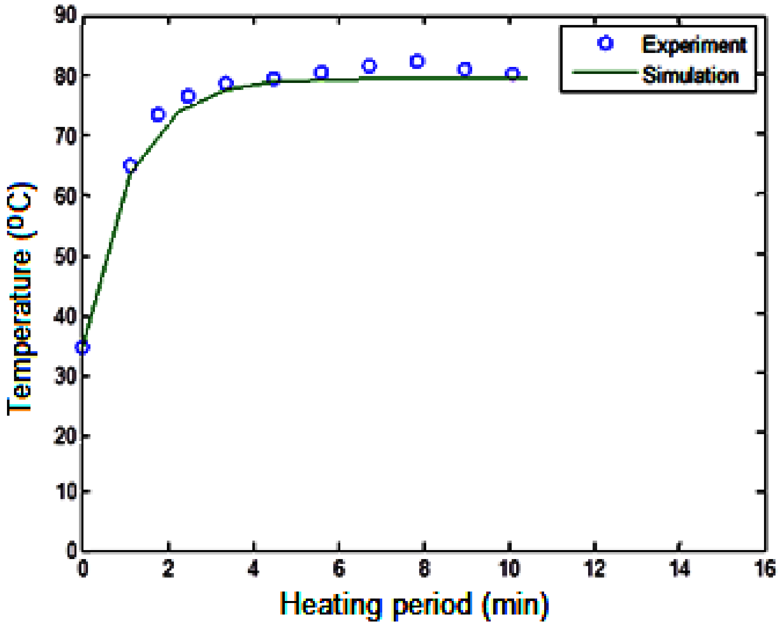

Figure 3. Curve fitting in this study at r=4.5 mm

Figure 4 indicates mathematic model of equation from this study could be used to estimate temperature distribution of oil palm fruit. Similar trend model of time-temperature distribution on microwave heating of ceramic material using different methods reported by others studies elsewhere [12, 13, 15, 19]. Figure 4 shows the temperature distribution in the oil palm fruit at kernel, endocarp, mesocars and exocarp. This simulation was performed at various power levels, and weight sample of oil palm fruit bunches. The temperature distribution was modelled at various thickness of mesocarp: r=3 mm (small fruitlet), r=4.5 mm (medium fruitlet), and r=6 mm (big fruitlet). The simulation shows temperature increased during the first 3 min. Temperature at the centre of the fruit is the highest during initial heating process, and the temperature will decrease along with an increase in the radial direction distance, from the centre towards the fruit exocarp. The lowest temperature is the temperature at the surface of the oil palm fruit (exocarp). It shows the process of heat generation takes place from the kernel, and so on heat to move toward the direction of endocarp, mesocarp and exocarp. However, after 3 min, the temperature in the kernel becomes constant, while the temperature in some hot spots in the mesocarp and exocarp showed different responses.

Figure 4 shows evaluation resulted from 0.5 kg sample that shows thermal runway for small fruitlet (r=3 mm) occurred at some hotspots, excluded at the exocarp. The thermal runway occurred from kernel into outer layer mesocarp after 3 to 5 min. Runway effect is uncontrolled rise in temperature in a material which cause damage of material [17].

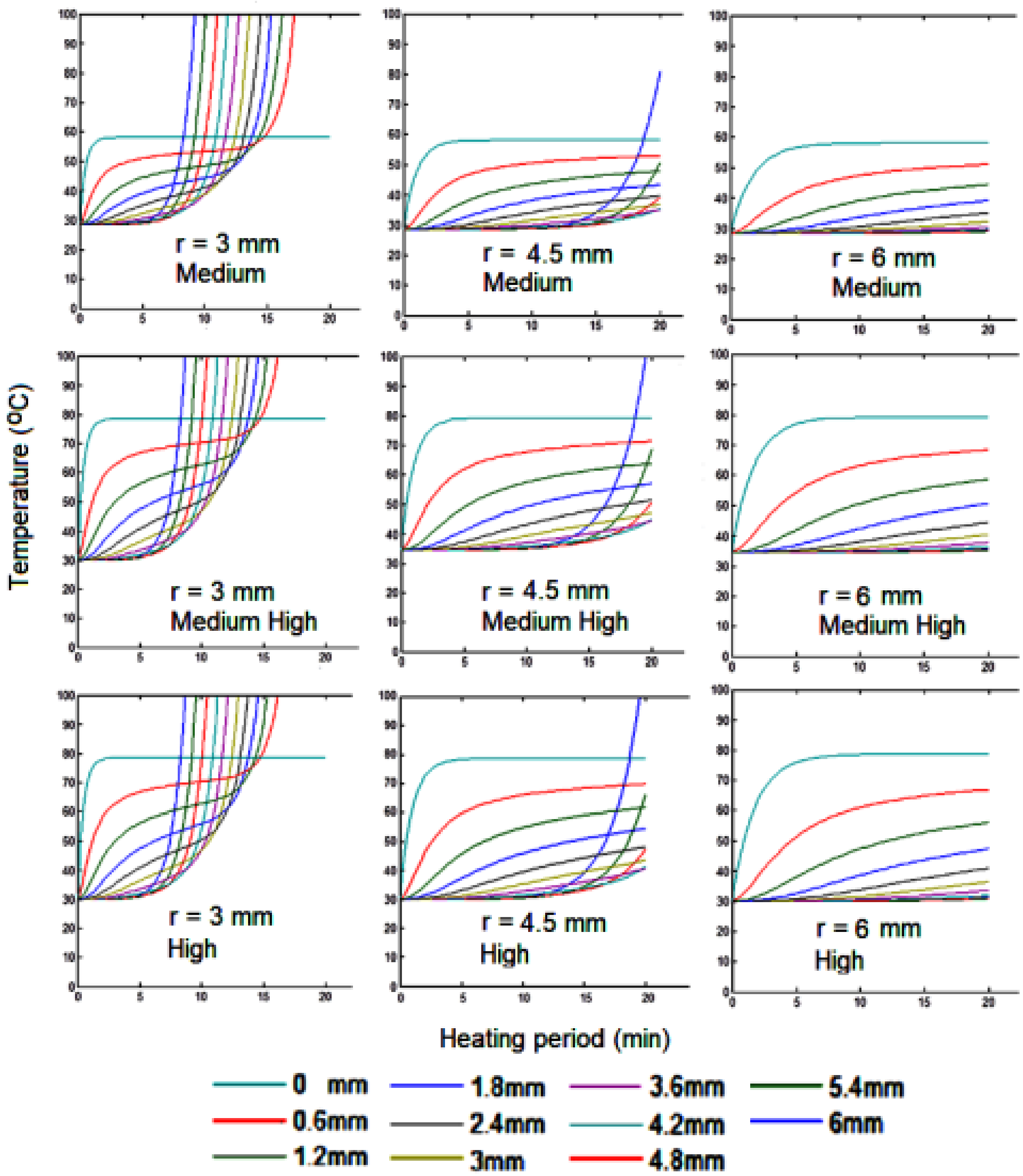

Figure 4. Temperature evaluation on 0.5 kg palm fruit sample at various size of fruitlets and power

Thermal runway indicated by the increase in local temperature exponentially arising from the absorption of microwave energy that is effective at higher temperatures in the oil palm fruit, especially in the endocarp. This is according to Clemens and Saltiel (1996) is due to an increase in the electrical conductivity of the oil palm fruit. It is also reported by Clemens and Saltiel (1996) who reported the same phenomenon when performing studies on ceramic heating in a microwave oven [20]. Thermal runway effect from microwave heating of medium size fruitlet (r=4.5 mm) occurred only in some hotspot location (radial distances were 0; 0.45; and 0.9 mm respectively). On the contrary no thermal runway effect occurred on microwave heating of big size fruitlet. Increment of microwave power from medium to medium high and high shows similar phenomenon.

Figure 5 shows temperature evaluation for 0.5 to 1.5 kg sample at high microwave power. Increment weight of the sample from 0.5 kg to 1 kg and 1.5 kg respectively, lowering the maximum temperature from 78.85 ^{o}C and 76.77 ^{o}C (for 0.5 and 1 kg respectively) into 71.53 ^{o}C (1.5 kg). This was due to power density variability obtained from ratio power to mass sample. Small sample gained higher temperature due to higher power density applied. Overall, excluded diameter of fruitlets, no significant parameters affect the temperature or heat transfer inside the palm fruit during irradiation period.

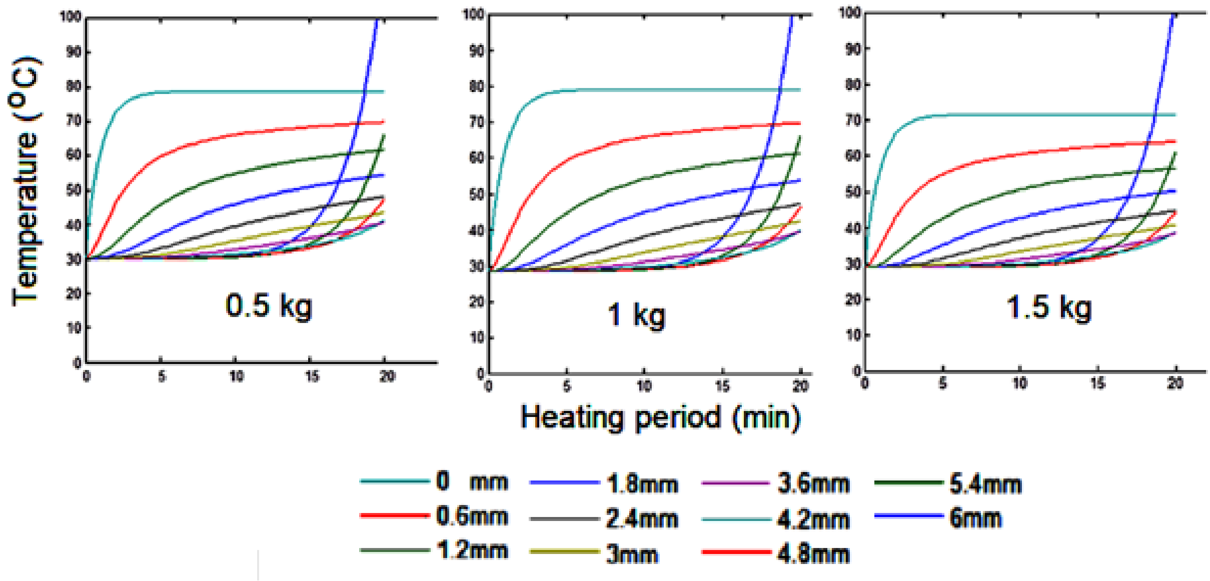

Figure 5. Temperature evaluation of sterilization with high microwave power at various mass

4. Conclusion

Microwave energy shows significant potency for sterilization of palm fruit with respect to their dielectric properties. Interior temperature in a single palm fruit was distributed inside out and it less influenced by power density but fruit's diameter. Greater power density provides high microwave energy per kg sample to attain greater temperature of microwave heating and vice versa. Distribution of interior temperature in the fruit with the thickness (r) of 6 mm and above indicated non-uniformity heating. Furthermore, interior temperature of fruitlet with r = 4.5 mm indicated distribution of temperature from endocarp to exocarp, meanwhile simulation temperature on smaller fruit diameter (r = 3 mm) indicated thermal runway effect after 5 min heating duration.

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