An Experimental Study of Thermo-syphon Solar Water Heater in Thailand

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Abstract

The thermo-sysphon solar water heater (TSSWH) is probably the most widespread application of solar thermal energy during the past years. This paper presents the experimental study and the mathematical models for prediction of hot water temperature produced from the TSSWH. Results are presented of collector temperature, storage temperature and thermal efficiency of the TSSWH. From the experimental study, it is found that the average TSSWH thermal efficiency was about 56% during the test days. The characteristics of this TSSWH are then used in simulation to predict its annual performance in Thailand using the three-year weather data during 2006-2008. Results from the simulation showed that the average year-round thermal efficiency is about 48%, average collector temperature is 51°C, and average hot water in the storage tank is 46°C. Finally, the technical and economic parameters of the TSSWH are used to assess its cost effectiveness under conditions in Thailand. Results from economic analysis revealed that TSSWH is competitive to the conventional electric heaters, especially when electricity price is high and utilization factor is high.

***Keywords**: Thermo-syphon solar water heater, thermal efficiency, collector temperature, storage tank temperature*

1. Introduction

Solar energy is a primary source of Earth's energy commonly used to supply heat and electricity. The flat-plate solar thermal collectors absorb and diffuse radiation from solar energy and transform them into heat. They are usually fastened on rooftop or wall facing the sun to absorb the maximum radiant possible. It should be tilted at specific tilt-angle to maximize the solar radiation collected from the flat-plate solar thermal collector. In Thailand it is best to be tilted at 14°, facing south [1]. Flat-plate solar collector is made of simple glass topping on the insulated box with a flat solar absorber made from sheet metal attached to copper pipes painted in black. The cover plates of the box are used to reduce convection and radiation heat losses to atmosphere while back insulation is used to reduce conduction heat losses. This absorbed solar energy is then used for heating the working fluid. The efficiency of the solar water heaters depend on the design of the solar water heater and the amount of solar radiations [2].

The TSSWH is a system used to produce hot water. It is considered as an appropriate technology for general heating purposes. The three-year weather data from Thai Meteorological Department during 2006-2008 show that the average solar energy received for 14 hours a day, is 16.65 MJ/m^2 and the maximum solar energy receive from the whole year is 20.20 MJ/m^2.

There are two main types of solar water heater using today [3], which depend on the amount of solar energy at different locations. The first type is called the “active system”. The active system includes a pump to circulate water between the collector and the storage tank, and a controller to turn the pump on and off. This pump operates only when the water in the collector is hotter than the water in the storage tank. Both pump and controller are driven by electricity. The second type is called the “Thermo-syphon”, or sometime called “passive system”, as shown in Fig. 1. This type of solar water heater does not depend on the use of pump but by natural convection for water to flow through the system. Here the tank itself acts as solar storage. They are pressurized and usually depended on gravity flow and convection of hot water to circulate water from collector to tank.

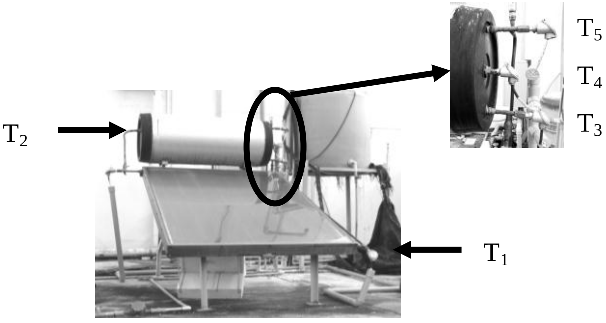

Fig. 1 The thermo-syphon solar water heater.

However, the system in this experiment falls into the second type of solar water heater, i.e. the passive system. The system is closed so the flow of water is due to the difference in water densities.

2. Experimental Setup

The TSSWH consists of one 2.16 m^2 flat-plate solar thermal collector, a storage tank with capacity of 150 litres placed horizontally above the solar thermal collector and the connecting pipes. Connecting pipes allow water to flow through the flat-plate collector to the storage tank and out of the storage tank to the collector for reheating. The pipes are covered with an insulated material wrapped with another layer of aluminum-foil sticky tape to prevent heat losses.

Water temperatures from different points and ambient temperature are measured by type K thermocouple sensors. These thermocouple wires run from the thermocouple sensors to the cabinet put up on the wall nearby. The cabinet stored two temperature displays. The upper one shows temperatures from point 1 to point 4 and the lower one shows temperature at point 5. The ambient temperature is also collected. Thermocouples from point 1 to 5 measure temperatures of water at different locations see

Fig. 1. The temperature at point 1 (T_1) is the temperature of water entering the flat-plate solar thermal collector. The second point (T_2) is the temperature of water exiting from the flat-plate solar thermal collector. Point 3, 4 and 5 measured the temperatures of water stored in the storage tank where T_3 is the temperature of water at the bottom of the tank, T_4 is the temperature of water at the middle of the tank and T_5 is the temperature at the upper part of the tank. The last point is the temperature of air, ambient temperature T_a, where the thermocouple sensor is set up in a caged device (see Fig. 2).

The solar intensity is measured by a pyranometer shown in Fig. 2. It is tilted at the same angle with the flat-plate thermal solar collector.

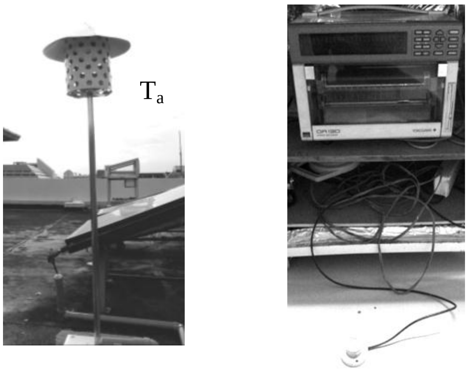

Fig. 2 Data collection system.

The experiment was done on sunny clear days. Before collecting any data, the temperatures of water storage measured by the three thermocouple sensors (T_3, T_4 and T_5) must show the same temperatures. Then water in the storage tank is drained out because water left inside has higher temperature than the tap water. After the storage tank was emptied, it was then filled with tap water. As T_3, T_4 and T_5 are equal the valve is closed and so is the system. The first set of temperatures and solar intensity were recorded in the morning times. During the start of the day, inlet temperature (T_1) and ambient temperature (T_a) usually show the same temperatures. All temperatures including solar intensity (T_1, T_2, T_3, T_4, T_5, T_a and I_t) were recorded every 15 minutes, and continued for nine hours. The last set of data recorded was at 5:30 pm.

The outlet water temperature (T_2) increases during the experiment. The hot water caused a decrease in density of water. Hot water moved to the top of the storage tank. Cooler water is then pushed down to the bottom part of the storage tank. Tube connected at the bottom part of the tank allowed cooler water to circulate back into the flat-plate solar thermal collector to be reheated so water in the storage tank could reach its maximum temperature. This circulation continued until T_2 stop increasing or solar intensity is zero. The experiment was continued for three days in January.

3. Analysis

This experiment could be evaluated and solved for parameters needed to calculate for the efficiency [4]. To find the collector efficiency, several equations are needed. The useful energy (Q_u) collected by the collector per unit time can be determined by mass flow rate m, inlet temperatures (T_1) and outlet of the collector (T_2), which can be expressed by Eq.(1).

$$Q_u = m\, c_p (T_2 - T_1) \qquad (1)$$

where c_p is the heat capacity of water c_p = 4186 J/kg·K. The useful energy can be found by the relation of energy change in the storage tank and the heat losses:

Energy change in the storage tank = (*F* x Useful energy from the collector) – Heat Losses *(2)*

where the control function *F* is either 1 or 0 depending on whether the outlet temperature of the collector (T_2) is greater or less than the storage tank temperature (T_s) respectively.

$T_2 < T_s$, $F = 0$

$T_2 > T_s$, $F = 1$

where T_s is the current storage tank temperature or the average temperature of T_3, T_4 and T_5.

$$T_s = (T_3 + T_4 + T_5)/3 \tag{3}$$

The energy change in the storage tank per unit time Q_s is found by:

$$Q_s = \frac{\rho V C_p}{\Delta t}(T_s^{+} - T_s) \tag{4}$$

where ρ is density of water (kg/m^3), V is the volume of water in the storage tank (150 litres), Δt is the time interval in second (15 x 60 = 900s). T_s^{+} is the storage tank temperature in the next period (^{O}C) that will be evaluated further. The heat losses defined in Eq.(2) come from two parts:

Connecting pipe,

$$\text{Pipe loss} = hA_p\left[\left(\frac{T_3 + T_1}{2}\right) - T_a\right] \tag{5}$$

where, hA_p is the heat loss coefficient of the pipe. The heat loss coefficient per meter long, hA_p/l_p is 0.764 W/m·^{O}C and the l_p, total pipe length, measured from the tested thermo-syphon solar water heater, is 1.8 m long. As l_p is cancelled out, hA_p is equaled to 1.3752 W/^{O}C.

Storage tank,

$$\text{Storage tank loss} = (UA)_s(T_s - T_a) \tag{6}$$

where $(UA)_s$ is the overall heat loss coefficient, $(UA)_s$ = 1.836 W/^{O}C.

The collector efficiency η is defined as the ratio of the useful heat gain over the same specified time period to the incident solar intensity over the same time interval.

$$\eta = \frac{\int Q_u dt}{A_c \int I_t dt} \tag{7}$$

where Q_u is the useful energy from the collector (W), A_c is the collector area (2.16 m^2) and I_t is the total hourly radiation (W/m^2).

The solar intensity I_t as read from the calibrated pyranometer showed the unit in voltage (mV). To transform unit from mV to W/m^2, a conversion factor (1 mV = 991.1 W/m^2) of the pyranometer is needed. T_c is the average temperature of T_1 and T_2 as shown in Eq(8).

$$T_c = \frac{T_1 + T_2}{2} \tag{8}$$

The efficiency function f_c is given in Eq.(9).

$$f_c = \frac{(T_c - T_a)}{I_t} \tag{9}$$

The efficiency curve shown in Fig. 3 is obtained by plotting out the efficiency function values f_c against the collector efficiency values η.

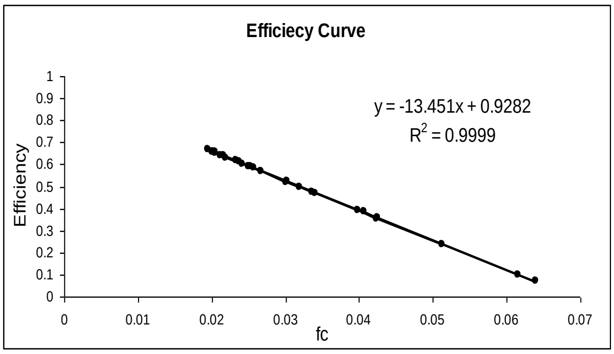

Fig. 3 Efficiency curve of the tested TSSWH.

The useful energy from the collector Q_u is evaluated by using Eq.(10).

$$Q_u = A_c(\tau\alpha)I_t - A_c U_L(T_c - T_a) \tag{10}$$

where $\tau\alpha$ = 0.9387 and U_L = 13.61 W/m^2

The predicted temperatures of the storage tank in the next period can be determined from Eq. (13).

From Eq. (2)

$$mC_p(T_s^+ - T_s) = F \times Q_u - \text{Losses} \qquad (11)$$

$$mC_p(T_s^+ - T_s) = \{F[A_c(\tau\alpha I_t - A_cU_L(T_c - T_a)\Delta t) - hA[(T_3 + T_1)/2 - T_a] - (UA)_s(T_s - T_a)\} \qquad (12)$$

After rearranging, T_s^+ is obtained.

$$T_s^+ = T_s + \frac{\Delta t}{mC_p}\{F[A_c(\tau\alpha)I_t - A_cU_L(T_c - T_a)] - hA[(T_3 + T_1)/2 - T_a] - (UA)_s(T_s - Ta)\}$$

$$T_s^+ = T_s + \frac{\Delta t}{mC_p}\{F[Q_u - \text{Loss}_{\text{Pipe}} - \text{Loss}_{\text{Tank}}]\} \qquad (13)$$

4. Results and Discussion

This study determines the system efficiency of the tested TSSWH, and predicts the year-round efficiency using three-year weather data in Thailand. The energy change in the storage tank Q_s is found from Eq.(4). To find the useful energy from the collector Q_u, losses from Eq.(5) and Eq.(6) must be added to the energy change in the storage tank Q_s. Next the efficiency function f_c is found from Eq.(9) and the collector efficiency η from Eq.(7). The efficiency curve in Fig. 3 is plotted. Linear equation was applied to this efficiency curve to find the coefficients in the equation, where the new effective absorptance $\tau\alpha$ is shown as the y-intercept and the new overall heat loss coefficient U_L is shown as the slope of the graph. The new $\tau\alpha$ is found to be 0.9282 while U_L is found to be 13.451 W/m$^2 \cdot {}^{\circ}$C.

Fig. 4 shows average temperatures of water in the storage tank against the time recorded of the whole day. The four lines represent the average water temperatures of the storage tank T_s, the water temperature of the lower part of the storage tank T_3, the water temperature of the middle part of the storage tank T_4 and the water temperature of the upper part of the storage tank T_5. This graph shows that the temperatures in the storage tank tend to increase gradually with increasing time. T_3 has the lowest temperature among other temperatures while T_5 shows the highest temperature.

Fig. 5 shows the average solar intensity and average ambient temperature against the time recorded during the day. The solar intensity curve shows that the flat-plate solar thermal collector absorbs high solar intensity during 12pm to 2pm. The least amount of solar intensity collected is during the start and the end of the day.

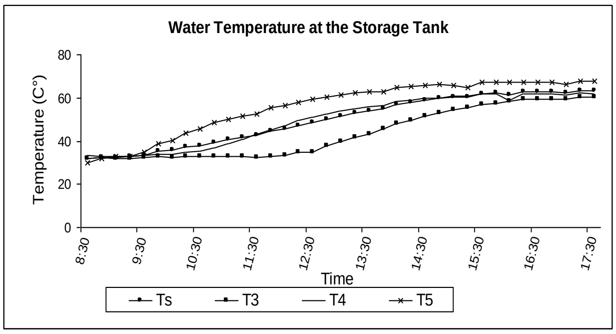

Fig. 4 Water temperatures in the storage tank.

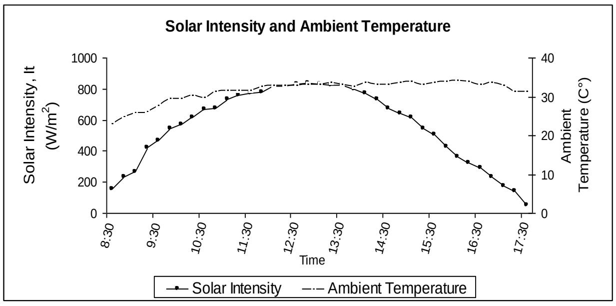

Fig. 5 Solar intensity and ambient temperature.

The $\tau\alpha$ and U_L were used to find the useful energy from the collector Q_u and estimated for the storage tank temperatures in the next period T_s^+. To find the estimated value T_s^+, the solar intensity I_t and the ambient temperature T_a of the specified period must be known. In this experiment the specified period is during 2006 - 2008. The solar intensity and the ambient temperature used during these years were taken from the Meteorological Department. The useful energy from the collector Q_u is found from Eq. (10). After the calculation is completed the efficiency function f_c is found from Eq.(9) while the collector efficiency η is found from Eq. (7). These values of η were plotted in Fig. 6 showing the trend of the percentage of the average efficiency during the year. The period with the maximum percentage of efficiency is in October and the least percentage of efficiency is in September due to raining season.

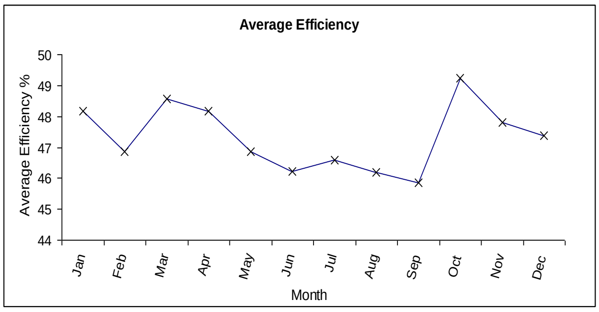

Fig. 6 Average annual efficiency.

Fig. 7 shows the average output temperature of hot water. It shows that the highest temperature of the outlet water T_2 is in March and April while the least temperature of the outlet water is in November.

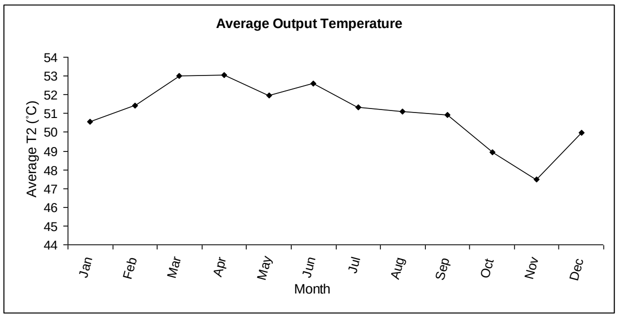

Fig. 7 Average outlet temperature of collector.

5. Economic Analysis of TSSWH

Before TSSWH could be put to work, it should be proved that the TSSWH is worth of investment as compared to the electric water heater (EWH) [5]. In economic analysis, three main costs in this study are investment and installation cost, maintenance cost, and the electricity cost. These costs are then summed to find the total cost of the TSSWH and EWH for a lifetime of 15 years.

Table. 1 Costs for TSSWH and EWH

Cost	TSSWH	EWH
Investment + Installation	40,000 Baht	10,000 Baht
Electricity Cost /per year	0 Baht	4,599 Baht
Total Present Worth of Cost	40,000 Baht	44,980 Baht

The investment and the installation cost of the TSSWH is higher than the EWH as presented in Table 1. The maintenance cost of the TSSWH is 20,000 Baht [6] for 15 years and the EWH are assumed to be zero since the lifetime expectancy of the EWH is approximately more than 15 years. The last cost component is the electricity cost. The TSSWH needs no electricity to operate so electricity cost is not included in the calculation while calculations are done for the electricity cost of EWH. The EWH maximum power is about 3,000 W. Load factor of 0.6 is included in the calculation. With load factor of 0.6 we find the number of units of electricity per day by multiplying the power of EWH (in kW) with the number of continuous hours used per day which is 2 hours per day. It is the same time used with the TSSWH, and 7 days per week. The number of units per day [7] is 3.6 kWhs. From this value, the number of unit per year is found to be 1,314 kWhs. The average electricity price is 3.5 Baht/kWh in Thailand. Eventually the electricity cost of EWH per year is 4,599 Baht.

The total present worth (PW) [8] of costs are then calculated for both TSSWH and EWH for 15 years. The total cost of EWH is found to be higher than the total cost of TSSWH (see Table 1).

6. Conclusion

The objectives of this study are to determine the solar collector efficiency, to predict the storage tank temperatures, and to assess economics of TSSW in Thailand. This paper shows mathematical model of the fat-plate solar thermal collector. The effective absorptance $\tau\alpha$ and the overall heat loss coefficient U_L were found to be 0.9282 and 13.451 $W/m^2 \cdot {}^{o}C$, respectively. These two parameters are used to find the predicted storage tank temperature with the use of three-year weather data from the Thai Meteorological Department. The weather data from 2006 to 2008 were applied to the TSSWH system in this experiment. It shows that the most useful heat gained from the solar intensity occurred during 12pm to 2pm because the maximum solar intensity gained during this period. Results of the daily efficiency calculation ranged from 45-50%, and the average temperature output was found to be 47-53 ^{o}C. The economic analysis shows that the PW of costs are 40,000 Baht and 44,980 Baht for TSSWH and EWH, respectively.

7. Acknowledgement

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8. References

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