Thermal analysis of compact solar water heater under local climatic conditions☆

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A B S T R A C T

Extensive experimental studies on a compact solar water heater were carried out, in order to evaluate the performance of the heater and determine the optimal depth of the storage tank. The experiments were conducted for tank depths of 5, 10 and 15 cm with single and double glazing. Experimental results show that a temperature rise of about 68 °C during the month of July at storage tank depth of 10 cm can be achieved by the heater. The 10 cm depth of the tank is optimum which can supply hot water for 24 h. The rise of water temperature is slightly higher in the case of single glazing than the double glazed system, while the double glazed system is more effective in retaining higher temperatures during night hours.

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1. Introduction

Solar water heating for domestic purposes is at present the most attractive way of utilizing solar energy. This is largely due to the regular daily demand of hot water at moderate temperatures, resulting in an efficient collection of the incident solar radiation without the necessity of large storage. Solar water heating systems (SWH) are popular in Jordan, about 24% of the dwellings are equipped with one form or another of SWH system [1,2]. Mohsen and Akash [3] used a multi criteria analysis to evaluate the domestic SWH systems in Jordan, the systems were considered in terms of benefits and costs. It was found that SWH system is the most beneficial system when compared to other systems which are presently employed.

Most of the used SWH systems are of the thermosyphon type that consists of a grid of water carrying tubes bonded to the absorber plate, or with channels to flow the fluid, together with a separate storage tank. These systems are not very efficient due to the unavoidable losses by conduction, convection and radiation caused by the temperature difference apart from problems because of leakages through joints and corrosion. The increased cost due to separate storage tank and absorber unit as well as the slightly lower efficiency is the demerits of such a solar water heater. Solar water heater of built-in-storage type incorporating the storage volume and collector in a single unit is an attractive alternative to the thermosyphon system, which is free from welding, joints, bends, etc. The elimination of the vertical storage tank in the compact unit could markedly reduce the cost of solar water heater. Similar units are used in different countries such as Japan, Israel, South Africa, and Ghana [4–8]. The simplicity and relatively low cost of fabrication and installation of the compact SWH make it an attractive option to be used in Jordan especially in rural areas and Badia region. These regions are considered to be a national target for sustainable development.

In a recent paper [9], Mohsen and Akash conducted an experiment on the performance of compact SWH under local climatic conditions. The tested collector in this experiment was of a box type with single glazing. It was found that a temperature rise of 30 °C can be achieved by the system for a particular sunny day during the month of November. The loss of accumulated energy during night from the collector is the major drawback of the system. However, the collector can be covered throughout the night, or the hot water can be transferred to another storage tank. In Jordan, the use of the system can be directed towards applications, where hot water is not highly needed the following morning, such as in workshops and small plants in the Badia region. Mohsen and Nuseirat [10], evaluated the long term performance of the compact SWH using computer simulation and the results were compared with those obtained experimentally. The location used to perform the analysis is Amman (32° N latitude), the capital of Jordan. The average values of ten year measurements of daily global and diffuse radiation, wind speed, and an ambient temperature at this location were used. Wherein, actual climatic data for this location were used in the simulation as recorded by the Meteorological Department [11]. Experimental measurements show that a temperature rise of about 37 °C with collector inclination at 45° and a maximum cumulative efficiency of 0.59 can be achieved by the heater. A satisfactory agreement between the experimental and predicted trends for the collector is noticed.

Dharuman et al. [12] evaluated the performance of an integrated solar water heater as an option for building energy conservation and
The energy balance on the collector plate and storage tank, respectively, is given by:

\[ A_p I_i(t) = U_L(t) A_p (T_p(t) - T_a) + U_w(t) A_p (T_p(t) - T_w(t)) \]  \hspace{1cm} (1)

\[ (M_w C_p + M_s C_p) \frac{d T_w(t)}{dt} = A_p F_m(t) I_i(t) - U_o (T_w(t) - T_a) \]  \hspace{1cm} (2)

where all terms mentioned in the above equations are defined in the nomenclature.

The absorbed hourly solar radiation is given by

\[ I_i = I_{0,p} R(\tau(\alpha t)) K(\theta_i) + I_{0,1}(\tau(\alpha t))(1 + \cos(\beta))/2. \]  \hspace{1cm} (3)

The top loss coefficient \( U_o \), overall loss coefficient \( U_{ow} \), plate-to-water unit conductance \( U_w \), and collector efficiency factor \( F_m \), respectively, are calculated according to:

\[ U_o = \left[ \frac{1}{C \left( \frac{A_p}{F_p} \left( 1 + \frac{1}{T_a} \right) \right)^{0.522} + \frac{1}{F_w}} \right]^{1/ \left[ 1 + \frac{\alpha(T_p + T_a)}{F_p} \right]} \]  \hspace{1cm} (4)

\[ U_{ow} = U_L + \frac{U_L}{F_m} (1 + A_{sd}/A_p) \]

\[ U_w = \frac{N w L}{K w} \]

\[ F_m = U_w / (U_w + U_L) \]

Where the exact expressions for \( I_{0,p}, R, K(\theta_i), C, f, d, \) and \( h_{in} \) are found in the reference [10]. A stepwise solution procedure with 1 hour driving periods may be used to solve the model Eqns. (1) and (2) for the plate, and water temperatures. The mathematical model and the numerical solution are fully described in reference [10].

3. Results and discussions

Fig. 2 shows the experimental performance of the system for a sunny day in the month of December 2007 and the months of January, February, March, April and July 2008. It is clear from the figure that the system can heat the water up to a temperature of 52, 50, 53, 68, 69 and 68 °C, respectively. The maximum water temperature reaches at about 4 pm. Fig. 3 shows the effect of glass covers on the performance of the system. The results are shown for the same months, when the depth of the storage tank is 10 cm. It shows that the rise of water temperature is slightly higher in the case of single glazing than that of the double glazed system. The rise of water temperature is less in double glass system due to the reduced incident solar radiation. During the night cooling hours the outward heat losses are more pronounced in the single glass cover case than the double one. As a result, the water
Fig. 2. Performance of the system for a clear day in the months of Dec. 2007, Jan., Feb., Mar., Apr., and Jul. 2008.
temperature falls at a slightly faster rate than the double glazed system.

Fig. 4 shows the effect of tank depth and glazing on the performance of the system. Water temperature is plotted at different hours of the day during the month of March for single and double glazed systems when the depth of the storage tank is 5, 10 and 15 cm, respectively. The mass of water in the tank is 45, 90 and 135 kg, respectively. The rise of water temperature is maximum in the case of 5 cm depth which is about 77 °C in single glazing and 76 °C in case of double glazing. But the fall in temperature is also very sharp during the night hours. Minimum rise of water temperature occurs in case of 15 cm depth and hence the fall in temperature occurs at a more gradual manner. Water temperature is 66 and 62 °C for single and double glazing, respectively. For the case of 10 cm depth, water temperature rises up to 69 °C in case of single glazing and it goes up to 67 °C in case of double glazing at 3:30 pm in the afternoon. During the night hours since the outward heat losses in double glazed system are lower than the single one, hence the water temperature in the following morning is slightly higher in double glazed system. It is also clear from the graph that the water temperature in the early morning is almost the same with 10 and 15 cm depth of the tank. Since the rise of water temperature is lower in case of 15 cm depth due to the large water capacity of the tank, hence the hot water of proper temperature requirement cannot be obtained in this case. In the case of 5 cm depth rise of water temperature is very sharp, but due to the great temperature difference during cooling hours the outward heat losses are highly prominent here, hence the temperature falls abruptly so neither 5 cm depth is advisable nor 15 cm depth cm fulfill the hot water requirement. Only the 10 cm depth of the tank is suitable which can supply hot water for 24 h; with a minimum of water temperature of 37 and 35 °C for double and single glazing, respectively, at 7:00 in the morning.

Fig. 5 shows the inverse variation of maximum water temperature with the depth of the tank for single and double glazing. From the figure it is clear that, the single glazed system performs better in comparison to the performance of double glazed system. From the efficiency curve it can be seen that efficiency is higher for single glazing and increasing faster with the depth of the tank.

Fig. 6 shows the rise of water temperature at different hours of a day for three consecutive days on the basis of experimental observations. Water is not drained out from the tank for the whole period. It is clear from this graph that the rise of water temperature is 67, 69 and 68 °C on the consecutive days. Water temperature in early morning hours for all the three days is about 31, 34 and 35 °C.

4. Conclusions

The following conclusions are drawn from this study:
1. For domestic hot water requirement at moderate temperature, single glazing should be used, while the double glazed system is more effective in retaining higher temperatures during night hours.
2. Performance of the system is optimum with 10 cm depth of storage tank.
3. The system can be used efficiently in rural areas and the Badia of Jordan, where hot domestic water requirements is not very large in the early morning.

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References


Fig. 4. Effect of depth and glazing on the performance of the system.
Fig. 5. Variation of maximum water temperature with the depth of the storage tank for single and double glazing.
Fig. 6. Rise of water temperature at different hours of a day for three consecutive days on the basis of experimental observations.