Development of TRNSYS Models for Predicting the Performance of Water-in-Glass Evacuated Tube Solar Water Heaters in Australia

I. Budihardjo, G.L. Morrison and M. Behnia
School of Mechanical and Manufacturing Engineering
The University of New South Wales
Sydney 2052
AUSTRALIA
E-mail: indra.budihardjo@student.unsw.edu.au

Abstract

The performance of a solar water heater incorporating water-in-glass evacuated tubes was evaluated using a transient simulation program, TRNSYS. This paper outlines the experimental and numerical techniques used in modelling each component of the solar water heater, such as the collector efficiency, the tank heat loss coefficient and the natural circulation flow rate through the evacuated tubes. The solar contribution relative to a conventional 135-l tank with electric heater element was evaluated when the system is used as a solar pre-heater in Sydney. The results show that the evacuated tube pre-heater system gives 45% annual saving in Sydney.

1. INTRODUCTION

Evacuated tube solar water heaters have better performance than flat plate solar water heaters in particular for high temperature operations. A number of heat extraction methods for evacuated tube have been developed, namely the U-tube manifold, heat pipes and flow-through absorbers. The most successful arrangement is the water-in-glass concept with direct connection to a horizontal tank which has been widely used in China. Heat transfer in this type of solar water heater is driven by natural circulation of the fluid in the collector and storage tank. Water in the collector tubes conveys the heat to the storage tank and is replaced by water with a lower temperature from the storage tank. Inside the tubes, the flow is bi-filamental, the opposing streams of cold and heated fluid separated by a shear layer. This type of solar water heater is used in China mainly as a pre-heater or a falling-level system.

The aim of this stage of the research is to develop a model of a commercial-type water-in-glass evacuated tube solar water heater that can be used to predict the long-term performance of the system. Detailed system simulation has been performed using a transient simulation program, TRNSYS. This paper outlines the modelling procedure of each component of the solar water heater to be incorporated into TRNSYS for system simulation. The performance of the solar water heater as a pre-heater system in Australia has been evaluated.

2. EXPERIMENTAL SETUP

The system evaluated in this research consists of 21 water-in-glass evacuated tubes coupled to a 150-l horizontal tank. The tube absorber length is 1.42 m and the diameter is 37 mm. The tubes are mounted at 45° inclination over a diffuse aluminium reflector. Schematic of the outdoor test is shown in Figure 1. The tank temperature was taken as the volume-weighted average of thermocouple readings placed at seven different heights in the tank. A mixing test was used to ensure that the error from averaged thermocouple readings was small. A heater element was used to pre-condition the tank to its initial temperature at the start of the day and the tank volume is mixed to a uniform temperature using a submergible pump mounted at the bottom of the tank. This arrangement helped eliminate significant heat loss in the previous measurement from pipe connections to an external circulating pump. A pyranometer was mounted near the system at 45° inclination to record the irradiation on the collector plane. The ambient temperature was recorded throughout the measurement using a T-type thermocouple placed in a shielded area.

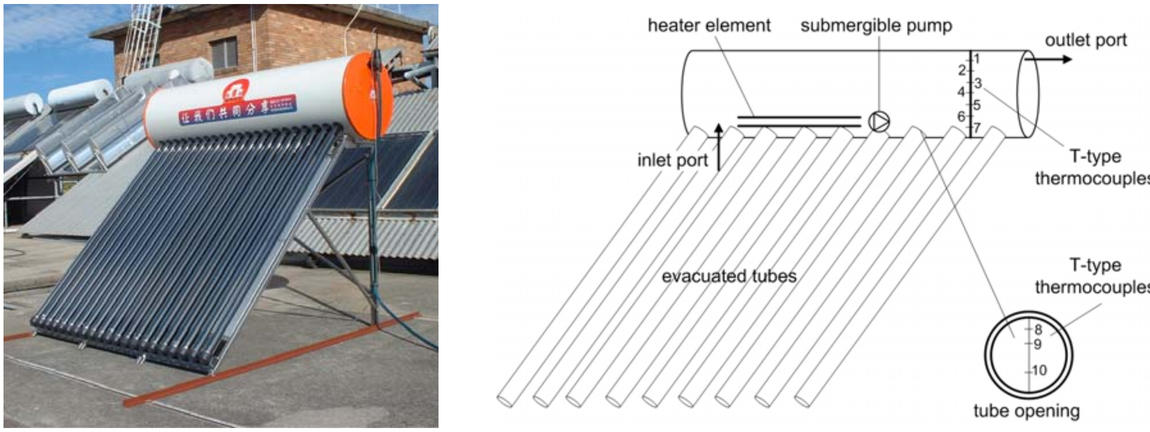

Figure 1 Schematic of outdoor measurement setup, showing locations of thermocouples in the storage tank and across tube opening.

3. TRNSYS MODELLING

Detailed system simulation has been performed using TRNSYS, in which the performance of the system can be simulated over small time increments by collectively simulating the performance of the components. This simulation requires detailed information about each component of the solar water heater, such as collector efficiency, natural circulation flow rate through the tubes and heat loss coefficient of the storage tank. This section outlines the measurement and simulation techniques to determine the parameters of the individual components, followed by the description of the system simulation.

3.1. Solar collector model

The collector consists of 21 evacuated tubes with fluid in direct contact with the glass tubes. The absorber diameter is 37 mm and the tubes are spaced 70 mm apart. The aperture area of the collector is 2.1 m^2, and the aluminium diffuse reflector covers only 80% of the length of the absorber. Due to the geometry of the tube array, evacuated tube collectors mounted facing North-South have different off-angle response to flat-plate collectors, because there is a peak efficiency when the radiation falls off-normal East-West to the collector plane. The optical behaviour of the collector has been taken into account in the TRNSYS model by implementing East-West incidence angle modifiers adopted from Chow et al. (1984).

3.1.1. Collector efficiency

A collector efficiency test is usually undertaken under constant radiation by mounting the collector on a sun-tracking frame. Flow rate through the collector is controlled and the useful energy from the collector can be determined by measuring the inlet and outlet temperatures under steady-state conditions. An attempt was made to use this method to measure the efficiency of an array of 10 evacuated tubes mounted over a diffuse reflector. The tube openings were connected using a copper manifold of 20 mm diameter. Flow rate through the header pipe was controlled at 2 l/min and the inlet temperature was varied between 20°C and 80°C. Using this procedure, a number of data points can be obtained over a short time period. However, for the water-in-glass system that was tested, it did not give reliable measurements because of the following reasons. Natural circulation in the water-in-glass tubes depends on the inclination angle. During the sun-tracking test, collector inclination varied transversely and longitudinally, which resulted in different natural convection through the tubes, and hence might result in discrepancies in the results. Other problems included difficulties in sealing the metal manifold to glass tubes joints and protection of header insulation from rain and moisture.

An alternative method of determining the collector efficiency is illustrated in Figure 2 and was derived from experimental measurement described in Section 2. The measurement was undertaken over a period of half-hour across solar noon under clear-sky condition. Solar radiation was integrated over this period (eqn.(1)) and the increase of internal energy of the system (dE) can be calculated by monitoring the increase of tank temperature. The increase of internal energy is the net result of the useful energy transferred from the collector minus the heat loss from the storage tank (eqn.(2)); the latter could be calculated knowing the heat loss coefficient of the tank (section 3.2). Therefore, useful energy gain of the collector over this short period of peak radiation can be determined. Collector efficiency is the fraction of solar irradiation which is converted into useful energy to the tank (eqn.(3)) and is a function of the operating temperature of the collector. At higher temperatures, heat loss from the collector is higher, therefore, the useful energy gain is smaller for the same amount of radiation.

$$G = \int_{t_1}^{t_2} I dt \tag{1}$$

$$Q_{u-collector} = dE_{system} + Q_{loss-tank} = mc_p (T_2 - T_1) + \int_{t_1}^{t_2} U_{loss-tank} A_{tank} (\overline{T} - T_a) \tag{2}$$

$$\eta = \frac{Q_{u-collector}}{GA} \tag{3}$$

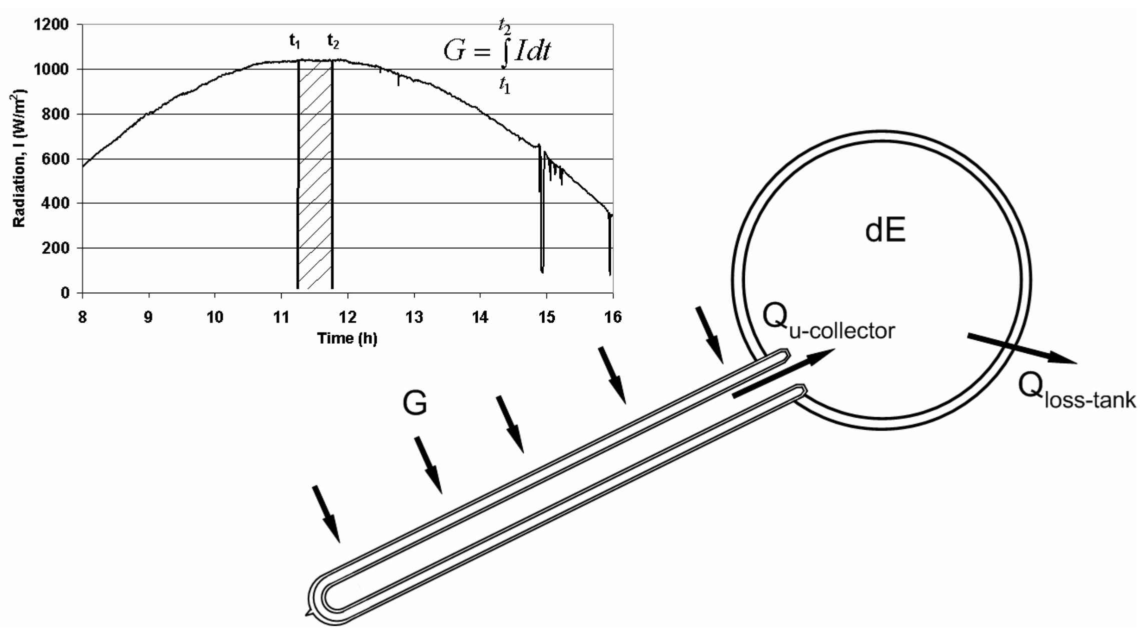

Figure 2 Calculation of useful energy gain from the collector.

The efficiency points obtained from the measurement are presented in Figure 3. The heat loss coefficient of the evacuated tubes is known to vary with temperature (Budihardjo et al., 2002), hence, the efficiency can be modelled as:

$$\eta = \eta_0 - a_1 \frac{(\overline{T} - T_a)}{G} - a_2 \frac{(\overline{T} - T_a)^2}{G} \tag{4}$$

Evacuated tube collectors have relatively small heat loss compared to flat-plate collectors and thus the decrease in efficiency over the measured temperature range is small, and extrapolation for higher temperature range is difficult. The optical efficiency of the collector (η_0) was obtained to be 0.58 using a linear regression of the measured points. The coefficients a_1 =0.9271 Wm^{-2}K^{-1} and a_2 =0.0067 Wm^{-2} K^{-2} were determined from the tube heat loss measurement described in Budihardjo et al. (2002). Heat loss coefficients of the 21 evacuated tubes installed in the collector were measured using a cool-down test in a temperature controlled room, and the average value was used in the efficiency model in TRNSYS.

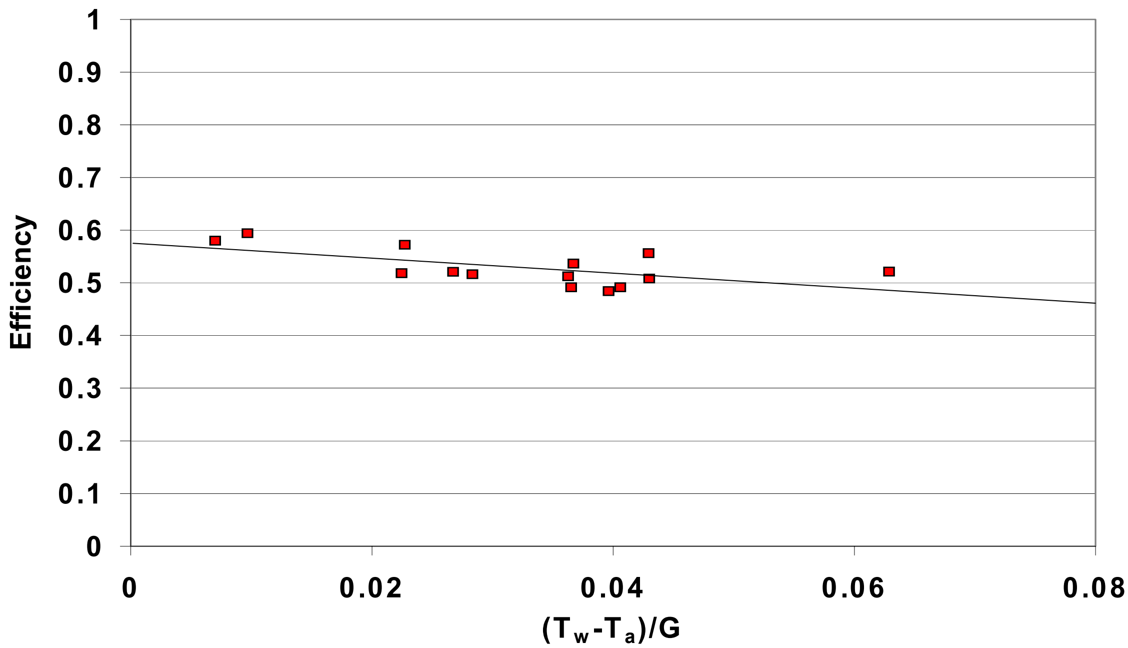

Figure 3 Collector efficiency data extracted from experiments.

3.1.2. Natural circulation flow rate through the collector

As mentioned earlier, the single-ended evacuated tubes used in the solar water heater in this study were the fluid-in-glass type, in which the heat transfer and water flow-rate were driven by natural convection only. This type of evacuated tube can be modelled as an inclined open thermosyphon. Although studies of open thermosyphons – pioneered by Lighthill (1953) - have been extensive, most of them focused on the heat transfer from the tube wall to the fluid, and no correlation is available for the rate of natural circulation in and out of the tube. Flow rate through the collector is a major factor influencing the stratification inside the storage tank. A series of experimental investigations on single-ended evacuated tube collector undertaken in early 1980s presented the thermosyphon flow rate for tubes utilising heat extraction manifolds; but little has been done to determine the natural circulation flow rate inside the fluid-in-glass type. The rate of natural circulation through the tubes is influenced by radiation intensity, operating temperature of the collector and the collector design (e.g. tube aspect ratio, reflector curvature, collector inclination).

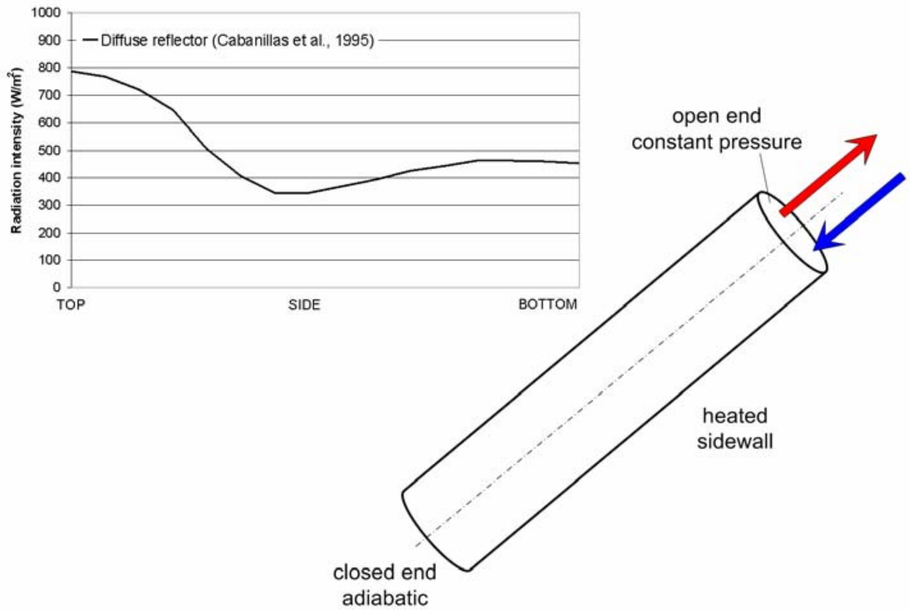

Figure 4 Open thermosyphon model used in the simulation showing the boundary conditions used e.g. circumferential heat distribution for evacuated tubes with diffuse reflector (adopted from Cabanillas et al. (1995)).

Numerical simulation has been undertaken to investigate variation of natural circulation flow rate through the single-ended evacuated tubes under various radiation inputs and operating temperatures. The simulation model was an open thermosyphon with a constant pressure condition on the open surface and variable heat flux around the tube wall (Figure 4). Heat-flux distribution around the tube circumference was adopted from Cabanillas et al. (1995) who presented measurements of circumferential heat distribution around evacuated tubes mounted over a diffuse reflector. The tubes that were used in Cabanillas' measurement had an absorber diameter of 27 mm and the selective surface was on the inner surface of the inner tube. It is shown that the distribution on the top half of tube circumference can be represented as a cosine function with minimum intensity on the sides of the tube. The radiation intensity is almost uniform on the bottom half of the tube. For solar irradiation of 1 kW/m^2, Cabanillas' results show that the average heat flux around the tube circumference is approximately 500 W/m^2. The range of heat flux being investigated in the current research was between 125–500 W/m^2, and the operating temperature was 17–60 °C. Flow measurement in a tube using PIV technique has been undertaken in a laboratory-scale setup on the central-plane of the tube opening to a tank to validate the numerical model. Details of the experimental setup and the validation results were presented in Budihardjo et al. (2003).

The natural circulation flow rate obtained from numerical simulation was compared against experimental results obtained from outdoor measurement. In the experiment, temperatures of the in-flow and out-flow of the single-ended tubes were monitored using thermocouples positioned across the tube opening, one at 8 mm from the bottom edge, and two at 5 and 10 mm respectively from the top edge (Figure 1). The outlet temperature was taken as the average of the top two thermocouples. The useful energy absorbed by a single tube during the half hour period across solar noon was calculated from the total energy collected by the collector (eqn.(2)) divided by the number of tubes; assuming each tube has the same circulation flow rate; and the mass flow rate can be determined from eqn.(5).

$$\dot{m} = \frac{Q_{u-tube}}{c_p (T_o - T_i)} \tag{5}$$

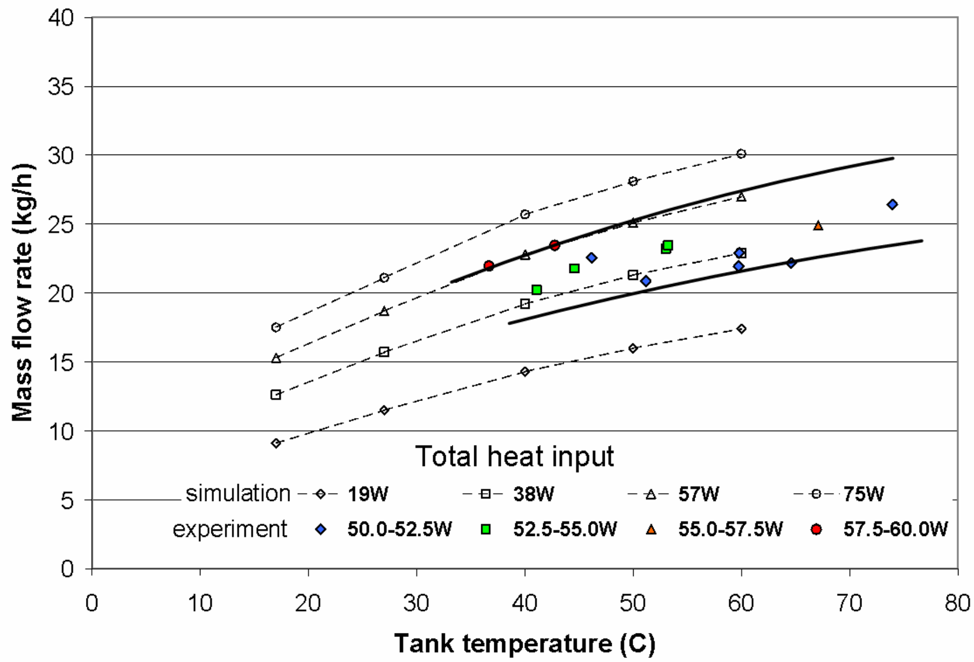

Figure 5 Natural circulation flow rate through an evacuated tube under a range of operating temperatures and heat inputs.

Figure 5 shows comparison between the measured and simulated natural circulation flow rate through a single evacuated tube mounted over a diffuse reflector for a range of heat inputs and operating temperatures. It is shown that fluid temperature is an important factor influencing the rate of circulation between the tank and the collector. For a maximum heat input of 500 W/m^2, there is a significant increase in flow rate from 17 kg/h at 17°C to 30 kg/h when water is at 60°C. This is mainly because over that temperature range the viscosity of water changes by a factor of three. At higher temperatures, there is also a higher rate of change of density with temperature; as it is the density gradient of the fluid along the tube which drives the natural circulation, this also results in a higher flow rate at higher operating temperatures. In the system that was analysed in this paper, the maximum flow rate corresponds to 4 tank-volume exchanges per hour. The difference between the experimental results and the computed values is less than 10%, with experiments consistently give lower values. This discrepancy can be attributed to the limitation of the number of thermocouples used in the measurement. Furthermore, flow rate calculation in eqn.(5) is sensitive to the error of the thermocouple measurement. It can be shown that an error of 0.1 K in the inlet and outlet temperature measurements could result in 5-10 % error in flow rate calculation.

Various forms of Reynolds and Rayleigh or Grashof numbers have been used in correlating natural convection flow rate [Bau and Torrance (1981), Huang and Zelaya (1988), Misale et al. (2000), Cammarata et al. (2000)]. Non-dimensional natural circulation flow rate through individual tubes mounted over a diffuse reflector is presented in Figure 6 as Reynolds number versus modified Rayleigh number. The characteristic length used in the non-dimensional terms is the tube inner diameter. Modified Rayleigh number is used in the correlation to take into account the substantial variation of Prandtl number of water with temperature over the temperature range being investigated. The modified Rayleigh number used in this paper is adopted from studies by Vliet (1969) and Vliet and Liu (1969) and is defined as:

$$Ra_d^* = Gr_d^* Pr \qquad (6)$$

where $$Gr_d^* = Gr_d Nu_d = g\beta q_w d^4 k^{-1} \upsilon^{-2} \qquad (7)$$

In this study, the heat flux, q_w, is in W/m^2, and is based on the total heat input to the tube averaged over the circumferential area. The Reynolds number is calculated based on an average velocity over

the cross-sectional area of the tube, and is defined as:

$$Re_d = 4\dot{m}\pi^{-1}d^{-1}\mu^{-1} \tag{8}$$

where $\dot{m}$ is the natural circulation flow rate in kg/s obtained from simulations. Fluid properties in Rayleigh and Reynolds number are evaluated at the mean temperature of the inlet and outlet flows. The relation between Reynolds number and modified Rayleigh number shown by the data in Figure 6 is

$$Re_d = a_0 Ra_d^{*a_1} \tag{9}$$

where a_0=0.003558 and a_1=0.6749. This correlation applies for single-ended evacuated tubes of absorber diameter 37 mm (34 mm I.D.) mounted over a diffuse reflector at 45° inclination. This correlation can be used in a simulation model of evacuated tubes to predict circulation flow rate between the collector and the tank (Figure 7).

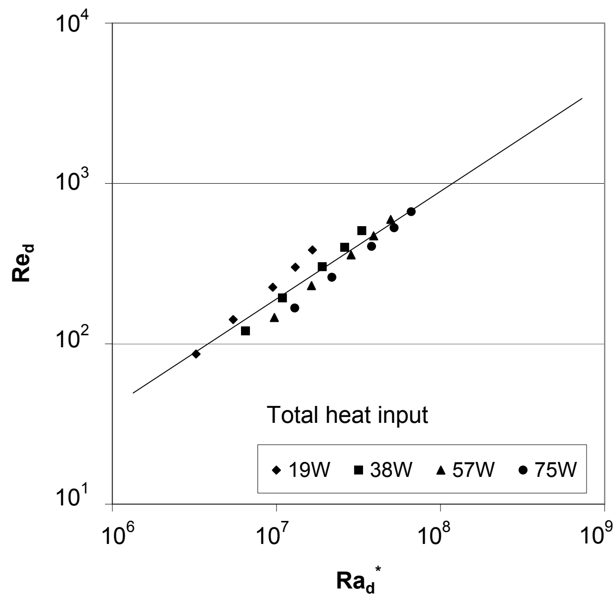

Figure 6 Non-dimensional natural circulation flow rate through a single-ended evacuated tube mounted over a diffuse reflector at 45° inclination.

3.2. Simulation model

The horizontal tank used in the solar system has 360 mm diameter and 150 l in volume, made of rolled stainless steel with 40 mm thick insulation. The inlet port for replacement fluid is located at the bottom of the tank, and the outlet to the load is at the end wall, at the highest level of the tank. The evacuated tube opening is located approximately 50 mm from the bottom of the tank and the evacuated tubes sit on a plane which intersects the centre-line of the tank. This arrangement results in 9% of the water at the bottom of the tank unheated when the collector is mounted at 45° inclination and this inactive portion increases as the inclination angle to horizontal is reduced. Thermal stratification in the tank was modelled by dividing the tank into 10 fully-mixed equal-volume segments. Due to the high circulation rate through the 21 tubes stratification in the tank was not significant. The inlet flow stream was assumed to enter the tank node that is closest to it in temperature. At each time step, the differential equations for each node are solved, and temperature inversions are eliminated by mixing adjacent nodes.

The heat loss coefficient of the tank was determined from cool-down test and incorporated into the

TRNSYS model. Detailed procedure of the test has been presented in Budihardjo et al. (2002). Water in the tank was pre-heated to 80°C using an electric heater element. At the start of the measurement, the heater was turned off and tank temperature was recorded over a few days. During the measurement, the tank was isolated from the tubes using 40-mm-thick rubber stoppers. The collector was covered to prevent heating from the tubes. The UA value of the tank was calculated using the correlation specified in the ISO9459-2 (1995) and assumed to be uniform around the tank wall.

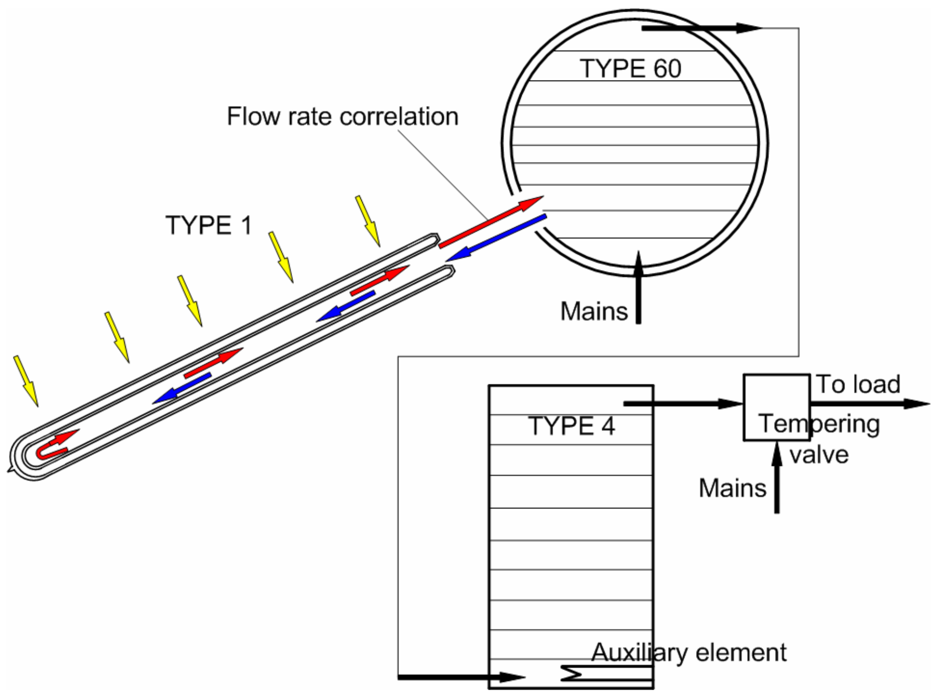

Figure 7 Schematic of pre-heater system, showing the inter-connection between the TRNSYS modules.

The performance of the solar water heater as a pre-heater (Figure 7) in Australia was evaluated and the fraction of energy saving was determined in comparison to conventional electric energy cost. For this application, the solar system acts as a pre-heater for a conventional tank with an auxiliary heater, where hot water from the solar-system's tank is used as a replacement fluid for the conventional tank. The conventional tank is 135 l in volume and the heat loss coefficient is 1.9 kWh/day. A standard pattern AS4234 (1994) of hot water consumption was used in the simulation and the temperature of hot water supply to the household was 60°C.

4. RESULTS AND DISCUSSIONS

Auxiliary energy consumptions using a conventional system and evacuated tube pre-heater system are presented in Figure 8 for Sydney. As a comparison, the purchased energy using a typical flat-plate system in Sydney is included. The rating factor that is commonly used to assess the performance of a solar water heater is the solar contribution relative to a conventional energy source, f_R, which is how much the auxiliary energy consumption would be reduced by changing to a solar system.

$$f_R = \frac{Aux_{conventional} - Aux_{solar-pre-heater}}{Aux_{conventional}} \qquad (10)$$

The monthly variation of the energy saving relative to a conventional system, f_R, is shown in Figure 9. It is shown that the water-in-glass evacuated tube solar water heater gives 45% annual energy saving when used as solar pre-heater in Sydney. A typical flat-plate system with an aperture area of 3.7 m^2

and collector inclination of 20° can save up to 72% on the auxiliary energy consumption; the majority of which was due to maximised energy collection during the summer, when over 95% of the energy consumption was contributed by solar radiation. The performance of evacuated tube pre-heater system during the winter period in Sydney was close to that of the larger flat-plate stand-alone system.

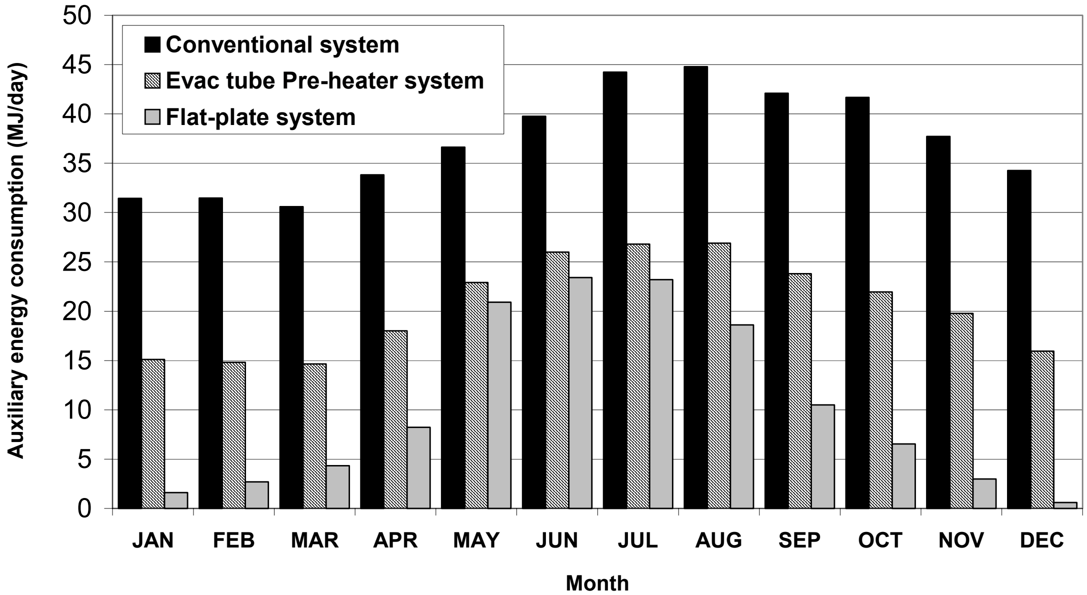

Figure 8 Comparison of auxiliary energy consumptions using conventional system, evacuated tube pre-heater system and flat-plate system in Sydney.

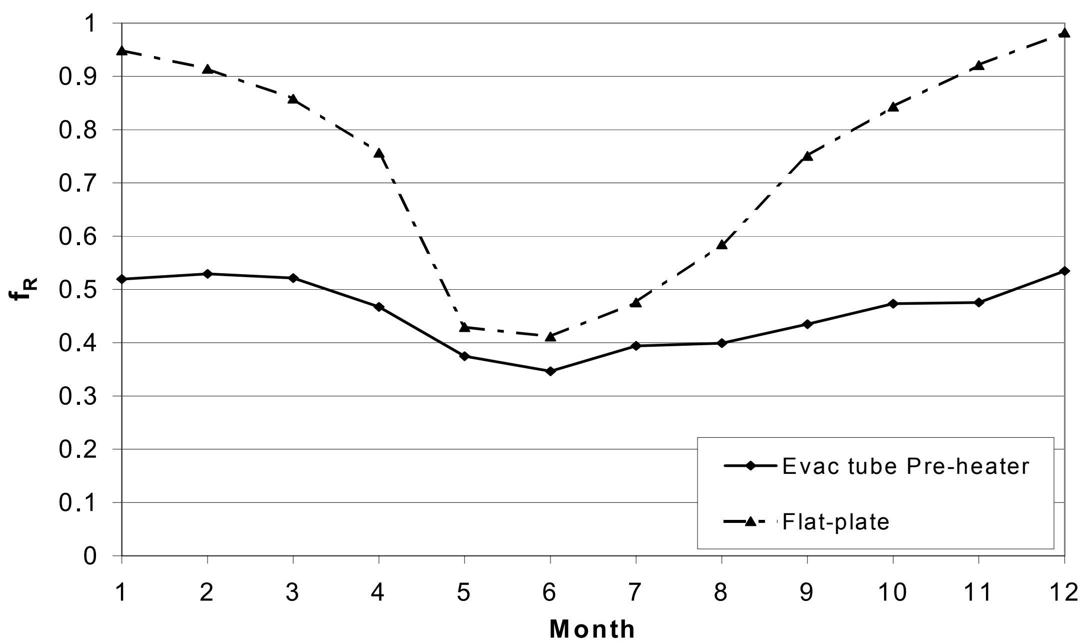

Figure 9 Solar contribution relative to a conventional energy source for the evacuated tube pre-heater system and a flat-plate system in Sydney.

5. CONCLUDING REMARKS

A simulation model has been developed to model the performance of a water-in-glass evacuated tube solar water heater. This paper outlines the modelling procedure of each component of the solar water heater, e.g. the collector efficiency, the tank heat loss coefficient and the natural circulation flow rate through the tubes. It is shown that as a pre-heater to a conventional 135-l tank system, this solar water heater gives 45% annual saving in Sydney.

6. ACKNOWLEDGMENT

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