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Experimental study on the performance of a prism-shaped integrated collector-storage solar water heater

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Abstract
This paper presents an experimental investigation on the thermal performance of a 500-liter integrated collector storage system in the shape of a prism with a right angle. A grid of 45 thermocouples was assembled inside the storage tank to monitor the temperature distribution, which was utilized to estimate the mass-weighted average temperature inside the tank and the heat gain. The total stored energy for a day in August was found to be 105.92 MJ/m^3 with a temperature increase of 25.2˚C. In November, the total stored energy was 65.86 MJ/m^3 with a temperature increase of 15.5˚C while it was 56.92 MJ/m^3 for January with a temperature increase of 13.6˚C. A comparison between the present experimental results and published theoretical results for a similar shape showed good agreement.

Keywords: Integrated storage; Prism solar collector; Hot water.

1. Introduction
Solar domestic hot water (SDHW) systems can be designed in many ways and manufactured with a variety of techniques. Conventional SDHW systems consist generally of one or more solar collector connected to a thermal storage tank through suitable piping. A storage system differs from the conventional one by integrating the collector and storage tank into one piece of equipment. The design of collector-storage systems vary by the collector type used and the combination method with the storage.
A prism shaped solar storage collector was investigated numerically by Joudi et al. [1] using the ANSYS software. A storage collector that is constructed from six 80-mm-outside diameter copper tubes, 150 mm long each acted as a collector and storage was investigated experimentally by Khalifa and Abdul Jabbar [2]. An integrated collector storage solar water heater with compound parabolic concentrating reflectors was investigated experimentally by Helal et al. [3]. Stratification in a simple flat plate integrated collector storage type heater was studied theoretically and experimentally by Junaidi et al. [4]. Tripanagnostopoulos and Souliotis [5] proposed systems consisted of single cylindrical horizontal water storage tanks placed inside stationary truncated asymmetric compound parabolic concentrating reflector troughs of different designs. Tarhan et al. [6] investigated the temperature distributions in three trapezoidal built in storage solar water heaters with and without phase change materials (PCM). Eames and Griffiths [7] developed a transient finite volume model to predict collection and retention of heat for rectangular cross section solar collector/storage systems when filled with water and various concentrations of PCM slurries.
The present research investigates the actual performance of a large capacity integrated collector storage solar water heater in the shape of a right angle prism-shaped tank covered with glass during several months of the year. The heat gain and the increase in the mass-weighted average temperature of the solar

storage collector have been obtained by examining the hourly temperature distribution inside the storage tank. A comparison between the experimental performance of the present system and published theoretical results for this type is another objective of this study.

2. Experimental Setup and test procedure

The experimental storage tank fabricated for the purpose of this investigation was a single slope prism-shaped integrated collector storage system with a right angle as shown in Figure 1. The 500-liter tank has a basement area of $1m^2$ and a height of 1m on the backside. The body of the storage tank was constructed from 1.5-mm-thick galvanized iron sheet that were painted black on the interior surfaces to increase the solar energy absorption. A 10-mm-thick tempered glass sheet of dimensions 1 by 1.45 m was assembled on the bended free edges with bolt and nut clamps and silicon sealant to insure water tightness. The sides and bottom of the tank were insulated with 6-cm-thick polystyrene sheets.

A mesh of 45 calibrated copper-constantan (type T) thermocouples, as shown in Figure 2, was employed to measure the temperature distribution of water inside the system using a digital multi-meter (Type MS8221B with an accuracy of ± 1%). The thermocouples were distributed at a distance of 10 cm apart in both the horizontal and the vertical directions using a right-angle aluminum support that holds a mesh with 3-cm diameter openings made from a fine non-conductive string to avoid the disturbance of water circulation and to insure accurate temperature measurement. Reflecting shields were used on the tip of the thermocouple junctions to minimize the effect of direct solar radiation on the temperature measurement. The measurements were taken at an hour time interval from sunrise to sunset. The south-oriented system was tested in Erbil- Iraq (latitude 36.11° N, longitude 44° E and 430 meter above sea level) on sunny and clear days.

Figure1. The experimental integrated collector storage system

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Figure 2. Thermocouples distribution inside the tank

3. Results and discussion

The hourly temperature distribution inside the tank for August, November, and January are shown in Figures 3 to 5 respectively. Using these measurements, the mass-weighted tank average temperature (T_{av}) and the stored energy per unit volume (Q) were calculated using the following formulae respectively:

$$T_{av} = \sum_{i=1}^{N+1} \frac{(M_i T_i)}{M_{tot}} \quad (1)$$

$$Q = \rho C_w (T_{av} - T_i) \quad (2)$$

where,

T_{av} Average temperature, °C

M_i Mass of specific film, kg

T_i Temperature of specific film, °C

M_{tot} Total mass, kg

Q Stored energy, MJ/m^3

C_w Specific heat at constant pressure, kJ/kg °C

ρ Density, kg/m^3

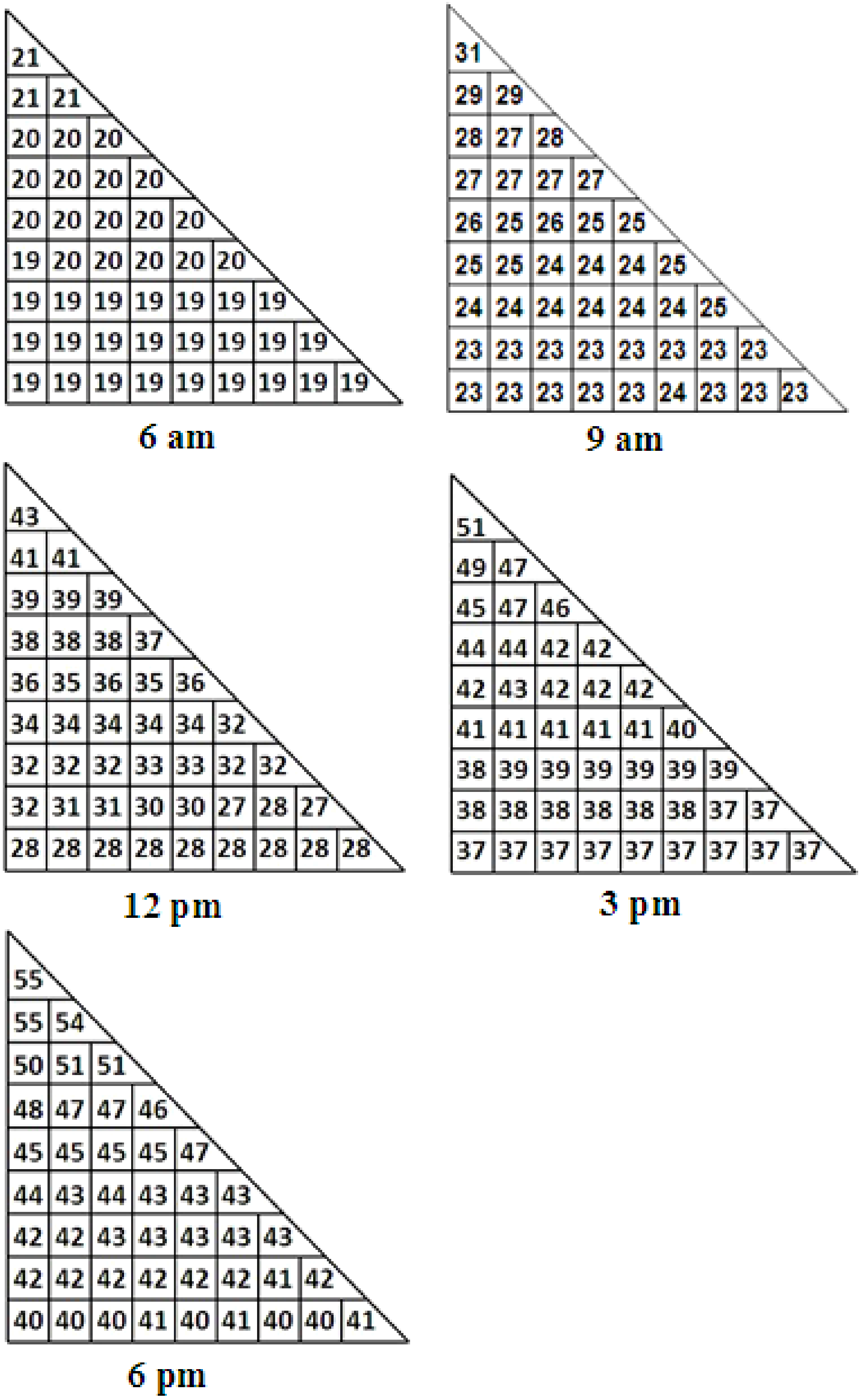

Figure 3. The temperature distributions for the 18 August 2009 for different hours of the day

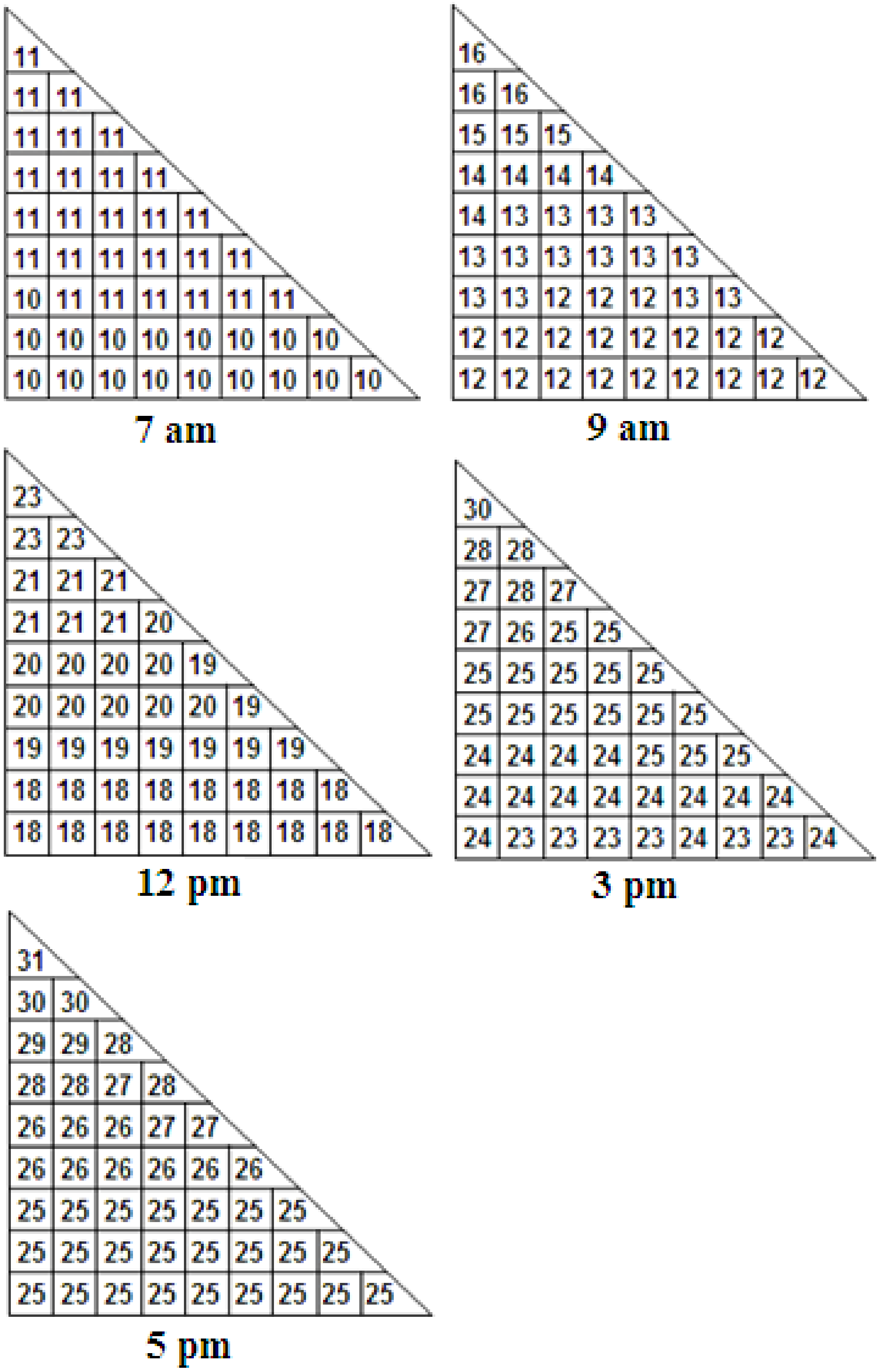

Figure 4. The temperature distributions for the 1 November 2009 for different hours of the day

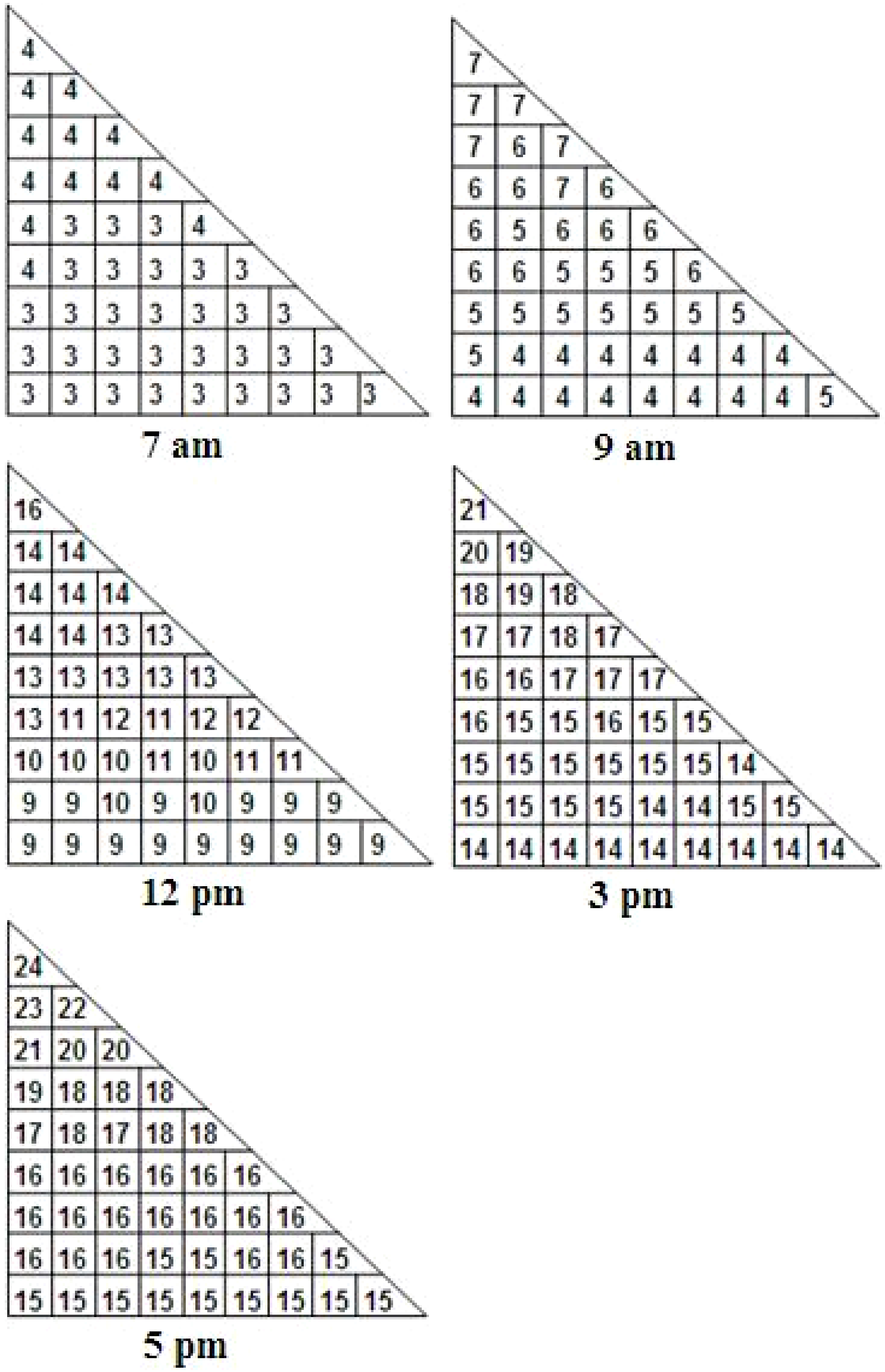

Figure 5. The temperature distributions for the 5 January 2010 for different hours of the day

The total stored energy on the 18 August was found to be 105.92 MJ/m^3 with a temperature increase during working hours of 25.2˚C (from 19.2˚C to a maximum of 44.4˚C) as shown in Figure 6 at an incident solar radiation of 19.16 MJ/m^{2}day. On the 1 November, the total stored energy was 65.86 MJ/m^3 with a temperature increase of 15.5˚C (from 10.6˚C to a maximum of 26.1˚C) as shown in Figure 7 at an incident solar radiation of 12.81 MJ/m^{2}day. The total stored energy on 5 January was 56.92 MJ/m^3, with a temperature increase of 13.6˚C (from 3.3˚C to 16.9˚C) as shown in Figure 8 at an incident solar radiation of 9.81 MJ/m^{2}day.

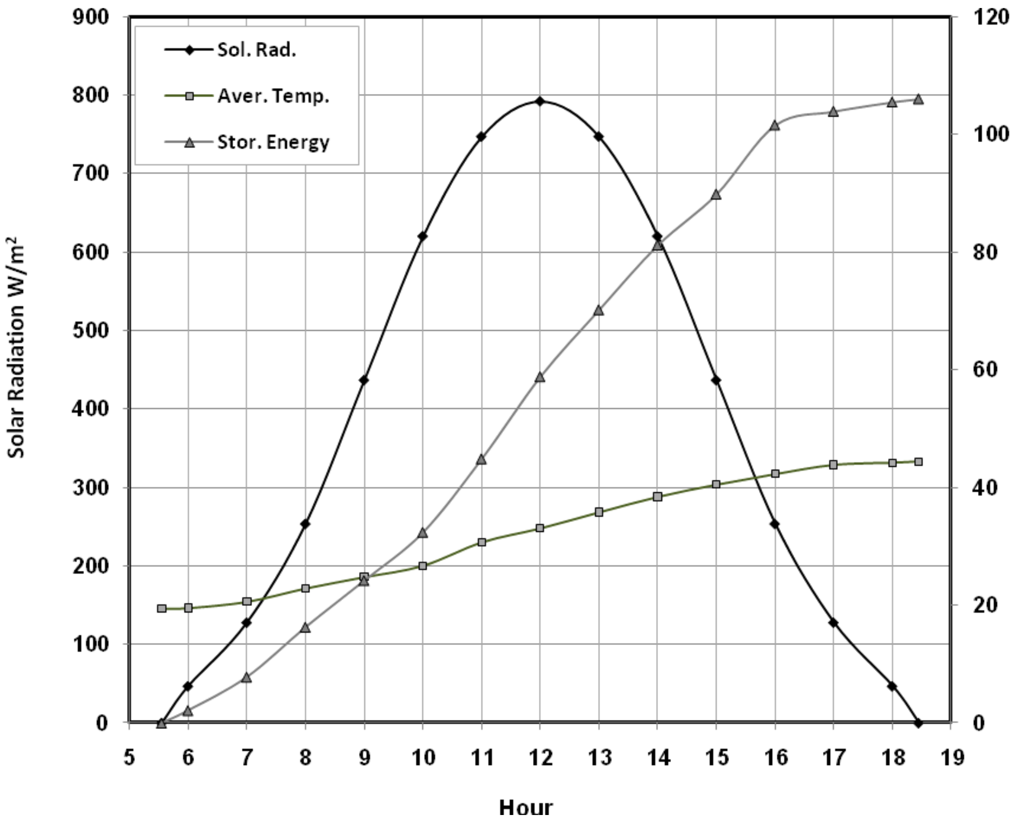

Figure 6. Time variation of solar radiation, stored energy and mass-weighted average temperature in August

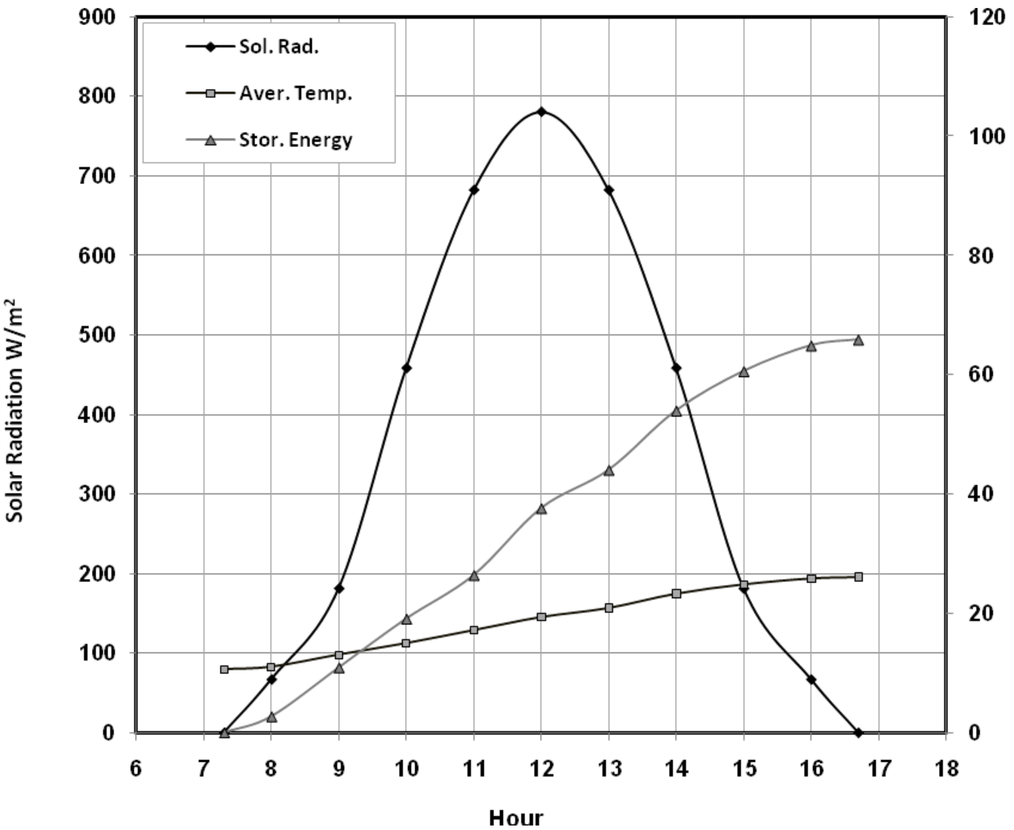

Figure 7. Time variation of solar radiation, stored energy and mass-weighted average temperature in November

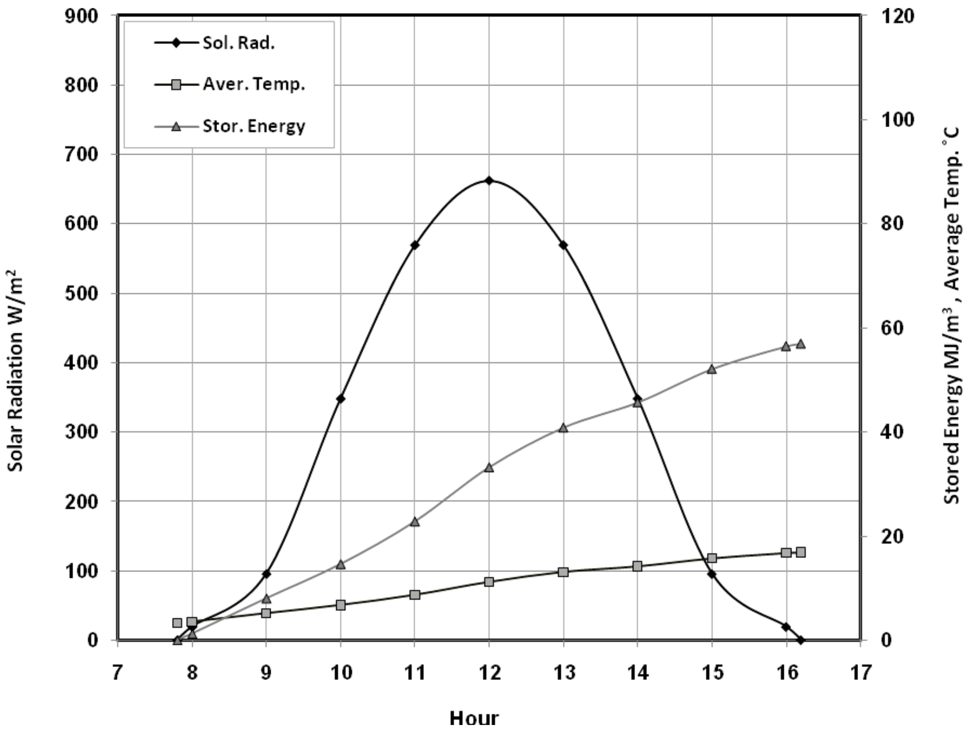

Figure 8. Time variation of solar radiation, stored energy and mass-weighted average temperature in January

It is observed that the temperature, and hence the stored energy, increase with the incident solar radiation. Low temperature gradient is noticed at the beginning of the day due to the heat storage in water. Afterwards, as more radiation is absorbed, the temperature gradient starts to be more noticeable. The cold water accumulates at the bottom while hot water ascends to the top of the tank. It is originated from the fact that, after gaining heat from the solar radiation, the tank wall heats a thin vertical layer of water along the tank wall. Part of this heat is then transferred by diffusion towards the core of the tank. The water of the vertical layer becomes lighter than its surrounding and then ascends towards the top of the tank creating the stratification.

Joudi et al. [1] had presented a numerical study on a similar system for January and June. In the present investigation, the tests were conducted in August, November, and January. A comparison between the experimental results of August and the theoretical results of [1] in June is shown in Figure 9 for solar radiation and average tank temperature with time, while that for solar radiation and stored energy is shown in Figure 10. Likewise, Figures 11 and 12 show similar comparisons for January.

It is observed that the values of solar radiation used in the present experimental study are different from those reported by the theoretical study of [1]; therefore, it is necessary to relate the comparison between the results of the two studies to a single parameter that takes into account such difference. A factor equals to the ratio of the stored energy to the solar radiation in each case is used for this purpose. Equation (2) indicates that the stored energy is function of the density, specific heat capacity and the initial and mass-weighted average temperatures of water; with all the values, apart from the mass-weighted average temperature, are the same in both studies. Accordingly, a parameter equals to the ratio between the mass-weighted average temperature and the solar radiation may be used for the purpose of the comparison, which should reflect the effect of solar radiation on the temperature attained by the two systems.

Figure 13 shows the time variation of such parameter for summer (August for the present study compared to June in [1]). A difference of around 19% may be noticed between the two values, noting that the comparison is for two different months. The comparison for January is shown in Figure 14; it is observed that the results are much closer with a difference of around 3% for the most of the day. In both comparisons, the experimental study gives lower values for most hours of the day, which may be attributed to different kind of thermal losses that are usually ignored by numerical models. The relatively larger difference in the morning hours is caused by the storage effect in water. Such comparison verifies the model used by [1] to predict the performance of the prism-shaped solar collector with a reasonable accuracy.

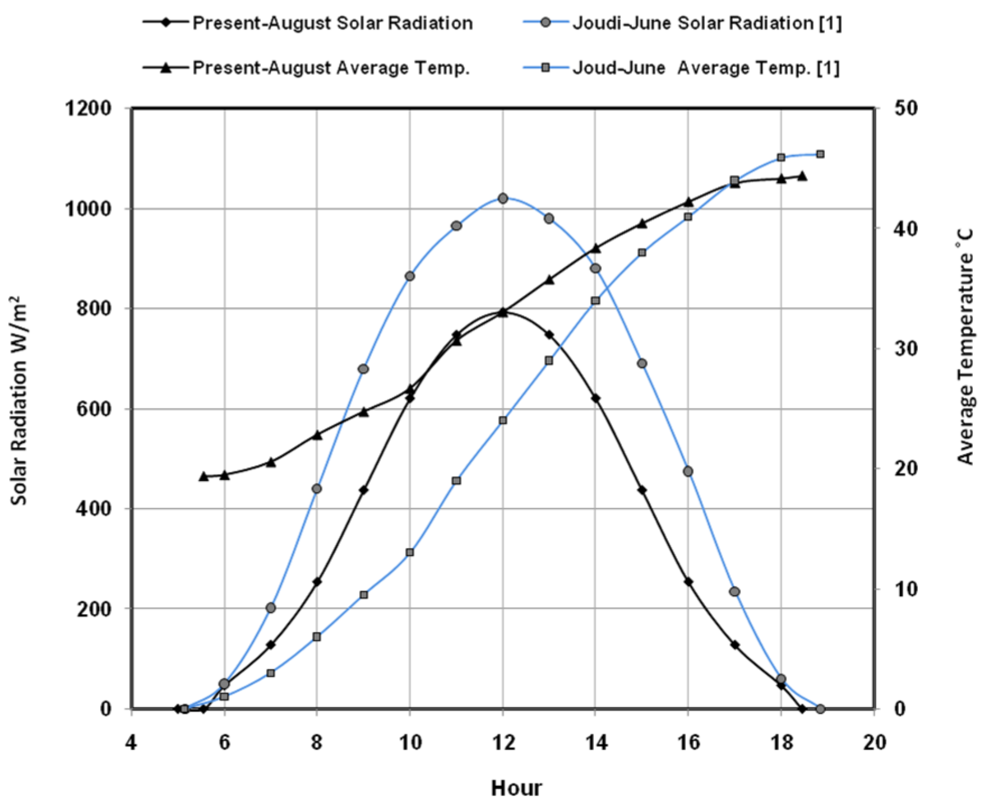

Figure 9. The time variation of solar radiation and average temperature of the present experimental study in August and the theoretical results of [1] in June

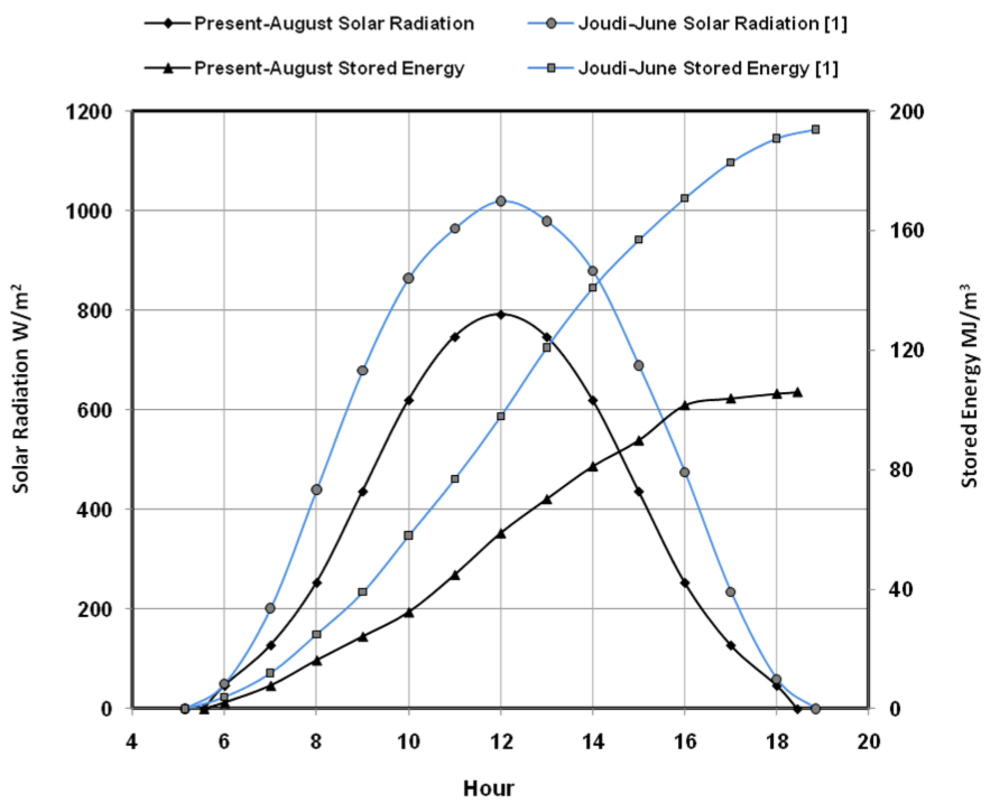

Figure 10. The time variation of solar radiation and stored energy of the present experimental study in August and the theoretical results of [1] in June

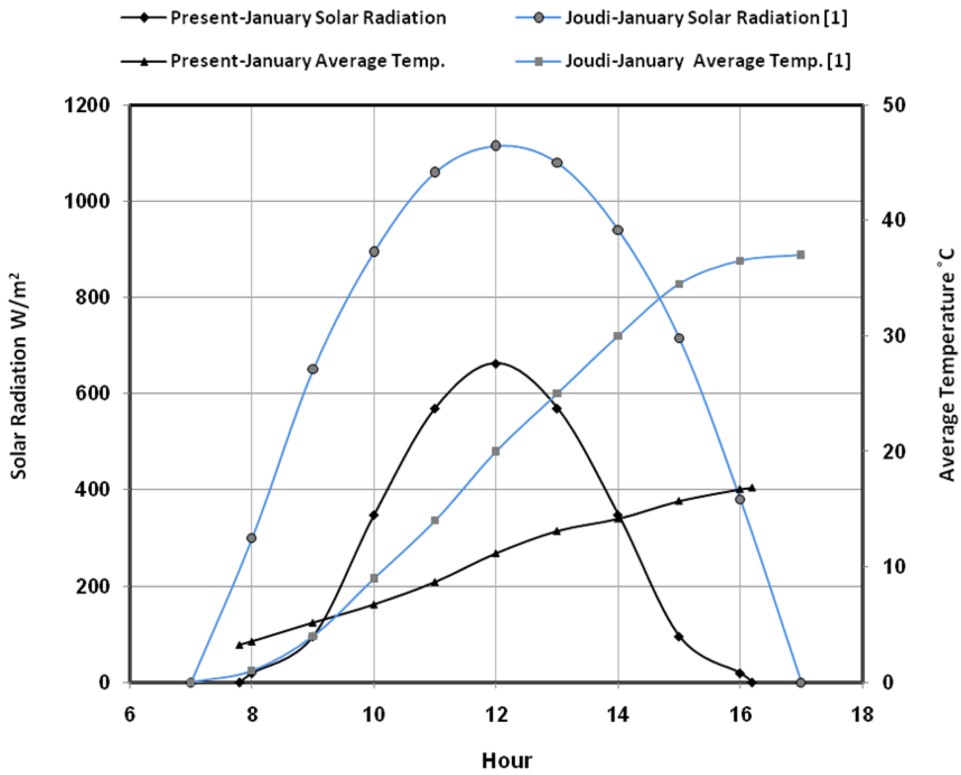

Figure 11. The time variation of solar radiation and average temperature of the present experimental study and the theoretical results of [1] in January

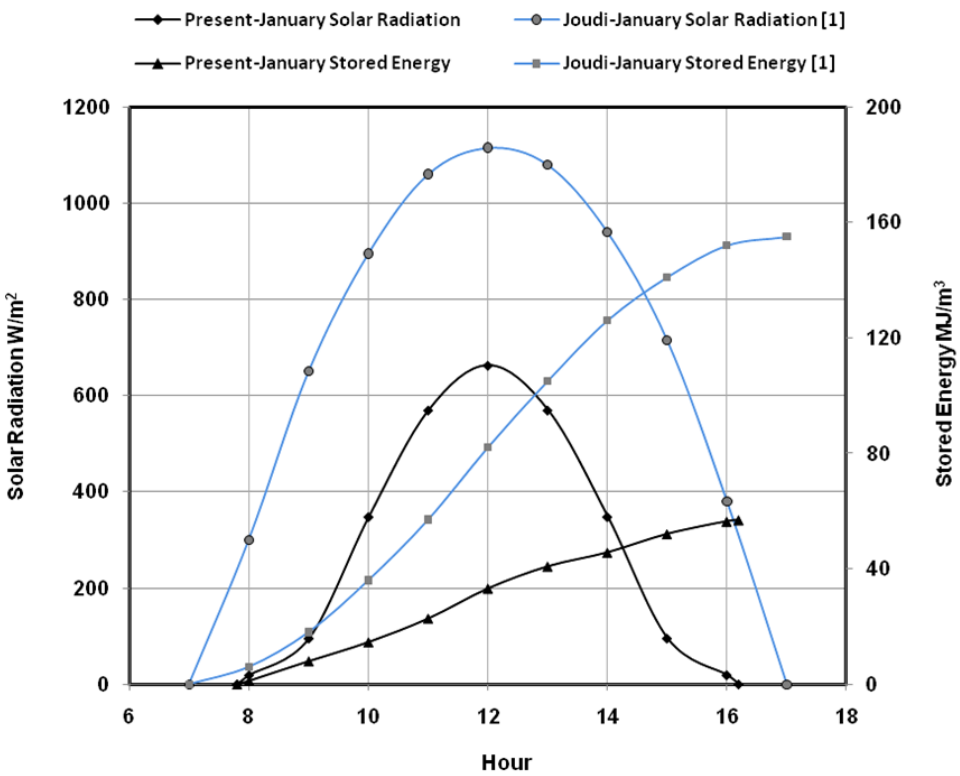

Figure 12. The time variation of solar radiation and stored energy of the present experimental study and the theoretical results of [1] in January

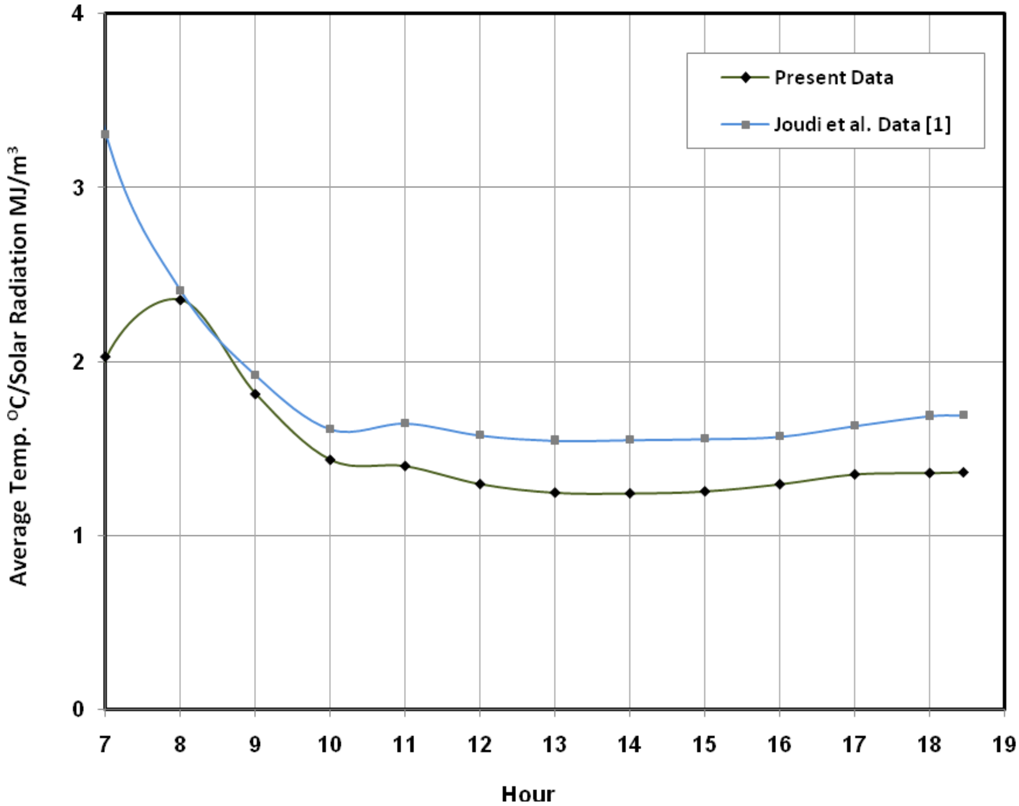

Figure 13. The time variation of the parameter "average temperature/solar radiation" for August from the present study and the published data [1] for June

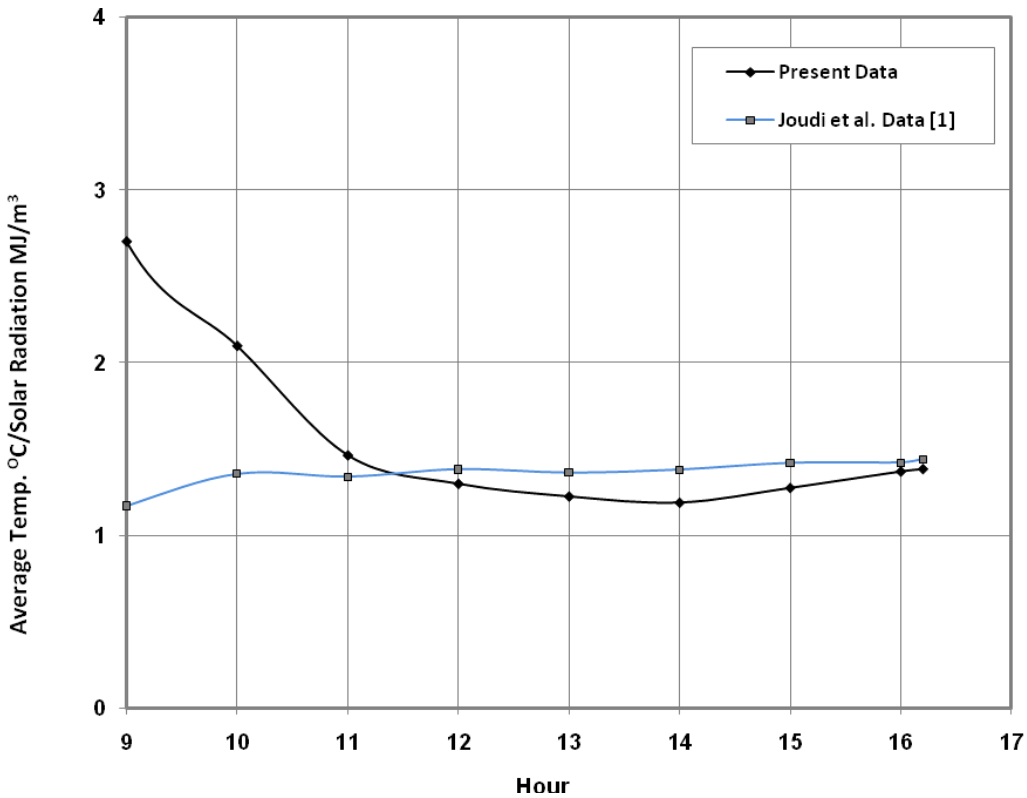

Figure 14. The time variation of the parameter "average temperature/solar radiation" from the present study and the published data [1] for January

4. Conclusion

An experimental study is conducted on a 500-liter prism-shaped water heating system. The temperature variation inside the tank and the stored energy were monitored for August, November and January. The results were compared to those obtained by a computational model reported in the literature. It was found that despite the large volume of water, the temperature of water is increased from 19.2˚C to 44.4˚C in August, from 10.6˚C to 26.1˚C in November and from 3.3˚C to 16.9˚C in January. Low temperature gradient is noticed at the beginning of the day due to the heat storage in water followed by a more temperature gradient as more radiation is absorbed. The results of the present study verified the model used by [1] to predict the performance of the prism-shaped solar collector with a reasonable accuracy.

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