Effect of storage tank geometry on performance of solar water heater

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A computer simulation program has been developed to predict the performance of solar thermosyphon domestic water heater. The model has standard configuration of solar collector (2m²) and 150 litres vertical storage tank. Malaysian hot water consumption profile has been used. Increasing the storage tank height above 1.0 m has no significant effect on solar fraction, but the solar fraction is adversely affected, particularly at high set points, if considerably shorter tanks are used.

Keywords: Kuala Lumpur TMY data, Thermal performance, Thermosyphon solar water heater, TRNSYS

Introduction

In solar energy systems, careful consideration is vital to find out the system capacity for optimum useful energy collection. Most of the solar water heaters (SWHs) used in Malaysia are thermosyphon type and imported from Australia and US. A number of models have been developed to predict the performance of thermosyphon system. Marrison & Tran has developed a model to simulate the long-term performance of thermosyphon system. Computer simulation program TRNSYS modeled thermosyphon system with or without auxiliary electric heater in the tank, in one component based on Marrison & Braun model. TRANSYS program have been used to optimize the design parameters of thermosyphon system under a constant hot water temperature delivered to the load. Marrison & Sapsford used the model to study performance of thermosyphon system for typical domestic hot water loads. Akinoglu et al studied application of domestic SWH in Turkey using TRNSYS and concluded that the best region in Turkey was with Mediterranean climate where a 2 m² heater with high efficient collector system or 3 m³ low-efficient system is sufficient for a load of 180 l. Hussein concluded that for heating load volume equals to the internal volume of the storage tank, increase in optimum tank volume to collector area ratio \( V_t / A_c \) increases the heater annual specific useful energy and decreases its annual solar fraction.

In terms of hot water consumption pattern, most families in Malaysia use hot water in evening and nights. A survey among 62 families (Seri Petaling, KL) done in March 2004 indicated that most of the families use hot water just for shower (56 cases) after 6 pm and just once a day. Others (6 cases) use it two times a day, in the evening and in the early morning. Average number of family members in urban areas in Malaysia is 5 persons and for each person, 25-30 l hot water is adequate (JKR standard). It means 150 l/day/family should be enough as hot water consumption in Malaysia.

Operation of thermosyphon SWHs depends on local weather, design parameters, operating conditions, water temperature delivered to the load, hot water consumption profile, etc. This study presents the effect of annual performance of a thermosyphon system (Fig. 1) at daily hot water load of 150 l per family according to Malaysian hot water consumption pattern for different tank volumes and collector areas. TRNSYS simulation program was used to simulate performance of the system using meteorological data for Kuala Lumpur, Malaysia. Hot water consumption pattern by Duffie & Beckman is used for this project as it coincides with Malaysian requirements. The system should prepare hot water in early morning and also the evening and night. This consumption pattern starts at 6 pm and finishes at

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Fig. 1—Schematic diagram of the considered system

![Schematic diagram of the considered system](image)

Fig. 2—Hot water consumption profile

![Hot water consumption profile](image)

1 am and there is no consumption during midnight, 1-6 am (Fig. 2).

Materials and Methods

Model Description

Thermosyphon system (Fig. 1) consists of flat-plate collector connected to vertical storage tank. An electric heating element and thermostat are integrated into the top of the tank to maintain desired water temperature for the upper portion of the tank whenever the energy gain from the collector does not meet the load energy. A check valve on the collector return piping prevents reverse circulation in times of low and/or no solar radiation. The bottom of the tank is at level to the top of the collector.

Simulation Model

TRNSYS, a transient system program, normally comprises a solar energy system, which are connected together to form a complete system for simulation. The program models thermosyphon SWH as a single component using parameters that characterize collector, connecting pipes, storage tank, auxiliary heater, etc. Other inputs are incident radiation, outdoor temperature, hot water schedule, etc. The modular nature of TRNSYS permits the simulation of a great variety of a particular component of a physical system and facilitates the add-ons to the program of mathematical model not included in standard TRNSYS library. A typical thermosyphon solar domestic hot water system may be modeled by connecting thermosyphon collector storage subsystem (type 45), typical meteorological year (TMY), weather data reader (type 89), radiation processor (type 16), heating load component (type 14), integrator (type 24) and online plotter (type 65).

The systems were simulated with TRNSYS using TMY data for Kuala Lumpur, Malaysia. The selection of typical weather condition for a given location is very crucial in computer simulation for performance predictions. TRNSYS component type 89 is used to read hourly values of solar radiation incident on horizontal surface and ambient temperature for TMY at a particular location. TRNSYS component type 16 transforms TMY hourly radiation incident on horizontal surface into radiation incident upon a flat collector at a fixed slope with respect to the horizontal. The position of the Sun in the sky can be specified by giving the solar zenith and solar azimuth angles. The zenith angle is the angle between the vertical and the line of sight of the Sun. Four surface tracking modes are incorporated into TRNSYS for handling various surfaces for the determination of incident radiation. Tracking mode 1 was chosen in this project so as to maximize incoming radiation. The slope and azimuth inputs denote the position of the surface. In this study, the storage tank is not receiving solar irradiation. Thermal performance of a flat-plate collector is modeled as

\[ Q_u = rA_\Delta[FR(\tau\alpha)l_T - FR_lU_l(T_1 - T_a)] \]  

where \( r \) is the modification coefficient (flow rate correction factor), by which \( FR(\tau\alpha) \) and \( FR_lU_l \) are corrected and given as

\[ Q_u = rA_\Delta[FR(\tau\alpha)l_T - FR_lU_l(T_1 - T_a)] \]  

... (1)
Fig. 3—Variation of tank volume (collector area, 2 m$^2$) on solar fraction for different tank heights: A) $T_{set} = 40^\circ$C; B) $T_{set} = 50^\circ$C; C) $T_{set} = 60^\circ$C; D) $T_{set} = 70^\circ$C; and E) $T_{set} = 80^\circ$C
The storage tank is modeled as a stratified liquid tank, whose nodes are not fixed, but depend on simulation time steps, size of the collector and load flow rates, heat loss and auxiliary input. Because the thermal losses from the connecting pipes are usually small due to their small surface area, the pipes are modeled as single node. Bernoulli’s equation is applied to any node in thermosyphon loop to calculate the pressure drop. Thermal performance of the system, characterized by annual efficiency ($\eta$) and annual solar fraction ($f$), is defined as

$$
\eta = \frac{Q_u}{A \sum I_r} \quad \text{... (3)}
$$

and

$$
f = \frac{Q_u - Q_{aux}}{Q_l} \quad \text{... (4)}
$$

where $Q_u$, $Q_l$, and $I_r$, respectively are useful energy, energy delivered to the load, energy supplied by the auxiliary electric heater and hourly radiation on the surface of the collector.

**Results and Discussion**

When set point ($T_{set}$), which is a user specified maximum temperature of heater internal thermostat, is 40°C and 50°C, increasing storage tank volume
For higher set points ($T_{\text{set}}$ is increased little bit (Fig. 4A). When $A_c$ ratio caused decrease in SF; at $T_{\text{set}}$ the ratio of $V_t$ values of $T_{\text{set}}$ is 60°C, 70°C and 80°C, there is no effect in increasing $V_t$ more than 150 l, 125 l and 100 l respectively (Fig. 3). Increasing $H_t$ from 0.4 m to 1.3 m will result in increase in annual SF for all $T_{\text{set}}$ values. This improvement in SF is small when $T_{\text{set}}$=40°C. As $T_{\text{set}}$ increases from 50°C to 80°C, dependence of SF on $H_t$ increases slightly. A higher $T_{\text{set}}$ and shorter $H_t$ results in poor thermal stratification, or warmer water entering the collector from tank resulting in lower collector efficiency and lower SF. Thermal losses from tank will be increased in a short and fully mixed tank causing an additional decrease in SF. SF reaches maximum when tank is about 1.0 m. There is no significant increase in SF when $H_t$ is higher than this value. This suggests that the desired value of $H_t$ is 1.0 m for all considered values of $T_{\text{set}}$.

When collector area is small ($A_c=1\text{m}^2$), changing the ratio of $V_t$ to $A_c$ does not affect too much on SF. For higher set points ($T_{\text{set}}$=70 and 80°C), increasing ratio caused decrease in SF; at $T_{\text{set}}$=50°C, this amount is increased little bit (Fig. 4A). When $A_c=2\text{m}^2$ and $T_{\text{set}}$=70 and 80°C, optimum tank volume to collector area is 50. There is no significant increase in SF when $V_t/A_c$ is more than this value. For lower set points (50-60°C), $V_t/A_c$ is 60-80 (Fig. 4B). For bigger collector area ($A_c=3\text{m}^2$), for lower set points (50 and 60°C), increasing ratio results in increasing SF but for higher set points (70 and 80°C), optimum ratio is about 40. More than this value does not affect on SF (Fig. 4C). When $A_c=4\text{m}^2$, result is not far off from $A_c=3\text{m}^2$ (Fig. 4D). For all cases, increase in ratio results in increase in SF.

When $A_c=1\text{m}^2$ and $T_{\text{set}}$=50°C, there is no effect in increasing tank volume and for all tank volumes, SF has the same value (Fig. 5). When tank volume is increased from 60 l to 100 l, SF increases about 2% (Fig. 5). When collector area is increased to 2m$^2$ and $T_{\text{set}}$ is 50-70°C, it is obvious that SF is very low when tank volume is 60 l. Higher than this value, SF for all $T_{\text{set}}$ is not too much different but when $V_t$ =150 l, system has better performance specially for $T_{\text{set}}$ higher than 70°C. The effect of height on SF is significant and it cannot be accepted that in this specific configuration, the heat from natural circulation is dominance.

Conclusions

Increasing the storage tank height above 1.0 m has no significant effect on solar fraction, but the solar fraction is adversely affected, particularly at high set points, if considerably shorter tanks are used. For 150l / day hot water consumption, 2 m$^2$ solar collector is adequate. Using the optimum values of the design parameters for thermosyphon system could reduce the price of the system, as well as improve the system performance. Optimum ratio of tank volume to collector area ($V_t/A_c$) when $A_c=2\text{m}^2$ is 50 – 70 l/m$^2$.

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Nomenclature

\( A_c \) Collector area, 1-4 m\(^2\)
\( D_h \) Diam of collector header, 20 mm
\( D_i, D_o \) Diam of collector’s inlet and outlet connecting pipes, 
15 mm
\( D_r \) Diam of collector’s riser, 5 mm
\( F_R(\tau\alpha) \) Intercept of collector efficiency vs. \((T_i-T_a)/I_T\), 0.8
\( F' \) Collector efficiency factor
\( G_{test} \) Collector’s test flow rate, 72 kg/hm\(^2\)
\( H_{aux} \) Height of auxiliary heating element above the bottom 
of tank, \( H_i - 5 \) cm
\( H_v \) Vertical distance between the outlet and inlet of 
the collector, 1 m
\( H_o \) Vertical distance between outlet of the tank and inlet 
of the collector, 1 m
\( H_r \) Height of collector’s return above the bottom of the 
tank, 0.4 - 1.3 m
\( H_t \) Height of the tank, 0.4 – 1.3 m
\( H_{th} \) Height of auxiliary thermostat above the bottom of 
the tank, \( H_r - 5 \) cm
\( I_T \) Incident solar radiation on collector surface
\( L_h \) Length of collector’s header, 3 - 5 m
\( L_i, L_o \) Length of inlet and outlet connecting pipes, 4, 3 m
\( N_{B1}, N_{B2} \) Number of bends in inlet and outlet connecting 
pipes, 5
\( N_r \) Number of parallel collector’s riser, \( W/c_{0.15} \)
\( T_a \) Ambient temperature
\( I_T \) Total incident radiation on a flat surface per unit area
\( T_{main} \) Average cold water source temperature, 29\(^\circ\) C
\( T_{env} \) Temperature of heater surrounding for heat loss 
calculation
\( T_{load} \) Water temperature delivered to the load, 40 – 80\(^\circ\) C
\( T_{set} \) Set temperature of heater internal thermostat
\( U_{i}, U_o \) Heat loss coefficient for inlet and outlet connecting 
pipes, 10 kJ/hm\(^2\)C
\( (UA)_t \) Overall heat loss coefficient for storage tank, 5.4 kJ/ 
hm\(^2\)C
\( V_t \) Storage tank volume, 0.060 - 0.400 m\(^3\)
\( W_c \) Width of collector, 1.10 - 2.76 m
\( \rho_g \) Ground reflectance, 0.2
\( \beta \) Collector tilt angle, 15 degree
\( \eta \) Overall collector efficiency
\( \phi \) Latitude, 3.14 degree