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Optimization of Thermosyphon Solar Water Heaters Using TRNSYS. Part2: Parametric Study Using a Modified TRNSYS Model

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Abstract. This paper is concerned with the use of TRNSYS to study the effect on performance of the design parameters of a direct thermosyphon solar water heater. Changing some design parameters in the current version of the Type45 model in TRNSYS16 without incorporating the accompanied changes in the main collector and tank characteristics performance ($F_R\tau\alpha$, F_RU_L , UA_t) will probably led to inaccurate or incorrect results. In this study, a validated modified TRNSYS model that takes into account the changes in the collector and tank performance characteristics when changing some related design parameters is used. The study has shown that the modified TRNSYS model gives wider choices for conducting system parametric studies than is possible with the original TRNSYS model. The modified version is capable of use as a tool for optimizing the design of thermosyphon solar water heaters.

Keywords: thermosyphon solar water heaters, parametric study, TRNSYS.

1. Introduction

Many studies [[1]-[9]] have used the thermosyphon component model Type45 in TRNSYS to evaluate the performance of existing thermosyphon systems under different weather conditions and different usage data. However, only a few studies [7],[9] used TRNSYS to study the effect of the design parameters of a thermosyphon system on its performance. This could be attributed to the fact that, thermosyphon component Type45 contains many experimentally-determined values ($F_R\tau\alpha$, F_RU_L , b_o , $U1$,$U2$, UA_t); changing the design parameters of the system will change these values, whereas in the current TRNSYS model they are assigned as fixed values. None of the above studies have reported any changes to the experimentally-determined information when they changed the design parameters of the system under investigation.

In part1 of this two part paper, two new components were added to TRNSYS in order to predict theoretically the information that is normally experimentally-determined. These components are Type210: collector characteristics and Type211: pipe-tank heat loss coefficient. The new components were added to the modified thermosyphon-collector component Type245 that, in turn was connected to other components to constitute a new TRNSYS model for evaluating thermosyphon systems. The new TRNSYS model is referred to as the Modified TRNSYS Model (MM). The modified TRNSYS model was validated by comparison to the original TRNSYS model, the study showing that the maximum error in estimating the yearly solar fraction is less than 5%. In this part of the study, the modified TRNSYS model is used to investigate the effect on system performance of changing system design parameters.

The optimum design of a thermosyphon solar water heater system depends on many factors, such as weather conditions, operating conditions, and design parameters. These factors cannot be optimised separately to arrive at an optimum system design because they are strongly interrelated. The aim of this study

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is to use the modified TRNSYS model to investigate how each thermosyphon system design parameter behaves as its value is varied. This is conducted for fixed weather data and operating conditions.

2. Parametric Study

TRNSYS is equipped with a very powerful tool for conducting parametric studies that permits the testing of various parameters of different values in the same simulation run. However, in the current TRNSYS Type 45 model, caution is required in selecting the studied parameters as some of them are interrelated. For example, altering the number of risers, riser diameter or collector aspect ratio is likely to affect the collector performance characteristics $F_R\tau\alpha$ and F_RU_L. In the current TRNSYS Type45 model these are kept fixed throughout the run because they are determined experimentally. This, in turn, will lead to less accurate or possibly incorrect results, as well as limiting the number of parameters that can be studied.

In this investigation, the Modified TRNSYS Model (MM) is employed. This model permits variation in the system parameters that would otherwise have remained fixed. The modified TRNSYS model comprises the modified thermosyphon-collector component Type245, collector characteristics component Type210, pipe-tank heat loss component Type211, weather data component type109, load profile, in addition to flow mixer, output and utility components these are depicted in Figure 1.

The Modified TRNSYS model would be expected to give good predictions and to allow more parameters to be investigated. These aspects are addressed in this paper.

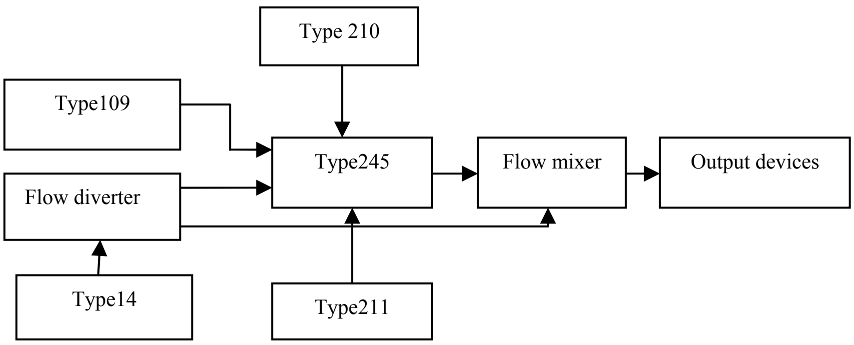

Figure 1 Schematic diagram of the major components of the Modified TRNSYS Model

3. Methodology

The study is conducted on a thermosyphon system assumed to be located in Libya, and with a specification as listed in Table 1 (all terms are defined in the Nomenclature). The daily quantity of hot water withdrawn is taken to be 130 litres at a temperature 60 ºC and according to a simple load pattern as shown in Figure 2. Weather data for Tripoli Airport-Libya as provided by TRNSYS is used in this study.

In this paper, annual solar fraction is used as the metric to represent the thermal performance of the thermosyphon system, and is defined as the ratio between the annual energy supplied by the solar resource to the total energy required for the load over the same period. In this investigation the design parameters examined are: riser diameter, number of risers, collector aspect ratio (collector length/ collector breadth), tank volume, and tank aspect ratio (tank height/ tank diameter).

4. Results and Discussion

4.1. Effect of Number of Risers

The effect of number of risers on the collector and the system are very important from the point of view of the thermal performance and the cost. In fact, there is an optimum number of risers that result in maximum collector efficiency. Increasing the number of risers beyond the optimum will increase the losses from the collector and, in turn reduce the efficiency [10]. The optimum number of risers of the collector might not be the same if the collector is incorporated in a thermosyphon system. Figure 3 shows the behaviour of the system solar fraction as the number of risers in the collector is increased. There is clearly a sharp increase in the system solar fraction for small number of risers until number of risers reaches five in number. Beyond this value, a very slight decrease in solar fraction is observed followed by more or less constancy.

Table 1: Thermosyphon system features

Ac	2.272 m^2	V_t	95 lit
$F_R\tau\alpha$	0.679	UA_t	6.78 kJ/h
F_RU_L	13.77 kJ/h m^2	$U1, U2$	8.79 kJ/h m^2 k
G_{test}	72 kg/h m^2	V_{load}	130 Lit/day
Dr	6.4 mm	H_t	0.60m
D_h	22 mm	H_r	0.55 m
Nr	8	H_{th}	0.50m
D_i, D_o	22 mm	H_{aux}	0.45 m
Hc	1.38 m	$NB1, NB2$	4
H_o	1.54 m	P_{aux}	10 MJ/h
L_h	1.087	T_{main}	20 ºC
L_i	2.5 m	T_{set}	60 ºC
L_o	1.5 m	β	43 deg

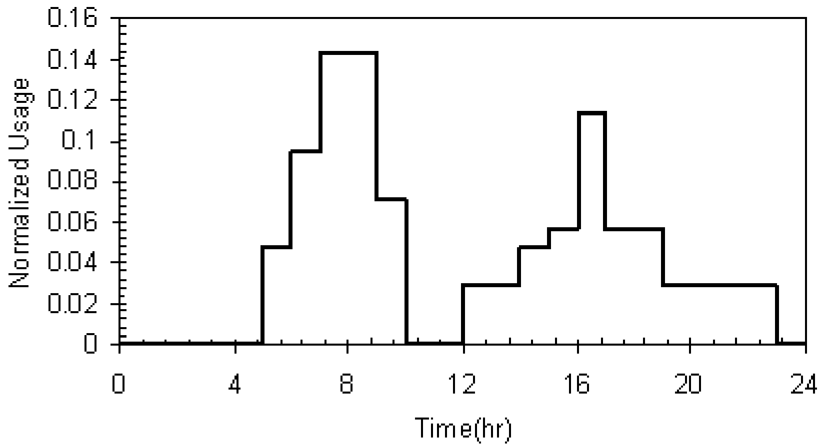

Figure 2: Hot water load pattern used for the study

4.2. Effect of Riser Diameter

The effect of increasing riser diameter on the thermosyphon system performance is shown in Figure 4. At very small riser diameters of less than 4 mm, the increase in riser diameter is accompanied by a sharp increase in the system solar fraction. However, behind 4 mm diameter, the increase in riser diameter causes a reduction in the solar fraction until a riser diameter of 10 mm is reached. Beyond this value, riser diameter has an insignificant effect on the solar fraction of the system being considered.

Figure 4 suggested that the optimum riser diameter is between 3.0 and 5.5 mm for the system in question which is very small in practical terms. In practice such diameters are to be avoided in order to prevent bore narrowing and loss of performance that might result from scaling.

4.3. Collector Aspect Ratio

The effect of the aspect ratio of the collector on system performance investigated for two cases, i) keeping number of risers fixed per unit area and changing the distance between the risers(W), and ii) keeping the distance between the risers fixed and changing the number of risers by changing the aspect ratio of the collector. The results are shown in Figure 5. In case i), (the broken line), the system performance increases gradually by increasing the aspect ratio or by changing the ratio of number of risers per collector breadth

(Nr/Wc) (in this case fixing the number of risers (Nr=8) and changing the width of the collector). This has similar effect as increasing the number of risers at one aspect ratio as shown in Figure 3.

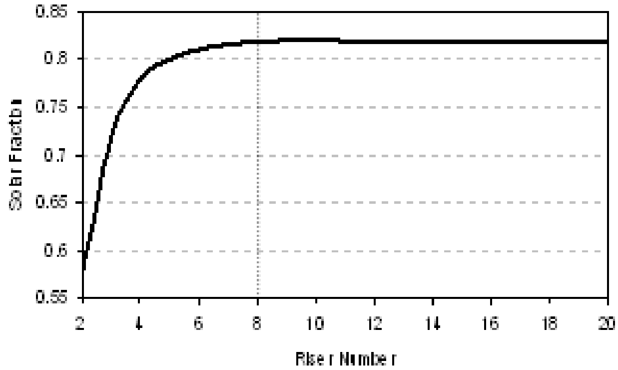

Figure 3 Effect of number of risers on the system solar fraction

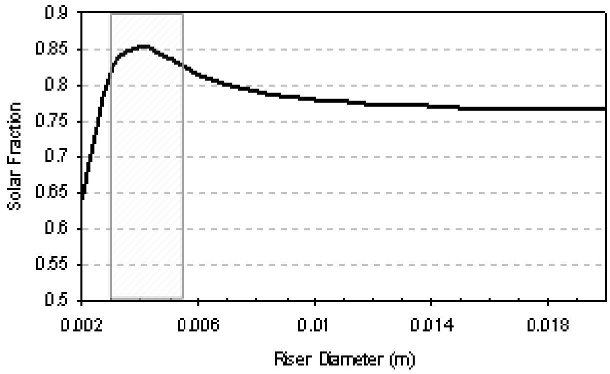

Figure 4 Effect of riser diameter on the system solar fraction

From Figure 5 it can be seen that increasing the aspect ratio will increase the solar fraction of the system in the case of fixing the number of risers in the collector. However, this increase might become undesirable from the point of view of aesthetics and handling problems.

In case ii), changing the number of risers per unit area while keeping the distance between the risers fixed (Nr/Wc=const) shows a steady improvement in the solar fraction as the aspect ratio of the collector increases. Beyond an aspect ratio of about 1.2 almost the same performance is obtained for both cases, as well as insignificant further increase in solar fraction. It can be deduced that increasing the collector length of the tested collector beyond the aspect ratio of 1.2 provides little improvement to the thermal performance of the system, and might be aesthetically unacceptable if the system was to be installed on flat roofs.

The results shown in Figure 5 for the case of fixing distance between risers agree to some extent with the results reported by Kirchhoff and Billups [11] where they reported that " plates designed for thermosyphon operation should be on the order of 1 meter in length to take advantage of increased efficiency without excessive loss of outlet temperature". It is clear that the increase in the system performance (solar fraction) beyond the value where the length of the collector is of the order of 1 meter (Lc/Wc =0.44) is less than 5%.

4.4. Effect of Tank Aspect Ratio

Changing the aspect ratio of the tank is likely to change the value of the overall heat loss coefficient between the tank and its surroundings. In TRNSYS Type45 the value of the tank loss coefficient is determined experimentally for a particular tank, hence changing the aspect ratio will change the surface area of the tank and, in turn the heat loss coefficient will also change. This is shown in Figure 6.

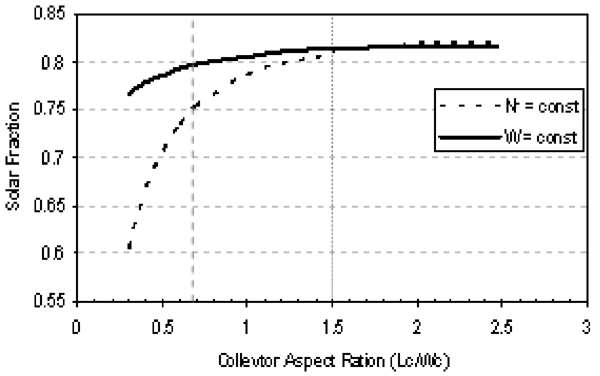

Figure 5 Effect of changing aspect ratio of the collector on the solar fraction

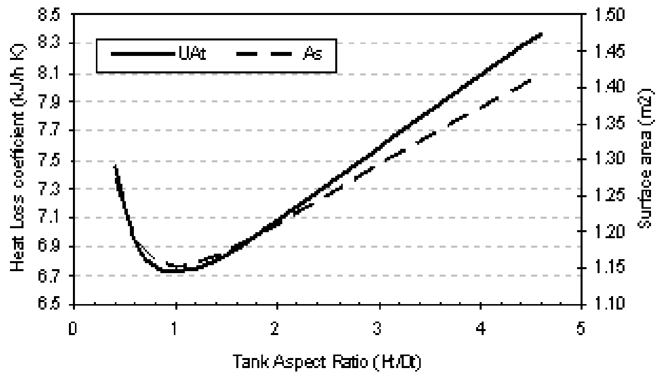

Figure 6 effect of aspect ratio on the heat loss coefficient

The minimum surface area of any cylindrical shape can be determined at aspect ratio (*Ht/Dt*=1) which is likely to give the minimum heat loss from the tank. However, does this configuration give the optimum performance when the tank is connected as part of the thermosyphon system, in view of stratification and thermosyphon head? In this context, Figure 7 (continuous line) shows that the optimum performance occurs when the tank aspect ratio is between 2 and 4 instead of an aspect ratio of 1 that would give minimum heat loss. This implies that stratification and thermosyphon head play an important role in the system performance. Decreasing the solar fraction beyond aspect ratio 3.7 is probably due to the increase of the heat loss from the tank. The heat loss coefficient can be minimized by increasing the insulation thickness as shown in Figure 7 (solid line) where UA_t is kept constant as given in Table 1. The results of Figure 7 (solid line) agree with the experiments of Hariharan etal. [12] who they found from the range of experiments carried out that the optimum value of *Lt/Dt* is between 3 and 4. Figure 7 is generated for the case of an auxiliary heater positioned in the tank 15 cm down from the top of the tank. However, many systems available in the marked with different auxiliary heater positions. Therefore, Figure 8 was generated to show different scenarios of the auxiliary heater position. It can be seen that the auxiliary heater position has a great influence on the system performance, and putting the auxiliary heater as high as possible in the tank is the most important if there is no any technical restrictions.

It can also be deduced from Figure 7 and Figure 8 that increasing the height of the tank will improve the system efficiency due to the improvement in the tank stratification and the thermosyphon head. Hence, it illustrates the advantages of vertical tanks over horizontal ones.

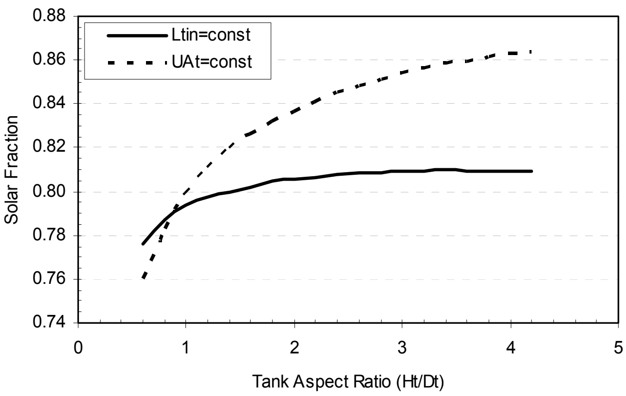

Figure 7 Effect of the tank aspect ratio on the solar fraction of the system

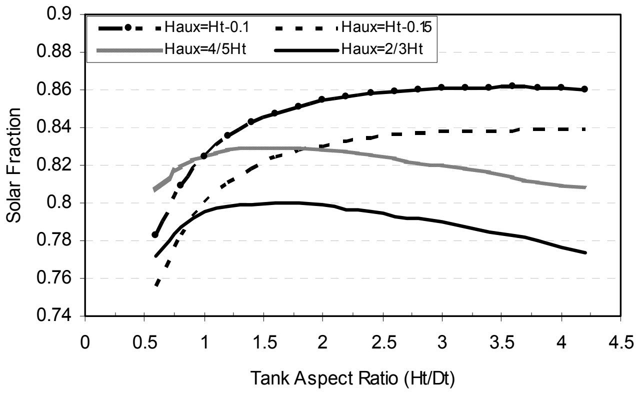

Figure 8 Effect of the tank aspect ratio on the solar fraction of the system

4.5. Effect of Tank Volume

Let us see what is the possible right volume of the tank in our case of drawing 130 lit per day at 60 ºC according to the load pattern shown in figure 2. as we have seen from figure 7 that the aspect ratio of the tank has a significant effect on the system performance, therefore, in this case different aspect ratios are considered for all different volumes. The effect of increasing tank volume on the system performance is shown in figure 9.

It can be seen that, the optimum tank volume would be around 90 litter (at *Ht/Dt*=3)when the daily hot water withdrawn was 130 lit at 60 ºC but also can be between 100 to 120 litter for other aspect ratio. Also increasing the volume behind 90 litter reduces the solar fraction of the system significantly. Let us see what is going to happen if we increased the amount of hot water withdrawn from the system. Figure 10 shows the optimum tank volume in case of the daily hot water withdrawn is increased to 180 litter, the optimum tank volume would be also around 110 litter. However, the system solar fraction reduced from 84% to 74.5%.

Of course, increasing the amount of energy withdrawn from the same system will reduce the solar fraction. Therefore, Figure 11 shows the effect of reducing the withdrawal hot water temperature to 45 C instead of 60 C and keeping the same energy extracted from the system by increasing the quantity of water withdrawn from 130 Litres to 208 Litres. Unexpected results are obtained, the maximum system solar fraction is reduced by 3.5% and the optimum tank volume is almost the same.

From the previous results and discussion, the question of the effect of the collector area rises itself. The effect of collector area (adding another collector to the system with the same specifications) on the optimum tank volume and solar fraction is shown in Figure 12. It is clear that, the optimum tank size would be around 140 litter which is bigger than the size in the first case. That means the collector area is more important in determining the optimum tank volume than the quantity of hot water withdrawn from the system.

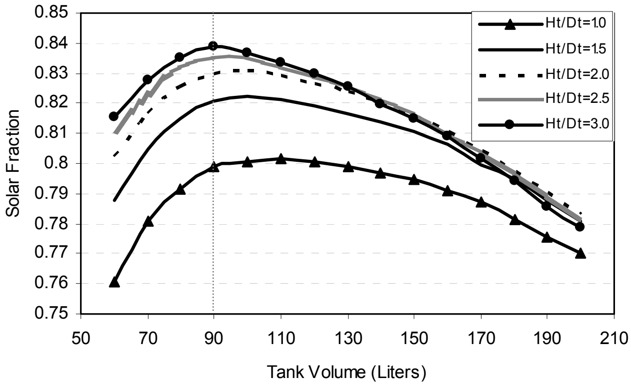

Figure 9 the effect of tank volume on the system solar fraction

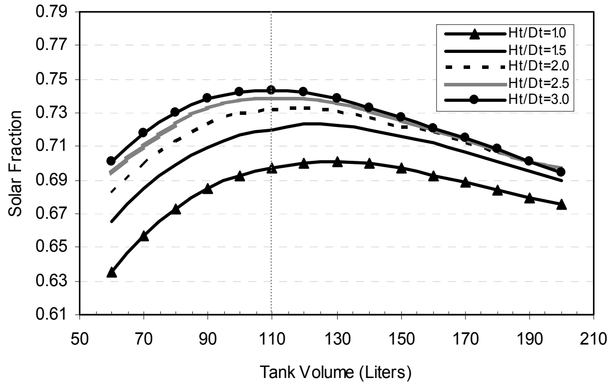

Figure 10 Effect of tank volume on solar fraction when the daily draw is 180 lit

Finally, it is become clear from the previous figures and the discussion that the strong interaction between different design parameters and their effect on optimal system design. Ultimately, the demand to conduct a multi-parameter optimization that takes into consideration the interaction between the design parameters, weather condition and usage data to find the optimum combination parameters is very important in such cases. This will be the work of the next paper by using genetic algorithm as an optimization technique.

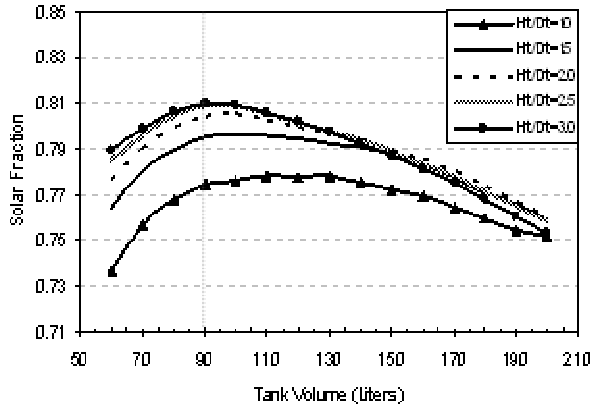

Figure 11 Effect of tank volume on the system solar fraction at different tank aspect ratio

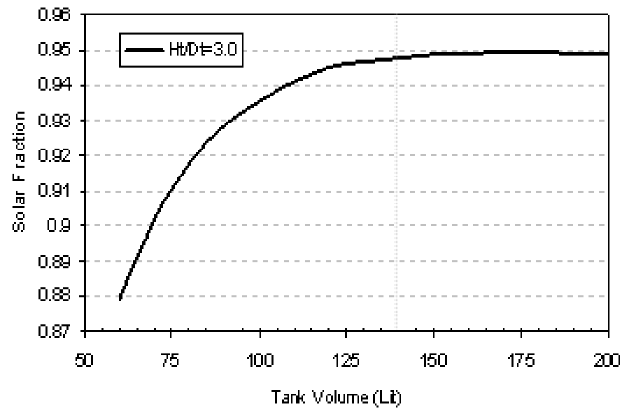

Figure 12 Effect of tank volume on solar fraction when the area of the system is doubled

5. Conclusion

Two new components were added to TRNSYS to be used with the modified Type45 to account for the experimentally determined information ($F_R\tau\alpha$, F_RU_L, b_o, $U1$, $U2$, UA_t) and a slight modifications were also made to type45 to accept the above data as an inputs instead of parameters. The modified TRNSYS model was used to conduct a parametric study on the design parameters of thermosyphon solar water heater.

The effect of different design parameters, such as number of risers, riser diameter, collector aspect ratio, tank volume and tank aspect ratio on the system solar fraction were studied and their behaviors are shown on figures.

The ultimate conclusion of the study shows that conducting a single variable optimization without considering the interaction between weather condition, design parameters, and usage data will not give the right system design for that particular condition. However, considering the effect of all the above factors simultaneously by conducting multivariable optimization technique is the only way to get the optimum design system.

6. Nomenclature

Ac	Collector area m^2	*Lc*	Collector Length (m)
D_h	Header diameter (m)	L_h	Header length (m)
D_i, D_o	Inlet and outlet connecting pipes diameter (m)	L_i, L_o	Length of inlet and outlet pipes (m)
Dr	Riser diameter (m)	*Ltin*	Tank insulation thickness (m)
Dt	Tank diameter (m)	*NB1, NB2*	Number of equivalent right angle bends in inlet and outlet connecting pipes.
$F_R\tau\alpha$	Intercept of the collector efficiency curve	*Nr*	Number of risers
F_RU_L	Slope of the collector efficiency curve	P_{aux}	Auxiliary energy input to tank (KJ/hr)
G_{test}	Collector flow rate at test condition (kg/s m^2)	T_{set}	Auxiliary heater setting temp (°C)
H_{aux}	Auxiliary heater position height (m)	UA_t	Overall UA value for tank (KJ/hr ° C)
Hc	Collector perpendicular height (m)	*U1,U2*	Loss coefficients for inlet and outlet pipes (KJ/hr m^2 ° C)
H_o	Height from datum to the tank bottom (m)	V_{load}	Hot water load (Lit/day)
H_r	Upriser height from the tank bottom (m)	V_t	Tank volume (Lit)
H_t	Tank height (m)	*Wc*	Collector Width (m)
H_{th}	Thermostat position height (m)	β	collector tilt angle (deg)

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