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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