Experimental Investigation of developing the Thermal Performance of the Integrated Collector Storage Solar System by Lateral Perforated Fins

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The Integrated Collector Storage (ICS) has a great application in the solar energy field such as instantaneous heating with little initial and operation cost as well as its resistance against the problems of overheating and freezing. In this research, an advanced ICS was designed and investigated with an array of 1.5 mm thickness galvanized lateral steel plate fins fixed in the storage tank. The new design was examined from 7:00 a.m. until 5:00 p.m. The results show an increase in mean storage temperature and collection efficiency of up to 20% and 37% respectively.

Keywords: Solar water heating system; Integral Collector storage; Perforated Fins; Thermal performance; Stagnation Collection efficiency; Water withdrawal Profile.

Introduction

Hot water is highly required by a human in domestic, commercial, and industrial purposes. Due to the rapid increase in the cost of traditional energy sources, renewable energy resources like solar energy become of great interest (Duffie *et al.*, (2013); Goswami, (2015)). Solar water heating systems directly convert solar energy into thermal energy. So, they are playing an important role in houses and industrial areas due to its simplicity of operation and maintenance (Gevorkian, (2008)). Most solar water heaters fall into three main types which are, forced circulation (active systems), natural convection (thermosyphon or passive systems), and the integrated collector-storage systems (Kreith *et al.*, (1978); Kumar *et al.*, (2011)). The household water heating system was approved as a successful application of solar energy. Flat plate collectors are frequently employed in such systems. They were developed and became with high efficiencies. The flat plate collector system requires the use of a separate heat storage system. The separate collector storage tank is huge and doesn't fit on most of the modern inclined roofs or multi-story buildings (Duffie *et al.*, (2013)). Unlike other heating systems, in the Integral Collector Storage solar systems (ICS), also named as batch or bread box water heating systems, the collector and the storage tank are combined into one single piece making the design more simple and lowering the operational cost since no moving parts were used (passive system). Also, it has a large thermal mass of working fluid preventing the freezing and the overheating problems in many conditions (Kumar *et al.*, (2011); Hasan, (2000)). The ICS systems suffer from heat losses to ambient, especially at night and during the periods where there is no insolation since the heat is collected and stored at the storage tank. Many novel methods for maximizing solar radiation collection and minimizing thermal losses were done to improve the performance of ICS. Improvements of ICS storage tank design included glazing system, insulation, reflector configurations, use of evacuation, internal and external baffles and phase change materials (Schmidt *etal.*, (1998); Smyth *etal.*, (1998); Smyth *etal.*, (1999)). The ICS system has lower efficiency compared to the flat-plate collector. The experimental results indicated that the ICS systems provide (72-75%) of the flat-plat collector output and its overall efficiency is about (72%) of that of the flat-plat collector systems (Smyth *etal.*, (2001)). The performance of the ICS system is affected by many factors like the geometric design of the storage tank, the optical cover system design, the insulation system design. (Garg *etal.*, (1982)) studied the effect of the storage tank geometric design on the ICS system on its performance. the storage depth was varied between (0.025 and 0.2 m). The low depth was found to result in the maximum daily temperature rise in the water temperature, however, the same depth results in the maximum temperature reduction during the no solar radiation periods and during the night. The minimum rise in the water temperature of the storage tank occurs in the case of 0.2 m for which the water temperature fall was very gradual as well. The case of 0.1 m depth of the storage tank is considered as the optimum which can supply hot water with a suitable temperature over most of the day (Garg *et al.*, (1982)). Many attempts have been conducted to improve ICS (as it appears the first time) performance. One of them was done by using longitudinal plate fins in the storage tank (AlEssa *et al.*, (2014)). Experiment investigation has done to improve the ICS performance by using lateral perforated plate fins in the storage tank of the ICS system. The conducted perforated fins introduce a good means of heat transfer enhancement in thermal systems as the heat exchangers (Al-Azab *et al.*, (2009); AlEssa, (2013); AlEssa *et al.*, (2018)).

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1 Materials and Methods

In this study, another investigation on the performance improvement of the ICS system was done experimentally through designing and fabricating two ICS solar systems. The first one is a conventional ICS system without fins (**Figure 1**).

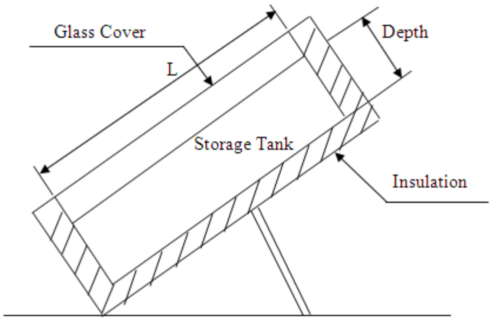


Fig. 1 Cross Section in the conventional ICS Solar System.

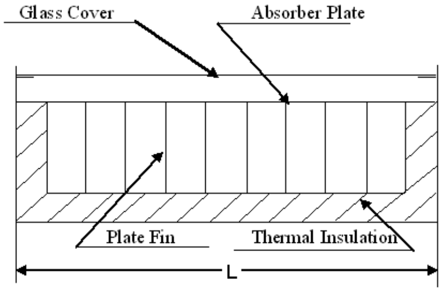


Fig. 2 Cross Section in the PFICS Solar System with 8 Lateral perforated Plate Fins.

The second one is an ICS system with lateral perforated plate fins (**Figures 2** and **3**). This system was referred to as the integrated collector storage system of perforated fins (PFICS). The above two systems were experimentally tested at the same time under the stagnation conditions (no water withdrawal from the tank). Also, ICS and PFICS are experimentally tested at the same time under the different load profiles according to the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) load profile (Fisher *et al.*, (1983)).

Fig. 3 Photograph of the perforated fins inside the PFICS Solar System.

1.1 Experimental Systems

The built test rig of the ICS system shown in Fig. 1, consists of the storage tank that is fabricated from galvanized steel plates of thickness 1.5 mm. The absorbing surface which is one of the storage tank sides with dimensions of (L=80 cm, W=60 cm) is coated with black paint. The depth of the storage tank was chosen as (h=10 cm) which is the optimum depth for the ICS system based on literature (Garg *etal.*, (1982)). The storage tank volume is (0.048 m^3). The mass of water in the storage tank is 48 kg. The optical system was constructed with a single glass cover of (5 mm) thickness located at the optimum air gap (5 cm) from the absorber plate. The inlet water enters the storage tank at the lower part of the tank. The outlet water is delivered from the higher part of the storage tank. The collector was insulated using (5 cm) thick polystyrene foam covered by thin metal sheets to support and protect the insulation. The PFICS system is shown in Figs. 2 and 3. It is designed and fabricated with the same collector area, absorbing surface coating, optical system, storage tank volume, and the same insulation. The two systems are fixed on a steel frame facing south with a tilt angle of (42°C), which is the latitude angle plus 10 which is suitable for winter months, and they are exposed to the same solar insolation and ambient temperature. The two systems were provided with two manual stop valves fitted at the delivery openings to control the water withdrawal. The systems were fitted on an open area avoiding shading and they are supplied by freshwater from a common water tank mounted at a suitable height over them.

1.2 Measurement Systems

Both ICS and PFICS systems were provided with a five (copper-constantan) thermocouple temperature sensors (type k thermocouple). These thermocouple temperature sensors are distributed in selected locations that yield the maximum information about the performance of the systems. Each storage tank is divided into five nodes where a thermocouple sensor is located at the center of each one as shown in **Figure 4**. Temperature measurements were obtained by using a digital electronic thermometer which is calibrated against a mercury thermometer. The hourly and daily integrated solar flux was measured using a total flux pyranometer. These measurements were done at the experimental location as shown in **Figure 5**.

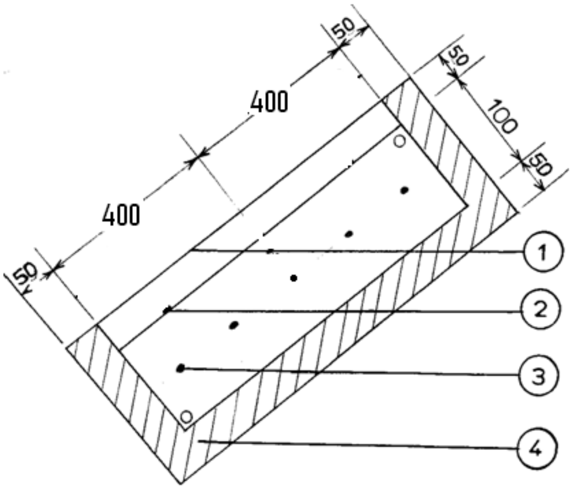


Fig. 4 Cross Section of the ICS System showing the thermocouple Sensors Locations. (1-Glass Cover, 2-Absorber Surface, 3-Thermocouple Sensor, 4-Insulation, Dimensions in mm.).

Fig. 5 Photograph of the two systems

2 Results and Discussion

After the installation of the two systems, they are checked up followed by stagnation and the water withdrawal tests. The two different experiments accomplished during the winter season could be summarized as:

2. 1 The Stagnation Test Experiment

The stagnation experiment was carried out to investigate and compare the performance of the two systems without water withdrawal. The experimental measurements were used to compute and compare the two systems temperatures, collection efficiency. The experiment was carried out over five successive days in a region of (Latitude 32°N, Longitude 36°E).

2. 1. 1 The Storage Tank Temperature Distribution

The temperature readings were taken every hour from 7:00 a.m. until 5:00 p.m. The temperatures of the ICS system nodes and that of the PFICS system (T_1, T_2, T_3, T_4, T_5) are presented in **Figure 6**. This figure shows an increase in water temperatures in the PFICS system above that of the ICS system by 20%. **Figures 7,** and **8**, show the temperature measurements and comparison for the other four days of the stagnation experiment. Again, these figures show higher water temperatures in the PFICS system than that of the ICS system.

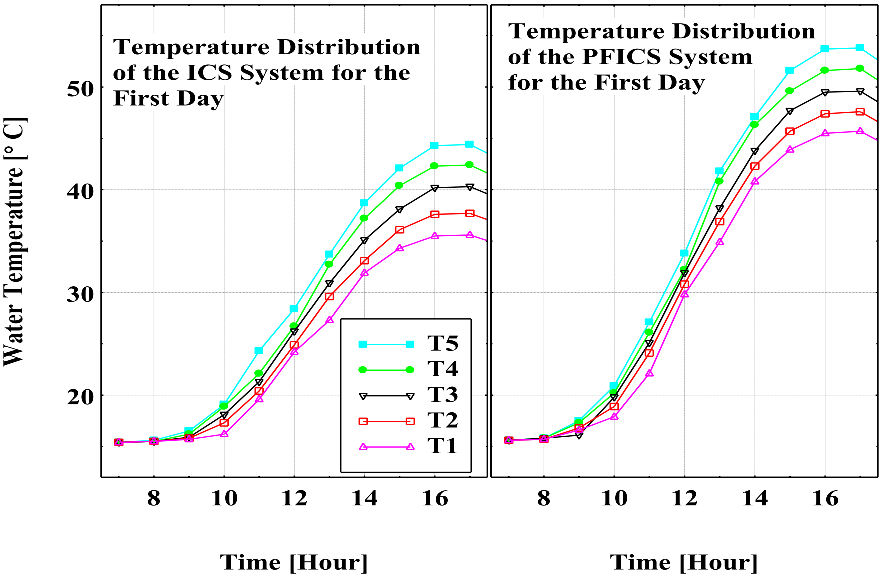


Fig. 6 The temperature distribution of the two systems for the first day.

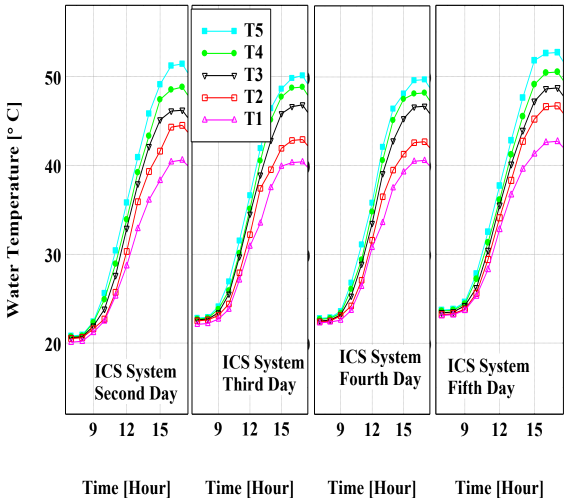


Fig. 7 The temperature distribution of the ICS system for the other four days.

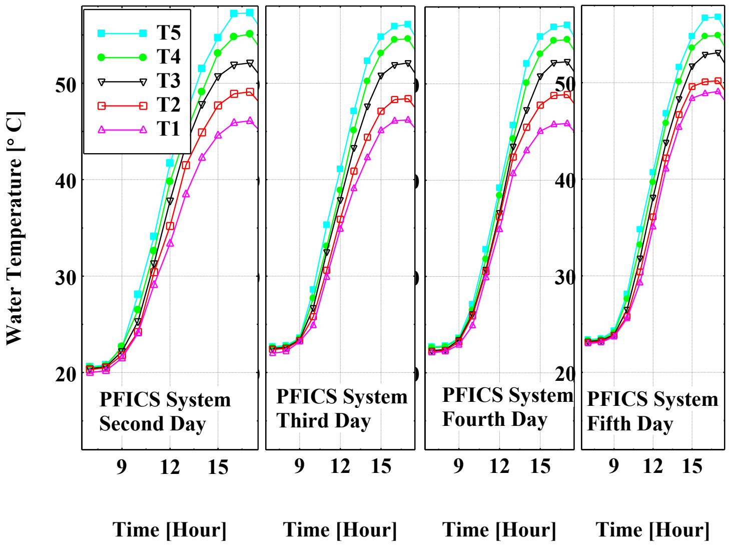


Fig. 8 The temperature distribution of the PFICS system for the other four days.

2. 1. 2 The Storage Tank Mean Temperature Analysis

The principle of mean temperature shows a good way of understanding and comparing between the two design systems. The mean temperatures are denoted as (T_{m1}) for the ICS system and as (T_{m2}) for the PFICS system. To compute these mean temperatures, the two systems are divided into five similar nodes with a temperature sensor located at the center of each one. Each node has the same mass of water which equals (1/5) of the total water in the storage tank. The water mass in each node equals 48/5=9.6 kg=m_i. The mean temperature can be calculated as:

$$T_m = \frac{\sum_{i=1}^{5} m_i * T_i}{\sum_{i=1}^{5} m_i} = \frac{\sum_{i=1}^{5} T_i}{5} \qquad (1)$$

The mean temperatures of the ICS storage tank system (T_{m1}) and that of the PFICS (T_{m2}) are shown in **Figure 9** for the first day of the stagnation experiment. The mean temperatures for the other four days of the stagnation test are shown in **Figure 10**. These figures show better performance of the PFICS than that of the ICS system.

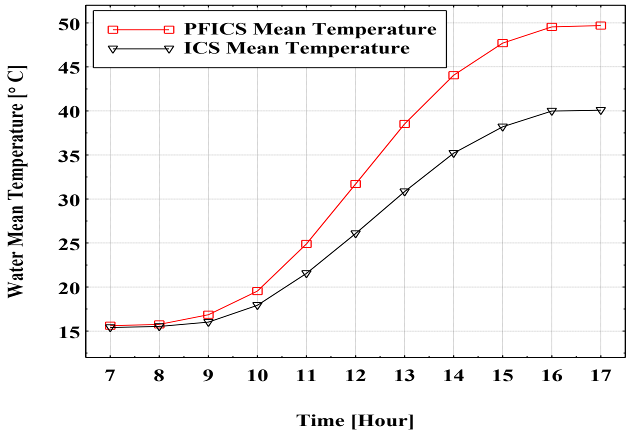


Fig. 9 The mean temperature variation of the two systems for the first day of the stagnation test.

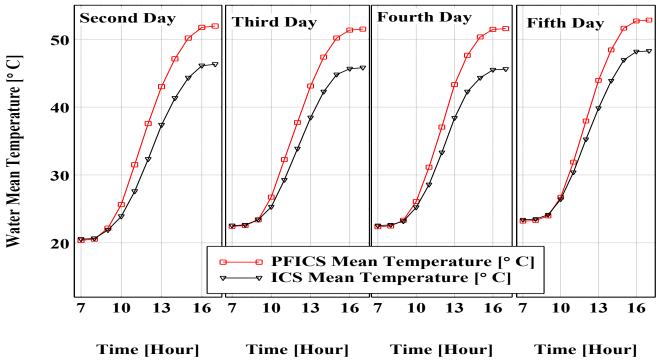


Fig. 10 The mean temperature variation of the two systems for the other four days of the stagnation test

2. 1. 3 The Hourly Collection Efficiency Analysis

The solar system performance can be expressed using the thermal efficiency. The solar system efficiency is simply the ratio of the collection or delivered energy to the total incoming solar energy. The instantaneous efficiency as a short-term performance is mathematically defined as:

$$\eta = \frac{Q_f}{A_p{*}\mathrm{G}} \tag{2}$$

Where (A_p) is the solar absorber surface area which equals (0.48 m^2). The average value of efficiency over an hour, termed as the hourly collection efficiency can be expressed as:

$$\eta_h = \frac{Q_{\mathrm{hf}}}{A_p{*}\mathrm{I}} \tag{3}$$

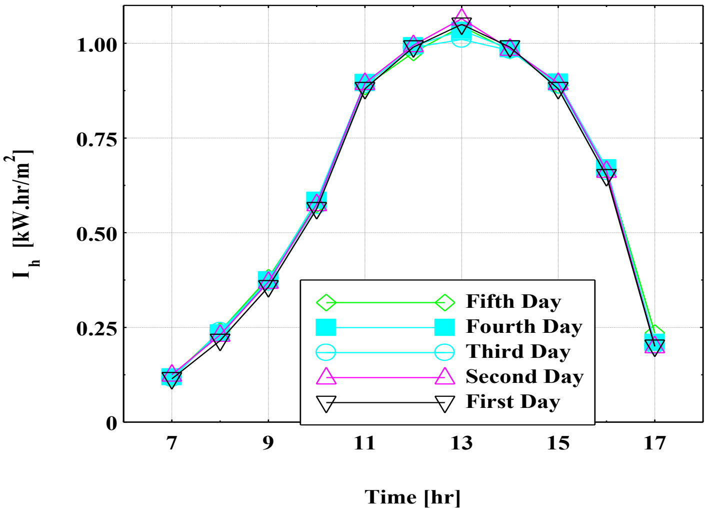
For the two systems, the hourly collection efficiency is calculated from the following equations:

$$\eta_h = \frac{m * C_p * (T_F - T_I)}{A_p{*}\mathrm{I}} \tag{4}$$

where (m) is the mass of water that has been heated during the day (kg). It is the same amount of water in the storage tank which equals 48 kg. (C_p) is the specific heat of the water (4.186 kJ/kg ^{o}C). (T_F) is the mean temperature of the storage tank at the final time of each hour (^{o} C). (T_I) is the mean temperature of the storage tank at the initial time of each hour (^{o} C). (I_h) is the integral hourly solar radiation (kW.hr/ m^2) which can be measured by the Pyranometer throughout each hour. The integral hourly solar radiation (kW.hr/ m^2) during the five days of the stagnation experiment graph is shown in **Figure 11**. The previous values lead, for the two systems to the hourly collection efficiency expression:

$$\eta_h = \frac{48 * 4.186 * (T_F - T_I)}{0.48{*}3600\ {*}\mathrm{I}_h} \tag{5a}$$

$$\eta_h = \frac{0.1163 * (T_F - T_I)}{I_h} \tag{5b}$$



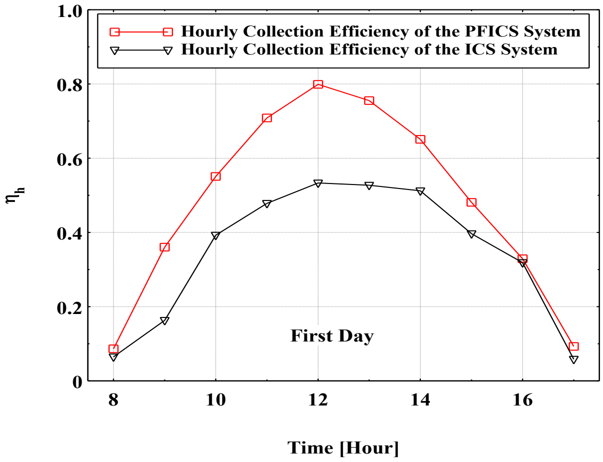


Fig. 11 The integral hourly solar radiation (kW.hr/m^2) during the five days of the stagnation experiment.

Fig. 12 The hourly collection efficiency of the two systems for the first day of the stagnation test.

The hourly collection efficiency is calculated for both systems over the energy collection periods of the stagnation test. The results are shown in **Figure 12** for the first day and in **Figure 13** for the other four days. The PFICS system collection efficiency is higher than that of the ICS system in the periods around the noontime.

2. 1. 4 The Daily Collection Efficiency Analysis

The daily efficiency without water withdrawal (stagnation experiment) is calculated from the following equation:

$$\eta_D = \frac{m * C_p * (T_{\mathrm{DF}} - T_{\mathrm{DI}})}{A_p * I_D} \qquad (6)$$

where (T_{DF}) is the mean temperature of the storage tank at the final time of each day (° C). (T_{DI}) is the mean temperature of the storage tank at the initial time of each day (° C). (I_D) is the integral daily solar radiation (kW. hr/ m^2) which can be calculated as a summation of I_h during each day. The previous values lead for the two systems to the daily collection efficiency expression:

$$\eta_D = \frac{0.1163 * (T_{\mathrm{DF}} - T_{\mathrm{DI}})}{I_D} \qquad (7)$$

The daily collection efficiency for the five consecutive days of the stagnation experiment is shown in **Figure 14**. The figure shows higher efficiency of the PFICS than that of ICS system.

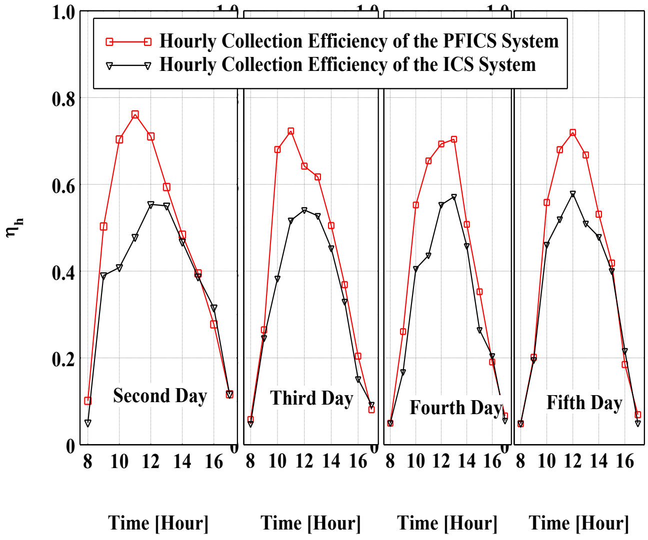


Fig. 13 The hourly collection efficiency of the two systems for the four other days of the stagnation test.

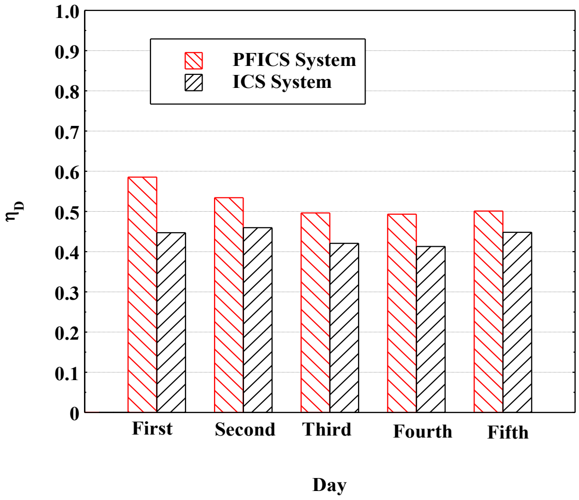


Fig. 14 The daily collection efficiency of the two systems for the five days of the stagnation test.

2 .2 The Water Withdrawal Experiment

The water withdrawal experiment is considered in line with the ASHRAE load profile (Fisher *etal.*, (1983)). According to this load profile, water is withdrawn in three equal consignments at constant rates over the hours (8:00 a.m.), (noon) and (5:00 p.m.). The daily mass flow rates which it tested is 48 kg/ day related to the tank turnover of 1. That is 16 kg for each withdrawal of the three withdrawals during a day. During this experiment, 16 Kg of water has been withdrawn from each system in three times the daily ASHRAE load profile. **Figures 15**, **16**, and **17** show the delivery temperatures of the two systems for each of the three days over which the experiment is performed.

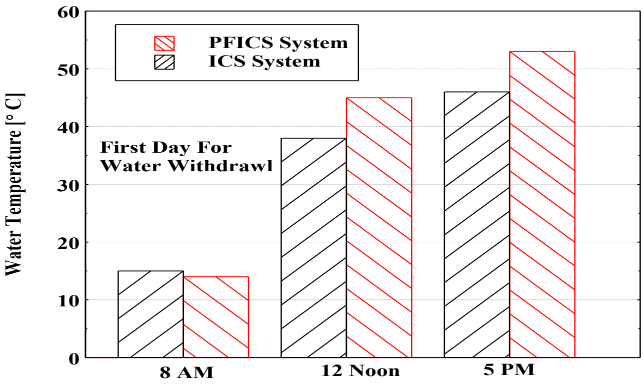


Fig. 15 The mean delivery temperatures of the two systems in the first-day experiment over which the withdrawal test is accomplished

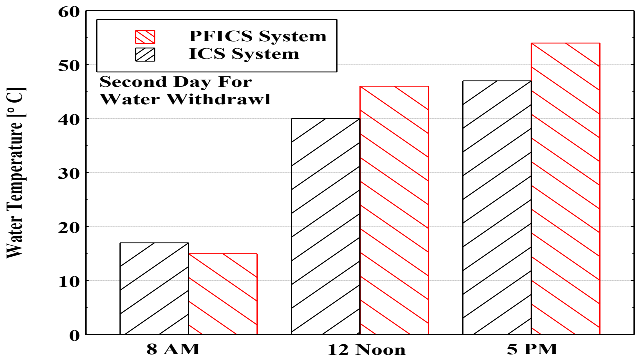


Fig. 16 The mean delivery temperatures of the two systems for the second day over which the withdrawal experiment is done.

The results undoubtedly show a high-quality outcome of the internal lateral perforated plate fins in the PFICS System. These fins improved the PFICS System performance as it is compared to that of the ICS System. The morning delivery temperatures of the two systems are little and it is not useful as familial hot water. This is due to high night heat losses. The noon and evening deliverance temperature of the PFICS system is always superior to that of the ICS system.

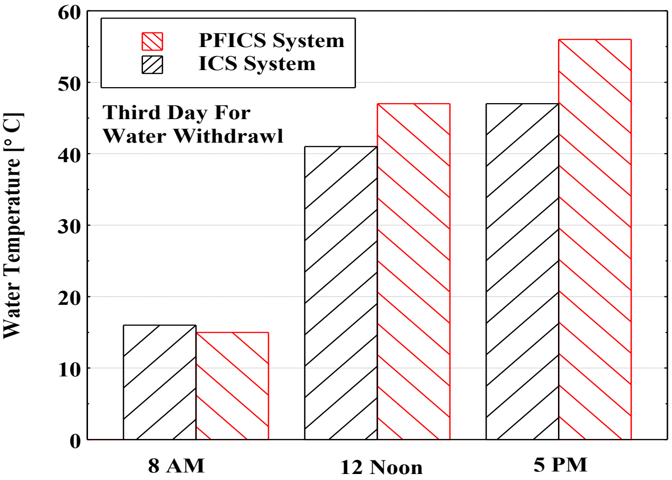


Fig. 17 The delivery temperatures of the two systems for the second day over which the withdrawal experiment is conducted.

Conclusions

This work presented the testing of two forms of integrated collector storage system. The first is the traditional rectangular one (ICS) based on the optimum dimensions given in the literature and the second is (PFICS) which is provided by internal lateral perforated plate fins. The PFICS is examined as a probable solution to augment the ICS Performance.

The main conclusions observed are: The PFICS system with its internal lateral perforated plate fins gives a satisfactory solution to enhance ICS system performance. The enhancement is 20%. The collection efficiency of the PFICS system is superior to that of the ICS system. The augmentation is 37%. For the ASHRE noon and evening load profiles, the water withdrawal delivery temperatures of the PFICS system is upper than that of the ICS system. So the PFICS system confirmed a better performance. For the noon load profiles, there is about 5^{o} C increment. For the evening load profiles, there is 7^{o} C increment. The PFICS system with its internal lateral perforated plate fins maintains the stratification in the storage tank

Nomenclature

Ap	=The absorber plate area	[0.48 m^2]
ASHRAE	=American Society Of Heating, Refrigerating And Air Conditioning Engineers	[-]
C_p	=Specific heat capacity of water	[J/Kg. K]
ICS	=Conventional integral collector storage solar system without fin	[-]
G	=The instantaneous incoming solar energy	[J/ m^2. Sec]
H	=The storage tank depth of the ICS system	[m].
I	=The hourly incoming solar energy	[J/ m^2]
I_h	=The integral hourly solar radiation measured by the Pyronomter each hour	[kW. hr/ m^2]
I_D	=The integral daily solar radiation measured by the Pyronomter each day	[kW. hr/ m^2]
L	=The storage tank length	[m]
M	=Mass of water	[Kg]
M_i	=The mass of water in each node	[-]
PFICS	=Integral collector storage with lateral perforated Fins	[-]
Q_f	=Instantaneous collection or delivered energy	[J/ Sec]
Q_{hf}	=Collection energy per hour	[J/ hr]
Q_{Df}	=Collection energy per day	[J/ Day]
T_{m1}	=Mean temperature of the conventional ICS system	[^{o}C].
T_{m2}	=Mean temperature of the PFICS system	[^{o}C].
T_d	=Delivery temperature	[^{o}C]
W	=The storage tank width	[m]

Greek Letters

η_D	=Daily efficiency	[-]
η_h	=Hourly efficiency	[-]

Subscripts and superscripts

D =Daily.
D =Delivery.
F =Final.
H =Hourly.
I =Initial.
I =The node number
M =Mean temperature

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