Development of Low-Cost Solar Water Heater Using Recycled Solid Waste for Domestic Hot Water Supply

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Abstract. This research is focused on the development of a low-cost solar water heater (SWH) system by utilizing solid waste material as part of system elements. Available technologies of the solar water heater systems, heat collectors and its components were reviewed and the best system combinations for low cost design were chosen. The passive-thermosiphon system have been chosen due to its simplicity and independency on external power as well as conventional pump. For the heat collector, flat plate type was identified as the most suitable collector for low cost design and suits with Malaysia climate. Detail study on the flat plate collector components found that the heat absorber is the main component that can significantly reduce the solar collector price if it is replaced with recycled solid waste material. Review on common solid wastes concluded that crushed glass is a non-metal material that has potential to either enhance or become the main heat absorber in solar collector. A collector prototype were then designed and fabricated based on crashed glass heat collector media. Thermal performance test were conducted for three configurations where configuration A (black painted aluminum absorber) used as benchmark, configuration B (crushed glass added partially) that use glass for improvement, and lastly configuration C (black colored crushed glass) that use colored glass as main absorber. Result for configuration B have shown a negative effect where the maximum collector efficiency is 26.8% lower than configuration A. Nevertheless, configuration C which use black crushed glass as main heat absorber shown a comparable maximum efficiency which is at 82.5% of the maximum efficiency for configuration A and furthermore have shown quite impressive increment of efficiency at the end of the experiment. Hence, black colored crushed glass is said to have quite a good potential as the heat absorber material and therefore turn out to be a new contender to other non-metal heat absorber such as plastic and rubber.

Keywords: Low cost heater, domestic hot water, recycled solid waste, crashed glass

1 Introduction

Currently, most of houses in Malaysia is using the “instantaneous” or “tankless” electric water heater type. As the name implies, this type of water heater does not require storage tank thus eliminates energy losses at the tank. Theoretically, this type of system is also enables an unlimited hot water supply. In addition to that, by detecting the water flow through the valve, it will ensure that this system is only works “on demand” as the heating device of the instant water heater is only operates when the hot water is in used [1]. This mechanism delivers another advantage of saving electricity through the elimination of unnecessary heating as it doesn’t require for the system to maintain the hot water temperature inside a storage tank. Basic construction of the electric tankless water heater can be seen in Figure 1.

Nevertheless, despite of these advantageous, “tankless” water heater consume quite a vast amount of electrical energy. Typical types of electric water heater that is used in Malaysia consume power of 3 kW and above, hence a simple calculation of constant use of an hour per day will contribute a minimum 90 kWh of monthly electrical consumption.

Figure 1: Example of Electric Water Heater System (Air & Water, 2015).

Electric water heater draws more instantaneous power at a time in order for the water to be heated quickly, hence the operational cost will be much expensive if the demand charge is introduce by the electric utility company [2]. In Malaysia currently, luckily the maximum demand charge set by Tenaga Nasional Berhad (TNB) is only applicable for commercial customer with a supply of 6.6 kV and above and does

not include the residential area [3]. Though, there is no guarantee that this tariff will remain as it is, especially when the trend of the energy pricing is increasing. Hence, for a long term benefits, a more sustainable and more economic technology such as solar water heater need to be promoted.

Principally, in determining the value of energy generated by RE system, there are two most critical factors that come into consideration which are the initial cost of the installation and the amount of energy that can be produced by the system annually [4]. Therefore, in the direction of increasing the awareness and promoting the use of green technology, it is very important to ensure that the technology is affordable for everyone.

Although the technology of the SWH system is readily available in Malaysia for a long time, the awareness on its existence and benefits is still very low mainly due to the high cost of this technology. Despite the promising annual solar irradiance in Malaysia which resulting an impressive annual saving up to RM 704 of the energy cost with a payback period of 7.4 to 10.7 years, the high initial installation cost of the solar water have made most of people in Malaysia prefer to choose electric water heater as the installation cost is very much lower in comparison with SWH [5]. Therefore, the idea for this project is to initiate the development of an affordable solar water heater by selecting a system types with a good potential of cost reduction. This will be done through the utilization of recycled solid waste as a material for its heat absorbing component.

In general, the municipal solid waste (MSW) comes from six typical sources which are residential, institutional, industrial, commercial, agricultural, and municipal services [6]. The most common method in organizing solid waste in Malaysia is through the landfill. Current numbers of landfills in Malaysia are listed in Table 1.

In Malaysia, it is reported that the generation of municipal solid waste is at approximately 30,000 tonnes for each day, or more than 11 million tonnes per year which has increased for about 60% for the last 10 years and 170% from the last 30 years [7]. As a consequence, vast amount of solid waste can cause shortage of the landfill, as the rate of the solid waste generation is much faster than the natural degradation process.

Furthermore, there are also environmental issues that will come up such as surface and ground water contamination, health hazard, bad odours and so on as most of the landfills in Malaysia are crude dumping grounds [8].

Table 1: Number of Operating and Terminated Solid Waste Landfill by State until 31 March 2015

State	Operating Landfill	Terminated Landfill	Total
Johor	14	23	37
Kedah	8	7	15
Kelantan	13	6	19
Melaka	2	5	7
Negeri Sembilan	7	11	18
Pahang	16	16	32
Perak	17	12	29
Perlis	1	1	2
P. Pinang	2	1	3
Sabah	19	2	21
Serawak	49	14	63
Selangor	8	14	22
Tergganu	8	12	20
Kuala Lumpur	0	7	7
Labuan	1	0	1
Total	165	131	296

Therefore, in order to reduce the environmental impact and creating a more sustainable society, good waste management practices need to take place and one of the ways is by promoting the 3R which stands for reduce, reuse, and recycle [9]. Hence, the aim of this project is to reutilize the solid waste from a worthless item to become a valuable and cost effective product which is the solar water heater, hence converting “waste” to become “wealth”.

The objectives of this research are:

- i. To conduct a review on recent technologies available for SWH systems and select a system that have potential for low-cost production.
- ii. To identify which components in the selected SWH system that have potential for significant cost reduction.
- iii. To identify the best solid waste material that can be used to build the selected component by performing experimental analysis to see its performance.

2 Theoretical Analysis

Fundamentally, in order to successfully design an efficient solar water heater, it is essential to understand the basic concept of the heat transfer. In thermodynamic knowledge, the interest is on the amount of heat that is transferred. On the other hand, in

heat transfer study the concern is more towards the rate of the heat transfer. There are three basic ways on how heat can be transferred which are conduction, convection and radiation. Conduction is a way of energy transfer from particles of a material that are more energetic to the adjacent less energetic particles by interacting each other's, and it can occur in solids, liquids or gasses. Convection on the other hand is a mean of heat transfer through the interaction that occurs between solid surface and moving fluid or gas which also involves conduction and fluid motion. Heat can also be transferred by radiation where the energy can be emitted through the electromagnetic waves form due to the alteration occurred to the atoms or molecules electronic configurations [10]. The basic equation for each of these mechanisms is as in mathematical models below.

2.1 Mathematical Model of the Solar Collector.

By taking the glazing transmittance (τ) and absorptivity (α) of the absorber plate into consideration, the rate of heat gain by the receiver $\dot{Q}_r$ is given as follows (Robert Foster, Majid Ghassemi, 2009):

$$\dot{Q}_r = \dot{q}_r A_c = (\tau\alpha)_{eff} I_T A_c \dots\dots\dots (1)$$

Where,

$\dot{q}_r$ = heat flux gain by the receiver,

A_c = collector aperture area,

$(\tau\alpha)_{eff}$ = effective optical fraction of energy absorbed,

I_T = incident radiation fof tilted solar collector.

Not all of the heat energy can be transferred to the working fluid. There are some heat loss occurred mainly through convection and radiation. The amount of heat loss by convection $\dot{Q}_{conv}$ is determined as below:

$$\dot{Q}_{conv} = \dot{q}_{conv} A_r = U A_r (T_r - T_a) \dots\dots\dots (2)$$

Where,

$\dot{q}_{conv}$ = heat flux loss by convection,

A_r = receiver's area,

T_r = receiver's temperature,

T_a = ambient's temperature,

U = overall heat coefficient.

The heat loss by radiation $\dot{Q}_{rad}$ is determined as below:

$$\dot{Q}_{rad} = \dot{q}_{rad} A_r = \varepsilon_{eff} \sigma A_r (T_r^4 - T_a^4) \dots\dots\dots (3)$$

Where,

$\dot{q}_{rad}$ = heat flux loss by radiation,

A_r = receiver's area,

ε_{eff} = effective emissivity of the collector,

$$\sigma = \text{Steffan Boltzmann constant} \\ = 5.67 \times 10^{-8} \text{ (W/m}^2 \cdot \text{K}^{-4}\text{)}.$$

By subtracting the rate of heat loss from the heat gain, we can get the useful energy collected, $\dot{Q}_u$ as follows:

$$\dot{Q}_u(t) = \dot{q}_u A_c = (\tau\alpha)_{eff} I_T A_c - U A_r (T_r - T_a) - \varepsilon_{eff} \sigma A_r (T_r^4 - T_a^4) \dots\dots\dots (4)$$

The thermal efficiency, η with respect to the useful heat collected and the incoming solar radiation at a particular moment are calculated as follows:

$$\eta = \frac{\dot{Q}_u}{I_T A_c} = (\tau\alpha)_{eff} - \frac{U A_r}{I_T A_c} (T_r - T_a) - \frac{\varepsilon_{eff} \sigma A_r}{I_T A_c} (T_r^4 - T_a^4) \dots\dots\dots (5)$$

Hence, the overall efficiency within a time frame are determined as:

$$\eta = \frac{\int_{t_1}^{t_2} \dot{Q}_u dt}{A_c \int_{t_1}^{t_2} I_T dt} \dots\dots\dots (6)$$

The heat loss due to radiation are relatively smaller than convection especially for a low temperature collector such as flat plate type hence it can be neglected:

$$\eta = \frac{\dot{Q}_u}{I_T A_c} = (\tau\alpha)_{eff} - \frac{U A_r}{I_T A_c} (T_r - T_a) \dots\dots\dots (7)$$

As the temperature of the receiver, T_r is hard to be measured as it is located inside the collector casing, a constant named as effectiveness removal factor, F_R is use to allow equation to be in the terms of inlet temperature, T_{in} of the working fluid:

$$\eta = F_R \left[(\tau\alpha)_{eff} - \frac{U A_r}{I_T A_c} (T_{in} - T_a) \right] \dots\dots\dots (8)$$

The useful energy collected therefore can be written as below:

$$\dot{Q}_u = \eta I_T A_c = I_T A_c F_R \left[(\tau\alpha)_{eff} - \frac{U A_r (T_{in} - T_a)}{I_T A_c} \right] \dots\dots\dots (9)$$

It can also be represented as below:

$$\dot{Q}_u = \dot{m} C_p (T_{out} - T_{in}) \dots\dots\dots (10)$$

Where,

$\dot{m}$ = fluid mass flow rate,

C_p = heat capacity at constant pressure ,

T_{out} = outlet temperature of the working fluid.

T_{in} = inlet temperature of the working fluid.

The last equation can be used to perform thermal testing for the solar collector in order to measure it performance.

2.2 Crushed Glass as Heat Absorber.

The findings from past research indicate [12], among all three solid waste materials of metal, plastic and glass that have potential to be used as material for heat absorbing component in a solar collector, it is found that glass waste is having the least scrap value among others. Glass is also listed among the highest solid wastes composition in Malaysia with 3.3 % as shown in Table 2.

Table 2: Solid Waste Composition In Malaysia for 2012 (KPKT, 2015) [11].

Waste	Percentage
Food waste	44.5
Plastic	13.2
Paper	8.5
Disposable diapers	12.1
Garden waste	5.8
Glass	3.3
Metal	2.7
Textiles	3.1
Tetra Pak	1.6
Rubber	1.8
Leather Goods	0.4
Wood	1.4
Household Hazardous Waste	1.3
Others	0.5
Total	100

It is also found in Table 2 that food waste, plastic, paper, disposal diapers, and garden waste are the top five of the highest solid waste materials in Malaysia. Nevertheless, these materials are either not suit for design or heat insulator material hence they are not suitable to be used as heat absorbing component in solar collector. Plastic material for instance is generally is an insulator, and only few types of plastic can be used as heat absorber but for low temperature collector and it might involve recycling process with advance material technology. Glass is listed as the sixth highest solid waste composition in Malaysia with 3.3 %. Therefore, glass have been chosen in this research due to the following reasons:

- 1) Glass holding quite a great portion of total solid waste composition in Malaysia.
- 2) Crushed glass is a free or a very cheap material.
- 3) Glass recycling facing a lot of challenges and is less worthy. Hence, a more creative solution is needed for glass to be reused for different purpose especially for non-container or mixed crush glass which cannot be recycled.
- 4) To avoid or reduce glass dumping in the landfill as it is non-biodegradable material which will create more environmental issue.

5) As suggested by the research conducted by Din et al.(2015) which shown that glass is among the materials that have shown good heat transfer performance after aluminum, iron and granite.

6) Although the thermal conductivity for glass ($k_{\text{glass}}=1.4$ W/m-K) is relatively very much lower than metals (e.g. $k_{\text{aluminum}} > 100$ W/m-K), it has a higher thermal conductivity than plastic ($k_{\text{plastic}} < 0.5$ W/m-K). Glass also have a lower thermal expansion ($\text{CTE}_{\text{glass}} < 9.0 \times 10^{-6}$ ($^{\circ}\text{C}^{-1}$)) which is better than plastic ($\text{CTE}_{\text{plastics}} > 70 \times 10^{-6}$ ($^{\circ}\text{C}^{-1}$)) (Callister, 1994). Therefore, these thermal advantage shown that glass can compete with plastic in non-metal heat absorber category.

7) There is still no research that have been conducted to see the performance of a solar collector that use glass as it heat absorber or enhancer found in previous literature. Therefore, the prototype that using crashed glass was fabricated and tested in this project to see the performance and efficiency of crushed glass for the development of low cost solar collector.

3 Methodology

In order to answer all of the research questions, a proper arrangement of activities is required. The research process flow was started with the identification of the existing technologies of the solar hot water system that are available in the market. The low cost system with low operation was selected as a “guide system” for this research. It is called the “guide system” as it will only be used as guidance in developing the collector since the scope of this research is to focus on the collector and not the overall system. Next, numbers of collector types were studied and a low cost solar water heater that is suitable for Malaysia climate was selected. Each of the components of the selected collector was studied and the component that can significantly reduce the cost of the collector and have prospect to make use of recycle solid waste was selected. Subsequently, the selected component was studied in detail to know the basic requirement on its material properties and characteristic in order to be able to perform its function. Few solid wastes materials were evaluated and the one that fulfill the basic requirement and have the potential to replace or enhance the efficiency of the selected component was chosen. The following are summary of the selected “guide system”, collector type, component, and solid waste in this research:

1) Guide system	: Passive, Thermosiphon.
2) Collector type	: Flat plate
3) Component	: Heat absorber.
4) Solid waste	: Crushed glass.

The test rig for the above elements with 3 type of configuration A,B and C were brought to the test lab to proceed for the official experiment and the experimental data were recorded. The data were then analyzed and will then be repeated for different

configurations A, B and C which will be explained in details later in this chapter. The experimental setup is as per shown in figure below.

Figure 2: Schematic Diagram for Thermal Performance Test Rig.

Figure 3: Actual Setup of Thermal Performance Test Rig.

Configuration A, B and C are similar set up as the above diagram in Figure 2 with difference in heat absorber materials. Configuration A having Non-Selective Black Painted Aluminum Absorber Plate. Configuration B having Non-Selective Black Aluminum Absorber Plate with crushed Glass as the filler medium. While configuration C having Non-selective Black painted Aluminum Absorber Plate with black crushed glass.

4 Results and Discussion

The results that were obtained from the thermal performance test are presented and discussed. Results from each configuration are delivered separately, then compared to each other, and finally discussed at the end of the research.

By following the measurement procedures that were described in the previous section, the result that have been obtained for the water mass flow rate by manual measurement are as follows:

$$\begin{aligned} \text{Time, } t &= 46.50 \text{ s} \\ \text{Flow Rate, } \dot{V} &= \frac{V}{t} = \frac{250 \text{ ml}}{46.5 \text{ s}} = 0.0054 \text{ l s}^{-1} \\ &= 0.0054 \times 10^{-3} \text{ m}^3 \text{ s}^{-1} \\ \text{Mass Flow Rate, } \dot{m} &= 0.0054 \times 10^{-3} \text{ m}^3 \text{ s}^{-1} \times 1000 \text{ kg m}^{-3} \\ &= 0.0054 \text{ kg s}^{-1} @ 19.44 \text{ kg h}^{-1} \end{aligned}$$

The flowrate which is measured at 19.44 kg h^{-1} , is assumed to be constant for all configuration A,B and C. The water volume inside the tank was set to 20 liters to allow the water to circulate in 2 cycle within 2 hours so that the effect of the temperature rise inside the tank can be seen clearly.

The thermal performance test were then proceeded for each configuration and the data that were measured and recorded every 10 minutes are shown in Figure 4, 5 and 6 in the following section.

4.1. Configuration A: Non-Selective Black Aluminum Absorber Plate

The test data that were measured and recorded for configuration A are summarized and plotted in the following graph in Figure 4.

Figure 4: Graph of The Temperature Result for Configuration A.

Thermal performance test for configuration A were conducted at the noon. The drizzle environment that occurred during that time have caused the ambient temperature a bit fluctuating with a minimum temperature of 26.9°C (minutes of 80) and a maximum temperature of 29.3°C (minutes of 40 and 70). Whereas, for the collector inlet temperature, the minimum temperature occurred at the first 10 minutes with a value of 28.9°C and gradually increase its temperature with time in a nearly linear pattern until it reach the maximum temperature of 48.1°C before the test ended (minutes of 120). The outlet temperature on the other hand have the highest temperature among all with a minimum temperature of 39.3°C (minutes of 10)

and gradually increase until a maximum temperature of 59.1 °C (minutes of 120). The water temperature inside the tank were slightly higher than the inlet temperature with a minimum of 29.7 °C (minutes of 10) and a maximum of 48.4 °C (minutes of 120). The trend of temperature increase for inlet, outlet and water inside tank temperature is quite parallel. The above configuration A only serve as a bench mark to observe the performance of the crushed glass in absorbing heat.

4.2 Configuration B: Non-Selective Black Aluminum Absorber Plate with Crushed Glass.

The test data for configuration B are summarized in Figure 5 below

Figure 5: Graph of The Temperature Result for Configuration B.

For configuration B, the thermal performance test were conducted at 30 minutes pass noon. The ambient temperature is quite steady during the test as it is a sunny day outside with a minimum temperature of 29.2 °C (minutes of 60) and a maximum temperature of 31.3 °C (minutes of 110 and 120). The collector inlet in this configuration shown a steady temperature increase of its temperature with minimum temperature occurred at the first 10 minutes with a value of 28.9 °C and until it reach the maximum temperature of 43.2 °C at the end of the test (minutes of 120). Whereas for the outlet temperature, the temperature rise is quite slow with the minimum value is only at 34.5 °C (minutes of 10), ramp up for the next 10 minutes but almost flat after that. Then after 30 minutes onwards, the temperature was gradually increase until it reach a maximum temperature of 50.4 °C (minutes of 120). As what have been shown in previous test, the water temperature inside the tank temperature were also slightly higher than the inlet temperature with a minimum of 28.8 °C (minutes of 10) and a maximum of 44.0 °C (minutes of 120).

4.3 Configuration C: Non-Selective Black Aluminum Absorber Plate with Black Crushed Glass.

The data for ambient temperature together with water temperature at collector inlet, collector outlet and water tank for configuration C were plotted in Figure 6.

The last thermal performance test is for configuration C which is conducted earlier (morning) than configuration A and B. Hence the ambient temperature a bit fluctuating during the first hour with a minimum temperature of 26.6 °C (minutes of 40) and become more stable after that and reach it maximum temperature of 29.6 °C at the end of experiment (minutes of 120).

Figure 6: Graph of The Temperature Result for Configuration C.

For the collector inlet temperature, the temperature gradually increase where the minimum temperature occurred at the first 10 minutes with a value of 28.2 °C and reach the maximum temperature of 42.7 °C before the test ended (minutes of 120). The outlet temperature have its minimum temperature of 33.7 °C (minutes of 10) and gradually increase until a maximum temperature of 52.6 °C (minutes of 120) which is higher than configuration B. The water temperature inside the tank have a minimum of 28.5 °C (minutes of 10) and have a maximum temperature of 43.3 °C (minutes of 120). The temperature growth in this configuration is quite different from previous configuration especially for outlet temperature.

Based on the equation described in section 3.8, the efficiency data for each configurations were plotted against time in Figure 7.

From the graph in Figure 7, we can see that the highest efficiency is configuration A which is the benchmark in this test.

Figure 7: Graph of the Thermal Efficiency vs Time for Configuration A, B and C.

The efficiency for configuration A is a bit fluctuating with time with the minimum value of 26.1 % at the first 10 minutes of the experiment with no significant rise until after 40 minutes, it start to increase until it reach its highest value at minutes of 60 with 34.3 % efficiency. However, the following value of the efficiencies shown a wavy trend until the experiment ended. For configuration B, the efficiency is very low at the first 10 minutes but ramp up after that until it reach it highest value at minutes of 20 with 25.1 % efficiency. However the trend was not last long where it start to show fall and rise pattern and become worst after 70 minutes where it gradually decrease until the experiment ended. Lastly, configuration C shown almost same efficiency with configuration B for the first 10 minutes but have shown a steady increase after that. Although shown a decrease pattern after 50 minutes, it start to rise again and have shown significant increase after that where the efficiency have reached the value of 28.3% which is much better than configuration B and almost reach the same efficiency of configuration A in the first place.

5 Conclusion

Based on the study on the state-of-the-art technologies of the solar water heater, the passive-thermosiphon system have been identified as the most suitable solar water heater due to its simplicity and no need of external power or conventional pump. This advantage contribute to the reduction of the manufacturing, operating, and maintenance costs respectively. Next, it is also found that flat plate type solar collector is the best collector for low cost design and suit with Malaysia climate. This study on solid waste concludes that crushed glass have been selected due to it has low scrap value, abundant, have good potential as heat absorber [12] and have not been explored by previous researchers. From the test result of the thermal performance test, it is also found that black colored crushed glass have a good heat absorber properties which is good for the low-cost solar water heater.

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