EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE OF THERMOSYPHON SOLAR WATER HEATER IN THE SOUTH CASPIAN SEA

by

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In the present study, a natural circulation closed thermosyphon flat plate solar water heat has been tested at the Faculty of Engineering of University of Mazandaran located in Babol city (36N, 52E). Data were collected for several sunny and cloudy days. Dynamic response of the system to variations in solar insolation was studied and analyzed. It was found that such systems can provide ample energy to satisfy the demand for hot water, contrary to misperception among locals.

Key words: *solar water heater, thermosyphon, Caspian sea*

Introduction

Solar water heating systems (SWHS) can either be open loop (also called "direct") or closed loop (also called "indirect"). An open-loop system circulates household (potable) water through the collector. This design is efficient and lowers the operating cost but is not appropriate if water is hard or acidic because scale and corrosion will gradually disable the system. Overnight freezing is also an important problem. Open-loop systems are popular in regions that do not experience subzero temperatures.

A closed-loop system uses a heat-transfer fluid (water or diluted antifreeze) to collect heat and a heat exchanger (usually of mantle type) to transfer the heat to domestic water supply. A disadvantage of closed looped system is that heat is lost during the heat exchange process. Sitzmann [1] recommended utilization of such systems and provided basic information to manufacture and use closed-loop systems.

SWHS are also characterized as active or passive. An active system uses an electric pump to circulate the fluid through the collector. A passive system moves supply water or a heat-transfer fluid through the system without any pumps and relies on thermo-syphoning to circulate water. This phenomenon is often made use of in the design of solar water heaters, particularly of small capacities. In these systems, heat transfer fluid rises up from the solar energy collector to the hot water store due to the action of buoyancy forces and is replaced by colder water from the bottom of the tank. A continuous circulation is thus established between the collectors to the tank which helps in heating up water in the storage tank.

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The performance of the thermosyphon system depends upon the size and capacity of the storage tank, the thermal capacity of the collector and the connecting pipes including fluid flow and on the pattern of hot water use.

Experiments are necessary to understand component behavior and lend confidence to corresponding mathematical models. System scale experiments are necessary to bring to light many practical problems inherent in any complicated system that simulation can not model.

The first published analysis of thermosyphon solar water heater circuit was by Close [2]. There have been many other publications on the analysis of these systems but they are all based on the original formulation. For verifying the theoretical results, he tested two thermosyphon systems with different characteristics and the results conformed well to those predicted.

Gupta *et al.* [3] modified the model of Close to take into account the heat exchange efficiency of the collector absorber plate, and thermal capacitance. They also found experimentally that the flow rate of a thermosyphon water heater can be increased by increasing the relative height between the collector and storage tank, but the efficiency is not increased. The efficiency can be increased by reducing the loop resistance.

Ong [4] extended the work of Close and Gupta *et al.* by using a finite difference solution procedure. The theoretical prediction of flow rate has been compared with the measured flow rate using dye trace inject. Morrison *et al.* [5, 6] investigated the response of thermosyphon systems to step changes in solar radiation. Measurement of the transient flow rate was obtained using a laser-Doppler anemometer.

Hussein [7] obtained a comprehensive understanding of the transient thermal behavior of a two-phase thermosyphon flat plate solar collector. He investigated theoretically and experimentally under unsteady-state conditions. His governing equations of the different components of the collector are presented and generalized in dimensionless forms, and comparison between the experimental and simulated results showed considerable agreement.

Zerrouki *et al.* [8] considered natural circulation of a compact thermosyphon solar water heating system produced and commercialized in Algeria. Their calculations and measurements were performed on mass flow rate, temperature rise and fluid and absorber temperatures inside the thermosyphon of parallel tube design.

Karagholi *et al.* [9] analyzed the thermal performance of the thermosyphon water heater unit to show its applicability in Bahrain. Their results show that the system is quite suitable for application in Bahrain weather conditions.

Chuawittayawuth *et al.* [10] presented details of experimental observation of temperature and flow distribution in natural circulation solar water heating systems. They found that the temperature values at the riser tubes near the collector inlet are generally much higher than those at the other risers on a clear day, while on cloudy days, the temperatures are uniform. They concluded that the temperature of water in the riser depends on its flow rate. They also carried out the measurements of the glass temperature.

As far as analytical studies concern, they can only predict the overall performance of the system in whole and no detailed information can be obtained from them. Belessiotis *et al.* [11] performed analytical study of a thermosyphon solar water heater with horizontal storage tank and verified the results by experiments.

The only journal articles that report study of a solar collector system in the climate region of South Caspian Sea are the one by Mohseni *et al.* [12] which is done on a solar air heater system and that by Fooladi *et al.* [13] which is a report on integrated solar collector

storage (ICS) system. ICS systems' performance in humid climate has been also reported by Varghese *et al.* [14]. The mentioned articles proved that employment of solar collectors in those regions is in fact feasible.

The climate of Iran is diverse. The central part is arid. Hot and humid weather prevails in the Persian Gulf region south of the country. The humidity in the south Caspian Sea region is high with lots of precipitation and cloudy days, while the winters are mild. There has always been present a misperception among residents of South Caspian Sea region that thermosyphon systems would not work properly as the humidity is high and solar insolation is inadequate. This has severely obstructed extensive use of thermosyphon systems in the mentioned region. The current experiments were conducted to study the performance of nationally made thermosyphon solar water heaters as shown in fig. 1 in the said region and to prove otherwise. The work reported in the paper is new in the sense that it is the only study that demonstrates performance of the entire system. All previous studies on thermosyphon water heater systems with horizontal mantle tank (which are extremely scarce) either focus on the performance of the collector or the tank. Other significances are that it shows utilization of a non-intrusive method for measurement of flow rate which is always a challenge for thermosyphon systems since any flow obstruction will alter the actual performance of the system. It shows the length of time delays in the collector and the tank. It demonstrates level of thermal stratification in the horizontal tank.

Experimental set-up and test procedure

The tests were conducted on a commercial thermosyphon solar water heater that was manufactured by Kian Energy Company and donated to the University of Mazandaran. The system was installed at the Faculty of Mechanical Engineering of University of Mazandaran located in Babol city (36E, 52N) and mounted facing south at a tilt angle of 45° to the horizontal which is the appropriate tilt angle corresponding to the location latitude.

The system consists of two flat plate collectors, a horizontal storage tank equipped with mantle heat exchanger, an up-riser and a down-comer pipe (3/4" diameter). Collectors were of single glazed aluminum flat-

Figure 1. Picture of the tested system in location

plate absorber type formed from 7 copper finned tubes. Each riser has an inside diameter of 12 mm with a 140 mm center to center spacing. The cross-section of the risers is of rhombic shape with round corners. Other specifications are given in tab. 1.
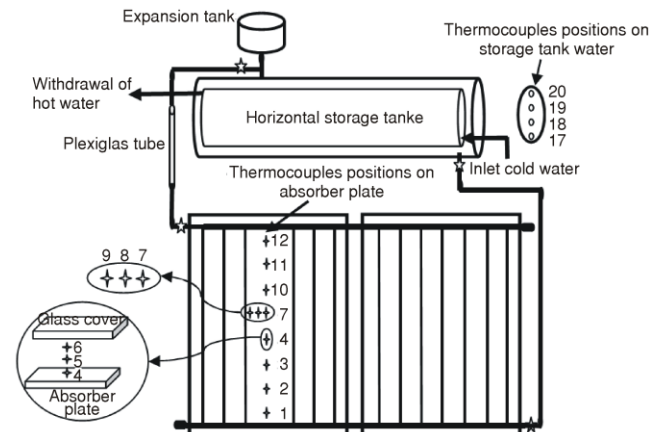
450

Riahi, A., *et. al.*: Experimental Investigation on the Performance of …
THERMAL SCIENCE, Year 2011, Vol. 15, No. 2, pp. 447-456

Table 1. Specification of the system tested in the study

Collectors		Storage tank	
Type	Flate plate	Type	Horizontal
Tilt angle	45°	Material	Galvanized iron
Absorber area	$1.75 \text{ m}^2 \times 2$	Plate thickness	3 mm
Inner diameter of risers	12 mm	Insulation	Glass wool 5 mm
Absorber plate thickness	0.5 mm	Volume	180 liter
Absorber plate absorptivity	0.92	Connecting tubes	
Glass cover	Tempered glass, 3 mm thick	Inner diameter	21 mm
Number of risers in the collector	7	Insulation	Foam, 2 mm
Insulation polyurethane	45 mm thick		
Frame	Aluminum		

The monitoring campaign consisted of several measurements of temperatures and mass flow rates. Temperature measurements were done on the surface of absorber plate (which were placed at 8 locations in vertical direction), air space between absorber plate and glass cover (TC# 4, 5, and 6), distance between two risers (TC# 7, 8, and 9), storage tank (at 4 locations in vertical direction: TC# 17, 18, 19, and 20), inlet and outlet flowing flow of collector and storage tank (marked in fig. 2 by ☆) and the temperature in the air gap between absorber plate and glass cover. These temperatures were measured by K and T type thermocouples (TC). Solar radiation on the plane of the collector was measured using a silicon pyranometer manufactured by Onset Computer Corporation with an accuracy of ±5%. The ambient temperature was measured by an 8-bit digital sensor system. Two separate data logging systems were employed. The first one was a HOBO Micro Station data logger for collecting solar insolation and ambient air temperature data. The second and main data logger which was used to collect temperature data from the absorbers and mantle tank was a 16--channel Campbell Scientific data logger equipped with a 1 to 4 relay multiplexer. Data were collected every 15 minutes for an entire day and the experiments were repeated for several days.

Because of the low pressure head in thermosyphon systems, and the resulting low velocities, conventional flow measurement methods (venturi meter, orifice meter, turbine meter, *etc.*) are not appropriate. Thus the measurement of mass flow rate is difficult. Consequently only a few investigations have attempted to measure the flow rate in these systems. Dye injection (Ong [4]) thermal tracing (Shitzer [15]), laser-Doppler anemometry (Morrison [6]), self heated thermistor (Fanney [16]), and hydrogen bubble method (Bannerot *et al* [17]) have been proposed and used to measure flow rates in solar thermosyphon systems.

Figure 2. Location of measurement sensors

Riahi, A., *et. al.*: Experimental Investigation on the Performance of …
THERMAL SCIENCE, Year 2011, Vol. 15, No. 2, pp. 447-456

451

In this study we have used the hydrogen bubble method to measure the flow rate. This method uses the electrolysis of water to introduce small bubbles of hydrogen gas into a stream of flowing water in order to make the flow lines visible.

In a typical hydrogen bubble flow visualization installation, a very fine wire is stretched across the region of flow which is to be investigated. A pulse of electrical energy is fed to the wire and the hydrogen formed is swept of the wire by the passing water. Oxygen is of course formed at the anode which is located elsewhere. In general, hydrogen bubbles are smaller and are easier to see so they are used instead of the oxygen bubbles as the flow tracer. The time of the bubbles displacement is measured. Hence, using the measured time of travel of the bubbles and the dimension of the pipe, the mass flow rate can be determined.

In this work, a 12 mm length of 0.3 mm nickel-chromium wire was used. The wire was insulated with a thin coat of water proof paint along its entire length except at the tip where the hydrogen bubbles were produced. The cathode wire was inserted into an 80 cm section of a 26 mm diameter clear plexiglas tube through a 1 mm opening in the wall and then sealed with glue. The circuit was completed by simply attaching the anode to the metal piping. The electrical supply was capable of providing 0-300 VDC continuously. The calibration of the hydrogen bubble device as a flow meter was carried out in the fluid mechanics laboratory with the aid of a hydraulic bench.

Results and discussion

Experiments were conducted for several days of summer.

To study the temperature and flow distribution in the system during its daily operation, experiments were conducted by filling the storage tank with cold water every morning. The period of testing for each run was from 6 a. m. to 21 p. m. and during the tests, no water was withdrawn from the storage.

The variation of temperatures of different locations along the absorber plate during a sunny day is shown in fig. 3. The measured solar irradiation on the plane of the collector is also shown in the fig. 3. It can be seen that a sudden drop in solar insolation at about 12:30 has been sensed on the absorber plate with a one-hour delay. The maximum temperature on the absorber plate occurs at 14:00 when it reaches 88 °C. On this day the maximum incident energy on the plane of the absorber is 1050 W/m^2 which only lasts for a short period of time. After 13:00, although incident radiation starts dropping, the absorber temperature continues rising for two more hours. The curve labeled by the letter S in fig. 3, represents the measured solar insolation.

A comparison with the temperature profiles of the central riser of the collector reported by Chuawittayawuth *et al.* [10] confirms current measurements. They reported that the maximum temperature of the central riser of the collector plate
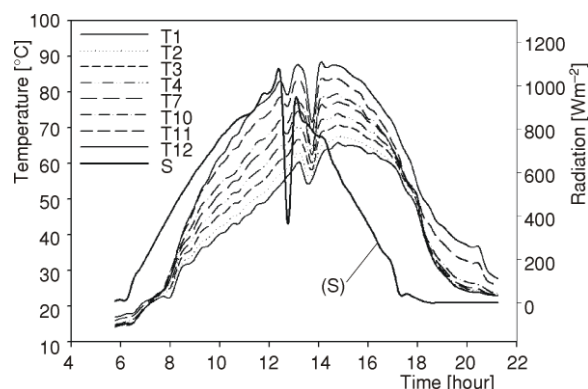

Figure 3. Time variation of absorber plate temperatures on a sunny day

452

Riahi, A., *et. al.*: Experimental Investigation on the Performance of …
THERMAL SCIENCE, Year 2011, Vol. 15, No. 2, pp. 447-456

occurred at 15:00 which is consistent with fig. 3. The magnitude of the maximum temperature observed in their collector is lower than the current study. This is attributed to more efficient design of the current collector which uses risers manufactured by sandwiching a copper tube between two aluminum plates as opposed to their design which introduces larger contact resistance between absorber plate and water tubing.
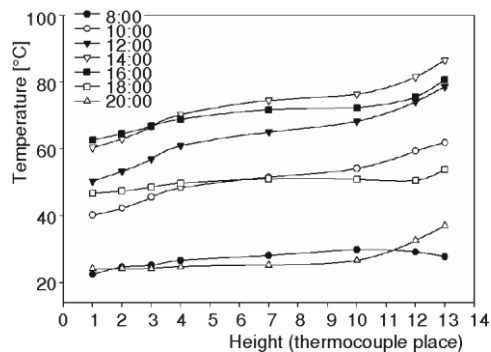
Figure 4. Temperature variation along absorber plate at different times of day

The time variation of temperature along the absorber plate has been shown in a different way in fig. 4. At 8:00 a. m. when the solar insolation is 413.1 W/m^2, the top two locations of the absorber are still cold. At 10:00 a. m. a linear temperature distribution is well established with the lowest point at 40.3 °C and the highest one at 59.4 °C. The linear distribution then begins to be disturbed at 2:00 p. m. with a break in the mid-height of the collector. Afterwards, the temperature distribution starts to flatten while moving downwards to the lower temperatures where finally at 8:00 p. m. the situation is similar to that at 8:00 a. m. except for the top two locations which are warmer.

As shown in fig. 5, the temperature was also measured at 4 points along the height of the storage tank. Our results can be compared to those by Sako *et al.* [18] for generally the same system tested in Côte D' Ivoire, Africa. Their system incorporated 2 m^2 of solar collector and a horizontal storage tank. However, they do not elaborate on the type of heat exchanger used in their storage tank. They found that the average storage temperature reaches 60 °C at 16:00. As can be seen in fig. 5, the average water temperature in our storage tank is slightly higher than 60 °C at 16:00. The larger collector surface area of our system is expected to deliver more energy and thus higher average water

Figure 5. Time variation of storage tank temperature on a sunny day

temperature. Zerrouki *et al.* [8] found that the average tank temperature reaches its maximum of 54 °C at 18:00 in the climate of Algiers, Algeria. The system they used had 1.8 m^2 of solar collectors and 120 L of water storage capacity. However, their system is not a closed system. The system tested by Belessiotis *et al.* [11] was a closed system.

The time variation of temperature for these points is shown in fig. 6 for a sunny day. Thermal stratification is evident in the tank such that the temperature difference between the bottom layer and the top layer is 23 °C at noon. It can also be seen that the temperature of the top of the tank starts to increase rapidly from the early morning hours while the lower parts do not experience a considerable temperature rise. When time passes 16:00, the temperature at point 20 starts to decrease, whereas at other locations it stays unchanged. That is due to a lack of sufficient energy input that causes the water inside the tank to transfer heat within itself, *i. e.* from upper layers to the ones beneath. At 8:00 p. m. the temperature difference between the

Riahi, A., *et. al.*: Experimental Investigation on the Performance of …
THERMAL SCIENCE, Year 2011, Vol. 15, No. 2, pp. 447-456

453

top layer and the bottom layer of the tank is small indicative of an almost isothermal storage tank at a temperature of 62 °C available for hot water consumption.

Figure 7 shows the temperatures in the air gap between the absorber plate and the transparent cover of the collector. As it can be seen, there is a sensible temperature gradient in this area at noon. The difference between the plate temperature and temperature in the air gap is at its highest at 3:00 p. m., which is equal to 13 °C. When the sun goes down, the plate and the air above it quickly reach equal temperatures. Comparing this to fig. 3 it is evident that the drop in solar irradiation is sensed in the air above the plate with 1.5 hours delay.
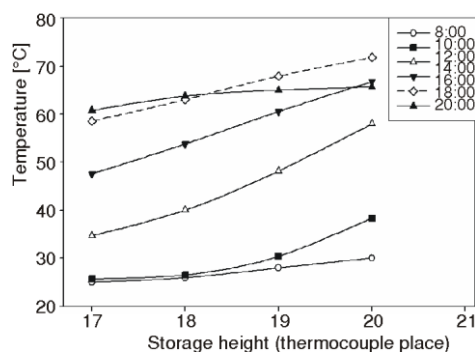

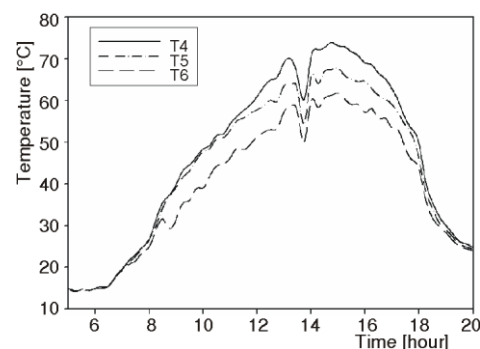Figure 6. Storage tank temperatures at different times in a sunny day

Figure 7. Time variation of air temperature between absorber plate and glass cover

Figure 8 indicates that there is a transverse temperature gradient on the fin, such that as we move away from the tube to the center of the fin, the temperature increases. This is in accord with what one should normally expect to happen. The gradient starts to be of noticeable value at around 9:30 in the morning and vanishes again at 17:00 in the evening.
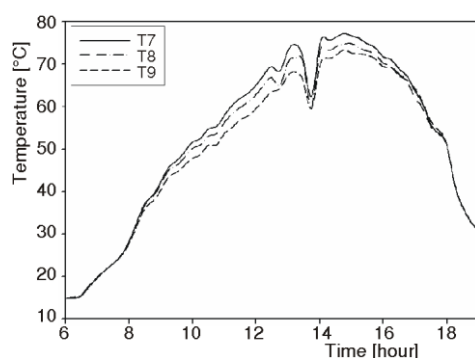

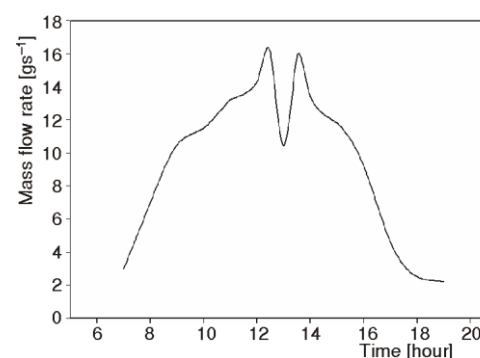Figure 8. Time variation of absorber plate temperature along the fin width

Figure 9. Time variation of mass flow rate on a sunny day

The collector loop mass flow rate was measured using a hydrogen bubble flow visualization technique. The result is shown in fig. 9 for a sunny day. At noon the flow rate has reached its peak value of 16.5 g/s while at 7:00 the value is 3 g/s. It can be seen that the mass flow rate changes according to the drop in solar insolation with a half-hour delay. The maximum mass flow rate reported by Zerrouki *et al*. [8] was 8.5 g/s at 13:30 which in terms

454

Riahi, A., *et. al.*: Experimental Investigation on the Performance of …
THERMAL SCIENCE, Year 2011, Vol. 15, No. 2, pp. 447-456

of time of occurrence corresponds to the time obtained in the current study. The lower value of the mass flow rate in their study is due to their smaller collector area because, increasing collector area will increase flow potential. The data reported by Belessiotis and Mathioulakis [11] is more consistent with current results. They observed a maximum flow rate of 18 g/s at 13:15 local time, which is very close to what is visible in fig. 9.

In fig. 10 the temperature of the liquid leaving the collector, entering the mantle heat exchanger, and exiting it is shown. The collector liquid temperature follows the changes in solar insolation with a one-hour time lag. It has reached a maximum temperature of 80 °C at 14:00 when the maximum receiving solar energy flux for the day is 1050 W/m^2. There is a small difference between the collector outlet temperature and the temperature of the liquid entering the mantle of the storage tank *i. e.* the latter is slightly lower than the former. This is due to a lack of insulation on the up riser of the system since the flow measuring system is of visual type. Sako *et al.* [18] recorded a temperature of ~85 °C at 14:15 hours where the maximum solar insolation is slightly less than 1000 W/m^2 at noon. Their reported results confirm the results reported in the current study. The collector water outlet temperature was 58 °C in the research reported by Belessiotis *et al.* [11]. The reason for lower water temperature compared to the current results is their collector's higher flow rate and smaller surface area.

At around 17:30 the mentioned temperature difference is reversed *i. e.* the liquid temperature measured in the entrance to the mantle is quite higher than that at the outlet of the collector. The authors' conclusion is that this is so due to tube wall conduction from the hot water stored in the tank compared to the liquid temperature at the outlet of the collector at times that the incoming heat flux from the sun is low. The temperature leaving the mantle side of the storage tank follows a different trend. It does not closely follow the variations of the solar irradiation flux. The fact that it continues rising well after the sun starts losing power is due to mixing of hot and cold layers inside the storage tank. When the sun sets, the mantle outlet temperature starts to increase after a while.

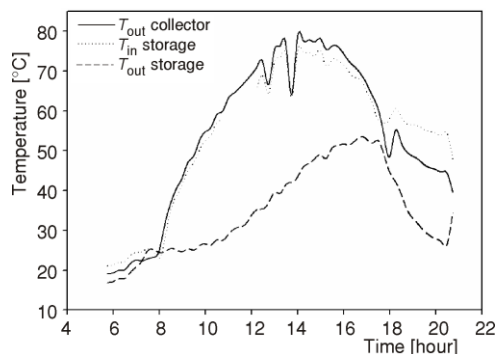Data were measured at the day with ambient temperature change given at fig. 11.

Figure 10. Time variation of input and output temperatures of collector at storage tank
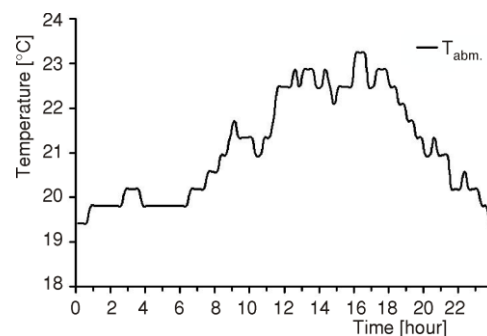
Figure 11. Time variation of ambient temperatures on a sunny day

In order to study the performance of the system under changing climate measurements were taken on a cloudy day having a maximum of 950 W/m^2 insulation at 10:15 with periods going down as low as 200 W/m^2 for example at 13:50. Figure 12 shows the collected data of absorber plate temperatures for such a day. The time lag in following ups

and downs of solar influx is evident from the figure. When the time has passed 15:00, the solar flux has declined considerably whereas the absorber plate temperature stays well above 50 °C for quite some time after that.

Variation of temperature of the water stored in the tank with height is shown in Figure 13 for a cloudy day. The maximum temperature still reaches about 68 °C at 14:00. The thermal stratification is evident even in such a day. The drop in the tank temperatures at different layers is also evident after the sunset. Also it can be seen in the figure that the upper layers do transfer heat through conduction to each other.
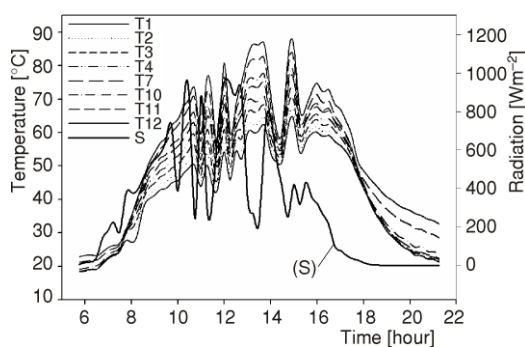

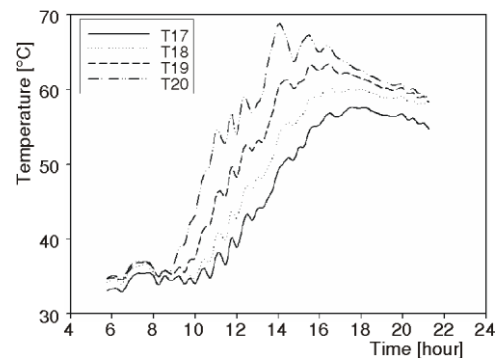**Figure 12. Time variation of absorber plate temperatures on a cloudy day**

Figure 13. Time variation of storage tank temperatures on a cloudy day

Since these systems store hot water for morning use, the ability to keep the water warm was also investigated. It was found that in the particular climate under study, a maximum of 8 °C drop in the temperature of the topmost layer of the storage tank occurs in the winter. This is shown in fig. 14. The drop is almost a linear one through the night. At the time of utilization in the morning water at 55 °C is available for consumption.
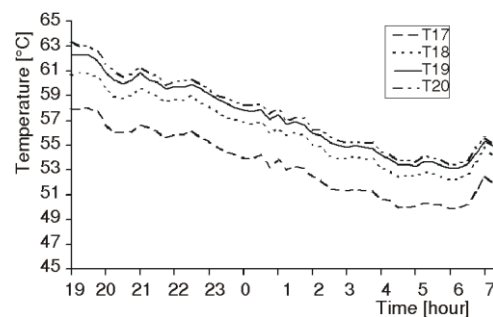

Figure 14. Time variation of storage tank temperature at night

Conclusions

Performance of a thermosyphon solar water heater equipped with a horizontal mantle storage tank in the mild winter of the south Caspian Sea region was studied experimentally. The system was equipped with several thermocouples to measure and collect data via a data logger. The collector temperature reached 90 °C and the time that maximum temperature occurred was about one hour after the point of maximum solar irradiation flux. A quite satisfactory state of thermal stratification was observed in the storage tank and the temperature of the top layer of water was 72 °C on a sunny day. It was shown that these systems work well in the climate under consideration even in days with cloudy periods. The measured thermal performance of the system compares well with the data reported by other researchers for relatively similar systems.

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