AN EXPERIMENTAL STUDY FOR A NEW DESIGN OF A STORAGE SOALR COLLECTOR [+]

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Abstract :

An experimental study was carried out on a new design of a storage solar collector to verify its suitability for domestic use. The storage collector can be used as storage water tanks to replace the ordinary cubical or cylindrical tank commonly used in Iraqi houses. Experiments were carried out for both summer and winter weather conditions with and without hot water removal. The hourly system performance parameters were investigated systematically for all test conditions. These included the mean storage temperature and total stored energy. The day-long collection efficiency of the triangular collector under no load condition in winter (13-November-2004) was found to be 48.7% for a maximum mean storage temperature of 40.5 ^oC and a maximum hot water temperature at the tip of the collector of 65 ^oC. In summer (9-July-2004), the day-long collection efficiency was found to be 62.2% for a maximum mean storage temperature of 57 ^oC and a maximum hot water temperature of 70 ^oC. At continuous loading, the collection efficiency was 55.7% in winter, and 65.1% in summer. Also, in winter the maximum difference between the outlet and inlet water temperatures were 12 ^oC at 2 p.m. and 9 ^oC at the end of the day.

Key Words : **Triangular storage solar collector, Novel storage collector.**

دراسة عملية لمجمع شمسي خازن ذو تصميم جديد

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المستخلص :

يتضمن البحث دراسة عملية لتصميم جديد لمجمع شمسي خازن وتحقيق ملاءمته للاستخدامات المنزلية. يمكن استخدام المجمع الشمسي المقترح كخزان ماء بدلا من الخزانات المعتادة المكعبة أو الأسطوانية الشكل المستخدمة في البيوت العراقية. أجريت سلسلة تجارب منتظمة لدراسة أداء هذه المنظومة خلال فصلي الشتاء والصيف و بظروف تحميل و كذلك بدون تحميل وتم تحليل هذا الأداء لمختلف الظروف. تمت دراسة تأثير المتغيرات الأساسية على أداء المجمع الشمسي الخازن والتي تضمنت متوسط درجة حرارة الخزين وكفاءة المجمع. بلغت كفاءة المجمع الإجمالية بدون تحميل 48,7% لفصل الشتاء (13- تشرين الثاني -2004) بينما بلغت متوسط درجة حرارة الخزين العظمى

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حوالي 40.5 درجة مئوية و في فصل الصيف (9-تموز-2004) بلغت الكفاءة الإجمالية 62,2% وكان متوسط درجة حرارة الخزين العظمى نحو 57 درجة مئوية. في حالة التحميل المستمر بلغت الكفاءة 55,7% و 65,1% لفصلي الشتاء والصيف على التوالي وكان الفرق بين درجة حرارة الدخول والخروج في فصل الشتاء حوالي 12 درجة مئوية عند الثانية بعد الظهر و 9 درجة مئوية عند نهاية اليوم.

1. Introduction :

All the classical solar water heater systems contain two main components; the collector and the storage tank. Joudi [1] suggested new storage solar collectors for domestic hot water supply. They designed that these serve as a collector and storage tank in one component. The invention includes different principal engineering forms derived from cutting a cube at inclined planes. The new designs possess several advantages over the other types. First, a higher efficiency during the daytime owing to the fact that primarily there are no heat losses in the circulation of water. Second, the superior contact of water with the absorber plate results in better heat transfer in comparison with poor bond conductance, as is the case in the thermosyphon and forced circulation type flat plate solar water heaters. Also, low cost and easy manufacture from common materials without the need for high technology. Fig. (1) shows such a form with a triangular sunlit face. It is obtained by cutting a cube from one upper corner at 45^o down to the opposite hypotenuse of the base of the cube. It will be named the triangular storage solar collector. The storage collectors can be used to as a water tanks to replace the ordinary cubical and cylindrical tanks commonly used in Iraqi houses.

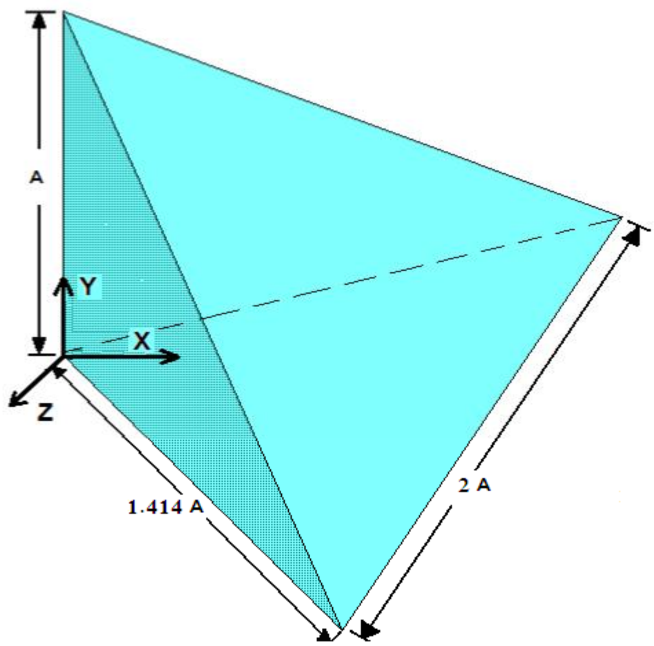

Figure (1): Schematic of the triangular storage collector.

The ideal inclination angle to collect solar energy in the winter season is 10 to 15^o more than the angle of latitude. The latitude for Basra, Baghdad and Mosul, which represent the south, center, and north of Iraq, are 31^o, 33^o and 36^o respectively. Therefore, a common inclination angle of 45^o would be suitable for ease and for unity of fabrication. The dimensions of each form can be changed to obtain different storage volumes by simultaneously changing the height and base dimensions. The sunlit surface is painted black to increase solar energy absorption. Glass or any other transparent material may be used as a cover to the tilted side facing the sun. Thermal insulation is used to insulate all other sides. Various technical aspects of these new forms are described by Joudi [1].
In recent years several configurations of solar integrated collector storage systems of hot water have been tested. The configurations are based on the storage water tank used for domestic and industrial hot water. Hamood and Khalifa [2], analyzed a configuration which consists of a storage water tank which is prism in shape, heated at the top surface and covered with opaque insulation on all other sides. An integrated collector storage solar water heater with compound parabolic concentrating reflectors was investigated experimentally by Helal et al. [3]. Tarhan et al. [4] investigated the temperature distributions in three trapezoidal built in storage solar water heaters with and without phase change materials (PCM).

2. Description of The Experimental Apparatus :

The experimental apparatus consisted of a triangular storage collector, which had a triangular irradiated face area and a triangular right angle pyramid for the storage as shown in Fig. (2).

Figure (2): A photograph of the triangular storage collector.

The back height was 500 mm giving a volume of 41.7 liters and a sunlit area of 0.35 m^2. The sunlit surface was painted with mat black paint. Visualization of the convection flow currents inside the triangular collector was accomplished by injecting small amount of a red dye with a syringe into the body of the water at two positions. At the tip of the collector (x = 50 mm, y =400 mm, z= 5 mm) and the second at the base of the collector (x = 50 mm, y = 50 mm and z= 5 mm, Fig. (3)). Observation of the subsequent dye motion was made through one of the side walls of enclosure, which was fabricated from clear 3 mm Plexiglas. The interior of a collector, at the apposite side, was enhanced by a white backaround to facilitate visual observation. The tilted side facing the sun was painted with mat black paint for absorbing the sun's radiation. The tank was connected with an inlet cold water pipe at the bottom, whereas the hot water was taken from the top of the tank. Ordinary window glass of 4 mm thickness was used as the top transparent cover for tilted surface facing the sun. The distance between the absorber plate and the bottom surface of the glass was kept at 45 mm, which is within the recommended value for solar collectors [5]. The glass cover edges were sealed with silicon tape to prevent the leakage of the hot air from the gap between the absorbing surface and the glass cover. The triangular storage collector was insulated with Styrofoam of 50 mm thickness on all sides. The storage collector and insulation were embraced by a wooden frame 300 mm above the ground. The irradiated face of all designs was inclined at 45^o above the horizontal and facing south. The collector storage was instrumented with 10 thermistors incorporated into five vertical probes. Probes A, B, and C were placed vertically along the section of symmetry of the storage collector as shown in section A-A at Fig.(3). Probe A holds one thermistor, Probe B holds two thermistors and probe C holds three thermistors. Probes D and E were placed at a distance of 250 mm away from the centerline of the tank as shown in section B-B at Fig.(3). Probe D holds one thermistor and probe E holds two thermistors. The last thermistor no.1 was placed at one of the lower front corners of the storage at a distance 500 mm from the centerline. Two separate thermistors were used to measure the inlet and outlet temperatures of the storage water. Also, two additional thermistors were used to measure the temperature of absorber plate and the glass temperature.

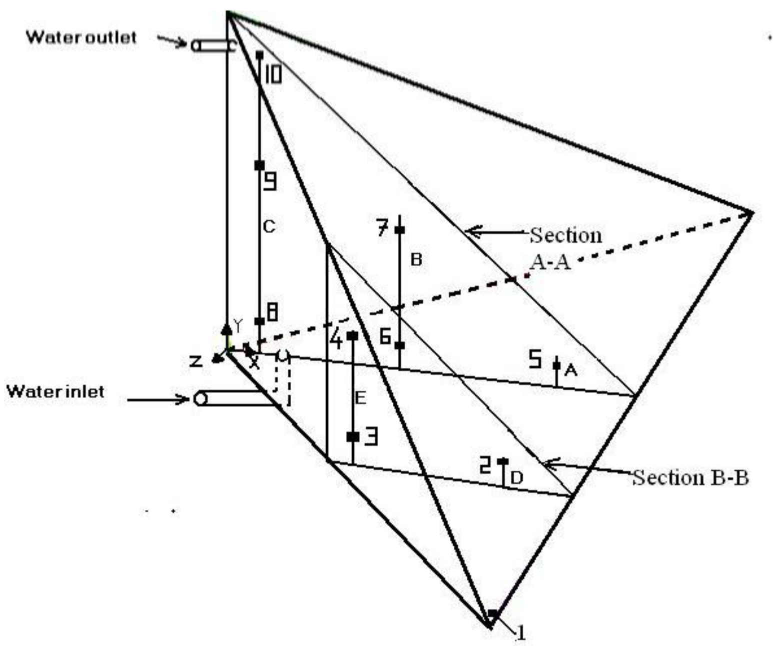

Figure (3): Positions of thermistors for temperature measurement.

3. Results and Discussions :

The experiments were carried out at the technical college of Kirkuk city in Iraq located at 35.33^{o}N latitude. At the onset of each experiment, the storage collector was filled with fresh water and the glass cover was thoroughly cleaned. Measurements of temperature and flow rate of water were recorded at each hour. Test with and without load (i.e with and without hot water withdrawal from collector) where conducted on the system throughout typical winter days (13th, 14th, 15th and 16th of November) and typical summer days (9th, 10th, 11th, and 13th of July). Solar irradiance was calculated by the ASHREA clear day model [6]. Typical results are presented. The results of the system performance at no load conditions are discussed first.

3.1 Mean Storage Tempratures :

The mean storage temperature is an important parameter. It is defined as a mass weighted average temperature, which is calculated by the equation given as:

$$T_{av} = \frac{\sum_{i=1}^{n} M_i * T_i}{M_{total}} \qquad \text{......} \; 1$$

Fig. (4) shows the variation of mean storage temperature during typical clear winter and summer days. It is observed that the mean storage temperature increased with time and reaches its maximum value at 2 p.m in winter. This is because the net energy absorbed becomes is just lower than the heat losses, which means that the useful energy transferred to the water is insufficient to cause any further increase in the mean storage temperature above the maximum value which was 40.5 ^{o}C for this particular winter day. The maximum value of the mean storage temperature depends on the solar radiation intensity, the prevailing weather conditions, the starting inlet temperature and the heat losses, which are different between the summer and winter months. The maximum value in Fig (4) was 57 ^{o}C for the particular summer day and it occurred at 4 p.m.

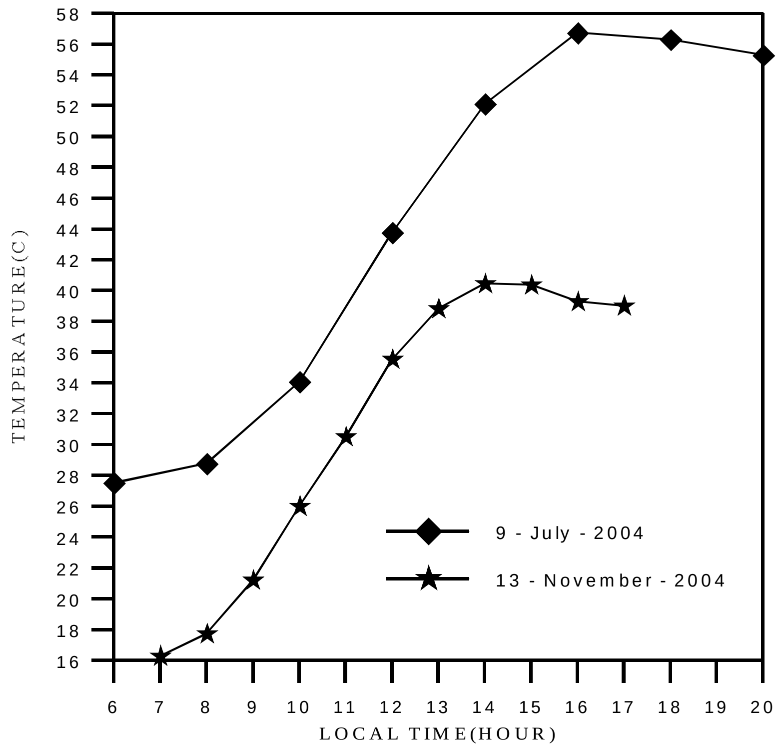

Figure (4): The variation of mean storage temperature of the triangular collector through the winter and summer seasons.

3.2 Storage Collector Operating Parameters :

One of the important criteria in a storage solar collector is the stored energy. Once the mean storage temperature and its rate of increase during the operation period have been determined, the stored energy can be calculated from the following equation:

$$q_u = m * c_w * (T_{av} - T_i) \qquad \text{.......................2}$$

Figure (5) shows the variation of the stored energy during the operation period. It is observed that the stored energy reaches its maximum value and then decrease after 2 p.m. in winter but after 4 p.m. in summer. Fig. (6) shows the variation of the solar radiation intensity, useful energy transferred per unit absorber area and the instantaneous collector efficiency during a typical winter day at no load conditions. The useful transferred energy was calculated from equation (2), and the instantaneous efficiency of the collector was calculated as:

$$\eta = \frac{q_u}{A_f * I_t} \qquad \text{.......................3}$$

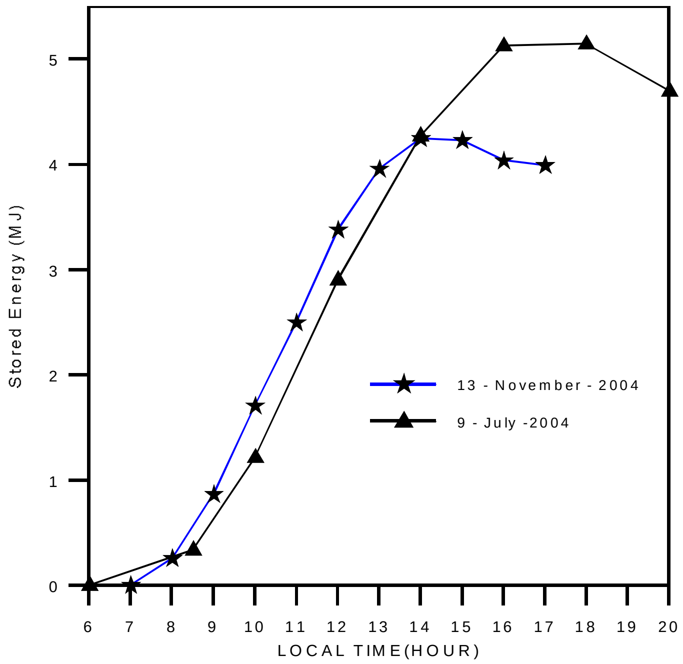

Figure (5): Variation of stored energy during the operation period

Figure (6) shows there is a high increase in the instantaneous efficiency during the first hours of the operating period 8-10 a.m. This is because the large increase in the net energy absorbed, coupled with relatively small heat losses from the collector to the ambient atmosphere. Also, the instantaneous efficiency reaches its maximum value of 80 % at 10 a.m. and then decreases. The variation of useful energy follows closely the variation of solar intensity and reaches its maximum value of 687 W/m^2 at 11 a.m. for this particular day.

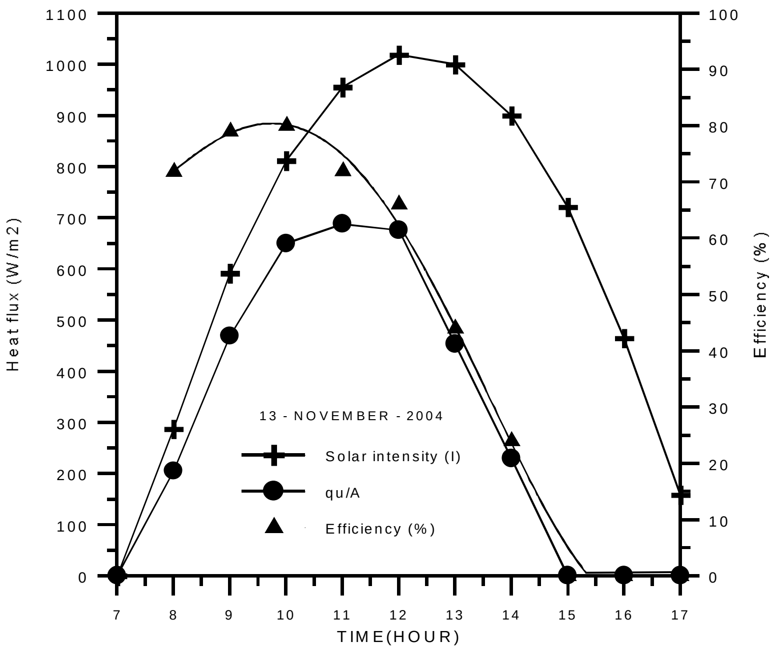

Figure (6): Variation of operating parameters on a typical clear winter day

The maximum value of the instantaneous efficiency for a typical summer day was 78 % at 12 noon and then decreases as shown in Fig. (7). The maximum value of useful energy was only 663 W/m^2 at 12 noon for a typical summer day during July as observed from Fig. (7). This trend is due to increasing heat losses with time of day, accompanied with decreasing net energy absorbed in the afternoon hours, the time at which the maximum instantaneous efficiency occurs was found to be different for different conditions. It is also observed that, at the second half of the day, there is a noticeable decrease in the instantaneous efficiency resulting from a large reduction in the useful energy transferred. Comparison with other works can be carried out meaningfully only for the overall bulk efficiency of the present work with those deduced from available literature. Direct comparison between temperature differences alone is not really valid. Table (1) shows the overall bulk efficiency obtained with conditions listed for this work and the works of Garg [7], Chauhan [8], Marzouq [9], and Sokolov [10]. The overall bulk efficiency η_b was calculated from the equation:

$$\eta_b = \frac{m * c_w * (T_{av} - T_i)}{A_f \int_0^{\theta} I(\theta)\, d\theta} \qquad \ldots\ldots 4$$

The present system is found to be less efficient than systems of the above workers in winter except for Marzouq because the area per volume is smaller for Joudi's design. In summer, it is higher than that of Sokolov.

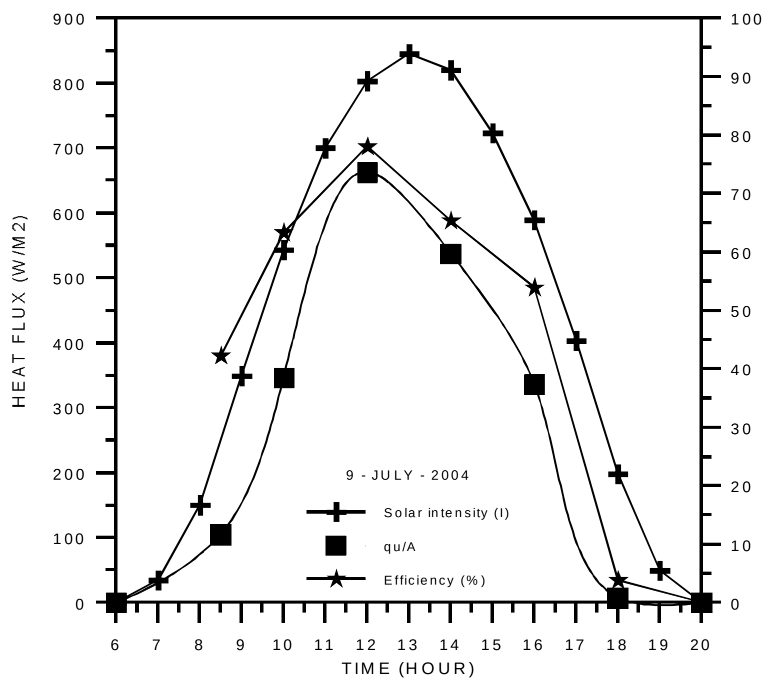

Figure (7): Variation of operating parameters on a typical clear summer day.

However, if we were to divide the efficiency η_b by the ratio of area to storage volume as in the last column of table (1), a new picture appears. It shows that this new triangle storage collector is superior to all the others. This number is not without meaning. It is similar to merit numbers and in this case gives a true compares. Even the numbers for η_b are actually comparable when the A_f/V_t values are comparating (Marzouq and Garge). The last column clearly demonstrates that a large A_f/V_t is not the only criterion for performance comparison, as in the cases of Sokolov and Chauhan.

Table (1) the efficiency of the present design and the previous studies.

		M (kg)	$(T_f - T_s)(^oC)$	A_f/V_t (1/m)	η_b
Present work	**Winter**	41	24	8.62	48.746
	Summer	41	29.5	8.62	62.2
Marzouq	**Winter**	176	30	10	47
Sokolov	**Summer**	110	40	16.3636	53
Garg	**Winter**	90	32	9.955	55
Chauhan	**Winter**	70	45	21.426	51.5

3.3 Convection Flow Patterns :

Absorbed solar radiation induces heat transfer throughout the body of the water with a resulting change in the fluid density. The buoyancy effect causes natural circulation of the fluid relative to the collector solid surface. The process is continuous as long as there is a heat influx. A general view of fluid movement in the collector is first presented in the z=0 slice which is a symmetric plane of the collector domain in contact with the hot inclined surface. The fluid rises under the effect of buoyancy forces. The experimental flow patterns illustrated in Fig. (8) shows the direction of fluid motion near the back of the symmetry plane inside the collector as a downward motion while, the fluid was moving to the right near the base of the collector as shown in Fig. (9).

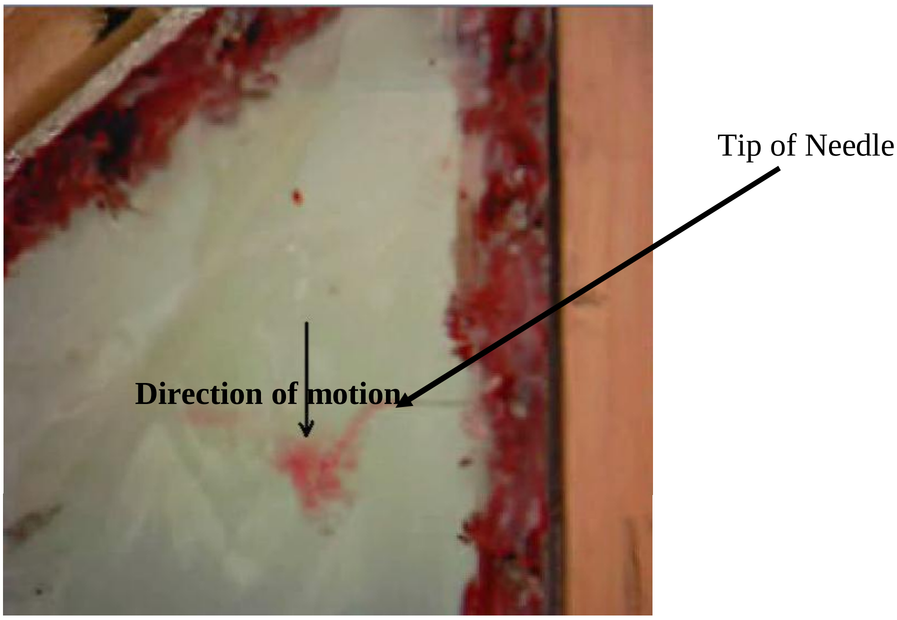

Figure (8): Experimental detection of flow pattern in the upper side of the triangular collector.

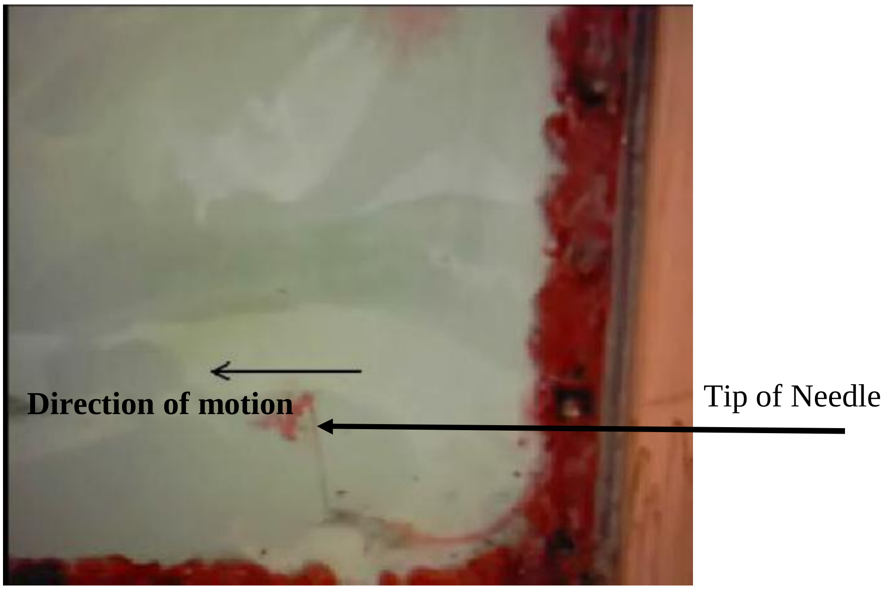

Figure (9): Experimental detection of flow pattern in the lower side of the triangular collector.

3.4 Effect of Loading :

In order to show the effect of loading conditions on the system performance, some experiments were carried out with hot water withdrawal from the collector during the operating period in November and July 2004. The hot water withdrawn was taking continuously. This was done by permitting cold mains water to enter the collector at its bottom, and the hot water was withdrawn from the top of the collector. Volumetric flow rate of the water supply through the test rigs was measured by a floating type rotameter. Before calibration, the flow meter was checked for scale formation inside the tube. Calibration of the flow meter carried out using a stopwatch and graduated container.

Figs. (10), and (11) show the variation of system temperatures for a clear day with continuous load condition. The mass flow rate of load water was 0.2 liter/min where the total hot water removed during the whole working period was 96 liters over the operating period. Fig. (10) shows the variation of inlet, outlet and mean storage temperature during a summer day. It is observed that the mean storage and the outlet temperatures are typical for a solar system. Fig. (11) shows the variation of system temperatures for a clear winter day. The outlet temperature reaches the maximum value of 34 ^{o}C at 2 p.m. in Fig (11) The temperature difference between the outlet and inlet temperature is 12 ^{o}C at 2 p.m. and 9 ^{o}C at the end of the day.

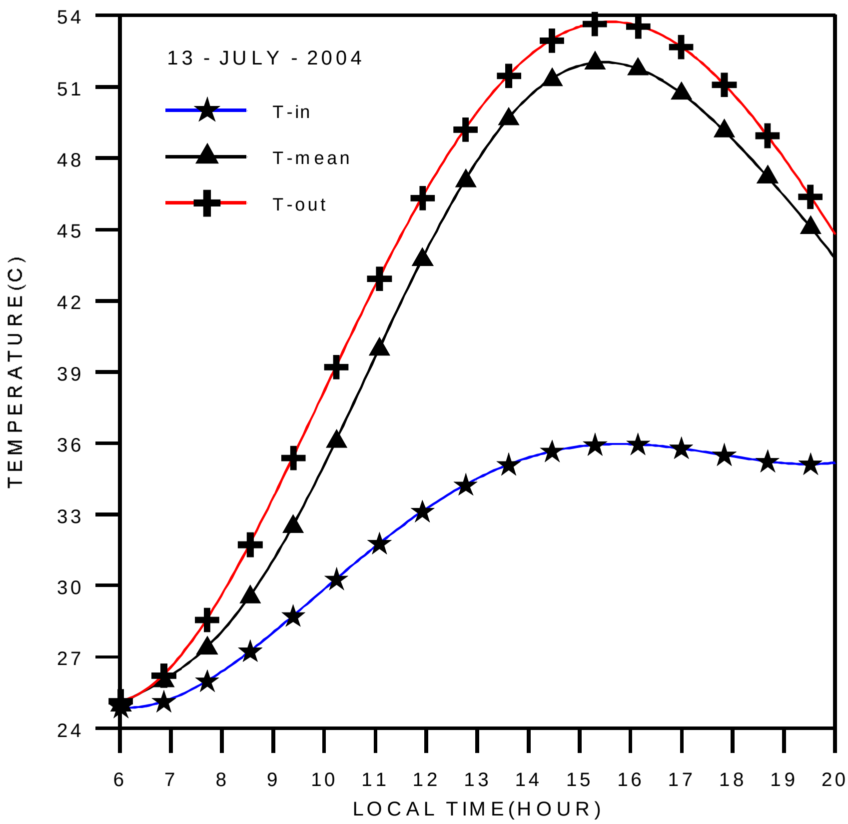

Figure (10): Variation of system temperatures of triangular collector with continuous load.

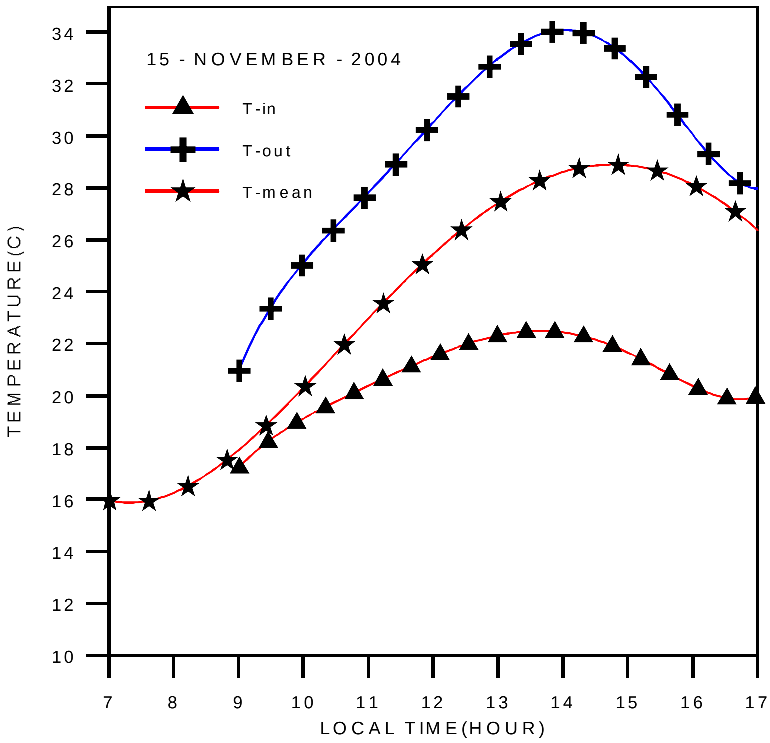

Figure (11): Variation of system temperatures of triangular collector with continuous load.

4. Conclusions :

From the results presented, the following main conclusions can be obtained:

1. At no load condition, the outlet temperature reaches a maximum value of 40.5 °C at 2 p.m for particular winter day and 57 °C at 4 p.m. for particular summer day.
2. In the continuous loading test for the triangular collector, the outlet temperature reaches a maximum value of 34 °C at 2 p.m. The temperature difference between the outlet and inlet temperature was 12 °C at 2 p.m. and 9 °C at the end of the day.
3. The nature of motion inside the storage collectors depended on the volume and loading conditions.
4. Operating the storage solar collector with an auxiliary heater to provide water at a constant supply temperature during the day.
5. Studying the experimental analysis of performance for parallel, series, and parallel-series connection of a bank of storage collectors.

5. References :

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Nomenclaturees :

A	Height of the collector [m]
A_f	Front area of the collector [m^2]
c	Specific heat [kJ/kg.K]
I_t	Total solar radiation on a tilted surface [W/m^2]
m	Mass [kg]
M_i	Mass of specified slice
q_u	Useful energy [kJ]
T	Temperature [^{o}C]
V_t	Collector volume [m^3]
y	Position of the partition [m]

Greek Symbols :

ρ	Density [kg/m^3]
η	Collector efficiency

Subscripts & Superscripts :

av	average
i	point
tot	total