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An Experimental Investigation of A Modified Heat Exchanger for A Solar Domestic Hot Water System Part (2)

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Abstract

The current paper is an extension of a previously published paper, where in this paper the first immersion heat exchanger (Immhx 1) was developed to the second heat exchanger (Immhx 2). The (Immhx 2) was inserted horizontally to avoid the elbow problem and to save space for heat transfer. Helical fins of 4.76 mm were added to (Immhx2) in order to improve the heat transfer rate. The results showed, that the immersion shell-and-coil (ImmS&Chx) delivers higher energy compared with immersion heat exchanger (Immhx 2), and the heat exchanger (Immhx 2) achieved better behavior compared with submerged heat exchanger (Immhx 1). Also, it was obtained that the collector surface achieved the highest accumulated heat. Concerning the thermal stratification, the heat exchanger (Immhx 2) achieved lower temperature difference in the tank compared with heat exchanger shell-and-coil (ImmS&Chx)

Keywords: *heat exchanger- heat exchanger of solar domestic hot water system*.

1. Introduction and Literature Survey

Solar domestic hot water (*SDHW*) systems perform three basic operations: collecting energy by a solar collector, transferring the energy to the water through a heat exchanger, and storing the energy in a storage tank for domestic use.

Collection process based on the "greenhouse effect", where sunlight is collected and converted to heat energy by a solar collector. The solar collector is mounted on or near the house, faced to the south. Sunlight is passing through glass to be absorbed by the collector flat plate. The plate converts the sunlight into heat, which is prevented from escaping by the glazing of the solar collector.

Transferring the thermal energy is carried by circulating the fluid through the solar collector and then transferred the heat to the tank by using a heat exchanger. Storing process involves the storage of heated water in an insulated tank. Solar water heaters usually have a slightly larger hot water storage capacity than other water heaters. This is because solar heat is available only during the day and enough hot water must be collected to meet evening and early morning needs **[1]**.

Two types of heat exchangers can be used to transfer the heat from the hot fluid to the cold water. The first type is called an external heat exchanger, where the heat transfers between the hot fluid coming from the solar collector and the cold water occurs outside the storage tank.

The second type is an internal heat exchanger, where the heat transfers between the hot fluid and the cold water occurs inside the storage tank, which is called an immersion heat exchanger.

Fozi S. Alsagheer, et al, presented a comparison of a thermal performance of two designs of heat exchanger of solar domestic hot water system. The comparison was carried out in terms of the heat exchanger overall heat transfer coefficient (*UA*) product, maximum tank temperature, thermal stratification. The tested heat exchangers were, an immersion heat exchanger (*Immhx1*) and an external shell-and-coil heat exchanger (*S&Chx*). The results showed that the heat exchanger of (S&Chx) achieved a higher value of overall heat transfer coefficient (UA), higher thermal stratification, and higher temperature in the upper layers of the tank compared with heat exchanger (Immhx1). Regarding the energy obtained from solar radiation, collected and transferred to the collecting tank, the performance of the heat exchanger (S&Chx) was better compared with heat exchanger (Immhx1)**[2]**. **MacLeod and Allen** carried an experimental work under a topic of Evaluation of components in Solar Water Heaters with Photovoltaic Powered Pumps. They stated that the collector flow rate and PV power were found to vary linearly with insolation (solar radiation level), and the flow was found to be laminar in the supply line and turbulent in the return line at full sun conditions. The study suggested two ways to increase the system flow rate using the same PV power. One was involving turning up the linear booster input voltage to maximize PV power output, and the other method involved reducing the hydraulic losses in the system by increasing the diameter in the return line **[3]**.

Sandnes, Rekstad designed and built a PV/T test collector using single-crystal silicon cells in combination with a solar heat absorber in polymer plastics. The system was tested experimentally to determine its thermal and photovoltaic performance, the efficiency of different collector configuration were compared with PV performance, and temperature readings were discussed. A comparison of PV/T absorber with pure thermal absorber showed a low thermal efficiency for the PV/T system. Significant cooling of the PV cells was achieved by low-temperature operation of the heat collector which resulted in improved PV efficiency. Good agreement was obtained between simulation and experimental results**[4]**. **Jardany and Allen** built and tested five configurations of immersion heat exchangers. Each one was tested for several weeks. The overall heat transfer coefficient (UA) was used to characterize and compare the performance of each heat exchanger in three different configurations of the SDHW system. The performance of each system configuration was analyzed in terms of heat loses, system efficiency, and tank thermal stratification. They concluded that the SDHW system with immersion heat exchanger of 0.170 m^2 in area was 34% more efficient than the identical system operated with side-arm heat exchanger of area 0.6 m^2. Moreover, they created five semi-empirical models to predict the UA values and to obtain information on the magnitude of the natural convection heat transfer coefficients for each of the immersion heat exchangers they tested **[5]**.

P.Ganesh Kumar et al., presented an innovative hybrid system that serves the dual purpose of heating air and water simultaneously. Based on the results of the experimental investigation, it was inferred that the collector efficiency is directly proportional to the volume percentage of the nanomaterial. The average temperature difference of 14.54°C was achieved in the solar collector, whereas a maximum temperature of 18.32°C was obtained for 0.2 volume percentage of MWCNT at a mass flow rate of 0.01 kg/s. Moreover, the maximum thermal efficiency of 51.03% was obtained for a 0.2 volume percentage SG/MWCNT **[6]**.

Jian Yao et al., suggested a residential heating system using Borehole Heat Exchanger (BHE) coupled with solar assisted PV/T heat pump with further performance analysis. The simulation results showed that a larger mass flow rate could increase the heat extract capacity of BHE's and also increases the flow resistance and pump power under nominal conditions. The circulating water could not extracted heat from rock-soil when the inlet temperature exceeds 48.5°C.

Furthermore, the maximum water temperature from hybrid system could reach 40.8°C with solar fraction of 67.5% at PV/T area of 1000 m^2, and the solar irradiation is 600 W/m^2 and depth of the BHE is 2500m. In the meantime, the heating C.O.P. of the hybrid system could reach 7.4 and the system could operate independently without power input from electrical grid **[7]**. **T. Mohapatra, et al.,** presented a study concerned, the thermal performance of a three fluid heat exchanger (TFHE) used in solar flat plate collector system is studied. The TFHE was an improved version of double pipe heat exchanger, where a helical tube was inserted between two concentric straight tubes for better performance. The study presents a new technique of simultaneous air and water heating in TFHE using solar energy. They reported that the heating cost can be minimized considerably by supplying the hot water or thermal fluid from a solar flat plate collector through the helical tube of TFHE to heat incoming cold air and water in the inner most pipe and outer annulus. The TFHE was investigated experimentally and validated by comparing the result of experimental approach with literature. Decent agreements between the experimental and literature values were observed. The purpose of the study was to determine the effect of Reynolds number and Dean number on performance of the TFHE in steady-state for both flow configurations. The overall heat transfer coefficients, varies directly and effectiveness, varies inversely with hot water volume flow rate, however hot water flow rate have least or no effect on coil side Nusselt number. The effect of inner Dean Numbers on overall heat transfer coefficients, and effectiveness, is negligible in parallel flow configuration **[8]**.

2. Experimental Work

Figure 2 and Figure 3 shows a schematic diagram of the two tested heat exchangers. The first heat exchanger was shell-and-coil heat exchanger (ImmS&Chx). This heat exchanger was modified by immersing it along with the hot water delivery pipe inside the tank, thereby avoiding the external pipe heat losses. In addition, the modified version had less cost compared with previous heat exchanger

In the second case a modified immersion heat exchanger (Immhx2) was used to operate the SDHW system. It is inserted horizontally in order to avoid the elbow shape and to save the area of heat transferred of the heat exchanger. Helical fins of 4.76 mm were added to the new version (Immhx2) in order to improve the heat transfer rate. Therefore, the tested heat exchangers are the modified shell-and-coil heat exchanger (ImmS&Chx) and the immersion heat exchanger (Immhx2). The experiments were carried in a clear sky day.

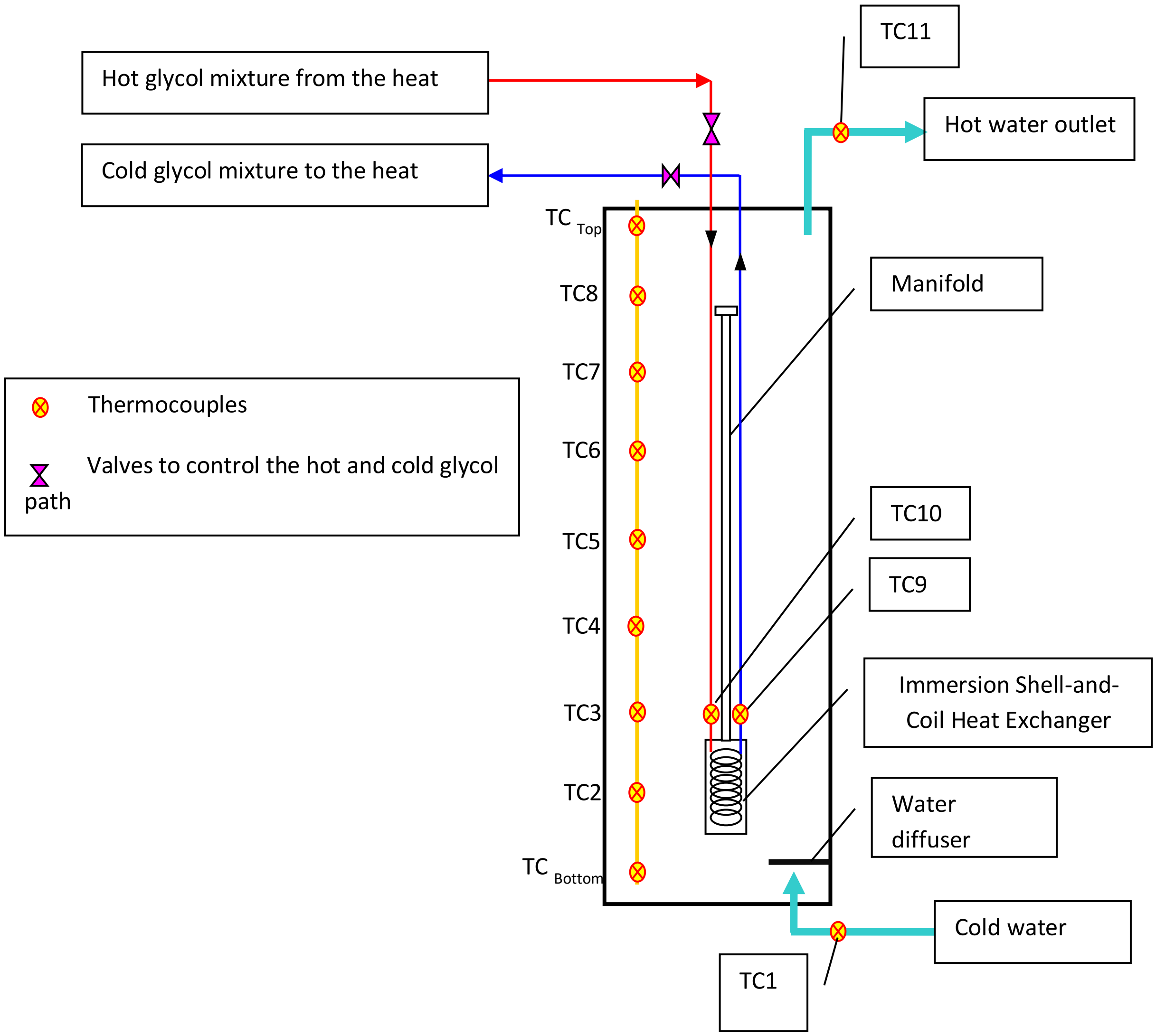

Fig. 2 schematic diagram of first immersion heat exchanger (Immhx1)

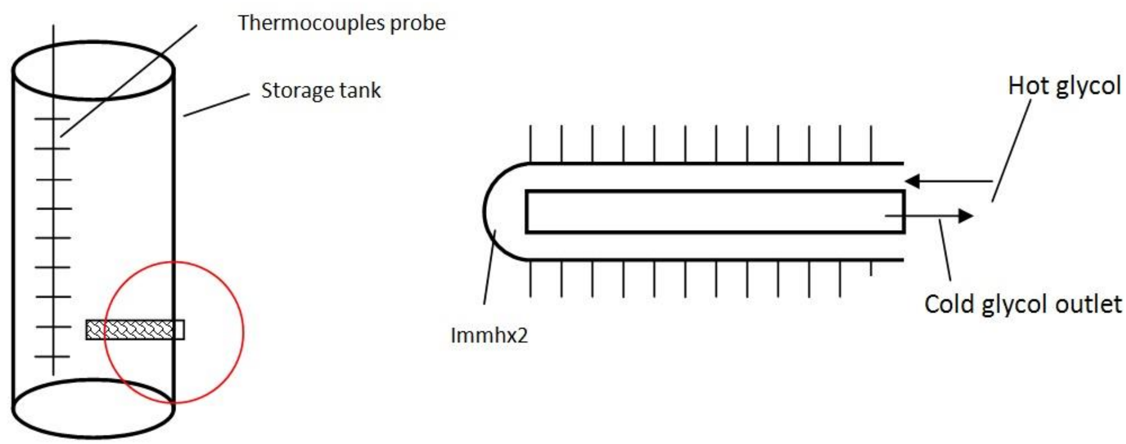

Fig. 3 Schematic diagram of second immersion heat exchanger (Immhx2)

3. System Analysis

The data acquisition system creates two data files for each day of the year; one for the system parameters, and one for the storage tank temperatures. These data are required for system performance analysis.

The following equations are used to calculate system performance parameters.

1. The glycol mass flow rate is calculated from the measured rate of rotation of the pump (*RPM*) by using the equation

$$GPM_R = \frac{GPH}{60} * \frac{RPM}{1725}$$

GPM_R	:	Gallons per minute based on revolution
GPH	:	70 GPH (constant for this pump)
RPM	:	Revolutions per minute
1725	:	Constant for the used pump (maximum *RPM* of the pump)

1.The collector heat transfer rate is calculated by equation

$$q_{coll} = G_T A_C \eta_{coll-\max} \quad (1)$$

$$\eta_{col\text{-}max} = F_R(\tau\alpha) - F_R\ U_L\ \frac{(T_{coll} - T_{air})}{G_T} \tag{2}$$

2. The rate of heat loss from the storage tank is calculated by equation:

$$q_{tank} = \frac{Q_{t2} - Q_{t1}}{t_2 - t_1} = \frac{m_w C_{pw} (T_{avr\ T} - T_{i,tank})}{\Delta t} \tag{3}$$

3. The accumulated heat addition to the tank, Q_T, is calculated with respect to the energy contained in the storage at the beginning of the day, Therefore; the variations in the $T_{avr,T}$ from one day to another are factored into the computation of η_{sys}. Q_T is calculated by equation:

$$Q_T = Q_{end} - Q_{start} \tag{4}$$

Both Q_{end} and Q_{start} are computed using,

$$Q = m_w C_{pw}(T_T - T_{cw}) \tag{5}$$

4. Results And Discussion

Figures 4 and 5 show the variation of solar flux for ImmS&Chx and Immhx2 respectively. In figure 4 the experiment was carried on October 21. It can be noticed that there was a fluctuation in the curve during the period from 13:00 to 15:00, and this mostly occurred due to wind and dust. After 15:00 o'clock there was a sharp drop in solar flux and due to the shading of adjacent building.

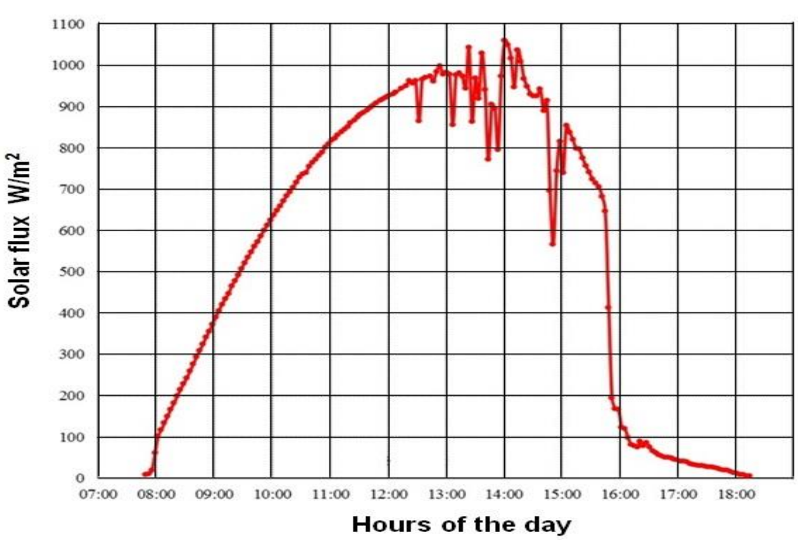

Fig. 4 Variation of solar flux using ImmS&Chx on October 21

In figure 5 the experiment was carried on October 31. It can be noticed that the increase of solar flux was rapid and sharp, compared with Figure 4. While the sharp drop, was almost equal in both cases. Also, Figure 5 shows that the increase and decrease of solar flux occurred smoothly, and the reason for this is often due to the development that was carried out on the heat exchanger Immhx2.

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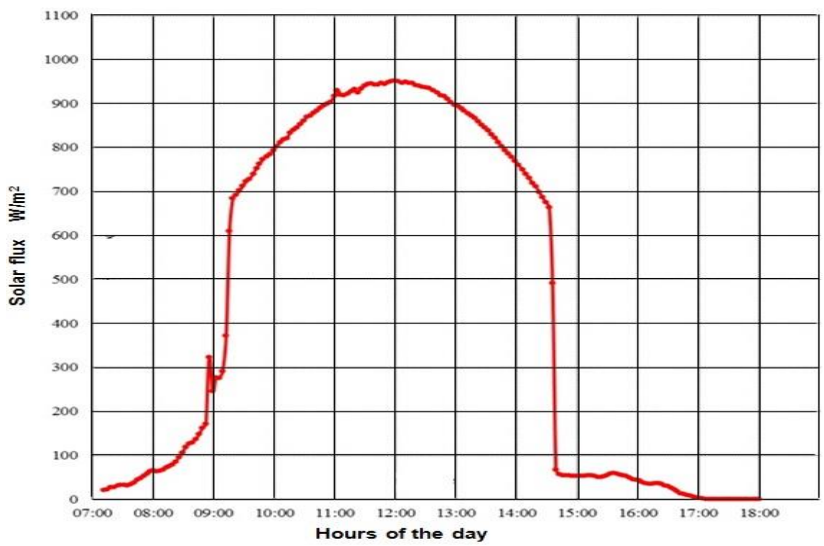

Fig. 5 Variation of solar flux using Immhx2 on October 31

Figure 6 shows the variation of overall heat transfer coefficient of the immersion shell-and-coil (ImmS&Chx), with heat transfer on October 21 during morning and afternoon periods. A small difference was observed between the values of heat transfer coefficients in both periods. The peak value of heat transfer coefficient was achieved at 2:00 and 1320 W which was about 93 W/K. This can be attributed to the fact that the system reaches its peak solar radiation absorption in the afternoon period.

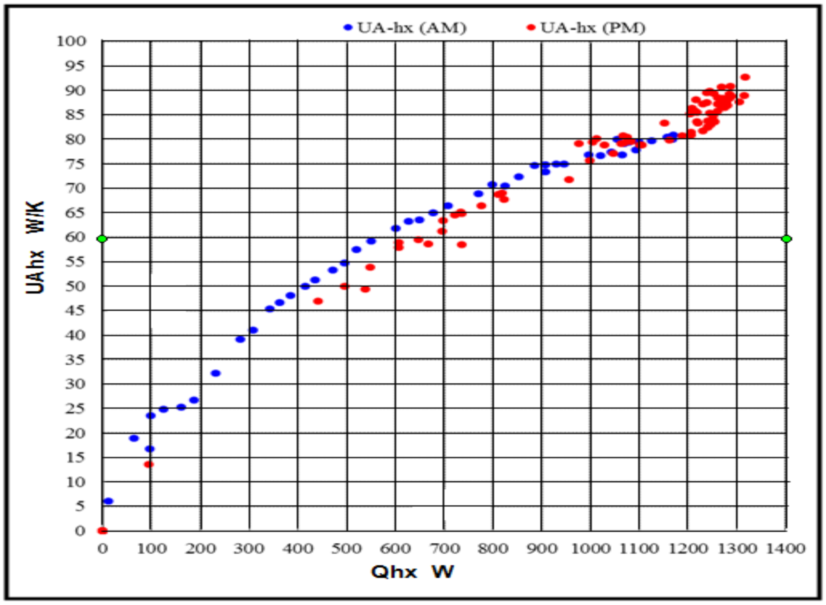

Figure 6 Heat transfer coefficients (UA), the heat transfer rate (qhx) of ImmS&Chx on October 21

Figure 7 shows the variation of overall heat transfer coefficient of the Immhx2 heat exchanger, with heat transfer on October 21 during morning and afternoon periods. It can be noticed that the UA values were lowest than that in the case of ImmS&Chx. The results of figure 7 may be attributed to the fact that the Immhx2 has a very low heat transfer area which limits the thermal performance of the exchanger. The peak value of heat transfer coefficient was achieved at 1320 W which was about 23 W/K. Improvement of Immhx2 reduced the area to about 50% and this cause a reduction in the efficiency by 20%.

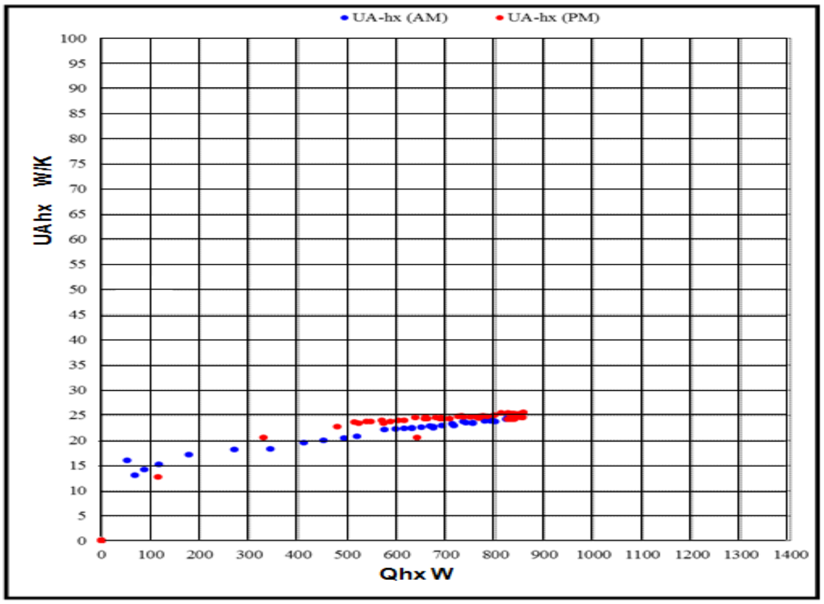

Figure 7 Heat transfer coefficients (UA) Vs. the heat transfer rate (qhx) of Immhx2

Figure 8 shows the thermal stratification in the tank for the 24 hours of Oct. 21. By comparing the temperature difference of thermocouple points at the beginning of the day with those at the end of the day a slight increase in the temperatures was obtained. This increase in the temperatures is more noticeable at the upper of the tank. The average temperature at the upper of the tank increased from 36°C to about 40°C while the bottom remained almost constant at about 21°C. This result can be attributed to the larger area of the ImmS&Chx and less resistance for glycol flow. The peak temperature at the top of the tank was 47°C and recorded at 3:30 PM after one hour and a half from the peak solar flux.

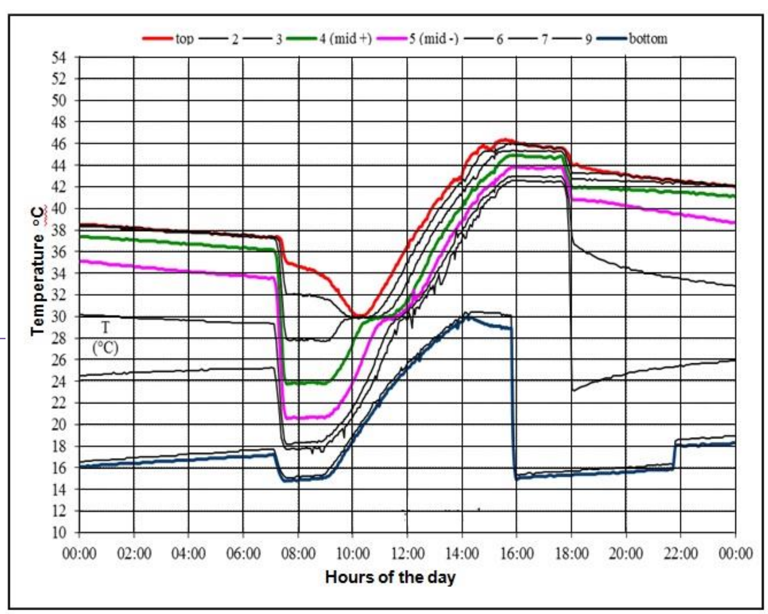

Fig. 8 The temperature distribution in the storage tank for the Immhx1

Figure 9 shows the thermal stratification in the tank for the 24 hours of October 31 using Immhx2 exchanger. At (12:00 PM), the tank becomes almost thermally homogenous (at about 25 ^{o}C). The peak temperature at the top of the tank (Ttop) was 31°C at 2:30 PM. As it is known the glycol was delivered by the DC pump which powered by the PV. It was noticed that there was no matching between the output of PV and output of the pump, and this mainly occurred due to shading of the adjacent building.

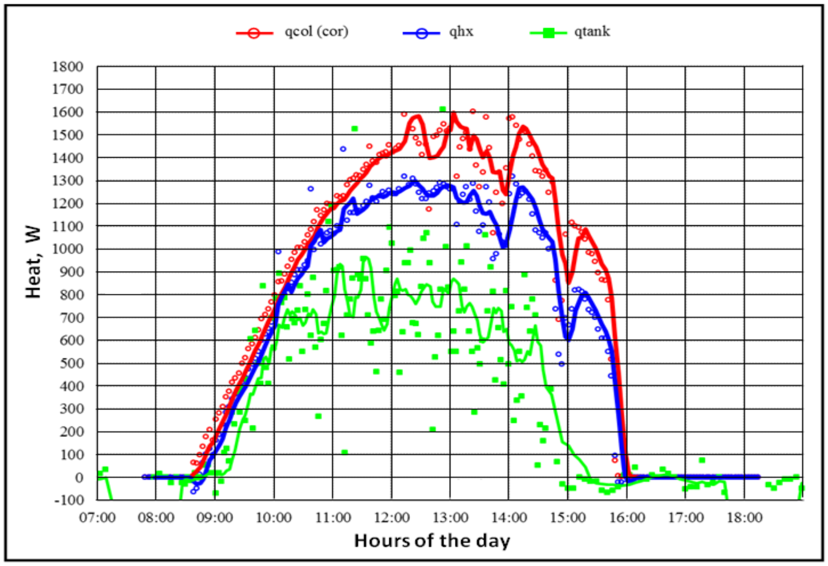

Fig. 9 The temperature distribution in the storage tank for the Immhx2

Figures 10 and 11 present the thermal performance of the SDHW system operated on Oct. 21 with the Immhx1 and on Oct. 31 with the Immhx2. It was noticed that the two figures had the same behavior but with higher values for the Immhx1 exchanger.

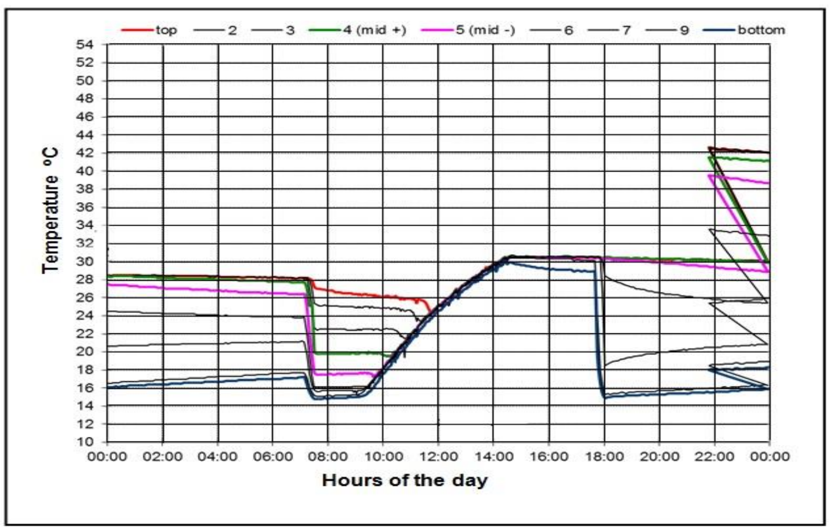

Fig. 10 Variation of heat transfer with the time on October 21 using Immhx1

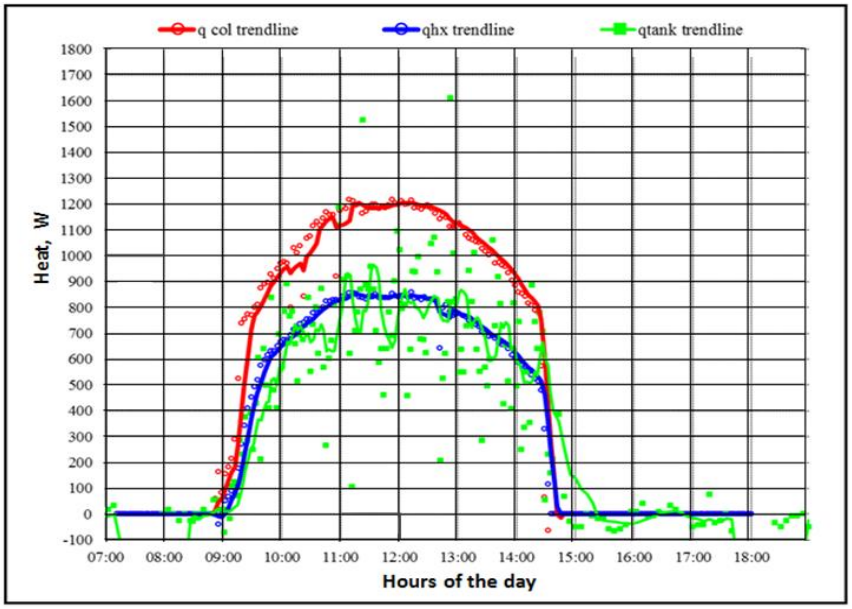

Fig. 11 Variation of heat transfer with the time on October 31 using Immhx2

Analyzing the thermal performance of SDHW system was shown in figures 12 and 13, where the accumulated heat was investigated in each component of the system.

It can be seen that the collector surface has the highest value of accumulated heat in both figures, while the storage tank achieved the lowest value of accumulated heat. The accumulated heat at the heat exchanger was in-between the collector. In both figures, the highest value of the accumulated heat was recorded at the collecting surface, followed by the heat exchanger and finally the storage tank. In figure 12 the values of incident heat radiation, the collector, and heat exchanger were 57MJ, 28MJ and 24MJ respectively. This means the collecting surface collect energy of 49% from incident heat radiation, while the heat exchanger collected energy of 85.7% from the collecting surface

In figure 13 the values of incident heat radiation, the collector, and heat exchanger were 46MJ, 20MJ and 14MJ respectively. This means the collecting surface collect energy of 43.5% from incident heat radiation, while the heat exchanger collected energy of 70%% from the collecting surface. Because both heat exchangers were immersion type, there were no losses between the energy transmitted by the heat exchanger (Qhx) to the storage tank (Qst).

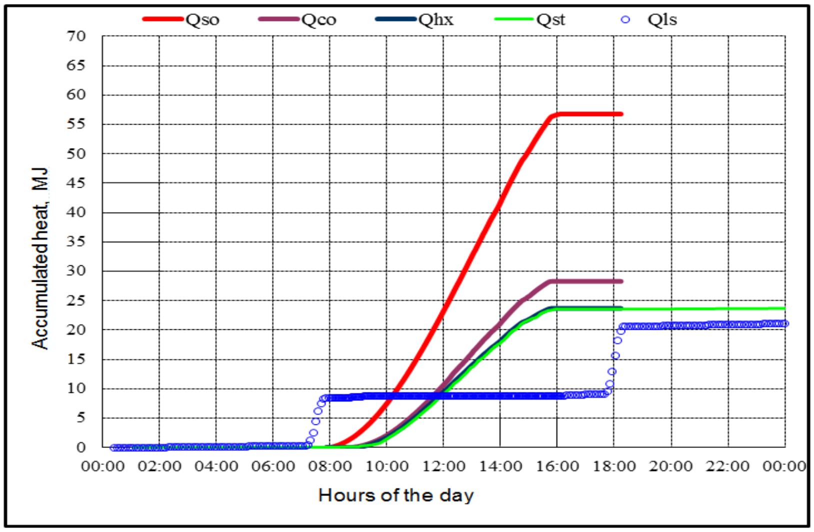

Fig. 12 Variation of accumulated heat with on October 21 using Immhx1

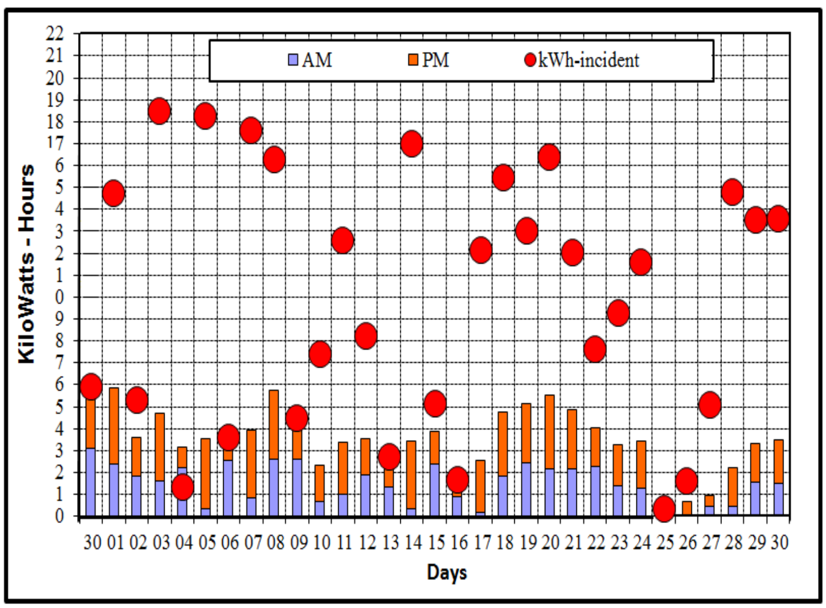

Fig. 13 Variation of accumulated heat with on October 31 using Immhx2

Figure 14 shows the amount of energy drawn at early morning and late afternoon. This figure couldn't be directly used to estimate the overall efficiency of the system, because the overall system efficiency depends on, the efficiencies of the different components (collector, heat exchanger, pump, piping, and storage tank), ambient conditions, time and quantity of the thermal load, overall system compatibility.

The heat exchanger (ImmS&Chx) delivered higher energy and this mainly due to the big heat transfer area of the and also this heat exchanger was more compatible with the collector. The ImmS&Chx was arranged inside the tank in such a way to promote a high degree of stratification. This makes the solar collector to operate with a big temperature difference, which in turn gives high collector efficiency, and small heat los

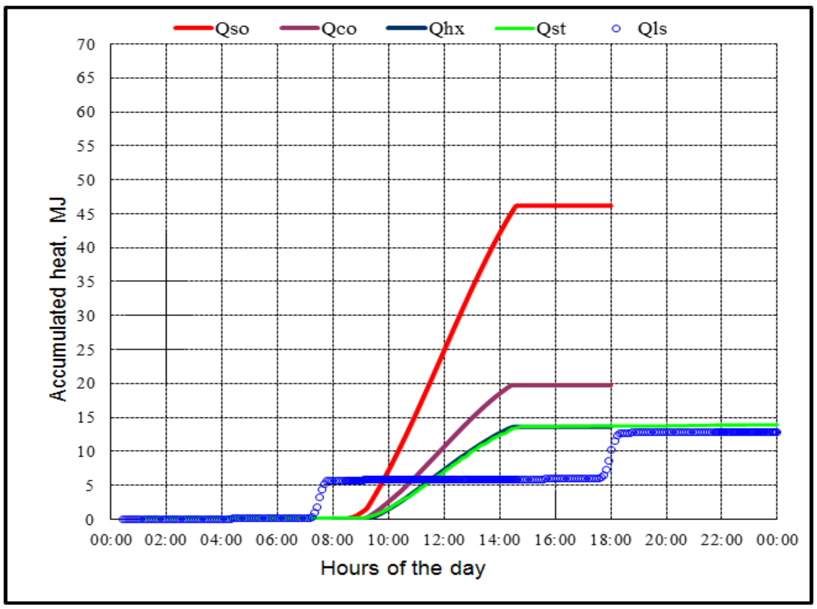

FIGURE 14 Drawn energy of October

5. Conclusion

1. The solar flux in the case of using the submerged immersion heat exchanger (Immhx 2) gave better behavior than the immersion shell-and-coil (*ImmS&C*)
2. The immersion heat exchanger (Immhx 2) achieved a lower overall heat transfer coefficient than the immersion shell-and-coil (*ImmS&C*) due to the small surface area of heat exchange
3. As for the thermal stratification, it was noted that the temperature difference between the top and bottom of the tank was greater in the case of the immersion shell-and-coil (*ImmS&C*) compared to the immersion heat exchanger (Immhx 2) due to the large surface area of heat transfer
4. Concerning the thermal performance of the of the SDHW, it was noticed that the two heat exchangers have the same behavior, but with a higher value for the immersion shell-and-coil (*ImmS&C*)
5. the collector surface achieves the highest accumulated heat, while the storage tank achieves the lowest value of accumulated heat
6. The immersion shell-and-coil (*ImmS&Chx* delivers higher energy compared with immersion heat exchanger (Immhx 2)

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