Comparative Studies of Built-in-Storage Solar Water Heaters

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ABSTRACT

Comparative studies of two built-in-storage-type solar water heaters with different storage configurations were conducted under identical operating conditions. One solar water heater is rectangular and the other is triangular; each has one glass cover, 0.7 m^2 of absorbing area, and approximately 75 litres of water storage capacity.

Results of the tests conducted between 9.00 a.m. and 4.00 p.m. with a mean global solar radiation of 550 W/m^2 (200 - 900 W/m^2) showed that the average efficiencies of the rectangular and triangular solar water heaters were 59% and 63%, respectively. The estimated effective heat transfer coefficients for both types were in the range of 80 - 140 W/m^2K, depending on the tilt angle of the absorber and the mean temperature difference between the absorber plate and water. Based on natural convective theory, the empirical correlations between the effective heat transfer coefficients and these two parameters were proposed for both types of solar water heater.

Results of the tests conducted at night between 5.00 p.m. and 7.00 a.m. showed that heat loss at night was less for the triangular solar water heater.

INTRODUCTION

In most solar water heaters, solar collectors are separated from hot water storages. The advantage of this design is the high efficiency of the storage of hot water. The other type, which is much less popular, is the built-in-storage solar water heater where the solar collector and the hot water storage are integrated. As a result, the cost is much reduced, compared with the former type. However, the storage efficiency is also much lower. The built-in-storage solar water heater was first developed by Tanishita (1964). Later on, related research and development works were undertaken by numerous researchers.

Garg (1975) studied the effect of the depth of storage water, from 5 to 20 cm, on the thermal efficiency. It was found that the optimum depth was 10 cm. At lower depth, the efficiency was low due to the high water temperature. At higher depth, the efficiency was about the same as that at the depth of 10 cm but the water temperature was low. Chauhan and Kadambi (1976) investigated the operating parameters on the efficiency of a built-in-storage solar water heater having the dimensions of 140 x 90 x 5.5 cm. These parameters are : a) using a circulating pump, b) operating with natural convection, c) draining out hot water when its temperature was about 50-60°C, and d) continuous flow of water through the storage with a flow rate of 39 and 76 kg/h. Experimental results indicated that the efficiencies of the first two systems were not significantly different, varying from 58-65%. The temperature of hot water was 60-70°C. The efficiency of the third system was 65%. Total quantity of water was 203 litres, heated up from 39°C to 58°C. The last system yielded the efficiency of 72% at the flow rate of 76 kg/h. Garg and Rani (1982) examined the effect of the following design parameters on the thermal efficiency of built-in-storage solar water heaters: a) one glass cover, b) two glass covers, c) one glass cover insulated on the top at night, and d) one glass cover with a baffle-plate underneath the solar absorbing plate. Conclusions were drawn as follows: a) single glass cover was recommended for moderate water temperature; b) double glass covers, or shallow depth of storage water, were recommended for high water temperature; c) the optimum depth of storage water was 10 cm; and d) insulation at the top of the glass cover at night improved the efficiency by reducing heat loss and yielded less heat loss, compared with installation of the baffle-plate beneath the solar absorbing plate.

Sokolov and Vaxman (1983) as well as Vaxman and Sokolov (1985) conducted a comparative study of two built-in-storage solar water heaters with different storage configurations, triangular and rectangular. Mean depth of the storage water was 10 cm and the storage capacity was 100 litres. The solar collecting area was 1 m^2. Results showed an efficiency of 53% for the triangular system and 35% for the rectangular one. Ecevit et al. (1989) also compared these two different types of solar water heaters. Both had the solar collecting area of 0.9 m^2, tilted at 45 degrees with a mean depth of the storage water of 10 cm and the storage capacity of 90 litres. It was found that the efficiencies of the triangular and rectangular systems were 63% and 57%, respectively. The heat transfer coefficient of the former varied from 120-200 W/m^2-K whilst for the latter it was 108 W/m^2-K. Ecevit et al. (1990) conducted a comparative study of solar water heaters with three different configurations, i.e. triangular storage, triangular storage with baffle-plate, and rectangular storage. Experimental results indicated that the triangular storage configuration yielded the highest efficiency while the rectangular storage configuration provided the lowest.

Clearly information on the heat transfer coefficient between the solar absorbing plate and the water in the storage, especially in terms of equations is still lacking. With this in mind the objectives of this paper are to conduct a comparative study of triangular and rectangular built in-storage solar water heaters and to develop equations for predicting the heat transfer coefficient. The performance of the systems at night is also investigated.

MATERIAL AND METHOD

The two hot water storages, triangular and rectangular, were made of stainless steel sheet, 3 mm thick (Fig. 1). The storage capacities were 82.5 and 75 liters, respectively. These figures were a bit higher than those obtained from Fig. 1 due to the storage expansion under operating pressure. Each storage top was covered with a glass sheet, 3 mm thick, 50 mm apart from the solar absorbing plate (Nahar and Gupta, 1989). The other sides were covered with glass wool of 100 mm thickness. The solar absorbing area was 0.7 m^2, facing south.

Temperatures of the absorbing plate, the walls, the bottom, and the storage water were measured each hour from 8.00 a.m. to 7.00 a.m. of the following day, by thermocouples, type K, which were connected to a data logger. The accuracy was ± 0.7°C. Details of points of measurement are shown in Fig. 1. It should be noted that the temperature distributions on the absorbing plate and on a parallel plane in the water were experimentally investigated, and results indicated that variation did not occur along the east-west but along the north-south direction. Global and diffuse solar radiations were

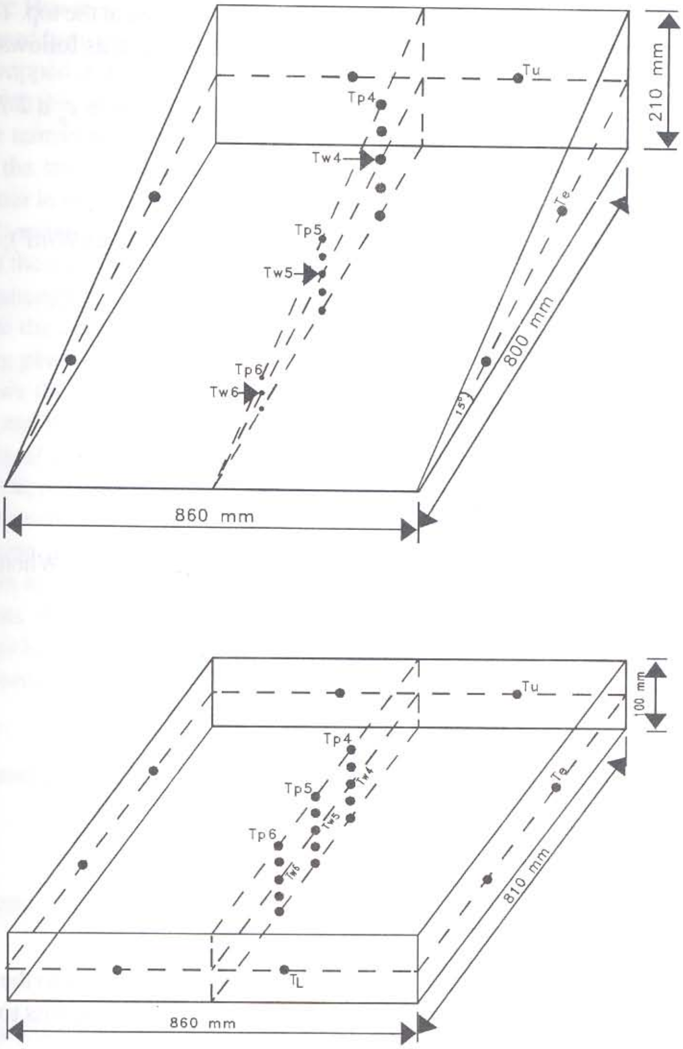


Fig. 1. Installation of temperature sensors (dimensions are in mm).

measured during the day time by pyranometers, Kipp & Zonen, and were integrated every hour. Tilt angles of 15°, 30° and 45° were studied. During each test, no water was extracted from both solar water heaters.

Mean temperature of the storage water was verified by comparing the mean temperature of drained hot water with the average value of water temperatures measured as shown in Fig. 1 (7 and 9 points for the triangular and rectangular solar water heaters, respectively). The result showed that they were nearly the same.

Due to very good insulation, heat losses at the walls and at the bottom were relatively low, compared with the heat loss at the top of the solar water heater. Experimentally, the top loss of the rectangular solar water heater was higher than 95% of the total heat loss and a bit higher for the triangular one. Therefore, it may be assumed that there is only heat loss at the top. The equation based on energy conservation at the solar absorbing plate can then be written as follows:

$$G A_p (\tau a)_e = U_T A_p (T_p - T_a) + h_{pw} (T_p - T_w) + m c_p dT/d\tau \quad (1)$$

where A_p = absorbing area (m^2),
c_p = specific heat (J/kg-K),
G = total solar radiation incident on the absorbing plate (W/m^2),
h_{pw} = effective heat transfer coefficient (W/m^2-K),
m = mass of the absorbing plate (kg),
T_a = ambient temperature (K),
T_p = absorbing plate temperature (K),
T_w = water temperature (K),
τ = time (s),
U_T = top heat loss coefficient (W/m^2-K),
$(\tau a)_e$ = effective transmittance-absorptance product.

U_T can be calculated by using the equation developed by Klein (1973). When the experimental data were inserted into equation (1), h_{pw} can be determined.

The performance of the solar water heater is defined as follows:

$$\eta = \frac{\int Q_u \, d\tau}{A_p \int G \, d\tau} \quad (2)$$

where η = thermal efficiency (decimal),
Q_u = useful heat (W).

Heat loss at night is explained as the ratio of the accumulated heat loss to the maximum storage of heat each day or it can be imagined as the ratio of the accumulative heat loss to the initial internal energy (T_o as the reference temperature). The equation is written as follows:

$$Q_{loss} = \frac{T_{max} - T_{(\tau)}}{T_{max} - T_o} \quad (3)$$

where

Q_{loss} = heat loss fraction,
$T_{(\tau)}$ = water temperature at time τ (K),
T_{max} = maximum water temperature each day (K),
T_o = initial water temperature in the morning (K).

RESULT AND DISCUSSION

As explained earlier, there was no variation of the temperature of the absorbing plate along the east-west direction. However, temperature variation occurred along the north-south positions. The temperature increased from the bottom (the south) to the top (the north). The variation increased during the day time and dropped in the evening. It was less obvious in the triangular solar water heater (Figs. 2b-4b). It appears that this was due to the better circulation of water in the triangular solar water heater, which reduced the temperature variation. The distribution of water temperature in the storage was similar to that of the solar absorbing plate (Figs. 5-7), which supports the hypothesis that water circulation was better in the triangular solar water heater. During the tests, solar radiation varied from 200 to 900 W/m^2 (a mean value of 550 W/m^2).

Evolutions of the mean temperatures at different parts of the solar water heater are shown in Fig. 8. The difference among them increased with solar intensity and was nil at night. Mean temperatures were obtained from the average values of those measured as shown in Fig. 1, e.g. $(T_{p4}+T_{p5}+T_{p6})/3$ as the mean absorbing plate temperature.

Figure 9 shows the relationship between the effective heat transfer coefficient, as determined from equation (1), and the mean temperature difference between the absorbing plate and the water at different tilt angles of the absorbing plate. It indicates that the effective heat transfer coefficient increases with the temperature difference and the tilt angle. Imagining that a fluid element is flowing along an inclined absorbing plate, there should be three forces namely, gravity force, buoyancy force and drag force, acting on the element. The components parallel to the plate especially the first two forces are written in terms of $\cos(90-\beta)$ in which β is the tilt angle and the difference of these two parallel components depends on the temperature difference between the fluid element and the surrounding. On this basis, the empirical correlations among the effective heat transfer coefficient, the temperature difference and the tilt angle were proposed for each type of the solar water heater as follows:

for the triangular storage,

$$h_{pw} = 121\,[\,(T_p - T_w)\cos(90-\beta)\,]^{0.153} \tag{4}$$

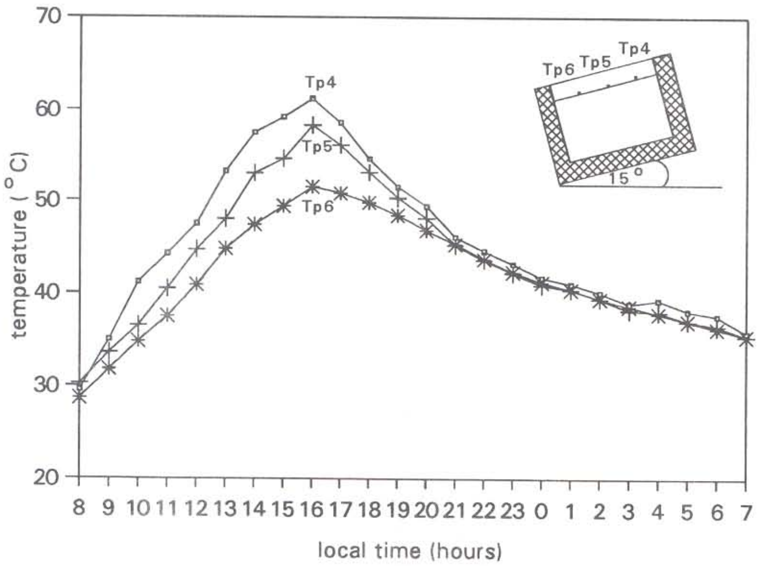
and for the rectangular storage,

$$h_{pw} = 99.6\,[\,(T_p - T_w)\cos(90-\beta)\,]^{0.217} \tag{5}$$

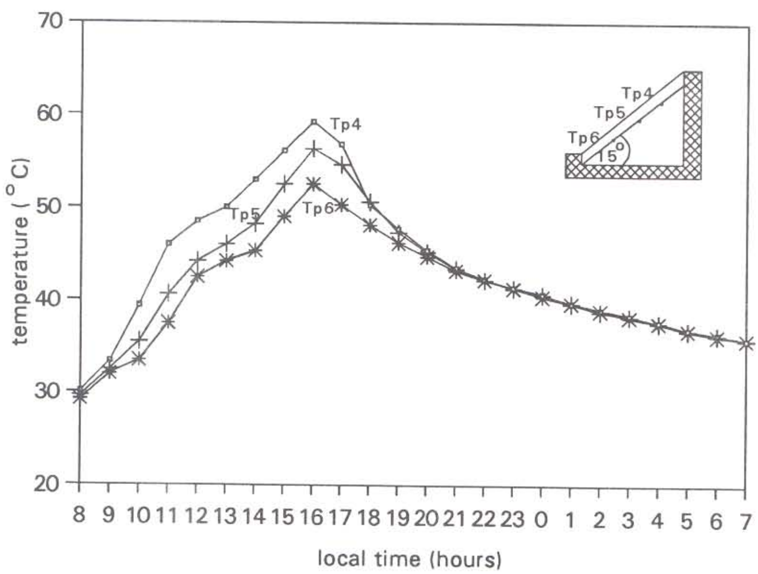
where β is the tilt angle of the absorbing plate, varying from 15 to 45 degrees.

The close correlation shows that the scattering due to unexplained disturbances is the same in both cases, but Fig. 10 shows that the difference between the two cases is significantly greater than the scattering. That is to say the triangular design is in fact better than the rectangular design. This may due to higher degree of water circulation in the former case. The effective heat transfer coefficient varies from 80 to 140 W/m^{2}K.

Comparatively, the accumulated average thermal efficiency of the triangular solar water heater is higher as shown in Fig. 11. Accumulated average efficiency is defined as the efficiency in equation (2) having the limit of integration from 9 o'clock in the morning to the time specified. Heat loss at night is also less. It is believed that these results are due to better water circulation during the day time and, on the contrary, worse circulation at night, respectively.

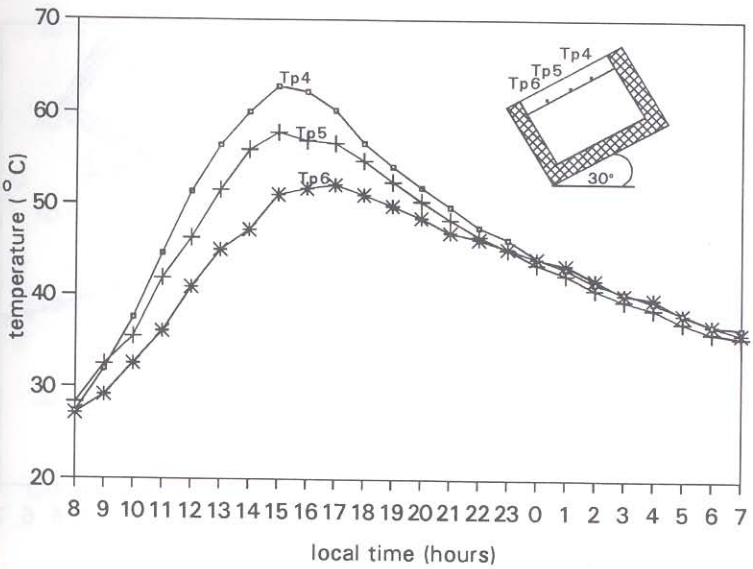


(a) Rectangular profile

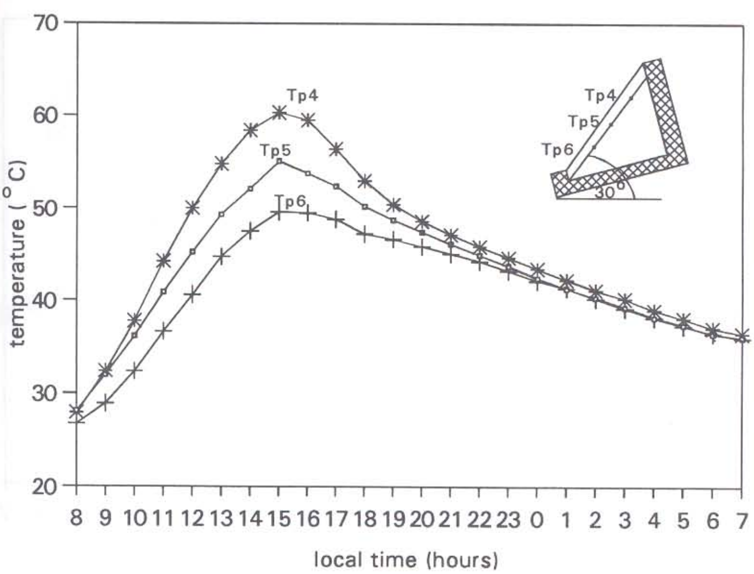


(b) Triangular profile

Fig. 2. Plate temperature at different nodes observed in two built-in-storage solar water heaters, tilt angle = 15° (03/12/91).

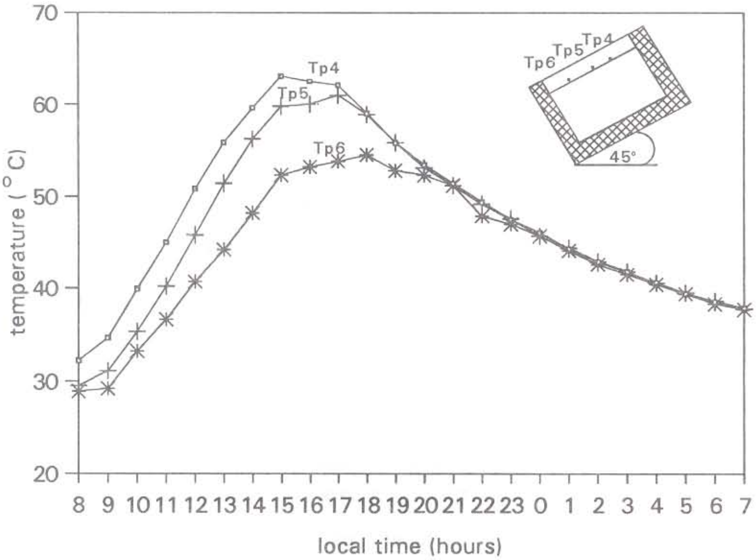


(a) Rectangular profile

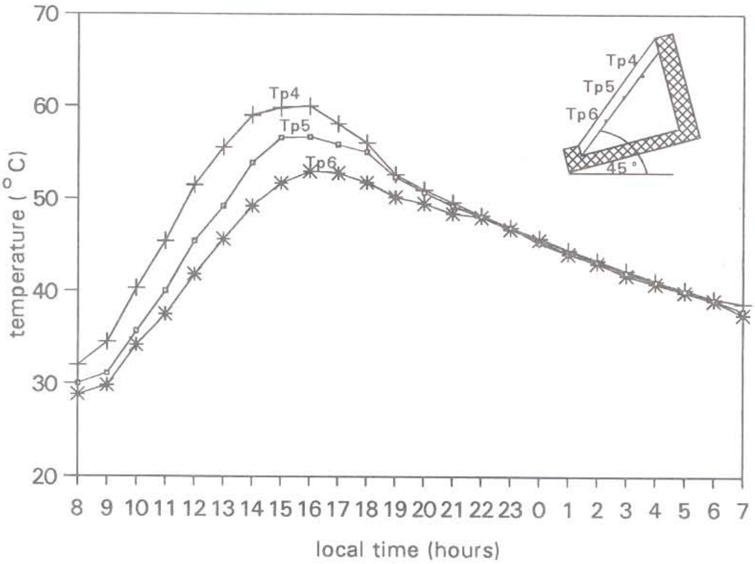


(b) Triangular profile

Fig. 3. Plate temperature at different nodes observed in two built-in-storage solar water heaters, tilt angle = 30° (21/12/91).

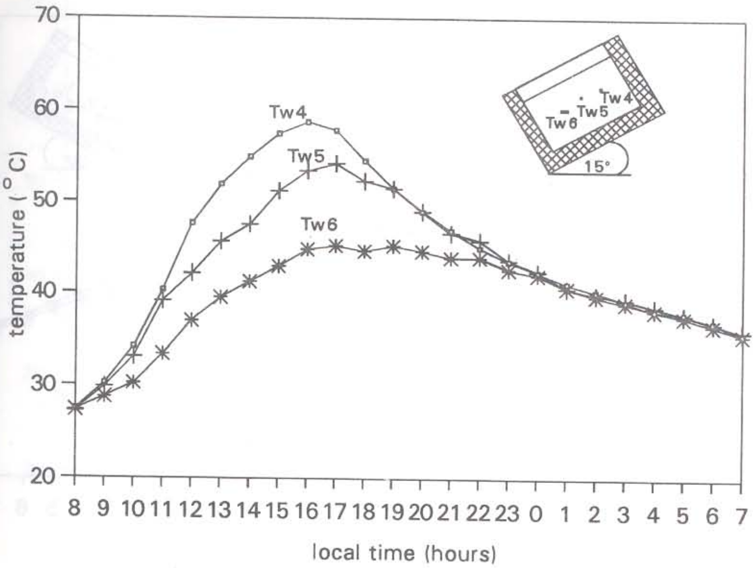


(a) Rectangular profile

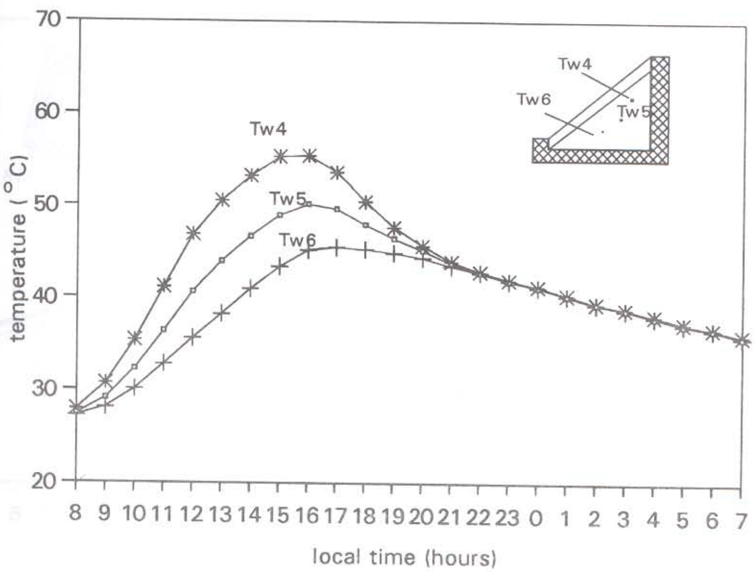


(b) Triangular profile

Fig. 4. Plate temperature at different nodes observed in two built-in-storage solar water heaters, tilt angle = 45° (03/02/92).

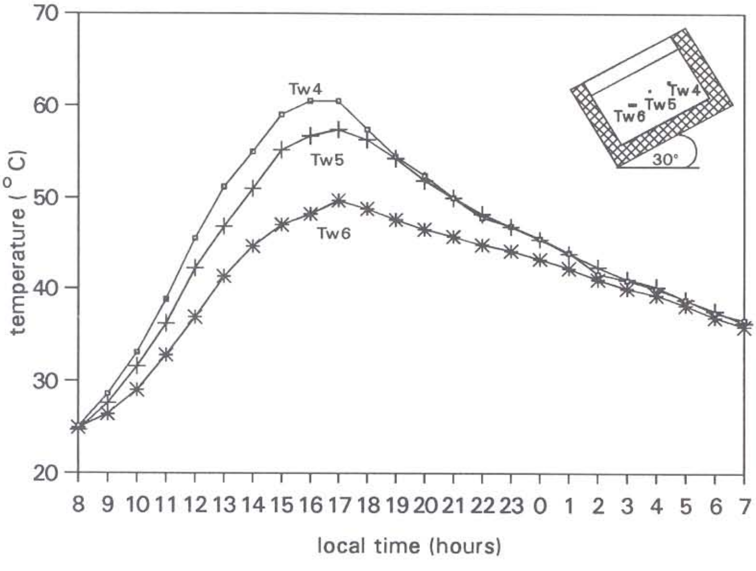


(a) Rectangular profile

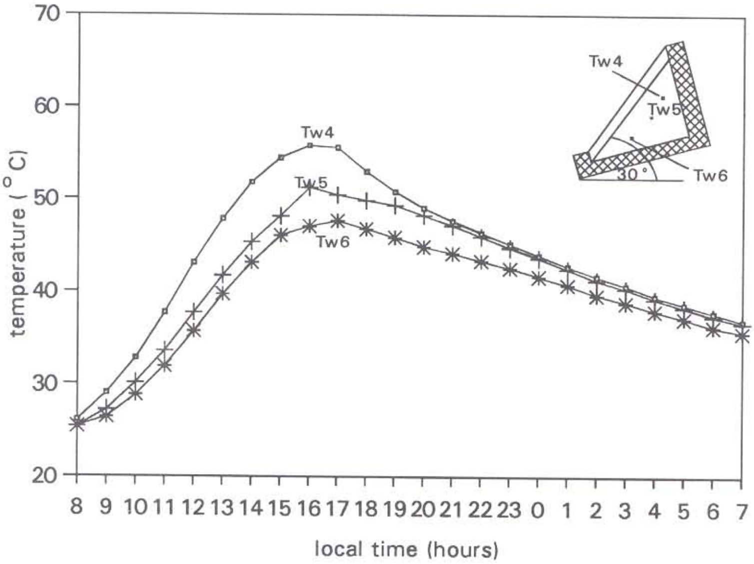


(b) Triangular profile

Fig. 5. Water temperature at different nodes parallel to the absorbing plate, observed in two built-in-storage solar water heaters, tilt angle = 15° (03/12/91).

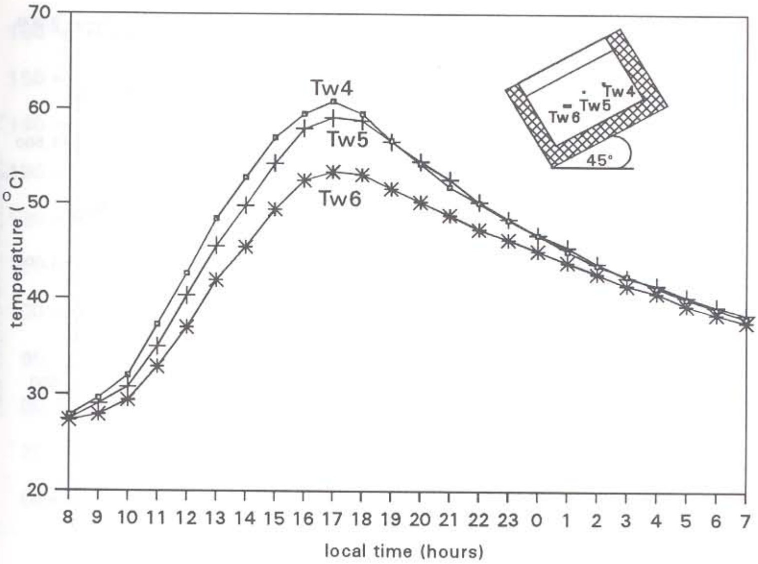


(a) Rectangular profile

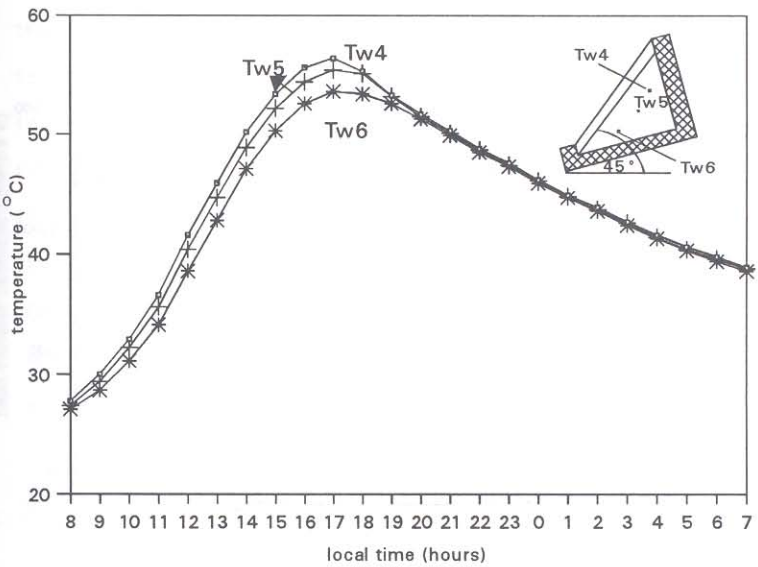


(b) Triangular profile

Fig. 6. Water temperature at different nodes parallel to the absorbing plate, observed in two built-in-storage solar water heaters, tilt angle = 30° (21/12/91).

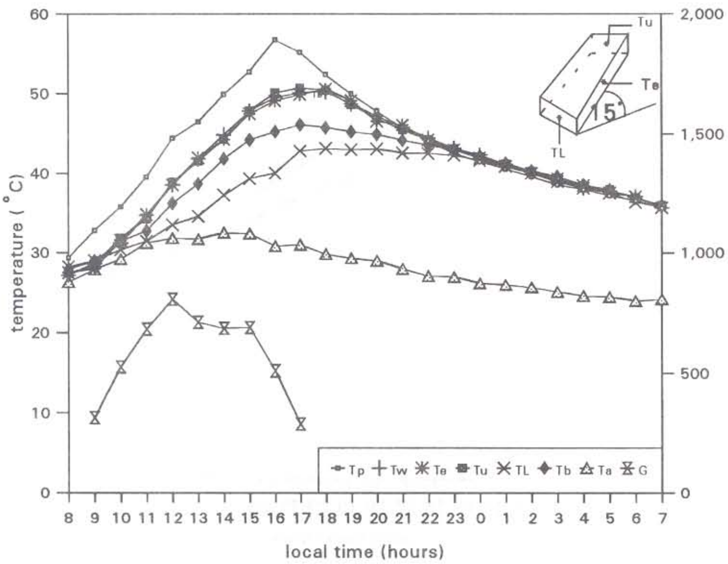


(a) Rectangular profile

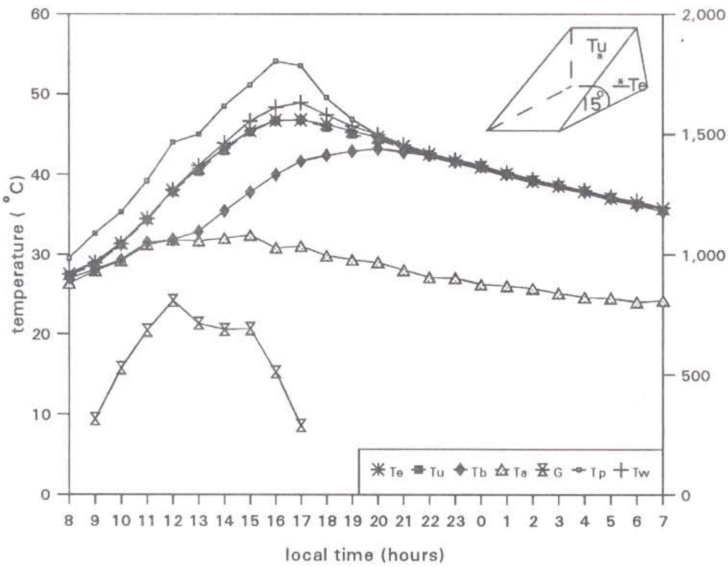


(b) Triangular profile

Fig. 7. Water temperature at different nodes parallel to the absorbing plate, observed in two built-in-storage solar water heaters, tilt angle = 45° (03/02/92).



(a) Rectangular profile



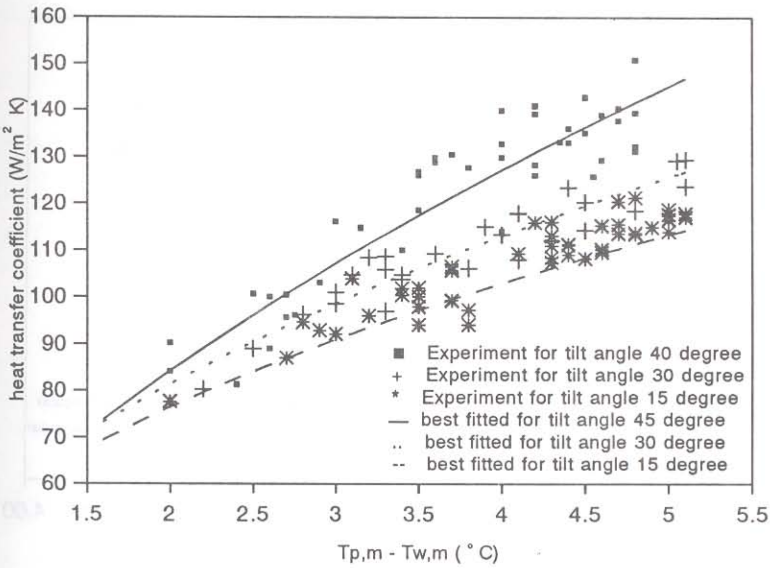
(b) Triangular profile

Fig. 8. Evolution of solar intensity and mean temperatures, observed in two built-in-storage solar water heaters, tilt angle = 15° (03/12/91).

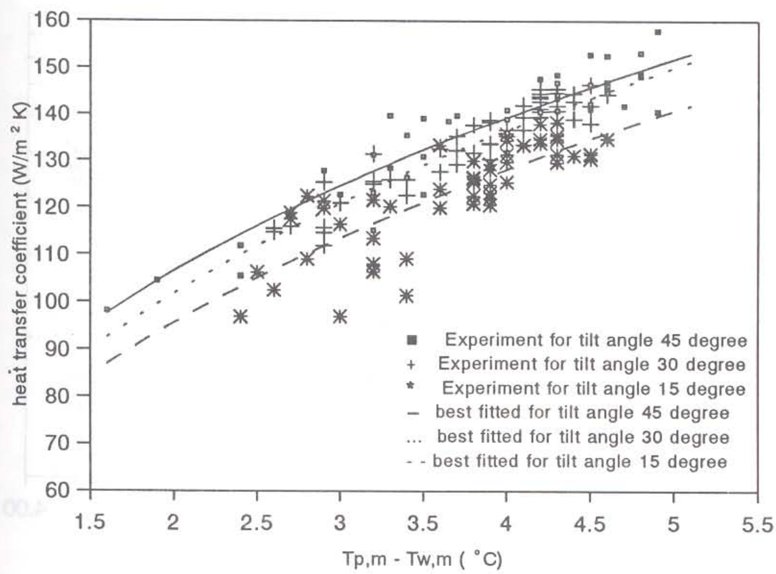
T_p = mean plate temperature T_w = mean water temperature

T_b = mean bottom temperature T_a = ambient temperature

G = solar intensity

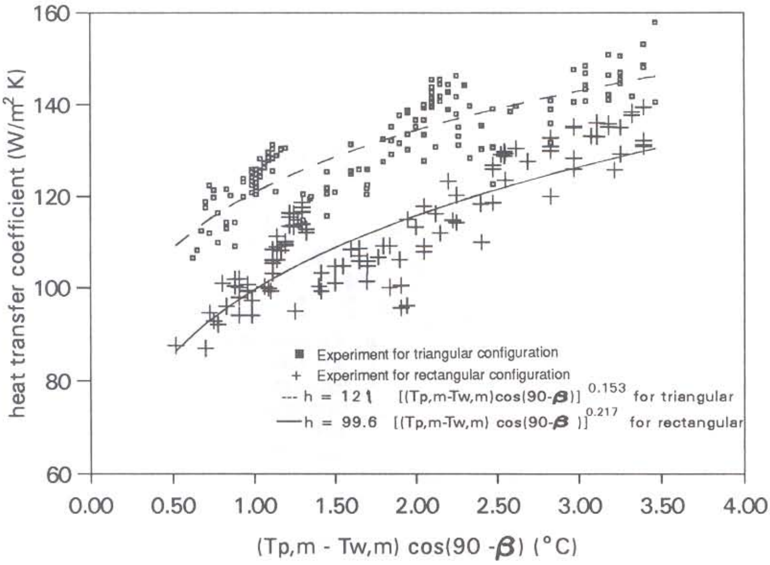


(a) Rectangular configuration



(b) Triangular configuration

Fig. 9. Effect of mean temperature difference on heat transfer coefficient for built-in-storage solar water heaters (tilt angle = 15, 30, 45°).



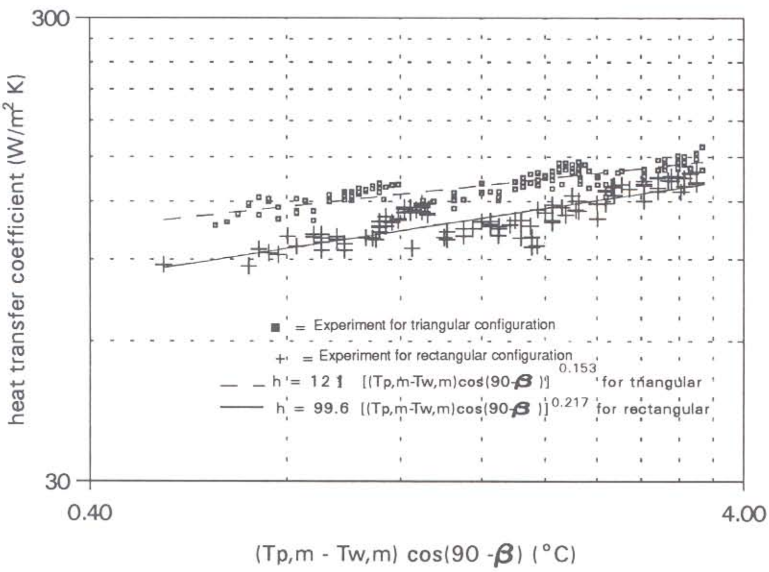
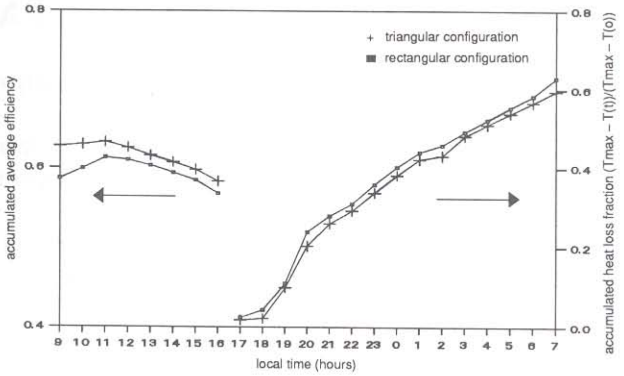
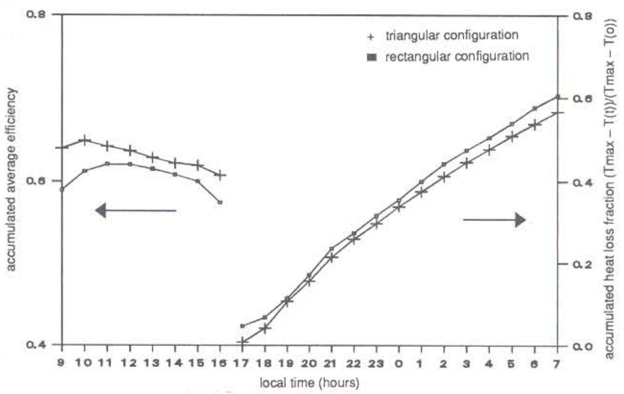


Fig. 10. Effect of (Tp,m – Tw,m) cos(90 – β) on effective heat transfer coefficient in two built-in-storage solar water heaters.

Tp,m = mean absorber temperature; Tw,m = mean water temperature; β = tilt angle



(a)



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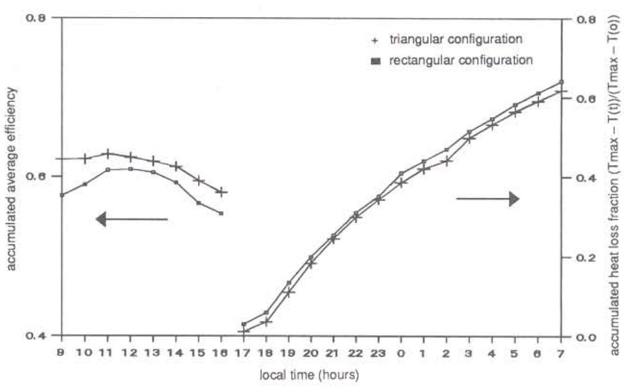

(c)

Fig. 11. Accumulated average efficiency and accumulated heat loss fraction of two built-in-storage solar water heaters for three tilt angles: (a) = 15°, (b) = 30°, (c) = 45°.

CONCLUSION

The following conclusions may be drawn from this comparative study on the triangular and rectangular solar water heaters:

1. The performance of the triangular solar water heater is better. The thermal efficiency of the former is higher than that of the latter, 63% vs 59%. Heat loss at night of the former is also less.
2. The effective heat transfer coefficient of the triangular storage is significantly higher. Based on natural convective theory, empirical equations are proposed.

REFERENCES

Chauhan, R.S. and V. Kadambi (1976), Performance of a Collector-Cum-Storage Type of Solar Water Heater, *Solar Energy*, 18 (4), 327-335.

Ecevit, A., A.M. Al-Shariah and E.D. Apaydin (1989), Triangular Built-in-Storage Solar Water Heater, *Solar Energy*, 30 (3), 253-265.

Ecevit, A., M.A.M. Chaikh Wais and A.M. Al-Shariah (1990), A Comparative Evaluation of the Performances of Three Built-in-Storage-Type Solar Water Heaters, *Solar Energy*, 44 (1), 23-36.

Garg, H.P. (1975), Year Round Performance Studies on a Built-in-Storage Type Solar Water Heater at Jodhpur, *Solar Energy*, 17 (3), 167-172.

Garg, H.P. and U. Rani (1982), Theoretical and Experimental Studies on Collector/Storage Type Solar Water Heater, *Solar Energy*, 29 (6), 467-478.

Klein, S.A. (1973), *The Effects of Thermal Capacitance Upon the Performance of Flat-plate Solar Collectors*, M.S. Thesis, University of Wisconsin, Wisconsin, USA.

Nahar, N.M. and J.P. Gupta (1989), Studies on Spacing Between Absorber and Cover Glazing in Flat Plate Solar Collectors, *International Journal of Energy Research*, 13 (4), 727-732.

Sokolov, M. and M. Vaxman (1983), Analysis of an Integral Compact Solar Water Heater, *Solar Energy*, 30 (3), 237-246.

Tanishita, I. (1964), Recent Development of Solar Water Heaters in Japan, *Proc. U.N. Conf. on New Sources of Energy*, Rome, 5, 102.

Vaxman, B. and M. Sokolov (1985), Experiments with an Integral Compact Solar Water Heater, *Solar Energy*, 34 (6), 447-454.