

Performance of Water-in-Glass Evacuated Tube Solar Water Heaters

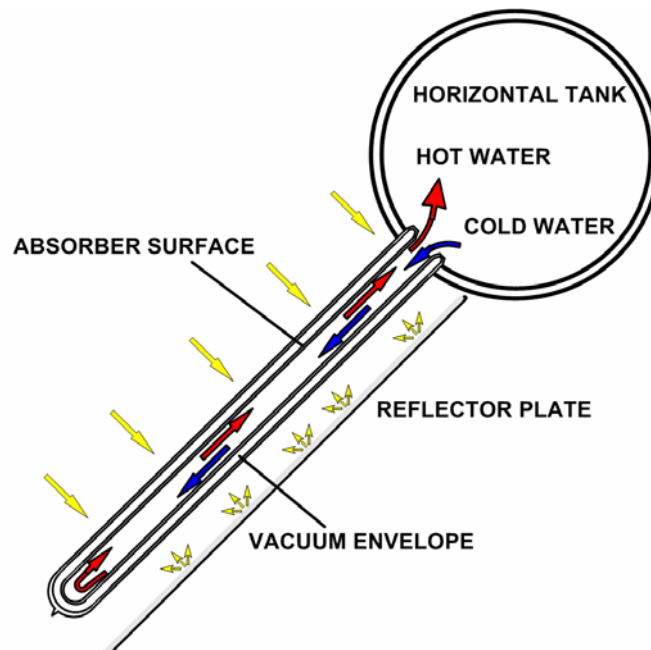
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Abstract

The performance of water-in-glass evacuated tube solar water heaters is evaluated using experimental measurements of optical and heat loss characteristics and a simulation model of the thermosiphon circulation in single-ended tubes. The performance of water-in-glass evacuated tube solar collector systems are compared with flat plate solar collectors in a range of locations. The performance of a typical 30 tube evacuated tube array was found to be lower than a typical 2 panel flat plate array for domestic water heating in Sydney.

1. INTRODUCTION

Evacuated tube solar collectors have higher efficiency than flat-plate collectors for high temperature operation because of reduced convection heat loss due to the vacuum envelope around the absorber surface, however for domestic water heating temperatures flat plate collectors usually have higher efficiency. The water-in-glass collector (Fig 1.) is the most widely used form of evacuated tube collector because it has higher thermal efficiency than other evacuated tube collectors employing metal-in-glass manifolds and has simpler construction requirements and lower manufacturing costs. A water-in-glass evacuated tube solar water heater typically consists of 15 to 40 flooded single-ended tubes in direct connection to a horizontal tank. The solar absorber tube consists of two concentric glass tubes sealed at one end with an annular vacuum space and a selective surface absorber on the outer surface (vacuum side) of the inner tube. The heat transfer in this collector is driven purely by natural circulation of water through the single-ended tubes. Water in the tubes is heated by solar



radiation, rises to the storage tank and is replaced by colder water from the tank.

Figure 1. Natural circulation flow in a water-in-glass solar water heater.

The performance of a solar water heating system is influenced by the product configuration and the local meteorological conditions. Solar water heaters can operate as a solar pre-heater in series with a boost tank or instantaneous gas heater or as a single-tank system with a boost element incorporated in the solar tank. The collector is usually mounted at a standard roof inclination, but can also be adjusted to optimise the performance during winter months when the hot water demand is the highest. The use of experimentation to study the effects of these parameters on the long-term performance of the system is expensive and time consuming. An alternative way to predict the long-term performance of a solar water heater is by transient system modelling. TRNSYS is a transient system simulation program that can be used to evaluate the performance of a solar water heater by simulating the performance of inter-connected solar water heater components i.e. collector, storage tank, heat exchanger, auxiliary heating and controller. A processor to compute the radiation on a given collector plane from a supplied weather data can also be incorporated.

This paper outlines the development of a simulation model of the water-in-glass evacuated tube system in TRNSYS. To model the water-in-glass solar water heater, an experimentation program and numerical modelling study were undertaken to characterise the system components i.e. collector optical efficiency, collector heat loss, storage tank heat loss and natural circulation flow rate through the single-ended water-in-glass collector tubes; the details of which have been presented in Budihardjo *et al.* (2003, 2005). The long-term performance of water-in-glass evacuated tube systems is predicted for a range of system configurations and operating conditions.

2. MODELLING WATER-IN-GLASS SOLAR WATER HEATERS IN TRNSYS

The primary difference in modelling a thermosyphon solar water heater and a pumped circulation system is the coupling between the heat transfer and the natural circulation flow rate computations. The natural circulation flow rate through the collector loop depends on the solar input and fluid temperature hence varies continuously across the day. In conventional thermosyphon solar water heaters, the circulation flow rate can be computed by equating the pressure head due to the density gradients in the loop and the pressure drop due to friction and the plumbing arrangement. The analysis of water-in-glass evacuated tube systems is more complex due to the unique relationship between the heat transfer and circulation flow rate through a single-ended tube. The difference in modelling a conventional thermosyphon solar water heater and the water-in-glass evacuated tube system in TRNSYS is outlined in this section.

A typical thermosyphon solar water heater consists of a collector and a storage tank connected by a downcomer and a return pipe. The storage tank is mounted above the collector to allow natural circulation to take place during the day and to prevent reverse circulation at night. The thermosyphon flow in the collector loop is driven by the weight difference between the hot fluid column in the return pipe and the collector risers and the cold fluid column in the downcomer. The circulation flow rate around the collector loop is influenced by the instantaneous solar input, fluid temperature and the collector configuration, i.e. piping arrangement and the distance between the tank and the collector. The simulation algorithm for this type of thermosyphon systems is incorporated into a standard Type 45 TRNSYS routine. The thermosyphon rate through the circuit is computed based on the difference of the weight of the hot and cold fluid columns and the frictional resistance along the loop. Temperature variations along the downcomer and the return pipes are calculated based on the circulation flow rate and the heat loss from the pipes. The temperature increase through the collector is determined from the useful energy gain from the collector and the circulation flow rate. The Darcy equation is used to compute friction pressure drop along the pipes, with pressure drop due to bends also accounted for. The circulation flow rate and temperature distribution around the loop are solved through iterative procedures until an energy balance and pressure balance in the loop is achieved..

The TRNSYS Type 45 routine for the conventional type thermosyphon solar water heating system cannot be used to simulate water-in-glass evacuated tube solar water heaters due to the different characteristics of natural circulation flow through the single ended collector tubes. The in-flow and out-flow from the tubes are from a single opening with a shear layer in between the opposite flows. For such a flow configuration the friction cannot be modelled analytically. The water-in-glass system has to be modelled as inter-connected components i.e. the storage tank (Type 60) and the collector (Type 1), with a model of flow circulation through single ended tubes as presented in Budihardjo *et al.*

(2005) used to connect the heat transfer and the circulation flow rate between the tubes and the tank. The incorporation of the circulation flow rate correlation into the water-in-glass evacuated tube solar water heater model is illustrated in Figure 2 and is the main difference from the conventional thermosyphon solar water heater analysis.

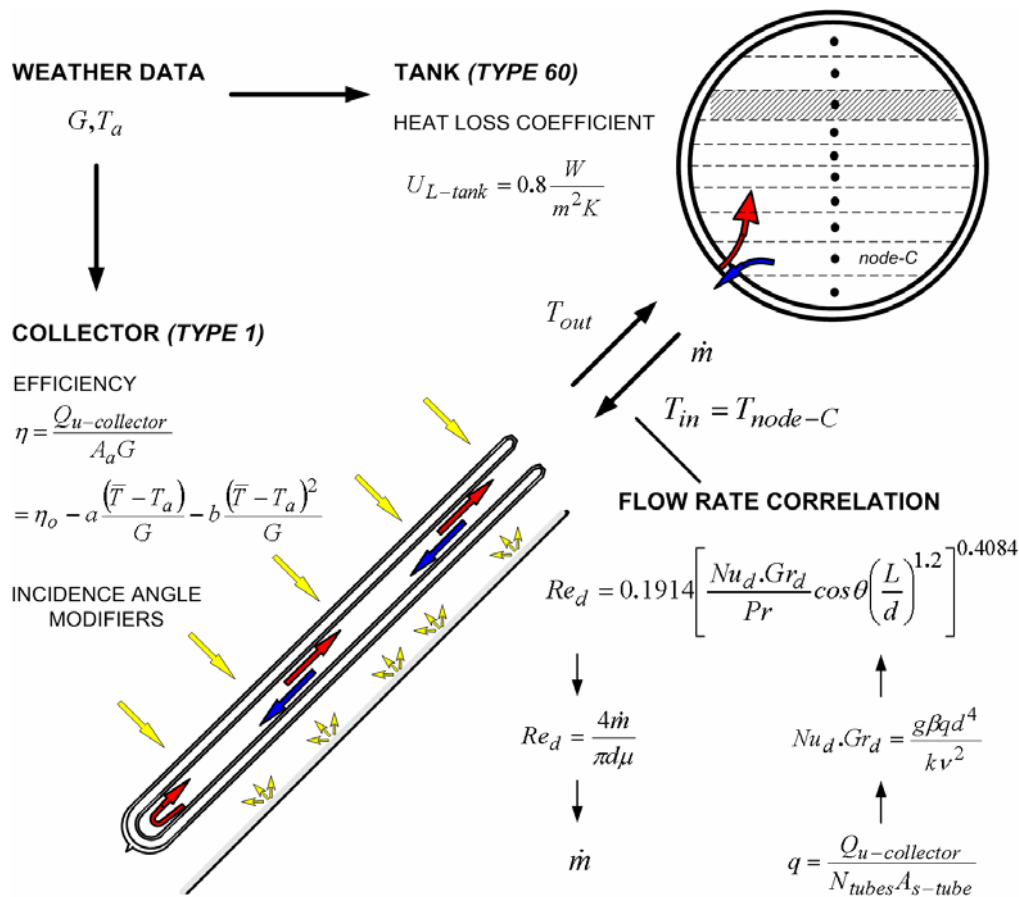


Figure 2. Water-in-glass evacuated tube system simulation model.

The steps in the performance evaluation of a water-in-glass evacuated tube collector are presented in Figure 3. At the start of each simulation, the tank is initialised to the required stratification condition. The inlet temperature to the collector is taken from the node temperature at the level of tube opening which may be well up the tank for low inclination tubes. The useful energy from the collector is computed from the efficiency equation and the radiation and ambient temperature. The efficiency equation is a function of the average collector temperature, which is unknown at the start of each simulation time step. The useful energy gain per tube is used with the Reynolds vs Nu.Gr correlation to compute the natural circulation flow rate through the collector. From the predicted collector flow rate and the useful energy gain, the temperature increase through the collector can be computed. The out-flow temperature is then compared to the guessed value and iterations are performed until an energy balance in the collector is achieved. Temperature distribution in the tank is updated at the end of each time step.

The TRNSYS Type 1 collector subroutine does not account for the thermal mass in the water-in-glass tubes. In this study the tube thermal mass is included in the tank. This leads to an assumption that the over night heat loss from the entire system (tubes and tank) occurs from the tank surface. When the system is used, the tubes are cold at the end of the day due to afternoon and evening draw-offs, hence differential heat loss between the tank and the tubes has negligible effect. .

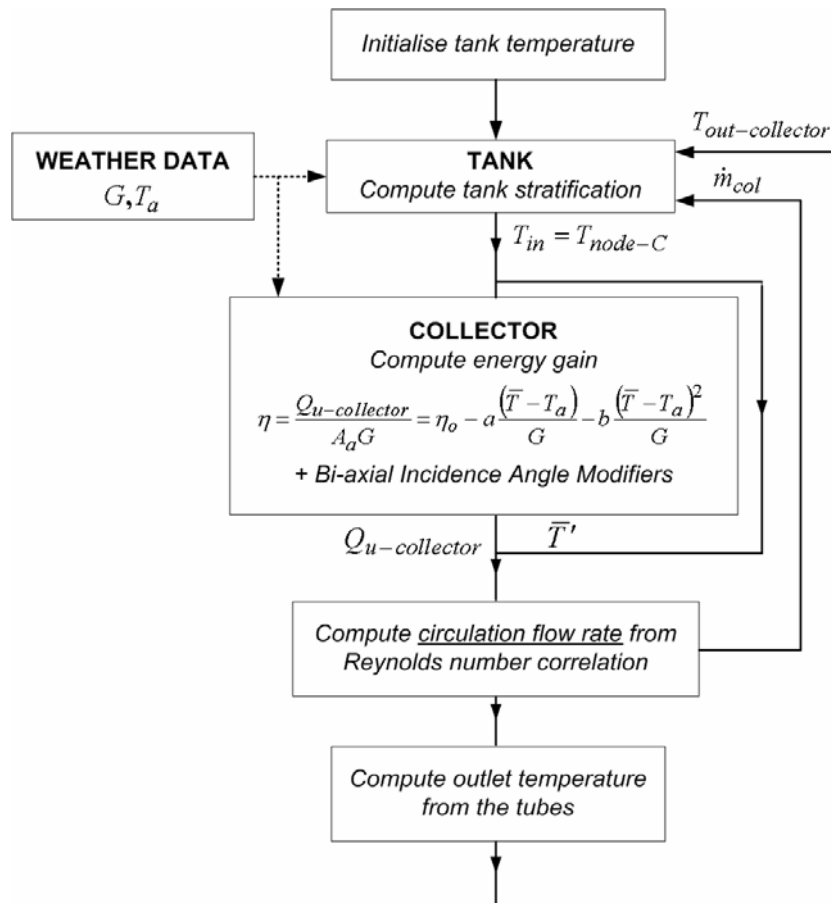


Figure 3. Computation procedure for a water-in-glass evacuated tube solar water heater.

3. COMPONENTS

3.1. Water-in-glass collector

There are three parameters which need to be defined in characterising a water-in-glass evacuated tube collector: optical efficiency, collector heat loss coefficient and the Incidence Angle Modifiers (IAMs). These parameters were determined from experimentations outlined in Budihardjo *et al.* (2003). The optical efficiency of the water-in-glass collector under test was found to be 0.536, determined from energy gain measurements across solar noon when the radiation level and incidence angle are approximately steady. The heat loss coefficient from the evacuated tubes (eqn. 1) varies with temperature, thus the efficiency of the collector is modelled as a second order equation as shown in eqn. (2). The coefficients in the heat loss terms in the efficiency equation were determined from tests done on individual tubes (Budihardjo *et al.* 2003).

$$\text{Tube heat loss coefficient: } \bar{U}_L = 0.00453(\bar{T} - T_a) + 0.540 \quad (1)$$

$$\text{Collector efficiency: } \eta = 0.536 - 0.8240 \frac{(\bar{T} - T_a)}{G} - 0.0069 \frac{(\bar{T} - T_a)^2}{G} \quad (2)$$

The optical efficiency of an evacuated tube array varies across the day depending on the configuration of the tube array, i.e. tube dimensions, tube spacing and the distance between the tubes and the reflector plane. The transverse incidence angle modifier of the water-in-glass collector under test is presented in Figure 4 (Budiharjo *et al.* 2003). The variation of the optical efficiency with longitudinal incidence angle is modelled as (Duffie and Beckman, 1991):

$$K_{\theta,L} = 1 - 0.1 \left(\frac{1}{\cos \theta} - 1 \right) \quad (3)$$

The total modifier is the product of the transverse and the longitudinal modifiers.

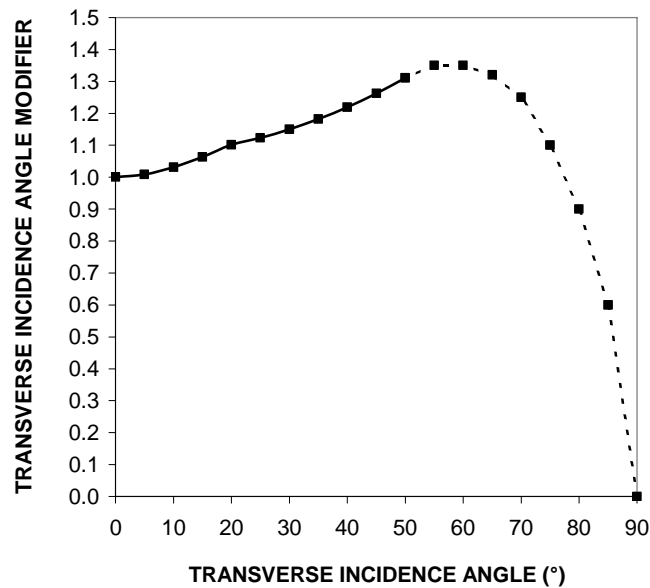


Figure 4. Transverse incidence angle modifier of water-in-glass evacuated tube collector under test.

3.2. Solar tank

The Chinese water-in-glass system under test uses a horizontal tank with an inner diameter of 360 mm and a volume of 153 L. The outlet port for the domestic load is located at the top of the tank and the replacement water from the mains enters the tank from the bottom. In the Type 1 solar collector model in TRNSYS, the thermal mass of water in the collector is not included in the computation. The mass of water in the 21 water-in-glass evacuated tubes accounts for approximately 15% of the total mass of the system hence cannot be neglected. Water in the 21 tubes (27 L) was added to the tank volume and the heat loss coefficient of the storage tank was adjusted to account for the increase in the surface area for the 180 L tank model.

In the simulation model, the tank was divided into 20 equal-volume segments. The effect of the number of segments on the predicted long-term performance was investigated by comparing the long-term performance to an 80-node tank model, and it was found that due to the high circulation flow rate in the tank, the top portion of the tank is relatively mixed during the day time, and therefore the number of nodes in the tank is not a critical factor affecting the accuracy of the computation.

3.3. Natural circulation flow rate correlation

The natural circulation flow rate through single-ended evacuated tubes depends on a number of factors, namely:

- *Heat input per unit absorber area.* Higher heat input results in higher density variation between the hot and cold streams in the tube, therefore higher driving pressure head.
- *Tank temperature.* The natural circulation through the collector is driven by the temperature difference between the hot and cold fluid. At higher temperature operation, the gradient of water density with temperature is higher, ie. for a given temperature increment, the change in density is higher at high water temperatures. Also, water viscosity is smaller at high temperatures. Within the operating range of the collector the variation of water viscosity is as high as a factor of three.

- *Collector inclination.* Collector inclination determines the axial and radial components of gravitational acceleration. The axial component of the gravity drives the primary natural circulation and the radial component determines the secondary circulation around the tube circumference. In general, inclination closer to vertical would result in higher natural circulation flow rates.
- *Tube length-diameter ratio.* This parameter is included in the Nusselt number correlation using the functional dependence suggested by Lighthill (1953) in the analysis of heat transfer in single-ended thermosyphons.
- *Circumferential heat flux distribution.* Varying the distribution of heat input around the circumference of the absorber changes the flow structure in the tube, and in turn affects the circulation flow rate.

The development of a correlation for natural circulation flow rate through water-in-glass evacuated tubes has been presented in Budihardjo (2005). The non-dimensional natural circulation flow rates (Re_d) obtained from both the simulation and experimental measurements were correlated as a function of the above-mentioned parameters as follows:

$$Re_d = a_0 \left[\frac{Nu_d \cdot Gr_d}{Pr} \cos \theta \left(\frac{L}{d} \right)^n \right]^{a_1} \quad (4)$$

where $a_0=0.1914$, $a_1=0.4084$, and $n=1.2$. In eqn. (4), the $Nu \cdot Gr$ term represents the average heat flux around the absorber, θ is the collector inclination from vertical and L/d is the tube length-diameter ratio. The coefficients a_0 , a_1 and the exponent n were determined using multiple linear regression of both the measured and simulated flow rate for single-ended evacuated tubes mounted over a diffuse reflector.

4. LOAD CYCLE SIMULATIONS

In this section, the long-term performance of water-in-glass systems used in three configurations is evaluated:

- Solar pre-heater in series with a 250-L electric boost tank
- Single-tank system with in-tank electric boost.

The long-term performance of the water-in-glass systems are compared to the long-term performance of a 3.7 m² flat plate collector with a high quality selective surface absorber mounted at 22° roof inclination. The collector is coupled to a mantle heat exchanger tank with 300 L storage volume, 450 mm diameter and 5 mm mantle gap. Two water-in-glass evacuated tube system sizes are evaluated: A 21-tube collector with 153-L tank (total volume = 180 L) and a 30-tube collector with 220-L tank (total volume = 258.5 L). The configuration of the water-in-glass collector is the same for all system simulations (tube length = 1420 mm, tube diameter = 34 mm, tube spacing = 70 mm) and the benchmark tank diameter is 360 mm. The tank size is proportional to the number of tubes and the collector aperture area. The water-in-glass system is simulated in Sydney, Melbourne, Darwin and Jakarta to evaluate the performance under different climatic conditions. In simulations in Sydney and Melbourne, the effect of varying collector inclination from a standard roof inclination of 22° to a winter-biased installation of 45° is investigated; for low latitude regions i.e. Darwin and Jakarta only shallow inclination is investigated. The seasonal load pattern for Sydney, Melbourne and Darwin is adopted from AS 4234 (1994) for peak winter energy delivery of 40 MJ/day. In Jakarta, the monthly average hot water consumption is approximately constant across the year because of the uniformity of weather conditions in the tropical climate, hence a constant monthly load pattern that gives the same total load as the other three cities is adopted. The daily load pattern used for the load-cycle simulations is also adopted from AS 4234 (1994).

The performance of a solar water heater is usually assessed by calculating the annual energy saving compared to a conventional electric water heater. The benchmark electric system has a storage volume of 250 L, UA of 1.9 kWh/day and a 3.6 kW heater element positioned at the bottom of the tank.

The energy saving, also referred to as solar fraction (f_R) can be computed as:

$$f_R = \frac{Aux_C - Aux_S}{Aux_C} = \frac{L + Q_{loss-C} - Aux_S}{L + Q_{loss-C}} \quad (5)$$

where: Aux_C = auxiliary energy consumption of a conventional water heating system,

Aux_S = auxiliary energy consumption of a solar system,

L = load energy,

Q_{loss-C} = heat loss from a conventional water heating system,

To compute the solar fraction of a solar water heating system, comparison has to be made between the auxiliary energy consumption by the solar system and the auxiliary energy consumption by the alternative conventional system. In a conventional system, the auxiliary energy consumption can be computed as the sum of the domestic load and the heat loss from the boost tank.

5. ANNUAL PERFORMANCE OF WATER-IN-GLASS SOLAR WATER HEATERS

5.1. Comparison of different system configurations

The performance of a selective flat plate system and two configurations of water-in-glass systems with 30 tube, 2.9 m² collector array at 22° inclination and 220-L tank operating in Sydney are compared in Fig 5. The flat plate system has an annual energy savings of 77%, the single-tank evacuated tube system has an annual saving of 70.9% and evacuated tube solar pre-heater with a boost tank has a savings of 66.2%. Flat-plate collectors usually benefit from separating the solar tank and the boost tank which results in improved stratification and as a result increased collector efficiency. This study shows that although operating at lower temperatures due to a larger solar volume, the performance of the pre-heater evacuated tube system with a separate boost tank is lower than the single-tank system. This is because the heat loss from evacuated tube collectors is small and the additional heat loss from the boost tank outweighs the advantage of having the collector operating at a lower temperature.

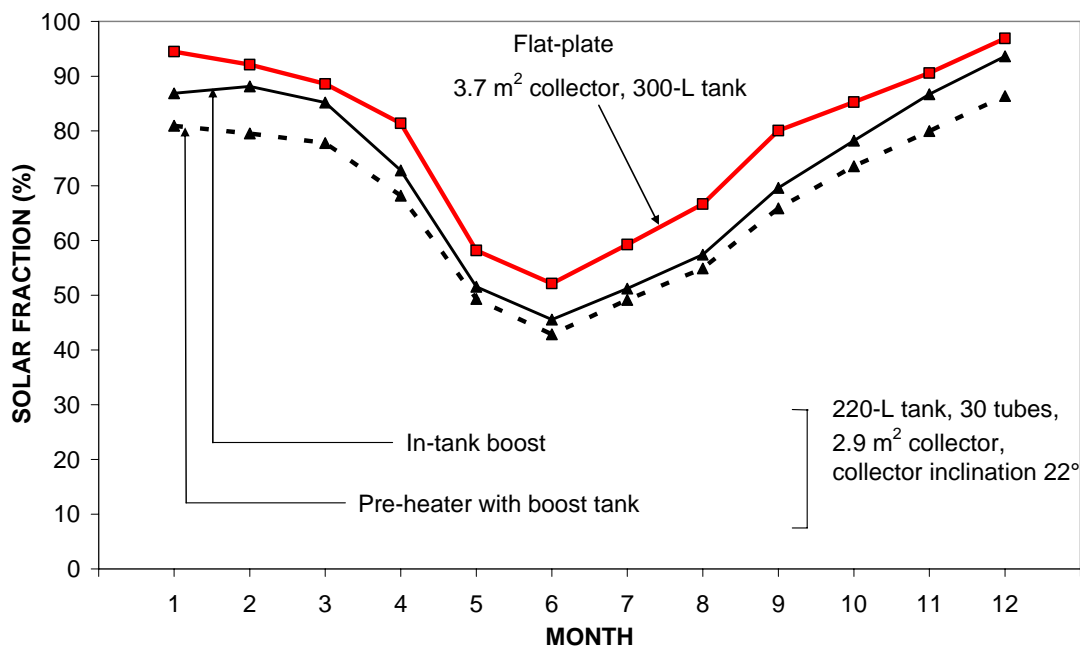


Figure 5. Comparison of the performance of 220L water-in-glass system with 30 tube, 2.9 m² collector array and a 300L flat-plate system with 3.7 m² collector both at 22° inclination in Sydney.

The performance of the 30-tube water-in-glass system used as a single-tank system is similar to a 300-L flat-plate system with a 3.7 m² collector. The annual solar fraction of the flat-plate system is 77.6%, out-performing the evacuated tube collectors because of the larger collector area. The purpose of this investigation is not to compare the performance of flat-plate and evacuated tube collectors of the same absorber quality and size, since an evacuated tube collector of the same size (3.7 m²) as the flat plate collector would overheat during summer periods. Instead, it aims to provide a reasonable evacuated tube collector size as an alternative to the typical flat-plate collector used in Australia. The single-tank system operates with a heater element located half-way up the tank. The hot water storage regulation, AS1056 (1991), requires the top (boost) portion of the tank to exceed 60°C at least once a day to avoid legionella growth. During the TRNSYS simulations, it was observed that the average temperature of the boost portion was above 60°C for most of the year.

5.2. System size

The effect of the product size on performance in-tank boost evacuated tube systems is shown in Fig 6. Performance is shown for a small 153L tank with 21 tube, 2.1 m² collector array and a 220L tank with 30 tube, 2.9 m² collector array in Sydney and Melbourne for collector inclination of 22°. For operation in Sydney, the annual solar fraction increases from 57.5% to 70.9% when the larger system is used. The annual savings in Melbourne are 48% and 58% for the small and large systems.

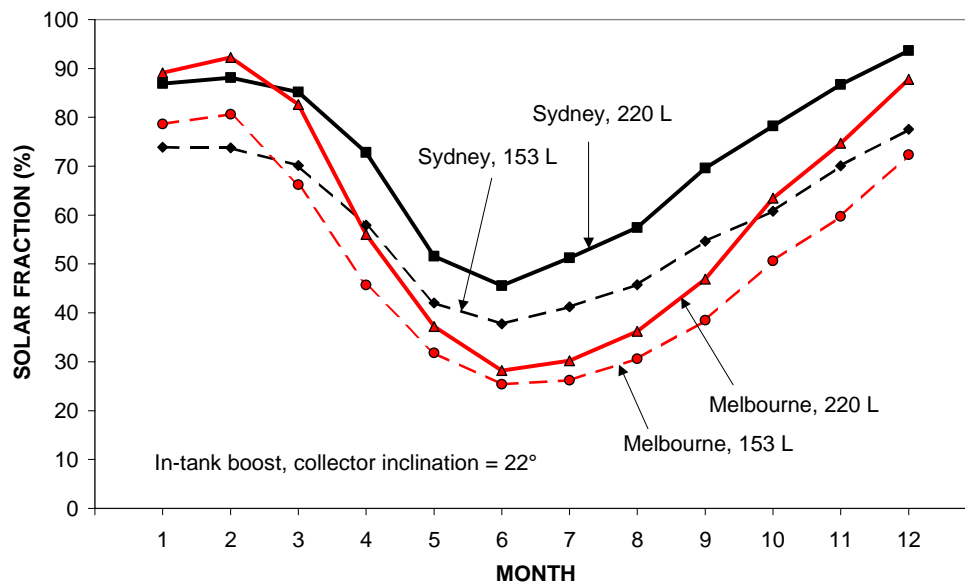


Figure 6. Monthly solar fraction of single-tank systems with in-tank boost, collector inclination = 22° and different system sizes in Sydney and Melbourne.

5.3. Performance in different locations

The performance of a 220-L 30 water-in-glass tube system in Sydney, Melbourne, Darwin, Auckland and Jakarta is shown in Figure 7. In Sydney and Melbourne, the monthly saving for collector inclination of 22° during the summer months is approximately 90%. During the winter, the monthly saving in Sydney is 45%, while in Melbourne the winter saving is 29%. The performance in Auckland was equivalent to Sydney in summer and between Sydney and Melbourne in winter. The annual performance in Auckland is approximately 60%. The 220-L single-tank system gives an annual solar fraction of 92.4% in Darwin, with excessive energy being dumped between April and June. The variation of solar fraction across the year in Jakarta is similar to the monthly variation in Darwin, however, the annual solar fraction in Jakarta (58.9%) is significantly lower than Darwin because of the relatively low irradiation level in Jakarta.

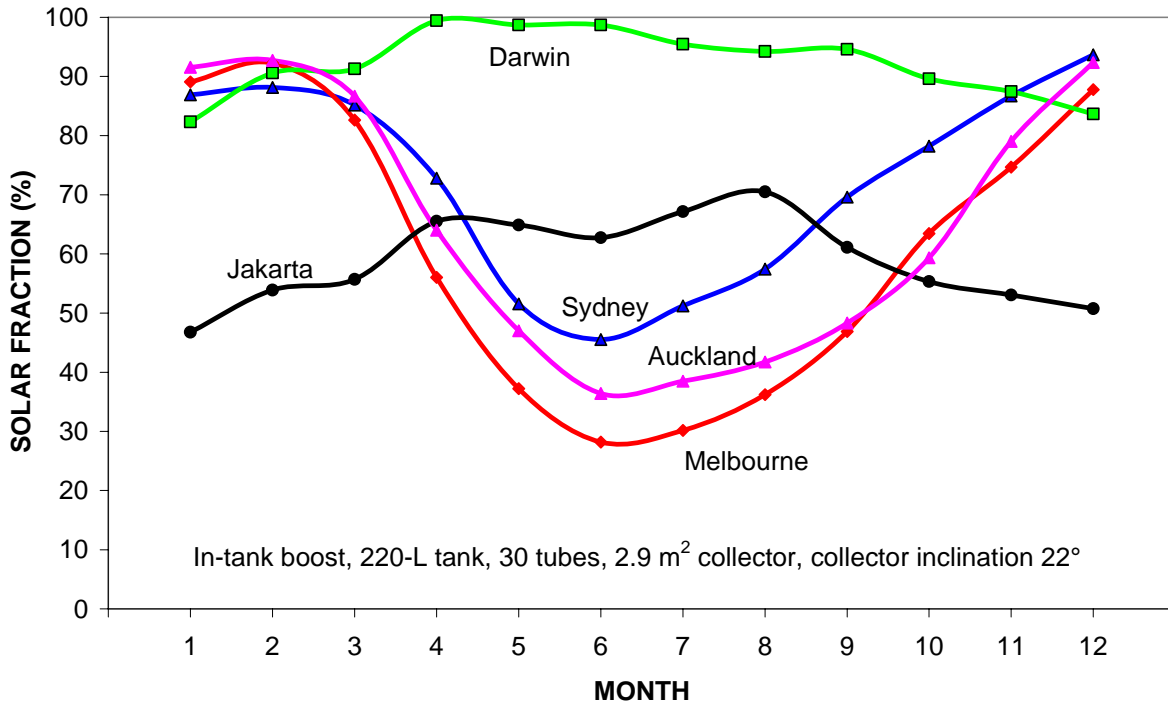


Figure 7. Monthly solar fraction for 220L single-tank water-in-glass system with a 30-tube 2.9 m² collector mounted at 22° inclination in Sydney, Melbourne, Auckland, Darwin and Jakarta.

5.4. Effect of collector inclination

Figure 8 shows the effect of varying collector inclination for a 220 L, 30 tube single-tank system with 2.9 m² collector in Sydney. When the collector inclination is increased to 45°, the annual saving during winter months is 12% points higher than when the collector is inclined at a standard roof inclination of 22°. When the collector is inclined at a smaller angle to horizontal, the portion of the cold volume below the level of the evacuated tube opening increases and the solar portion in the tank is reduced. For a flat-plate collector, it is important that the solar portion in the tank is big enough to avoid circulation of the boost volume into the collector. Experimental and numerical studies by Budihardjo *et al.* (2005) showed that the circulation rate through a 21 evacuated tube array was of the order of 3-4 tank volume exchanges per hour, hence the circulation of boost volume into the collector cannot be avoided. This factor is not critical to the performance of evacuated tube collectors since the heat loss due to high temperature collector operation is small. The annual solar fraction of the water-in-glass system with a winter-biased collector is 1.5% higher than the solar fraction with a standard 22° collector inclination.

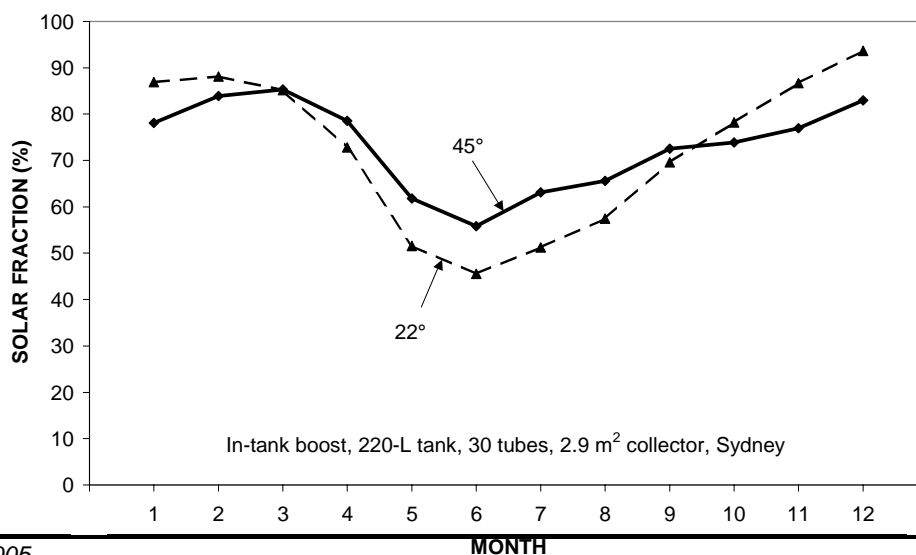


Figure 8. Monthly solar fraction for 220 L single-tank system with in-tank boost in Sydney for north-facing collector with inclinations of 22° and 45°.

5.5. Effect of increasing solar volume in the tank

To investigate the effect of increasing the solar volume in the tank, the performance of a water-in-glass system with a 21-tube, 2.1 m² collector area at 22° inclination and 220-L, 430 mm diameter tank was simulated in Sydney as a solar pre-heater and as a single-tank system with in-tank boost. The adoption of a larger solar tank in a pre-heater system results in a slight decrease in annual solar fraction, indicating that the improvement of collector performance due to lower temperature operation is not sufficient to compensate the increase in heat loss from the larger tank. Due to the very low heat loss from the evacuated tubes, the penalty from operating the collector at higher temperatures with a small tank is not as significant as the increased heat loss from a larger tank. For a single-tank system with in-tank boosting increasing the solar preheat volume under a fixed boost volume results in a very small increase in annual performance.

6. CONCLUSIONS

A procedure for simulating the performance of water in glass evacuated tube solar water heaters has been developed. Comparison between water-in-glass evacuated tube solar water heaters and flat plate systems operating in Sydney shows that an evacuated tube system with 30 tubes has slightly lower energy savings than a two panel (3.7 m²) flat plate system. The performance of evacuated tube collector system was shown to be less sensitive to tank size than flat plate collector systems

7. REFERENCES

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