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Experimental investigation of a finned pentaerythritol-based heat storage unit for solar cooking at 150-200 °C

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Abstract

An experimental study on the charging and discharging performance of a finned thermal energy storage unit (TESu) that utilizes pentaerythritol (PE) as phase change material (PCM) was conducted. It is known that fins enhance the heat transfer within TESu, however, the optimum PCM to fin volume ratio for a particular application is usually unknown. Therefore, this work compares the charging and discharging performances of three rectangular TESu prototypes with 6, 12, and 21 PE to fin volume ratio (P/F) per prototype. The performance comparison was in terms of (1) charging rapidity, (2) heat retention effectiveness, (3) temperature distribution, and (4) the cooking power. It is found that for $6 \leq P/F \leq 21$, charging rapidity decreases with PE/fins ratio. On the other hand, the PE/fin volume ratio of higher than $P/F > 12$ has great influence on heat retention effectiveness, temperature distribution in the TESu, and cooking power. Therefore, $6 < P/F < 12$ strikes a balance between charging rapidity and discharging performance (heat retention time, improved temperature field as well cooking power). However, generalization to TESu for cooking application pends extension of this work to other PCM operated TESu.

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Keywords: Pentaerythritol; fin; thermal energy storage; solar cooker.

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1. Introduction

Storing heat for later cooking is widely applied in solar cookers to afford off-sun as well as indoor cooking. The recent reviews [1-4] show that solar cookers with thermal energy storage units (TESu) are capable of storing sensible or combination of sensible and latent heat for off-sun cooking. However, latent TESu are preferred because of their high energy density and capability of operating at narrowly constant temperature during the discharge of latent heat [5, 6]. Nevertheless, the phase change materials (PCM) responsible for storing latent heat basically have low thermal conductivity [7]. Therefore, heat transfer enhancements are essential for rapid charging and discharging of the latent heat storage units.

Agyenim et al. [8] reported that the technique of using fins as the heat transfer mechanism in addition to application of cylindrical and rectangular PCM containers are the most common in latent TESu. In addition, it is known that fins enhance thermal conductivity of the PCM, but their inclusion in latent TESu requires a cut off PCM to volume ratio otherwise more fins would just reduce the amount of PCM in the storage. Despite this, the previous studies on solar cookers with finned TESu [9-11] did not investigate the effects of the number of fins on the cooking performance. Moreover, all the PCM employed were organic with phase change temperature, $\Delta_p T$ < 120 °C. This implied that latent heat was utilized for cooking at temperatures below 120 °C, which are low for faster cooking and frying of foods where temperature above 150 °C are involved [12]. Therefore, the quest for determining the influence of fins on cooking performance and utilization of PCM with $\Delta_p T$ > 150 °C is of huge interest.

Sugar alcohols are among the organic PCM with $\Delta_p T$ > 150 °C and substantial phase change enthalpies [6]. In particular, Waschull et al. [13] listed mannitol, pentaerythritol and galactitol as sugar alcohols with $\Delta_p T$ > 150 °C and specific change phase enthalpy, $\Delta_p h$ >150 J/g. Nonetheless, Solé et al. [14] and John et al. [15], correspondingly, showed that mannitol and galactitol are of little application importance especially in the applications where numerous thermal cycles are required. Pentaerythritol (PE), however, has small degree of subcooling [16] and was implicitly shown to be thermal cyclically stable for over 500 thermal cycles [17], which are essential attributes for applications such as cooking. Therefore, (PE) was the choice PCM in this study.

It was against this background that the aim of this study was to experimentally find out the effect of PE to fin volume ratio (P/F) on the charging and discharging performance of TESu that used PE to store sensible and latent heat for cooking at 150-200 °C. Specifically, the study sought the knowledge on whether increased number of fins consistently improves charging rapidity, heat retention effectiveness, temperature distribution within the TESu, and cooking power.

2. Methodology

2.1. Description of the TESu prototype

Figure 1 depicts the optical images and drawings that describe the TESu studied in this work. The unit was constructed from aluminium and had overall length, width, and height of 181, 160, and 107 mm, respectively. The uncertainty in the length measurement was ±0.5 mm and thus the inner volume of the aluminium container was (2.3 ± 0.2) x 10^{-3} m^3. Four heating elements (each 300 W and Ø8 mm) were inserted into a top plate of 20 mm thickness with thermal grease (80 % copper, 195 W/m/K thermal conductivity, and heat resistance up to 1000 °C) applied on the contact surfaces to reduce contact resistance. Fins were attached to base of the top plate by means of 5 mm tongue and groove joints. The fin dimensions were 144 x 80 x 1.5 mm. The container's volume was filled with fins and Pentaerythritol (98 % assay) purchased from Sigma Aldrich in Germany. The 12 thermocouples were inserted to monitor temperature on a vertical plane 40 mm from the front inner wall as shown in Figure 1(c) and the scheme of their spatial distribution are shown in Figure 1(d). Additionally, three thermocouples on a vertical plane 40mm from the back wall were positioned symmetrically to TC7, TC8, and TC9. Furthermore, the knowledge that the orthogonally intersected non-diagonal midplanes divides the rectangular container into four symmetrical quadrants, the temperature data in the first quadrant (TC1-9) were used in the analyses while the temperatures obtained from TC10-12 and the back thermocouples were used to check the symmetry of the temperature field in the container

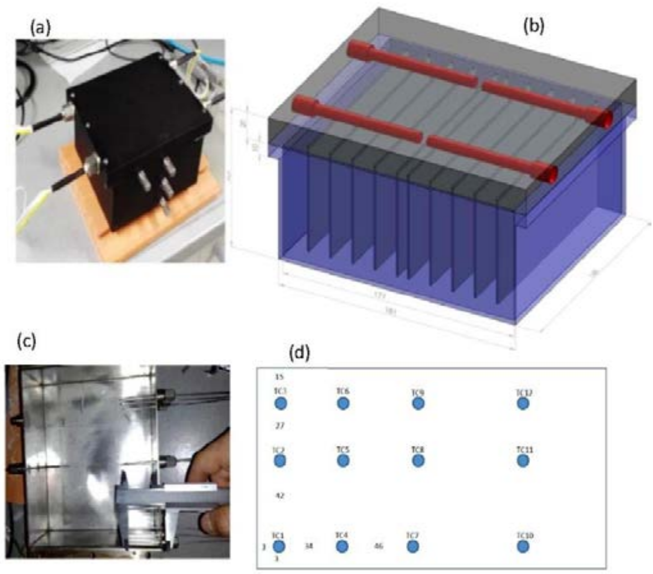

Fig. 1. Description of the thermal storage unit (TESu). (a) An optical image of the assembled TESu,(b) Transparent drawing showing aluminium container (blue), aluminium top plate (black), heating elements (red) and the fins inside the container, (c) an optical image showing location of thermocouples on a vertical plane 40 mm from the inner wall, and (d) schematic of the location of thermal couples TC1-12 on the vertical plane. The numbers placed between the thermal couples indicates the distance of separation in mm.

2.2. Experimental setup

The experiment was designed such that the performance of three TESu models with varying number of fins that corresponded to PE-to-fin volume ratios (P/F) of 6, 12, and 21 were compared. The TESu insulated with Rockwool was placed in 775 x 375 x 320 mm aluminium box. As per manufacture's datasheet, the values of Rockwool's thermal conductivity at 220 °C and heat resistance temperature were 0.064 W/m/K and 800 °C respectively. The ENDA ET2011 PID Temperature Controller - in ON/OFF mode – regulated the surface temperature of the heaters to 220 °C as well as sensed the active time of the heaters. Furthermore, the distribution box regulated the signal of the heater-adjuster to ensure that each heating element dissipated equal amount of heat. On the other hand, during both charging and discharging operations, K-type thermocouples sensed temperatures at the locations described in Figure 1. The data acquisition card read these sensed data at 1 s interval and with precisions of ±0.00005 °C and ±0.0005 s for temperature and active time of the heaters respectively. However, whenever a pot of water was placed on the TESu, the average water temperature was sampled every 60 s. Subsequently, LabView software assisted in the logging of these data into a computer.

2.3. Performance evaluation

Four performance indicators namely charging rapidity, heat retention effectiveness, temperature distribution, and cooking power were used to analyze the effect of P/F on the performance of TESu. The time (t_c) taken to raise the temperature of PE from 50 °C to a steady state temperature within the regulated upper temperature of 220 °C was used to determine the charging rapidity. Whereas the time (t_r) taken for PE temperature of an unloaded TESu to fall from upper end temperature (around 220 °C) to 150 °C was used to evaluate the heat retention effectiveness that is how good was the TESu in storing heat in its idle state. However, the P/F of 6, 12, and 21 entailed PE mass of 1.625, 1.670, and 1.742 kg in the corresponding TESu. The difference in mass of PE had an influence on charging rapidity and heat retention effectiveness. To eliminate this effect, charging rapidity (t_c) and heat retention effectiveness (t_r) were normalized to the mass of PE in the TESu. Moreover, t_r was further explored by loading a pot filled with 1 kg of water onto the TESu after 1, 2, 3, and 4 h form the time charging was terminated and TESu reached full state of charge. Then durations for which the TESu sustained the water boiling were compared.

It is known from the fundamentals of heat transfer that temperature fields within the TESu influences the charging and discharging performance. Therefore, the influence of P/F on the temperature distribution patterns on a vertical plane was determined from a degree of vertical (e.g. variation of TC7, TC8, and TC9) and lateral (e.g. variations of TC1, TC4, and TC7) temperature variations. Furthermore, cooking powers were evaluated using a 4 step procedure modified from cooking power estimation procedure reported in Park [18] and outlined as follows.

1. Calculating the cooking power (P_c) for every 60 s interval using P_c=6.9.77ΔT_w where ΔT_w is the change of water temperature in that interval and 69.77 is the output of mc_p/t for which mass of water (m) is 1 kg, specific heat capacity of water (c_p) is 4186 J/kg/°C, and time interval (t) is 60 s.
2. Calculating the temperature difference (T_w-T_a) between the average temperature of water (T_w) and average ambient temperature (T_a) per time interval. To avoid the negative (T_w-T_a) and effects of evaporation as water approaches boiling, the T_w in 40 -90 °C range were used.
3. Using linear regression method, the coefficient of determination (R^2) was determines and the data was linearly fitted only when R^2 > 0.75 and data points >30 were met.
4. The cooking powers at (T_w-T_a) = 50 °C were calculated from the best fit lines and later used in the analysis of the influence of P/F on cooking power.

2.4. Error analysis

The systematic errors arising from the measuring instruments were minimized by calibrating or checking the conformance of the measuring instrument to the standards. However, the uncertainty of the measured value was taken as the precisions of the measuring instruments. Therefore, the uncertainties of the evaluated t_c, t_r, P_c, and (T_w-T_a) were calculated using the formulations of summation and multiplication error propagations found in Taylor [19]. In addition, all in text measured or calculated values are given to four significant figures to indicate implicitly the least precision that could be obtained.

3. Results and discussion

3.1. The charging performance

The evaluated t_c in h/kg for each of the three TESu models are presented in Table 1 from which it is seen that t_c decreased with P/F. Moreover, the change of t_c with respect to change of P/F shows a more positive linear relationship between P/F and t_c.

Furthermore, Figure 2 presents instantaneous temperature readings of TC1-9 for a fully charged TESu from which it is found that temperature decreased from the top to bottom walls and laterally outwards from the middle vertical plane. Besides, the degrees of both vertical and horizontal temperature variations decreased with P/F. However, varying P/F showed trivial influence on the temperatures at locations < 42mm from the top wall (TC2, 3, 5, 6, 8, and 9). Therefore, employing vertical fins as means of facilitating charging in a top wall charged pentaerythritol based TESu that are at most 42 mm deep may not improve charging performance.

Table 1: The charging time (t_c) relative to the mass of PE for thermal storage units with varying PE to fin volume ratios (P/F).

P/F	t_c [h/kg]	Δtc/Δ(P/F)
6	0.541 ±0.003	
12	1.200 ±0.005	0.11
21	2.430 ±0.007	0.14

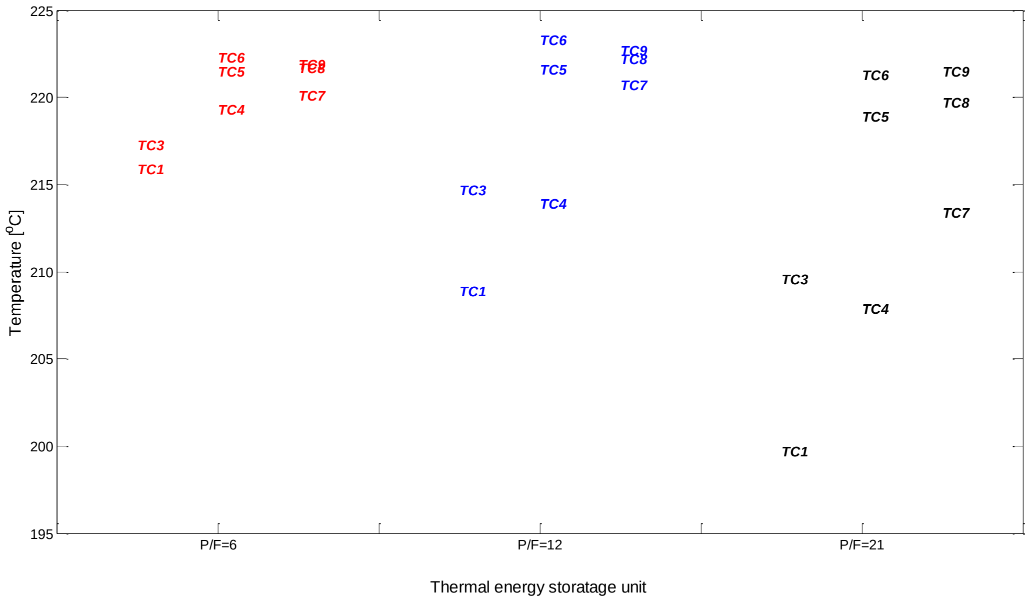

Fig. 2. The temperature distribution on a vertical plane 40mm from the inner sidewall of the fully charged thermal storage units with varying PE to fin volume ratios (P/F). A thermocouple TC2 malfunctioned and hence its reading is not displayed in the figure.

Nevertheless, as long as the TESu was charged from the top wall, temperature was expected to decrease vertically downwards and laterally outwards. Therefore, the trend of the temperature distribution shown in Figure 3 holds true for the entire charging cycle and thus degree of temperature variations decreased with P/F. This explains the effect of P/F on t_c because the level of charge directly links to the degree of temperature variation within the TESu. Therefore, there is a strong positive correlation between P/F and t_c as well as the degree of temperature variations within the TESu. This is in agreement with the obvious phenomenon that increasing the volume of high thermal conductive material in the TESu improves effective conductivity and uniformity of the temperature field within the storage unit. However, it is also obvious that making the volume of the fins as large as possible can defeat the purpose of storing the latent heat. Therefore, judgement of P/F cut point depends on the effect of P/F on discharging performance.

3.2. Discharging performance

As the fully charged and unloaded TESu was cooling to 150 °C, heat loss to the surrounding environment as well as entropy generation within the TESu contributed to the fall of temperature. Nevertheless, as observed in Figure 2, TESu with P/F of 21 and 6 correspondingly exhibited the widest and narrowest temperature variations. Therefore, the highest entropy generation and heat loss to the environment respectively occurred in TESu with P/F of 21 and 6. On the other hand, temperature distribution of TESu with P/F of 12 was intermediate but closer to that P/F 6 and thus its entropy generation was far much smaller than that of P/F 21. These explain the results given in Table 2 where it is shown that heat retention time t_r decreased with an increasing P/F and that a P/F > 12 sharply influenced t_r. It is therefore deduced that entropy generation contributed to temperature drop more than the heat loss to the surrounding environment did. As such, heat retention effectiveness was poor in the TESu with P/F of 21 because the stored heat was available for discharge at a lower temperature than its P/F 6 and 12 counterparts. This had an effect on the amount of energy delivered to the cooking load as Figure 3 portrays.

Table 2: The heat retention time (t_r) relative to the mass of PE for thermal storage units with varying PE to fin volume ratio (P/F).

P/F	t_r [h/kg]	$\Delta t_r/\Delta$(P/F)
6	5.860 ±0.012	
12	5.640 ±0.012	-0.04
21	4.320 ±0.010	-0.15

When the TESu was loaded at 1, 2, 3 or 4 h from the time it was fully charged, TESu with P/F of 6 and 12 sustained the water boiling for comparable durations which were consistently higher than those of P/F=21. When the TESu was loaded at 3 or 4 h from the time of full state of charge, the temperatures in TESu of P/F = 21 were too low to sustain the water boiling. On the other hand, TESu of P/F 6 and 12 sustained water boiling for comparable durations because their temperature distributions during the cooking tests were similar. See Figure 4. The interquartile range is the same for all models, implying that half of the time the temperatures stayed within the same temperature range. However, the temperatures of the P/F=21 were lower as shown by 25 and 75th percentile. Moreover, the narrower 3rd quartile of 6 and 12 P/F indicates that 25 % of the time was spent in the 177 to 182 °C range that coincides with solidification temperature range of the PE. Thus discharging of stored latent heat to the cooking load was more pronounced in 6 and 12 than in 21 P/F where entropy generation was greatest. This explains the better performance of 6 and 12 P/F shown in Figure 3. In overview, it found that during discharging of finned pentaerythritol based TESu, P/F >12 has a great influence on both heat retention effectiveness and the temperature distribution.

Furthermore, Figure 5 shows how the cooking power decreased the difference between water (T_w) and ambient (T_a) temperatures. The linear regression is satisfactory because data samples and coefficient of determination R^2 exceeded the minimum values recommended in Park [18]. The cooking powers evaluated at (T_w- T_a) = 50 increased as P/F decreased. Increasing the P/F of 6 by 100 % only yielded a 4 % decrease in cooking power while increasing P/F of 12 by 75 % yielded a 20 % decrease in cooking power. Therefore, P/F >12 has great influence on cooking power.

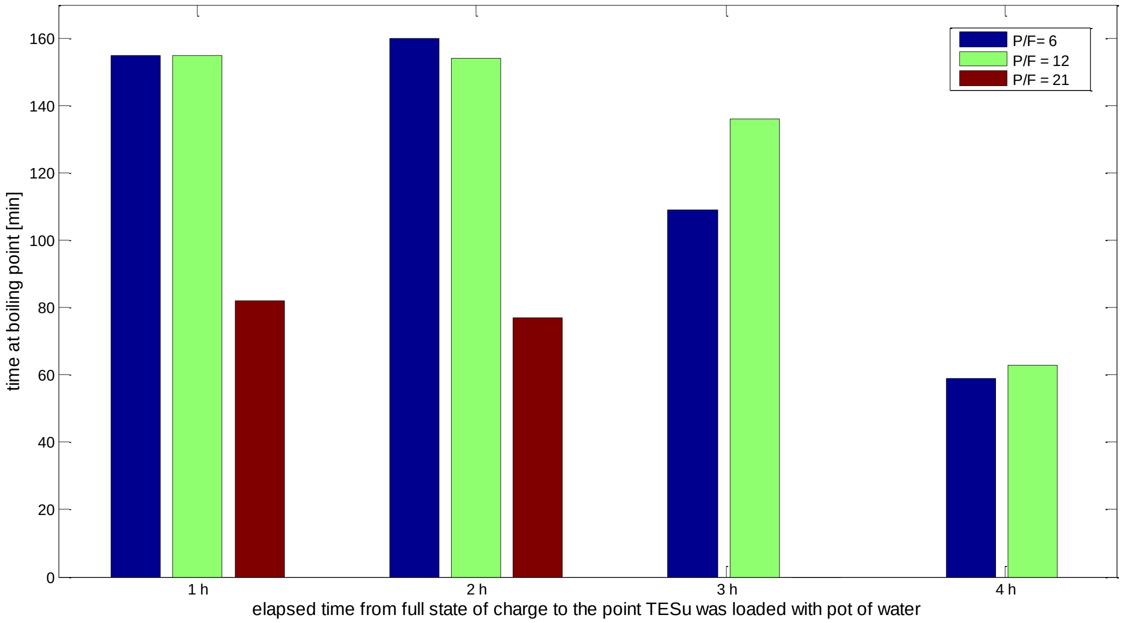

Fig. 3. Durations that the TESu with P/F of 6, 12, and 21 sustained water boiling when the TESu were loaded at 1, 2, 3, and 4 h from the time it was fully charged.

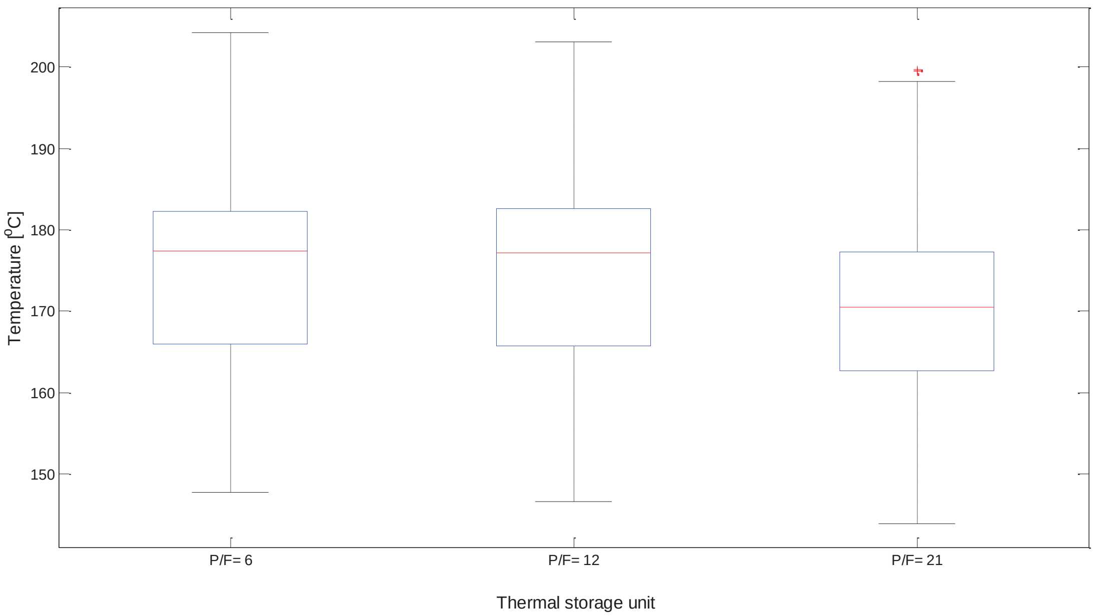

Fig. 4. Distribution of temperature data on a vertical plane from the time a pot of water was loaded on the TESu until the least recorded temperature fell to 150 °C

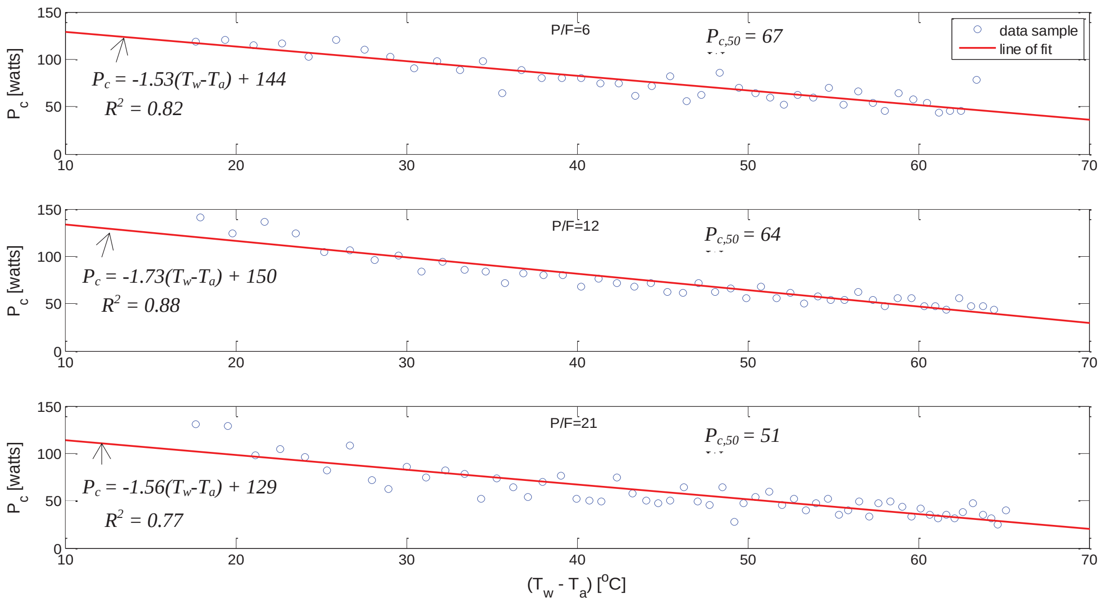

Fig. 5. Variation of cooking power (P_c) with difference between water (T_w) and the ambient (T_a) temperatures. The coefficient of determination (R^2), equation of the line of fit as well as the cooking power ($P_{c,50}$) at (T_w-T_a) = 50 °C for each TESu are shown in the figure.

These analyses suggest that for a finned pentaerythritol based TESu, a P/F <10 offer trivial improvements on discharging performance. On the other hand, it appears that P/F <5 may still offer better charging performance at the expensing of diminishing the volume for latent heat storage. Therefore, it is contingent that there is an optimum P/F that strikes a balance between charging and discharging performance. For TESu in the current work, a P/F = 12 accorded optimum performance.

4. Conclusions

This work aimed at finding the influence of PE to fins volume ratio on the performance of latent heat storage unit for cooking. Based on the results obtained and analysed in this study, the following conclusions are drawn.

1. Charging rapidity decreases with PE to fins volume ratio and basing on charging rapidity alone, the choice of PE to fin volume ratio that strikes a balance between charging rapidity and amount of stored latent heat is arbitrary.
2. The PE to fin volume ratio that exceeds 12 greatly reduces the discharging performance of the finned pentaerythritol based thermal storage unit.

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