New Solar Energy System to Provide Domestic Hot Water in Rural Housing in Tunisia

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Abstract: This paper deals with an experimental investigation of a low-cost solar storage collector, with a total aperture area of 5 m², used for providing domestic hot water in rural zone. The solar storage collector is mainly made up of a concrete absorber with a thickness of 50 mm covered with a double layer of transparent PVC. The matrix absorber of the solar storage collector allows the storage of the excess of solar heat. Inside the concrete absorber is incorporated a network of a capillary heat exchanger made of polypropylene used to carry heat from the concrete absorber. To evaluate efficiency of the solar collector, outdoor experiments were carried out under varied environmental conditions for several days. The results indicate that the solar storage collector is suited to the supply of heated water at a moderate temperature (above 318.15 K) during a typical day of high solar radiation and the water temperature at the outlet of the solar storage collector was kept over 313.15 K during the whole night in cold seasons. The results showed also that the instantaneous thermal efficiency of the solar collector was between 15 % and 50 %. Moreover it was found that the solar collector provides an acceptable heating rate by supplying approximately 90% of domestic hot water requirements for a rural household composed of 5-6 persons.

Keywords: A low cost solar storage collector, Domestic hot water, Rural zone

1. Introduction

Hot water was used in rural households predominantly for taking baths, washing clothes and hygiene purposes. For heating domestic water, Tunisian rural population exploits excessively traditional sources of energy such as firewood and fuel which has become scarce and expensive. Furthermore, the over-use of firewood and fuel has lead to environmental degradation in heavily populated areas. Thus, actually wide efforts have been undertaken to alleviate global warming of earth caused by the emission of carbon dioxide in atmosphere generated by intensive burning of fossil fuels. One way to reduce consumptions of the conventional energy sources is to employ solar energy through solar water heating systems. From the environmental point of view the use of solar water heating systems can play an important role to save the environment. Indeed, Tunisia is blessed with abundant sunshine thus making it appropriate to select solar energy for heating domestic water by means of solar collectors. The widely commercialized systems of the solar collector in Tunisia are the conventional forced circulation type or of the thermo-siphon type based on flat plate collectors and water storage tanks (Kerkeni *et al.*, 1993). Unfortunately, the investment costs for the commercialized solar water heating systems in Tunisia are still elevated. To overcome this problem, we have conceived and developed in our Laboratory (Laboratoire de Maîtrise des Technologies de l'Energie, LMTE) an affordable-cost solar collector system which does not require a storage tank. This environmentally friendly solar collector, having a total surface area of 5 m^2 is tilted at 37˚ from horizontal. This new type of solar collector provides a promising technology. It needs easy and simple maintenance and operation. This solar storage collector can be produced locally from locally available materials (Hazami *et al.*, 2005). Outdoor experiments were carried out under varied environmental conditions for several days using Huang and Taguchi experimental method (Lu *et al.*, 2003; Tsui, 1992) which allows predicting a performance of the solar storage collector. The main objective of this paper is to elucidate the potential of the conceived solar collector in supplying heated water at an acceptable temperature (45 ˚C) until evening on most days of a year, especially in cold seasons for the southern rural Tunisian houses.

2. Materials and Methods

The external casing of the collector was made of highly corrosion-resistant and galvanized steel sheet,

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sprayed with rust preventative paint. The casing was covered with a double layer of 4 mm-thick transparent PVC, followed by a 20 mm-air gap. The absorber plate was made of a 50 mm-thick concrete slab. High radiation absorption was achieved by the use of a matt black paint on the concrete surface. The undersides of the absorber plate and the side casing were well insulated with a 30 mm-thick polyurethane foam to reduce conduction losses. A capillary polypropylene heat exchanger, with an exchange surface equal to 5 m², was embedded inside the concrete absorber. Outdoor experiments were carried out in Borj Cedria (North of Tunisia): Latitude 36° 50' N, Longitude 10° 44' E. **Figure 1** illustrates a schematic diagram of the experimental loop for the solar storage collector tests. The water supplied by the heat pump replenish inside the polypropylene capillary heat exchanger. During the experiments, the following conditions have been taken into account (i) a constant water mass flow rate was maintained by using a flow-meter integrated at the experimental device, (ii) a total solar energy higher than 18 MJm^{-2}; (iii) the inlet water temperature and mass flow in the system was respectively fixed at 295.16 ± 2K and 0.0416 kg s^{-1} by the use of an electric heat pump. To measure the incident solar radiation, a pyranometre (Type Kipp and Zonen) was also placed inside the experimental device. Copper-constantan thermocouples were placed at concrete surface and at inlet and outlet of the solar storage collector. These thermocouples were connected to a multi-channel digital data acquisition. A meteorology station installed in (LMTE, Tunisia) supplies the information about relative humidity of the ambient air and wind speed during the experiments. The test began at 9:00 (solar time) when the data logger system was switched on and all of these parameters were measured at an interval of 5 min with a total accuracy assumed to be about 3 %.

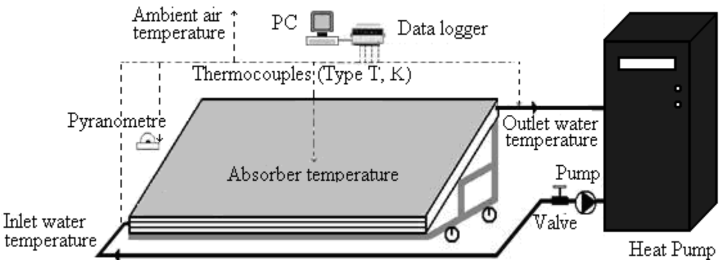

Fig. 1. View of the experimental device.

3. Energy analysis

According to the INPUT/OUTPUT standard (Hikmet, 2008), the energy gain (daily heat output) of the solar collector, Q_u (W), can be represented by the following empirical equation:

$$Q_u = \alpha_1 H + \alpha_2 (T_{a,av} - T_{e,av}) + \alpha_3 \qquad (1)$$

where H is the daily solar irradiation at the collector aperture ($W.m^{-2}$), $T_{a,av}$ is the average ambient air temperature (K), $T_{e,av}$ is the average cold-water inlet temperature (K) and α_1, α_2 and α_3 are constants for a system, determined from the test results; α_1,=30 m^{-2}, α_2 = 0.35 $W.K^{-1}$ and α_3= -12.7.

The overnight heat loss coefficient, U_c ($W/K.m^2$), of the hot water storage system is determined by measuring the temperature loss of the water during a 12 h nocturnal period (Souliotis *et al.*, 2004). The formula used is:

$$U_C = \frac{M_c C_{p,c}}{A_c \Delta t} \ln \frac{T_i - T_{a,av}}{T_f - T_{Abs,av}} \qquad (2)$$

where A_c is the surface area of the collector (m^2), $C_{p,c}$ is the specific heat of concrete absorber (J/(kg K)), Δt is the test period (s), T_i is the initial temperature of the water in the tank (K), T_f is the final temperature of the water at the solar storage exit after 12 h (K), $T_{a,av}$ is the average ambient temperature (K), $T_{Abs,av}$ is the average concrete absorber temperature (K) and M_c is the concrete mass (kg).

The daily thermal efficiency of the solar collector $\bar{\eta}_j$ is given by the expression:

$$\bar{\eta}_j = \int_{t1}^{t2} Q_u(t)\,dt \Big/ \int_{t1}^{t2} A_c.H(t)\,dt \qquad (3)$$

The daily thermal efficiency of the solar collector $\bar{\eta}_j$ is also given by the expression:

$$\bar{\eta}_j = \eta_o - U_c \frac{T_{Abs,av} - T_{a,av}}{H_{av}} - \frac{M_c C_{p,c}(T_{Abs,t_2} - T_{Abs,t_1})}{A_c.H_{av}} \quad (4)$$

where H_{av} is the average solar radiation ($W.m^{-2}$), $T_{Abs,\,t1}$ and $T_{Abs,\,t2}$ are the concrete absorber temperatures at the instants t_1 and t_2 respectively (K) and η_0 is the optical yield. It represents the fraction of the solar radiation absorbed by the concrete matrix. Eqs.3, 4 permits the experimental determination of η_0 ($\eta_0 = 0.7$).

4. Results and Discussion

The daily thermal efficiency of the solar collector is shown, in **Figure 2**, as a function of time. The thermal efficiency of the solar collector was increased with the increase in inlet water temperature. The net energy efficiency changed between 15 % and 50 %. The efficiency reaches the higher value at 12:30, and then, the temperature decreases continually. Figure 2 shows that the efficiency reaches its maximum point for solar energy radiation about 850 W/m^2 and for the environment temperature about 295.15 K. To evaluate the solar storage collector heat loss coefficient, U_c, another test was done. The test consists of covering the solar storage collector by a 30 mm-thick polyurethane foam while the circulation of water inside the heat exchanger is stopped. Then we followed the decrease in temperature of the concrete absorber during about 12 h. The overnight heat loss coefficient, U_c, is experimentally determined by equation 2. It is assumed to be equal to 14 W/K.m^2. In order to illustrate the thermal behavior of the solar storage collector, a winter day (cloudy day characterized by a harshly solar radiation oscillation) has primarily been chosen for the experimental study. The solar radiation and the water temperature at the outlet of the solar storage collector increases are represented in **Figure 3**. As expected, the outlet water temperature (T_o) of the solar storage collector depends on solar radiation. It increases to a maximum value of 318.15 K at 12:00 pm in the noon and remains almost constant during 4 h before it starts to decrease later in the afternoon. We noted also that the water temperature at the outlet of the solar collector was not affected by solar radiation oscillation. Indeed, while the solar storage collector was functioning, the absorbed solar energy was stored in the concrete matrix at a not negligible rate. The solar heat stored inside the concrete absorber is delivered to the heat exchanger whilst the insulation starts to decrease. To evaluate this amount of energy we have represented in **Figure 4**, the variations of stored energy as a function of time.

We noted that the stored energy inside the absorber matrix was almost constant during morning and it increased until noon at morning. A maximum peak of stored energy, about 2 kW, was obtained at 13:00 h and remained almost constant during 3 h. Then, the stored energy decreased as the solar radiation decreased. To improve the stored thermal energy conservation, we opted for covering the collector surface with an insulation blanket before the solar radiation remarkably decreased (around 16:00). After 18:00, a nightly withdrawal of water from the covered solar storage collector was performed (**Figure 5**). The results showed that the temperature of the extracted water decreased during the withdrawal process. In fact, the stocked thermal power inside the concrete absorber decreased continually according to the time. We noted that the solar storage collector supplied about 150 liters at a temperature of 318.15 K. This quantity

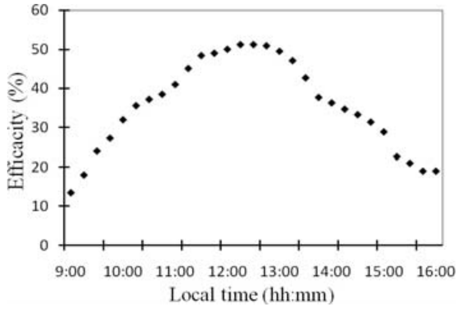

Fig. 2. The variation of the solar storage collector efficiencies versus time.

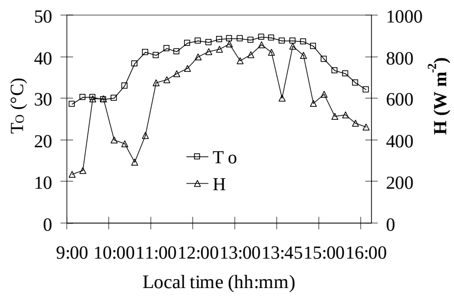

Fig. 3. Outlet water temperature increase versus time for a mass flow rate of 0.0416 kg s^{-1} and average ambient temperature of 295.15 K.

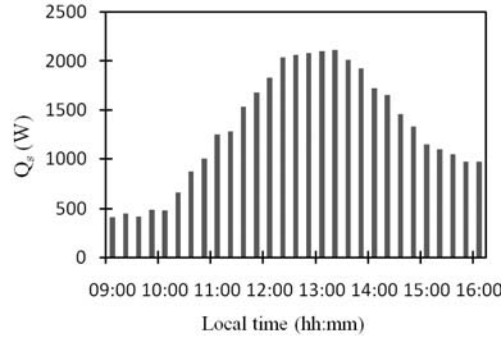

Fig. 4. Time change in energy stored in the solar storage collector.

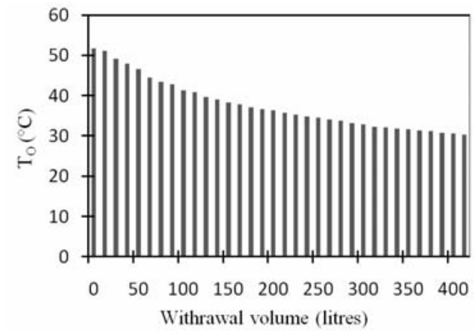

Fig. 5. The outlet water temperature as a function of withdrawal volume of water.

Table 1. Comparison between a conventional solar collector and solar storage collector.

	Conventional solar collector	Solar storage collector
Thermal efficiency	38 %	32 %
System cost	800 $	250 $
The annual energy gain	1450 kWh	1300 kWh
Cost payback	8 years	3 years

of water extracted can provide about 90 % of family's needs in hot water during one day and about 75 % of family's needs in hot water during one year. The test result obtained for the concrete solar collector that does not need a storage tank were compared with tests carried out for the most popular water heating system in Tunisia (Hasan, 2003) that consisted of a flat plate collector (2 m^2 aperture area) and a water storage tank (capacity 200 l) (**Table 1**). Results showed that for a rural housing the concrete solar collector produced from locally available materials (Galvanized iron, (80 $), PVC transparent cover (100 $), concrete absorber (15 $), polypropylene heat exchanger (20 $) and polyurethane (35 $)) is a promising solution, which can save a lot of fuel or firewood, especially for economical modest family.

5. Conclusion

The performance of a newly designed solar storage collector that does not need a storage tank has been presented. Results showed that the solar storage collector can be the most appropriate solution for domestic use especially for modest rural families. In fact, this system provides a substantial cost saving. When compared to the traditional solar system design, it is obvious that the use of this system is promising. It attained an efficiency of 32 %. The use of a solar storage collector can supply at minimum 90 % of the building's hot water requirements throughout the year saving the homeowner 75 % of his annual heating bill and reducing the need for non-renewable energy. In winter, water can be heated to 318.15 K so that it is still at a comfortable bathing temperature of at least 313.15 K in the evening. To reduce its installation costs in rural buildings, the cement concrete solar collector can be integrated with the roof structure.

References

Kerkeni C., Hamdi K., Dehmani L., Belghith A. (1993): Etude des Performances Thermiques à Long Terme d'un Système Solaire de Chauffage de l'Eau Sanitaire. *JITH*, **93**: 345–351.

Hazami M., Kooli S., Lazâar M., Farhat A., Belghith A. (2005): Performance of a solar storage collector. *Desalination*, **183**: 167-172.

Lu S.M, Li Y.C.M., Tang J.C. (2003): Optimum design of natural-circulation solar-water-heater by the Taguchi method. *Energy*, **28**: 741–750.

Tsui K.L. (1992): An overview of Taguchi method and newly developed statistical methods for robust design. *IIE Trans*, **24**(5): 44-57

Hikmet E. (2008): Experimental energy and exergy analysis of a double-flow solar air heater having different obstacles on absorber plates. *Building and Environment*, **43**: 1046–1054.

Souliotis M., Tripanagnostopoulos Y. (2004): Experimental study of CPC type ICS solar systems. *Solar Energy*, **76**: 389–408

Hasan A. (2000): *Comparing Integrated Collector-Storag Water Heater with Thermosyphon System*. WREC', pp.1031-1035.