Thermal Performance of Solar Hot Water Systems Using a Flat Plate Collector of Accelerated Risers

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Abstract: This study focuses on a comparison of the performance of two similar locally-fabricated solar water heaters. One of the collectors features a new design for accelerated absorber; its risers are made of converging ducts whose exit area is half that of the entrance. The other collector is a conventional absorber, with risers of the same cross sectional area along its length. Each collector is the primary part of an indirect thermosyphon circulation solar hot water system. Both collectors face south with a fixed tilt angle of 33.3° from the horizontal. A side-by-side experiment was conducted on the two solar water heaters from January to April of 2009 for different water withdrawal profiles, continuous, interrupted and no load, as well as for horizontal and vertical storage tank orientations. Two types of storage tanks were investigated, those with two concentric cylinders, and those with helically-coiled tubes in the cylinder. Results show that a considerable enhancement of thermal performance (approximately 60%) of absorbed heat (useful gain) at solar noon was obtained for the new design, in comparison with the conventional type. The instantaneous efficiency was 31.5% for the accelerated absorbed flat plate at solar noon, while that of conventional absorber was (16.5%). The longitudinal water temperature variations in the risers of accelerated absorber were larger than that of the conventional absorber. The stratification in the storage tank was significantly improved for the solar hot water system, with the new absorber design in which the maximum temperature measured was 50 °C (vertical storage tank), while that for conventional absorber was 37 °C. The stratification obtained for a coiled tube in a cylinder storage tank indicated a good thermal performance with less space requirements. Also, the circulation rate in the accelerated absorber was higher when it was connected to a coiled tube than when it was connected to the concentric cylinders.

Keywords: Solar, Accelerated flat plate collector, Storage tank, Coiled tube, Stratification

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الأداء الحراري لأنظمة شمسية لتسخين الماء باستخدام مجمع شمسي مسطح ذو أنابيب رافعة متسارعة

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الملخص: تركز هذه الدراسة على مقارنة أداء منظومتين شمسيتين متماثلتين مصنوعتين محليا تستخدمان لتسخين الماء. أحد هذين المجمعين ذو تصميم جديد إذ يضم أنابيب رافعة متسارعة لحركة الماء ذات مقطع متقارب (مساحة مقطع الخروج تساوي نصف مساحة الدخول). المجمع الآخر كان ذو تصميم تقليدي (الأنبوب الرافع له مساحة مقطع واحدة). كلا المجمعين يعملان بمبدأ الثيرموسيفون غير المباشر ويواجهان الجنوب بزاوية ميل ثابتة مقدارها ٣٣,٣. تم فحص أداء المنظومتين في آن واحد ولفترة امتدت من الأول من يناير إلى الأول من أبريل٢٠٠٩ ولمختلف حالات سحب الماء للاستخدام المنزلي (سحب مستمر، متقطع، أو بدون سحب) مع توجيه أفقي وعمودي لحوض التخزين. كما تم فحص نوعين من الخزان الحراري: حوض خزان ذو أسطوانتين متمركزتين، وأخر يتكون من أنبوب ملتف حلزونيا داخل خزان أسطواني. أظهرت النتائج تحسنا واضحا في الأداء الحراري للمنظومة الجديدة مقارنة بالتصميم التقليدي بما يقارب ٦٠٪ من الحرارة الممتصة عند الظهر الشمسي. كانت الكفاءة الآنية للسطح الماص الذي يتكون من الأنابيب الرافعة المتسارعة ٣١,٥٪ وكانت ١٦,٥٪ للسطح الماص التقليدي عند الظهر الشمسي، كما كان توزيع درجة حرارة الماء على طول الأنابيب الرافعة المتسارعة أعلى من نظيراتها المقاسة على السطح الماص التقليدي. لقد تحسن التراصف الحراري في حوض التخزين باستخدام السطح الماص الجديد حيث وصلت أعلى درجة حرارة ٥٠°م (لحالة وضع خزان عمودي) في حين وصلت ٣٧°م للسطح الماص التقليدي. كما بين التراصف الحراري في حوض التخزين باستخدام أنبوب ملتف داخل خزان أسطواني بأنه يؤدى إلى أداء حراري أفضل بأقل مساحة تخزين. كذلك كان معدل تدوير الماء أكبر في السطح المتسارع عند ربطه بالأنبوب الملتف مقارنة بالتدوير الذي تم الحصول عليه عند ربطه بالخزان ذي الأسطوانتين المترمكزتين.

الكلمات الدالة: شمسي، مجمع شمسي، مسطح متسارع، حوض التخزين، أنبوب ملتف، تراصف حراري

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1. Introduction

Solar hot water systems function as heat exchangers. They receive solar radiant energy and transfer it to the flowing fluid. The performance of solar systems varies as the design variables change, so it is therefore necessary to identify the parameters affecting this design and the operational variables.

Keltt *et al.* (1984) studied through experimentation the thermal performance of submerged coil heat exchangers for single wall coil and double wall coil for different tank sizes namely (300 L and 450 L) for different load flow rates. Khalifa (1999) investigated a thermosyphon domestic hot water system to show the important variables that affect the performance of the solar system such as the temperature variation along the absorber fins, tubes and in the flow direction as well as the thermosyphonic mass flow rate. The design of an efficient storage tank heat exchanger has been investigated by (Shokouhmand *et al.* 2008) with different coil pitches and curvature ratios. An enhancement in the heat transfer rate is obtained due to the centrifugal force due to the curvature of the tube, resulting in the secondary flow development. The objective of the present work is to compare experimentally thermal performance of a locally-made new solar flat plate collector (named here as accelerated solar collector) to a flat plate collector of straight risers the conventional type hot water system for a different water withdrawal pattern. Additionally, the study will show the stratification in the storage tank. In order to carry out a fair comparison, the collectors are made as identically possible.

2. Theory

Thermal analysis has covered in many solar thermal engineering texts (Duffie, Beckman 1974; Lunde 1980). Therefore, only equations which describe the thermal performance of the system will be described in this paper.

Actual Collector And Supply Useful Energy Gain

For the collector closed- loop cycle, the hourly useful energy gain can be calculated by:

$$Q_{coll} = \dot{m}_{coll}\, C_p\, (T_{out} - T_{in}) \qquad (1)$$

The heat obtained by the water withdrawal can be calculated as:

$$Q_{sup} = \dot{m}_{sup}\, C_p\, (T_{18} - T_{20}) \qquad (2)$$

Where Q_{coll} heat is transferred in W, m• mass flow rate in kg/s, C_p water specific heat in J/kg.K, T is the measured temperature at the collector inlet or outlet (ºC), and T_{20} and T_{18} are supply water temperatures at inlet and outlet from the storage tank, as shown in Fig. (1b) and Fig. (3).

The useful energy enhancement is calculated as:

$$\% \text{ enhance.} = \frac{(\text{useful energy})_{acc.} - (\text{useful energy})_{conv.}}{(\text{useful energy})_{conv.}}$$

$$(3)$$

The collector instantaneous efficiency can be determined according to:

$$\eta_{coll} = Q_{coll} / (A_{coll} * IG) \qquad (4)$$

IG is the global solar radiation on tilted collector at 33.3° from horizontal calculated from that measured on a horizontal surface.

3. Experimental Setup

Two identical solar water heaters are manufactured in this experiment; one is supplied with flat plate collectors of accelerated absorber, the other is supplied with flat plate collectors of conventional absorber. Figure 1 shows the configuration of solar water heater tested when its storage tank is composed of two concentric cylinders, and when it is a helical coiled tube in cylindrical shell.

3.1 Accelerated Flat Plate Solar Collector

A flat plate collector with an accelerator plate consists of nine equally-spaced parallel converging rectangular cross-sectional area copper risers (Fig. 2) with an inlet hydraulic diameter of 2 cm. The inlet dimensions are 20x20 mm, and the outlet hydraulic diameter 13.3 mm, while the outlet dimensions are 10x20 mm and tube length of 1.2 m. The riser to riser distance is 0.1 m, and each tube has an equal right and left fin length of 40 mm. These tubes are connected with two headers of rectangular cross sectional area one at each end to collect or distribute water from and into the risers, and from collector's outlet and inlet. The joints between the headers and risers ends are welded by using brass alloy.

A mat painted copper sheet is used as an absorbing plate of 1.20 x 0.9 m and of 1.9 mm thickness. This sheet is welded to the risers by brass alloy, the structure is good insulated with a fire wool coating of 70 mm thickness.
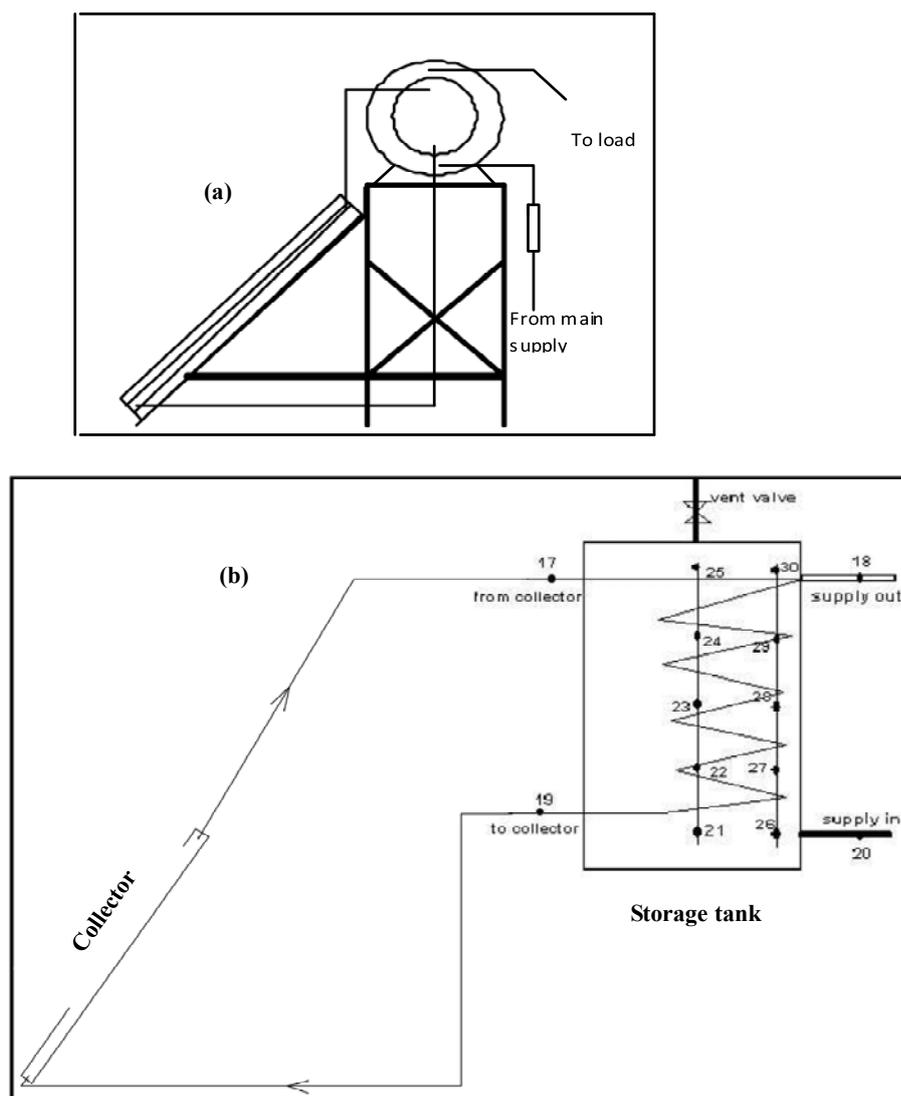
Figure 1. Close loop themosyphon solar water heater, the storage tank is a) Two concentric cylinders b) Helical coiled tube in cylindrical tank

3.2 Conventional Flat Plate Solar Collector

A conventional flat plate collector without accelerator plate is designed identical to an accelerated flat plate collector, and it consists of nine equal spaced parallel copper rectangular cross sectional area pipes of inlet and outlet with equal hydraulic diameters of 20 mm. In addition, the inlet and outlet cross sections dimensions are 20x20 mm and 1.20 m length, and the riser to riser distance is 0.1 m. Each tube has an equal fin length to right and left of 40 mm, and these tubes are connected with two headers of rectangular cross sectional area. The risers are welded to the header using brass alloy. A copper sheet is used as an absorbing plate of 1.20 x 0.9 m and of 1.9 mm thickness. This sheet is welded to the risers using a brass alloy, the pipes are supported from the bottom by a galvanized plate of 2 mm thickness. The structure is well-insulated with a glass wall coating of 70 mm thickness.

The collector box frame is manufactured from a 2 mm thickness galvanized sheet formed as a box, and the collectors are connected to their containers by screws. The collectors are well-insulated by using glass wool insulation of 70 mm thickness from the back of the collectors and 50 mm thickness from the perimeter of the collectors. A glass panel of 4 mm thickness is used as a transparent cover for the collector with area of 1.25x0.95 m². The glass cover lies on the collector frame in a small channel 25 mm wide, and is fixed by using a black silicon. A piece of rubber tape is fixed between the glass and channel to prevent air leakages. The cover-absorbing plate spacing is 70 mm.

3.3 Storage Tanks

3.3.1 Shell and Tube Storage Tank

Two concentric horizontal cylinders form the stor-

Glass cover — Glass cover – Absorbing surface Space — Absorbing Surface — Collector risers — Container frame — Insulation

a) Collector cross sectional view

b) Accelerated riser (front view)

c) Conventional riser (front view)
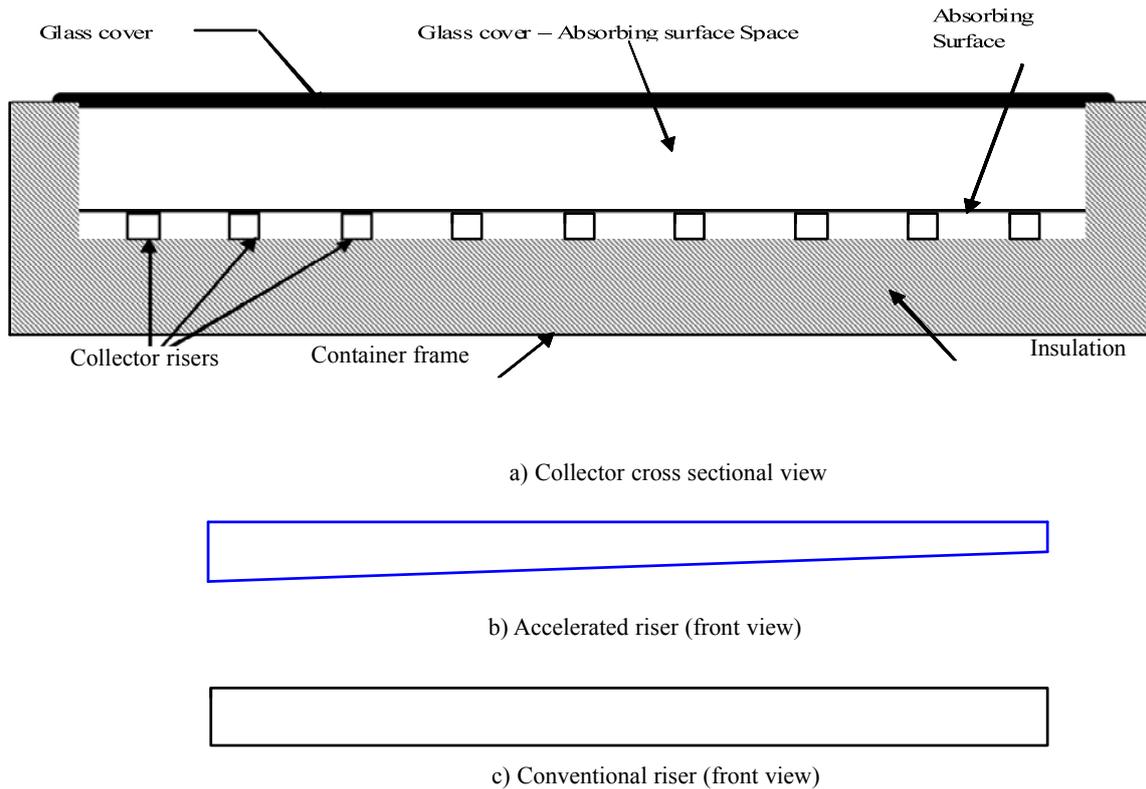
Figure 2. Configuration of manufactured flat plate collector

age tank made from a galvanized plate of 2 mm thickness. The internal cylinder has an inner diameter of 375 mm, 1 m length and capacity of 110 L. The outer cylinder has an internal diameter of 470 mm and a length of 1.2 m, forming an annular space of 90 L. The internal cylinder is used for the closed-loop water (energy carrier) while the annular space between internal and external cylinders is used for loading water (domestic use water). Each cylinder has two holes to form inlet and outlet ports. The tank is well insulated by a glass wool insulator of 70 mm thickness, and the storage tank can be oriented horizontally or vertically as required.

3.3.2 Coiled Tube In Shell

Another storage tank manufactured by (Karima *et al.* 2011) is used in the present work. This tank (made from a galvanized sheet) is of 125 L volume, 1m height and 0.4 m diameter. A coiled tube is inserted inside in the tank which in turn is well insulated with glass wool of 10mm thickness. A 0.6 m high coiled tube is made by winding a copper tube of 9.5 mm diameter around a cylinder to form twelve turns of 0.25 m outside coil diameter. A spacer was placed between each two consecutive coil turns to ensure a uniform pitch along the coil, which measured 0.05 m.

3.4 Temperature Measurement

One hundred and five (105) calibrated thermo-

couples (Type T Copper and Constantan) are used to measure the temperature at various points of water tubes, water storage tanks, inlet and outlet of collectors, inlet and outlet of the withdrawal water, ambient and glass cover, as shown in Fig. 3. The entire number of thermocouples are joined to Digital thermometer reader (Autonics-T4WM/ K(CA) 0-1200). The ambient temperature is measured by a using a mercury in glass- thermometer.

3.5 Flow Rate Measurement

The mass flow rate of the thermosyphon circulation flat plate collectors is so small tht only the laser flow meter can detect the flow which in not available, so a transparent tube of 250 mm length and 10mm diameter is connected between collector outlet and storage tank inlet. An ink injection is used to calculate the circulation rate by injecting ink and measuring the time required to pass the 250 mm distance using stopwatch to compute fluid velocity. The water load flow rate is measured by using a flow meter of 2-22 L/min. range.

3.6 Test Procedure

The thermosyphon circulation solar water flat plate collectors were connected as a closed loop (indirect) system. The experiments were carried out from January to March 2009. Before each test, the following preparations were made, the closed collector loop
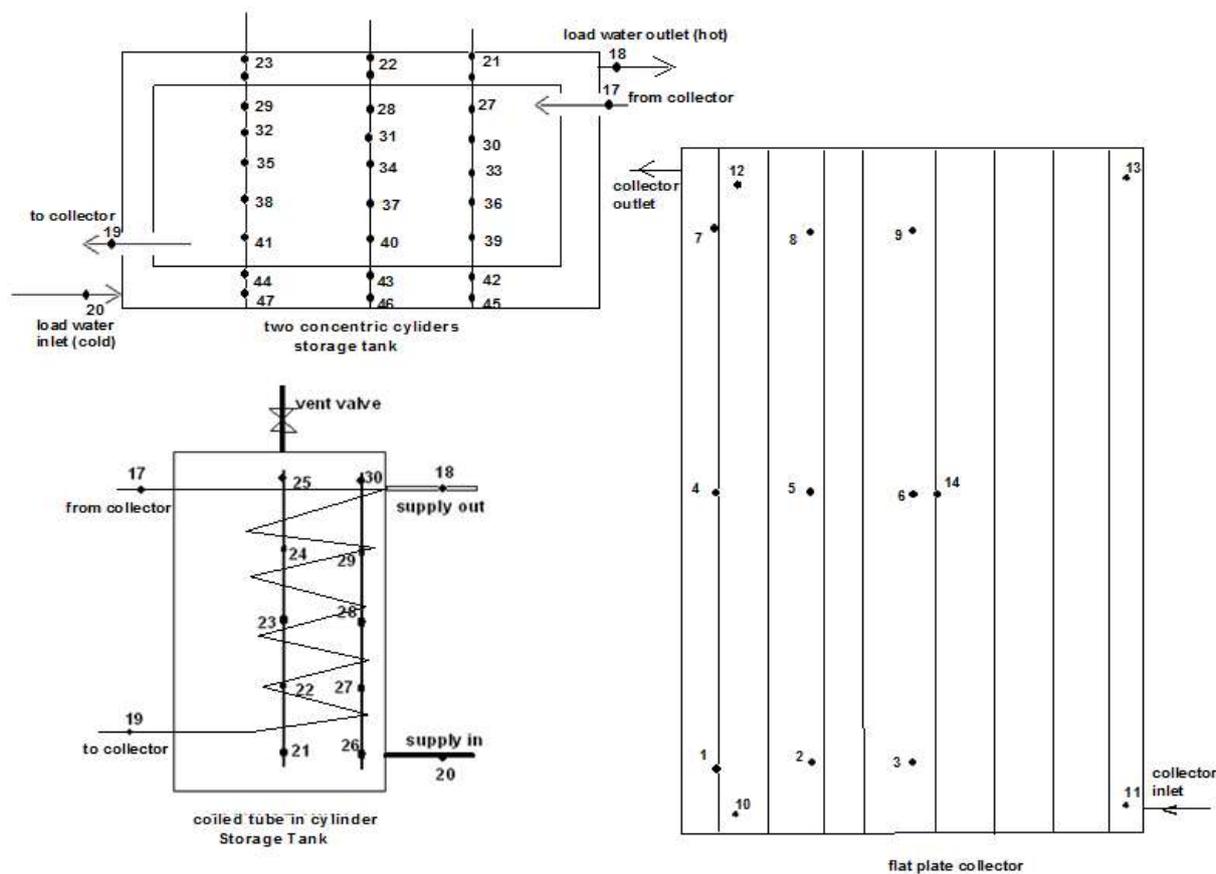
Figure 3. Locations of temperature measurements
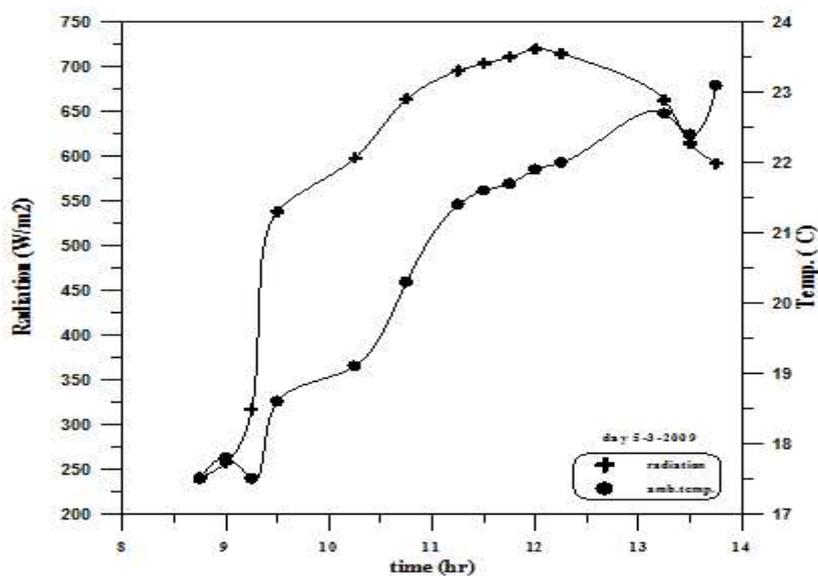
Figure 4. Solar radiation on horizontal surface and ambient temperature (5/3/2009 at 33.3° N. Baghdad)

was filled with water, the glass cover is cleaned thoroughly and the measurements and apparatus were checked. Then the storage tanks were filled with water and readings were taken each half hour from sunrise to sunset. The newly-designed system was tested side by side with the conventional type.

The test was conducted from sunrise to sunset for five different mass flow rates of load water withdrawal profiles. These profiles were: continuous load of 2.6 L/min, the profile (II) shown in Fig. 7 which is equivalent to daily consumption of single storage tank vol-
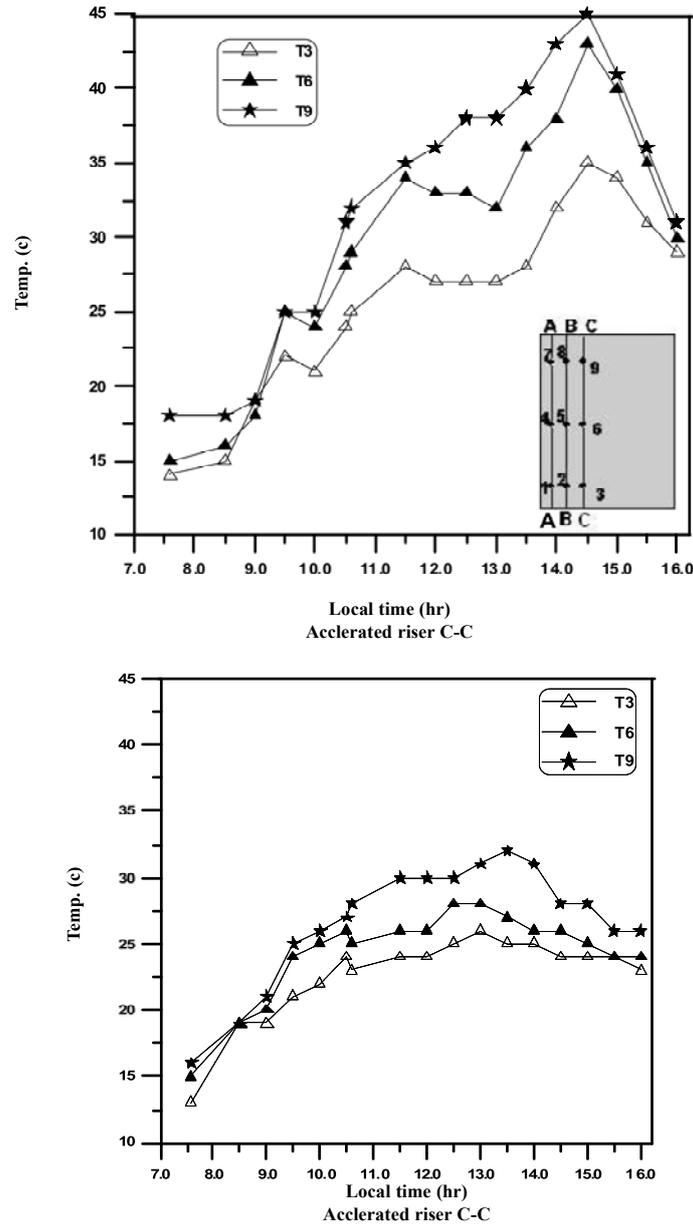
Figure 5. Water temperature distribution along risers

ume, emptying the storage tank twice a day and finally emptying it once a day. This propose is to test the effect of storage tank orientation (horizontally and vertically) on the thermal performance and study the effect of using a coiled tube for collector closed-loop instead of cylindrical tank. In all the above cases all temperature measurements, flow rate (circulation rate and loop flow rate), wind-speed are recorded.

4. Results and Discussions

Figure 4 shows the ambient temperature (measured (every 15 minutes) and solar radiation for the 24 hours of 27-1-2009 on the solar collector, which is obtained from the Ministry of Science and Technology Solar Center in Baghdad. It is clear that the peak solar radiation was between hours of 11 to 13. The peak ambient temperature was 19 ˚C.

Figure 5 shows the hourly water temperature rise along a selected riser C-C for the accelerated conventional type. It is clear that the temperature rises with time as water proceed along the risers length, but lesser temperature values are indicated for the conventional type since the accelerated riser occupies less water volume at the cross section especially at the riser on the upper part. Figure 6 (a & b) shows a comparison

Thermal Performance of Solar Hot Water System Using a Flat Plate Collector of Accelerated Risers
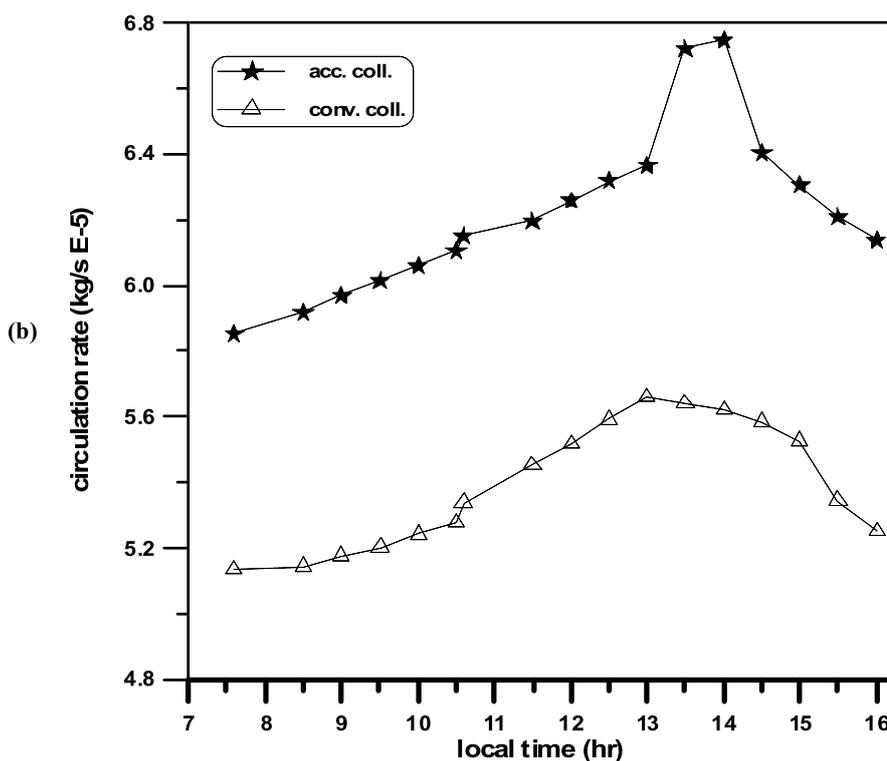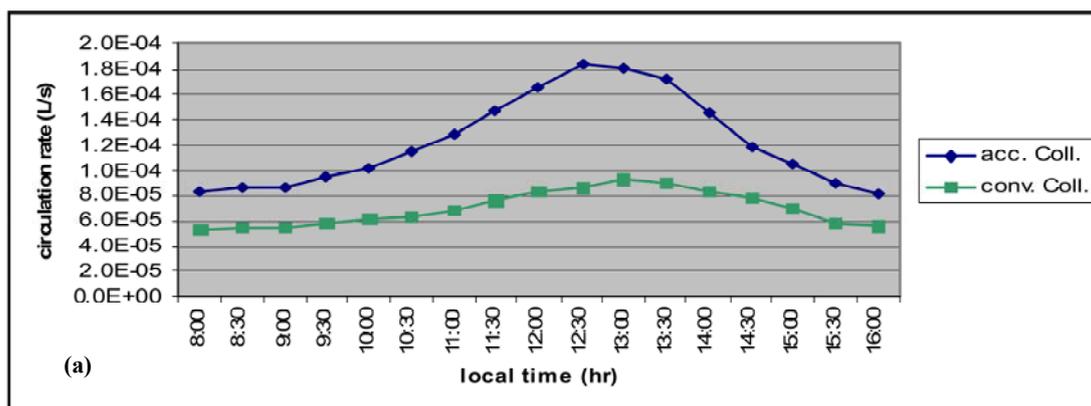
Figure 6. The thermosyphon circulate rate in the collector (33.3° N. Baghdad) a) Profile I, b) Profile II
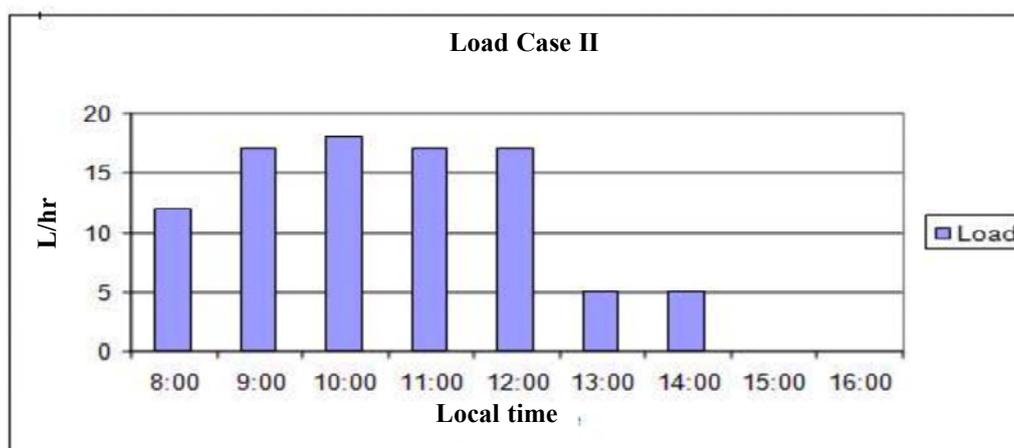
Figure 7. Water withdrawal profile (Case II)
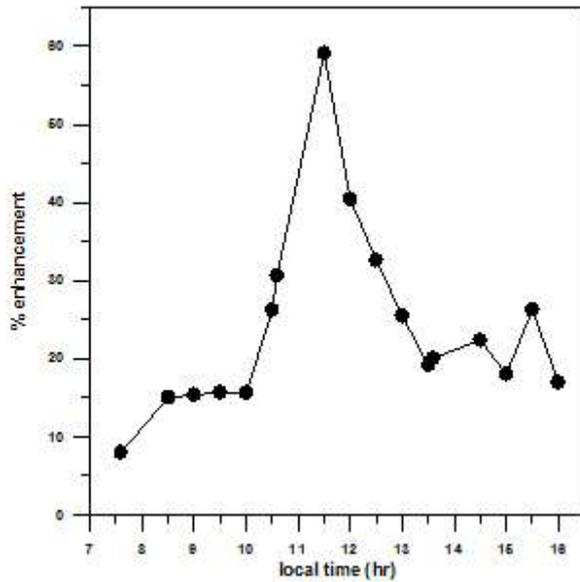
Figure 8. Percentage enhancement in absorbed heat when using accelerated collector compared with conventional collector (Horizontal tank case II)
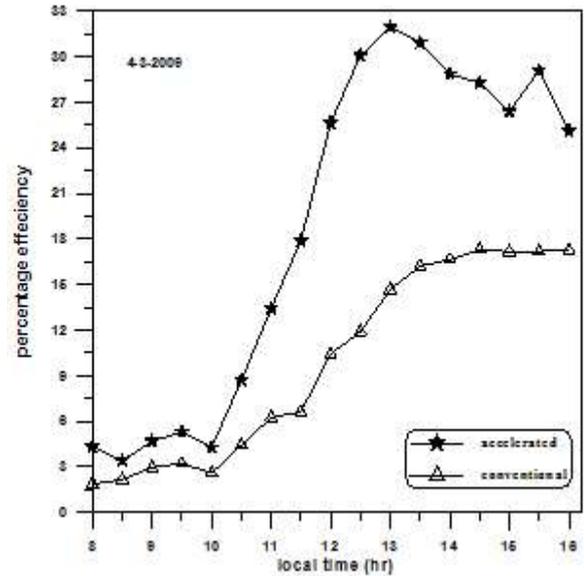
Figure 9. The instantaneous efficiency of the conventional and (accelerated collector for load Profile II)
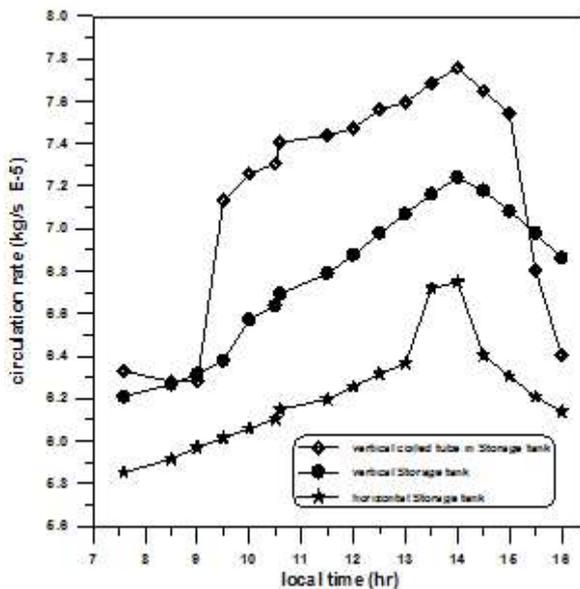
Figure 10. Effect of tank orientation and type on thermosyphon circulation rate (Profile II)
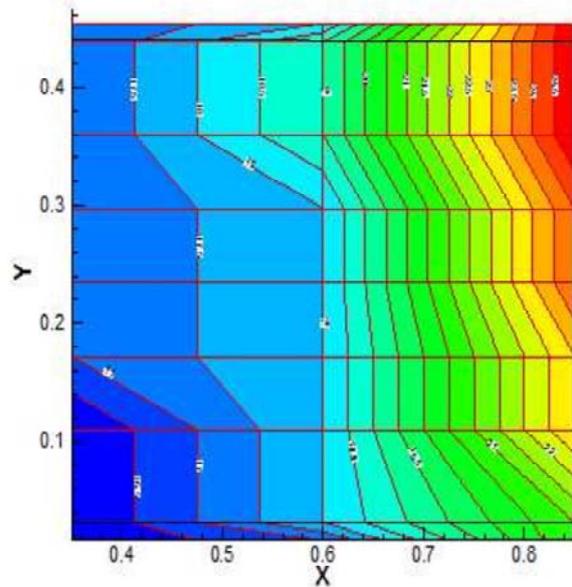
Figure 11. Stratification in shell and tube horizontal storage tank (accelerated collector load Profile I)

of the circulation rate between the accelerated and conventional flat plate for load profile I and load profile II shown in Fig. 7 respectively. A significant increase in the circulation rate is recorded from the first hour of day to the last hour, due to the new design criteria of the risers (converging cross sectional area). The maximum increase was at solar noon, and was due to exposing the same area to the same incident solar radiation. However, the water content in the converging risers was less than that in the straight riser so the temperatures increased and its density was lighter, resulting in it rising faster. Figure 8 shows the percentage enhancement in absorbed heat when using an accelerated collector compared to a conventional collector (horizontal tank case II). The useful energy enhancement was calculated using Eq. (3). The maxi-
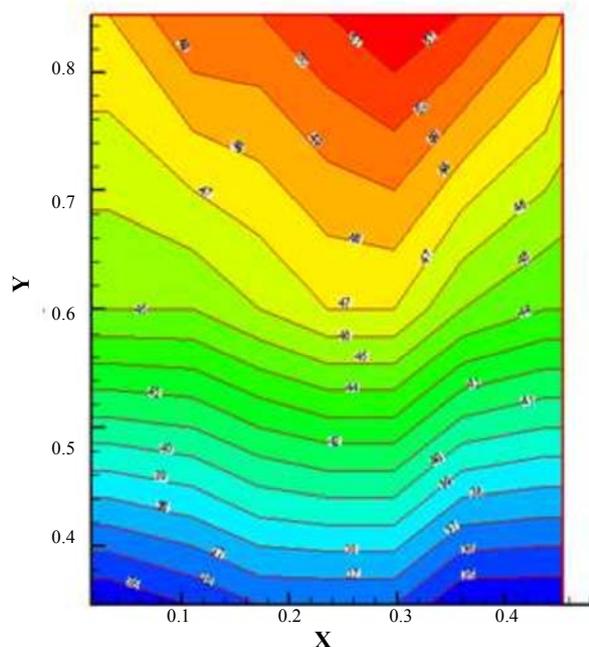
Figure 12. Stratification in two concentric cylinders vertical orientation (accelerated collector for no load)

Figure 13. Stratification in coiled tube in cylinder vertical storage tank (accelerated plate load II)

mum enhancement was 60% at solar noon and the minimum was measured at the day's run hour. Thus the new design recorded an instantaneous efficiency of 32.8% , while the conventional type indicated 17% as a maximum value, as shown in Fig. 9. Figure 10 shows that the vertical orientation of the storage tank enhances the circulation rate, and the coiled tube in cylinder has a much more effective design than the two concentric cylinders. Figure 11 shows the horizontal stratification in the concentric cylinders storage tank when connected to the accelerated collector. The upper right corner shows the hottest region (inlet of hot water from collector and exit of hot load water T=24.5 °C), while the lower left corner is the coldest region exit of cold water to the collector and the inlet of cold load water T=16.5 °C). Figure 12 shows the vertical stratification in the two concentric cylinders for no load where the maximum temperature indicated at the upper surface (inlet of collector hot water and exit of load hot water T_{max} = 51 °C). Figure 13 shows the vertical stratification in the coiled tube in the cylindrical storage tank for load profile II , where the maximum temperature indicated at the upper surface (inlet of collector hot water) and exit of load hot water T_{max} = 37.1 °C.

5. Conclusions

This research shows that the system thermal behavior

is sensitive to any component and can be enhanced further by modifying the design parameters and material selections. The following concluding remarks can be made, based upon this work.

* The stratification obtained in the storage tank is significantly affected by the collector inlet temperature.
* The stratification obtained in the storage tank relates proportionately to the type of load rate (or load withdrawal pattern).
* Increasing the flow rate of the load decreases the stratification in the storage tank
* The effectiveness of the storage tank (shell and coiled tube) reaches approximately 78% for (450 mL/min) load flow rate.
* Using a car radiator instead of the coiled tube enhances the thermal performance of the storage tank.
* Using an accelerated (converging) riser will enhance the thermal performance of the thermosyphonic solar collector because it will increase the circulation rate.

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