Development of Integrated Solar Water Heater Using Phase Change Material

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Abstract. Main barriers for installation of conventional solar water heating system (SWHS) are requirement of large installation area and heavy weight of the heat storage tank consisting water. A storage tank with minimum capacity of 230 liters are needed for household usage and this tank when empty can weigh up to 100 kg while a filled tank could weigh up to 400 kg. In reality, installation of this conventional system require more space and heavy structural support on the roof, which is not available in most houses. As a solution, a form stable light harvesting phase change material (FSLHPCM) integrated compact system is proposed. This new SWHS consists of glass – topped collector cum storage tank filled with FSLHPCM. This new FSLHPCM is form stable, does not leak and exhibit stable latent heat when tested to 1000 thermal cycles. It is capable to not only store heat but can improve the collector efficiency by harvesting the visible light and converting it to heat. The additional light to heat conversion efficiency was 22%. In the new system a maximum 75 liters’ glass-topped collector tank is sufficient to substitute a 230-liter tank. This will reduce installation, renovation and maintenance costs for the SWHS.

1 Introduction

According to statistics residential energy usage for hot water supply accounts for 26% of total residential energy usage in Australia [1], 18.3 % in USA [2] and 28.1% in Japan [3]. In most countries electrical water heaters and stove heating remain as main sources of hot water supply. Both of these system relies heavily in burning of fossil fuels which leads to CO2 emissions. Application of solar water heater system (SWHS) can reduce the reliance on fusil fuel based water heating and results in lower emission of CO2 into the environment. The current commercially available SWHS is proven to be able to reduce residential energy consumption for water heating between 50-85% [4]. Despite all these economic and environmental benefits, in reality the installation of SWHS even in well developed nations are far below expectation. In 2104 only 13% of households in Australia installed SWHS [5], 22% in Turkey as for 2016 [9] and 4% in Taiwan as for 2011 [10]. This is due to long payback period. A payback period of 7 years in Jordan [13], 9.2 years in Hong Kong for centralized SWHS in high rise building [6], 6 years for galvanized steel SWHS in Pakistan

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[7] and 8 years in Brazil after 5.5 % discount in installation cost by government had been reported [8]. The long payback period are mainly contributed by the initial capital cost of SWHS installation related to the building architecture required to support this system. To overcome this problem over the past two decades latent heat storage (LHS) using phase change material (PCM) had been extensively studied. LHS is used in SWHS to reduce the size of storage tank and enhance the performance and reliability of thermal storage system by extending its operational time [9]. A shorter payback period, less initial setup cost and more efficiency is expected from application of PCM.

2 Methodology

2.1 Materials

PMMA (molecular weight = 120, 000 kg/mol) was purchased from Sigma-Aldrich (M) Sdn. Bhd. (Subang Jaya, Malaysia). MA (purity ≥ 98%) and chloroform (stabilized with 0.6-1.0% ethanol) were supplied by Evergreen Engineering & Resources Sdn. Bhd. (Semenyih, Malaysia). NBR (total solid content of 44.70%) was obtained from Synthomer Sdn. Bhd. (Kluang, Malaysia). PA (total solid content of 36.35%) was synthesized in Universiti Tunku Abdul Rahman (UTAR) (Kampar, Malaysia). RGO was synthesized by oxidizing graphite nanofiber via conventional Hummer’s method [10] followed by reduction using hydrazine hydrate [11].

2.2 Preparation of RGO-PARB/MA tablet

RGO was mixed with Triton X-100 (dispersing agent) before blending with the PA coating solution. The solution was stirred for 1 h to obtain a homogenous blend. MA powder was compressed into a tablet using hydraulic press model E-Z Press™ supplied by International Crystal Laboratories, USA at the pressure of 4000 psi. The pressed MA tablet was then coated with NBR followed by a PA coating solution blended with RGO. For each layer of coating, the MA tablet was immersed in the coating solution for five seconds. After that, MA tablet was taken out and dried at room temperature for 4 days. The steps were then repeated with the same tablet being flipped upside down. RGO-PARB/MA tablets were prepared in 0, 0.5, 1.0, 1.5 and 2.0 wt% loading of RGO.

2.3 Testings

For outdoor solar energy conversion and storage efficiency measurement, RGO-PARB/MA tablets with different RGO loading were placed on a polystyrene sheet and covered with an acrylic transparent box as illustrated in Fig. 1. A pyranometer, model CMP3 supplied by Kipp & Zonen, Netherlands was used to measure the solar irradiance. Temperatures of the composite samples were recorded using thermocouples connected to the data logger, model GL820 supplied by Graphtec, Tokyo, Japan. The obtained solar energy conversion efficiency was used to calculate the size of the intergrated system.
Thermal cyclic test was carried out using a thermal cyclic system designed by the University of Malaya to determine the thermal reliability of FSPCMs over a period. In each thermal cycle, the tablet samples were put into a sample holder and heated from 30 to 80 °C and then the samples were let to cool to room temperature. This procedure was repeated for 1000 cycles. Each cycle represents a day of heat gain and heat release.

3 Results and Discussions

Compared with pure PANBR/MA pellet (0.0 wt% RGO), the temperature of all RGO-PANBR/MA pellet rapidly increased upon sunlight irradiation. This is because RGO in PANBR coating absorb sunlight and transform it into heat through non-radiation thermal decay. Similar finding was reported by Tang et al. who used dye as light absorptive material on PCM (Tang et al., 2016). Fig. 2 shows that 1.5 wt% RGO-PANBR/MA pellet had higher temperature (61.1 °C) than pure PANBR/MA pellet (55.2 °C) after exposing to sunlight for 8000 seconds. An increment of 10.69% in temperature was recorded.

The total heat energy stored in RGO-PANBR/MA pellet with different RGO loading is shown in Fig.3. The total stored heat energy is calculated over the period of 3 sunny days. The RGO-PANBR/MA pellet with 1.5 wt% RGO loading stored the highest amount of heat energy among the pellets: 49 wt% higher than the PANBR/MA pellet without RGO. The total stored heat energy was lower when the RGO loading is further increased to 2.0 wt%. This is because RGO is agglomerate at 2.0 wt% loading and thus reduce the effective surface area for sunlight absorption.
Solar energy conversion efficiency for RGO-PANBR/MA pellets with different loading is shown in Fig. 4. The efficiency is dependent on the solar energy absorbed by the top surface as well as heat loss to the environment which is mainly affected by the difference between the pellet temperature and the temperature inside the PMMA container. All pellets absorb the same amount of solar energy on their top surfaces. However, the heat loss is the same at the beginning of the experiment on each day, but the hotter pellets has significantly higher heat losses than the colder pellets after a short period of time. Therefore, to make a fair comparison of the solar energy conversion efficiency of all the pellets, only the results from the first 20 minutes are used in the calculation when the temperature difference is less than 5°C. The result shows that the 1.5 wt% RGO-PANBR/MA pellet had the highest solar energy conversion efficiency which was 21%. This is because 1.5 wt% RGO-PANBR/MA has the highest loading of RGO before RGO start to aggregate.
Fig. 4: Solar Energy Conversion Efficiency of RGO-PANBR/MA Pellets with Various Loading

Based on the energy conversion efficiency the tank size was calculated as following:

Total solar irradiation is;

\[ \frac{4.5 \text{ kWh}}{\text{m}^2} = \frac{16200 \text{ kJ}}{\text{m}^2} \]  
(1)

Sunlight to heat average conversion efficiency obtained = 22% from Fig.4

Daily hot water consumption for 4 person in a household is estimated as

\[ V_w = 4 \times 5 \left( \frac{1}{\text{min}} \right) \times 10 \text{ (min)} \]
\[ = 200 \text{ l} \]  
(2)

\[ C_p \text{ of water} = \frac{4.2 \text{ kJ}}{\text{kg} \cdot \text{C}} \]  
(3)

Required hot water temperature = 40°C

Inlet/cold water temperature = 22°C

Latent heat of FSLHPCM = 125 kJ/kg

Energy required to heat the water

\[ Q_w = 200(\text{kg}) \times 4.2 \left( \frac{\text{kJ}}{\text{kg}} \right) \times 18\text{C} \]
\[ = 15120 \text{ kJ} \]  
(4)
Surface area of the proposed prototype based on the conversion efficiency:

\[
A_c = \frac{19120 \text{ kJ}}{18200 \text{ kJ/m}^2 \times 0.22} = 4.2 \text{ m}^2
\]  

(5)

Thus it will be fixed to 4 m²

From the energy point of view, the required amount of FSLHPCM will be:

\[
\text{Mass of FSLHPCM} = \frac{0.22 \times 16200 \text{ kJ/m}^2}{125 \text{ kJ/kg}} \times 4 \text{ m}^2
\]

\[
= 114 \text{ kg}
\]  

(6)

From the point of view of design of the system as shown in Fig. 5.

![Design of the integrated system](image)

Fig.5: Design of the integrated system

The tank will have array of copper pipes (10 coils) = 13 mm OD x 10 m long
The volume of the pipes will be 0.0013 m³
Height of the tank is fixed to 50 mm (PCM filled up to 40 mm and 10 mm allowance)
l x w x h of the tank will then be: 2 m x 2 m x 0.04 m

The volume of FSLHPCM will then be: (volume of the filled tank) – (volume of pipe)

\[
= (0.16 \text{ m}^3 - 0.0013 \text{ m}^3)
\]

\[
= 0.1587 \text{ m}^3
\]

(7)

Density of FSLHPCM: 860 kg/m³
Mass of FSLHPCM required;

\[
0.1587 \text{ m}^3 \times 860 \frac{\text{kg}}{\text{m}^3}
\]

\[
= 136 \text{ kg}
\]  

(8)
Thus the mass based on the design is sufficient to store the energy required. The minimum mass of FSLHPCM required is only 114 kg.

**Total weight of the conventional system for a household of four:**

Sensible heat storage water tank (270 liter tank) = 400 kg
Collector panel: 50 kg
Total weight: 450 kg

**Total weight for the integrated system:**

Weight of insulated aluminum tank: 20 kg
Weight of FSLHPCM: 136 kg
Weight of PMMA panel: 5 kg
Total weight: 161 kg (latent heat storage thus there are no water storage and no collector panel)

Weight reduction percentage:

\[
\frac{450 - 161}{450} \times 100 = 64\%
\]

(9)

**4 Conclusion**

FSLHPCM filled system was found to be effective in reducing the weight of SWHS by 64%. The reduction in term of weight of the system is caused by high latent heat storage capacity of the FSLHPCM compared to water and additional light to heat conversion efficiency by 22%. The capability to reduce the weight of the SWHS will encourage the installation of SWHS in many households.

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