Experimental Study of the Thermal Performance of Flat Plate Solar Collectors Array by Different Connection Configurations

Dr. Jafar Mehdi Hassan
Professor
Department of Mechanical Engineering
University of Technology
Email : Jafarmehdi1951@yahoo.com

Dr. Qussai Jihad Abdul-Ghafour
Assistant Professor
Department of Mechanical Engineering
University of Technology
Emai:kaisyj@yahoo.com

Mohammed Fowzi Mohammed
Lecturer
Department of Mechanical Engineering
University of Technology
Email : mohammed2007msc@yahoo.com

ABSTRACT

The current research illustrates experimentally the effect of series and parallel connection (Z-I Configurations) of flat plate water solar collectors array on the thermal performance of closed loop solar heating system. The study includes the effect of changing the water flow rate on the thermal efficiency. The results show that, the collector's efficiency in series connection is higher than the parallel connection within flow rate level less than (100) ℓ/hr. Moreover, the collector efficiency in parallel connection of (I-Configurations) is more than the (Z- Configurations) with increasing the water flow rate .The maximum daily efficiency for parallel (I-Configurations) and (Z-Configurations) are (55%) and (51%) at water flow rate (150) ℓ/ hr. It was also noted that the thermal stratification of storage tank in case of series connection is higher than that of parallel connection. Also, when the flow rate increases, the thermal stratification of storage tank reduces.

Keywords: flat plate, solar collectors.

دراسة تجريبية للأداء الحراري لمصفوفة من المجمعات الشمسية المسطحة ذات اشكال ربط مختلفة

د. جعفر مهدي حسن
استاذ
قسم الهندسة الميكانيكية
الجامعة التكنولوجية

د. قصي جهاد عبد الغفور
استاذ مساعد
قسم الهندسة الميكانيكية
الجامعة التكنولوجية

محمد فوزي محمد
مدرس
قسم الهندسة الميكانيكية
الجامعة التكنولوجية

الخلاصة

يوضح البحث الحالي تجريبيا تأثير ربط التوالي، وربط التوازي (شكلZ–I) لمصفوفة من المجمعات الشمسية المسطحة على الاداء الحراري لمنظومة تسخين بالطاقة الشمسية مغلقة الحلقة .تضمنت الدراسة تأثير تغير معدل التدفق على الكفاءة الحرارية. بينت النتائج العملية ان كفاءة المجمعات ذات ربط التوالي اعلى من ربط التوازي عند معدل التدفق اقل من 100 لتر/ ساعة . كما بينت التجارب العملية ان كفاءة المجمعات ذات ربط التوازي (شكل–I–) اعلى من (شكل–Z–) عند زيادة معدل التدفق. ان الكفاءة القصوى لربط التوازي (شكلZ–I) خلال اليوم (55%) و(51%) عند معدل تدفق 150 لتر/ ساعة . كما لوحظ ان التدرج الحراري للخزان في حالة ربط التوالي اعلى من ربط التوازي . بالإضافة الى ان عند زيادة معدل التدفق تقلل من قيم التدرج الحراري للخزان .

الكلمات الرئيسية: صفيحة مستوية ، مجمعات شمسية.

1. INTRODUCTION

Many numerical and experimental studies were done by of many researchers. **Wamg, and WU, 1990.** studied the performance of flat plate solar collector arrays connected in parallel by analysis a new discrete numerical model is proposed to calculate the flow and temperature distribution in solar collector arrays. The numerical results show that, there are some difference in flow and heat transfer between single collector and large collector array because of the flow non uniformity. **Bong, et al., 1993.** studied a theoretical model for the determination of efficiency, heat removal factor and the outlet water temperature of single collector and an array of flat heat pipe collectors. The results show that ,for flat plate heat pipe collector ,or when two or more collectors connected in series ,there is linear relationship between the efficiency and parameter (T_{fi}-T_a/I) under steady state conditions . A solar heating system with a water source heat pump was investigated experimentally in north China by **,Kuang, et al., 2003.** The system consists of five flat plate solar collectors were combined in a parallel array with a total net area of (11 m^2). The results show that, a good thermal performance because of the low operating temperature. The high collector efficiencies were obtained, and the mean value was (67.2%) . The use of an auxiliary heater inside the storage tank lead to a waste of energy due to the large heat loss from the storage tank, **Myeong , et al., 2006** showed a collector consists of a network of riser tubes and headers. If the rows of the flat- plate collectors connected in series , they form a large flat- plate collector . They found that the thermal efficiency of the collector assembly is mainly influenced by the number of riser tubes, collector aspect ratio, mass flow rate, thermal conductivity and thickness of absorber plate. Differences in the range of (2.5%–8%) were detected depending on the specific parameter tested. **Yi-Mei, et al., 2012,** presented a Thermosyphon solar water heater employed in applications when considerable hot water consumption is required. In this experimental investigation, eight typical Taiwanese solar water heaters were connected in series. The temperature stratification and thermosyphon flow rate in a horizontal tank were evaluated. The system was tested under no-load, intermittent and continuous load conditions. The thermal efficiency for intermittent load conditions is about (5.8% to 7.0%) higher than the value for the no-load condition. **Khaled, et al., 2012,** presented two systems. The first, Solar Direct Hot Water, which is composed of flat plate collectors and thermal storage tank, the second, a Solar Indirect Hot Water in which they added an external heat exchanger of constant effectiveness to the first system. The total number of collectors is adjusted to sixty collectors. For the first system, they found the number of series collectors in solar thermal systems must be limited, the same for both direct and indirect systems. Both the series connection and optimized mass flow rate have a positive effect on the system performance, but the range of optimum mass flow rates decreases when a flat plate collector is added in series. The present work is study the effect of parallel and series connections of thermal performance and stratification of storage tank of three flat plate solar collectors array in closed loop system with different flow rates and different inlet and outlet flow directions.

2. EXPERIMENTAL WORK

The components of the experimental test rig consist of three identical flat plate solar collectors in closed loop system, each one with absorbing area of (80cm * 120cm) with one glass cover. Also ,it consists of eight equally spaced parallel copper riser pipes of (10.5mm inner and 11mm outer) diameters , and (1200mm) length. The distance between each centerline of tubes is (10 cm). These pipes are connected with two headers. The headers are made of copper material with (4.1cm) outside diameter and (80cm) length. Each of headers consists of several holes ,two holes in the sides and one in the middle (between riser 4-5) which lead to the inlet and outlet of the collector . The absorbing plate was manufactured in fabricated way through the work as curve surrounds riser pipes to increase the surface area of contacts between the plate and the riser pipe as shown in **Fig.1**. A copper sheet with (0.5mm) thickness is used as the solar radiation absorber The riser pipes are fixed on the absorbing plate by welding lead along the riser pipes as shown in **Fig. 2 .** The collector frame is made of aluminum bars of (1.5mm) thick as shown in **Fig.3 .** A glass sheet is used as a transparent cover of the collector with (4mm) thickness. A glass wool insulation of (50 mm) thickness was used as insulator to decrease the collector back and side heat losses. A cylindrical galvanized steel tank with (0.58 m) outside diameter and (1 m) height is used for storing hot water. The tank is insulated by a (50mm) thickness glass wool. **Figs. 4-a and 4-b** show the storage tank and position of thermocouple inside it .A plastic pipe of (15mm) diameter is used between the components of the closed loop system. They connect the storage tank, water circulation pump, flow meter and solar collectors with each other as closed loop system. The equivalent length of the closed loop in each system is (11 m) . The pipes in each loop are insulated with (25 mm) thick of glass wool insulation. In order to circulate the water in the system, a small circulation pump (CRS25/4-180) is used in closed loop to make the forced circulation. The water mass flow rate in the closed loop is controlled by using valves and measured with flow meter (lzs-15-Range (60-600LPH) with accuracy 4%. The mass flow rates used, are (60,100 and 150) ℓ/hr. The spray paint (RUSTOLEUM high heat) as the absorber surface paint is used. This Coating has high absorptance (0.92-0.96) for solar radiation is used to substrates with low emittance (0.24) **,Rhett,2013.**

2.1 Measuring Devices and Data Analyzing

In order to measure the temperature at various points of the absorbing plate, water storage tank, inlet and outlet of collectors, T type thermocouple (copper- constantan) with the accuracy of (±0.5 °C) is used. The thermocouples were calibrated before beginning of the experiments. The measurement of the temperature distribution of the absorbing plate is done by using three thermocouples, one located at the centerline of the absorbing plate and the others at top and bottom with space distance of (50cm) from the centerline from the absorber plate. All thermocouples are connected to the data logger, that's connected to a digital electronic thermometer (UT325-0.1C resolution). The data is interfaced to the computer and then displayed as a table. The ambient temperature is measured by using a digital electronic thermometer. The solar power radiation on the collector is record by solar meter with rang varied from (0 to 2000 W/m^{2}). This device measures the total solar radiation (beam and diffuse) per unit area of the collector surface. This device could be recorded the data and save them in (SD Ram). The solar power meter was oriented due to the south at a collector tilt angle (35). This angle has been adopted for all cases of examination. To calculate the solar radiation depending on the recommended average days for months and values of n by months **,Duffie and Beckman, 2006.** This is the recommended angle maximum yearly useful energy.

The governing relations used in the present work are:

1. Water mass flow rate ($\dot{m}_w$)

$$\dot{m}_w = \rho_w \, . \dot{V}_w \tag{1}$$

$\dot{m}_w$: mass flow rate kg /s

$\dot{V}_w$: Water volume flow rate (m^3/s)

The water density varies with its temperature according to the equation **,Sinem, E., 2011.**

$$\rho_w = 1000 * (1 - (T + 288.9414)/(508929.2 * (T + 68.12963)) * (T - 3.9863)^2 \tag{2}$$

2. Useful energy (Q_u)

$$Q_u = \dot{m}_w \, . (C_p)_{water} \, . (T_{fout} - T_{fin}) \tag{3}$$

Trapezoidal rule has been used to calculate the Useful energy (Q_u) for three flat plate solar collectors array **,Maytham, 2014.**

$$Q_U = \sum_{ti}^{tf} qt = b[\frac{Q_{U1}}{2} + Q_{U2} + Q_{U3} + - - - + \frac{Q_{Un}}{2}] \tag{4}$$

$$q_U = \frac{Q_U}{A_C} \tag{5}$$

3. The total solar radiation for the flat plate solar collectors array

$$Q_R = N * Ac * b * [\frac{GT_1}{2} + GT_2 + GT_3 + - + \frac{GTn}{2}] \tag{6}$$

4. To calculate the solar collector's array efficiency

$$\eta = \frac{Q_U}{A_c \, .Q_R} \tag{7}$$

The mean fluid temperature is calculate by

$$T_m = \frac{T_{fin} + T_{fout}}{2} \quad (8)$$

5. To calculate the instantaneous collector efficiency was taken as half an hour for one collector

$$\eta_i = \frac{Q_U}{A_C \cdot G_T} \quad (9)$$

6. The instantaneous collector efficiency for the flat plate solar collectors array

$$\eta_{i\,av.} = \frac{\eta_{i1} + \eta_{i2} + \eta_{i3}}{N} \quad (10)$$

2.2 Test Model

The model, consist of three flat plate solar water collectors connected parallel connection (Z-configuration and I configuration) as shown in **Figs. 5 and 6** and series connection as shown in **Fig.7** In this model three different flow rate of (60,100,150) ℓ/hr. are used in this study.

2.3 Test Procedure

The experiment was carried out in Baghdad from (10^{th} March to 15^{th} April 2014) and these experiments were carried out during sunny days only .The slope angle of three closed looped collectors is (35 deg.). The collectors was tested under steady-state conditions in which the solar intensity, ambient temperature, inlet and outlet temperature difference were considered constant for period of time. The period was taken as half an hour for a clear day. The type of test was to estimate the instantaneous performance of the system. Before each test, the following preparations were made.

- The closed collector loop was filled with water, the glass cover of the collectors were cleaned.
- The storage tank, was filled with water and the pump was operate with the maximum flow rate half an hour every day before starting the experiments, to eliminate trapped air from the system .
- The system was tested with three different flow rates of water through the collector loop.
- In each case, experiments usually started at (8 am and continued until 5 pm).
- In each test and each time period all the measurements of temperatures, solar radiation intensity, the instantaneous efficiency, heat collection and absorbing energy were recorded for each collector.

3. RESULTS AND DISCUSSION

3.1 Relationship between Solar Energy and Useful Energy and Absorber Plate Temperature

Fig.8 shows the relationship between solar energy and useful energy, for three different connections of flat plate solar collectors array at different flow rates and flow directions. It is clear that the useful energy curves have the same trends of the solar radiation. The results show that as the mass flow rate increases, the useful energy gain increase. The useful energy of the series connection is greater than parallel connections when the flow rate at (60) ℓ/hr. But when the flow rate increases the useful energy of series connection decreases. This effect, because of a long the path that the fluid interrupted by series connection than parallel connection .This confirms that the thermal losses in parallel connection less than series connections when the flow rate increase. In the parallel connection, the useful energy gain of (I-Configuration) greater than (Z-Configuration), because of increase the particle mixing due to increase mass flow rate in the middle risers than side riser pipes and hence the heat transfer coefficient increase. **Tables 1,2** and **3** show the variation of useful energy with time for different flow rates presented in this study. The behavior of useful energy obtained for one collector (Z-Configuration) at the flow rate 100 ℓ/hr. as compared with **,Maytham, 2014,** as shown in **Fig.9** . In **Fig .10** shows, the temperature distribution of the absorber plate and ambient temperatures with time as shown in. The temperature of the absorber plate is not the same, where ($T_{P3}>T_{P2}>T_{P1}$) because of, the temperature of the absorber plate increase along the direction of water flow in risers.

3.2 Performance Test of Solar Water Heating

The instantaneous collector efficiencies curves for three different connections are shown in **Fig's**. (11 and 12) they observed clearly that when the mass flow rate increases, the instantaneous collector efficiencies increases and the temperature difference decrease. This can be due to the lower mass flow rate which takes more time to absorb solar radiations **,Duffie and Beckman, 2006.** The decreasing of the temperature difference between absorber plate and ambient lead to decreasing thermal losses in collector, then the collector efficiency will increase, **Peter, 1979**. The instantaneous collector efficiencies curves for parallel connection is higher than series connection at flow rate increase, because of thermal losses in parallel connection less at rates greater than series connections when the flow rate increase. The results show the overall daily efficiency of 100 ℓ/hr. of parallel connection (I-Configuration) is (50%), while parallel (Z-configuration) and series connections are (47.6% and 42%) respectively .For increase mass flow rate to 150 ℓ/hr. , the overall daily collector efficiency increasing. In (I-Configuration) is (55%) while, (Z-configuration) and series connections are (51% and 48.4%) respectively. **Table 4.** Instantaneous collector efficiencies with time at flow rates (100-150 ℓ/hr.).The data of instantaneous collector efficiencies for one collector (Z-configuration) at 150 ℓ/hr. as compared with **,Herrero , et al .,** as shown in **Fig.13.**

3.3 Effect the Stratification of Storage Tank

Thermal stratification in storage tanks has a significant positive effect on the system efficiency. **Figs. 14 and 15** show the effect of stratification of storage tank for different flow rates. The water temperatures difference between the top and bottom in the storage tank in case of series connection for the mass flow rate of order (60,100 and 150) ℓ/hr. at (11 am) are (11.3^{o}C, 8.5^{o}C are 7.8^{o}C) respectively. While, the water temperature difference in case of parallel connection (Z-Configuration) are (9.3^{o}C, 6.5^{o}C and 5.8^{o}C) respectively, and in case of parallel connection (I-Configuration) are (8.1^{o}C, 7.1^{o}C and 6^{o}C) respectively for the same water flow rates and time period. Therefore the stratification of storage tank in case of series connection is higher than the parallel connection mode. The average water temperature of the storage tank at the end periods (3-5 pm) in case of parallel connection is higher than the series connection. Where the maximum average temperature at (5pm) for the flow 100ℓ/hr. in case of parallel connection (I-Configuration) is (64.2^{o}C) and in case of (Z-Configuration) is (63.5^{o}C), while the maximum average temperature in case of series connection is (61.2^{o}C). This because of the parallel connection stored larger quantities of energy than the series connection. Due to, increase the temperature drops, resulting in higher inlet temperature to the second and third collectors .That's leads finally to reduce the temperature difference significantly in case of series connection mode .

4. CONCLUSION

From the present work, we can conclude that:

- The efficiency of series connection greater than parallel connection at low flow rate.
- The useful energy gain of (I-Configuration) greater than (Z-Configuration) when increase mass flow rate.
- That higher thermal stratification in the storage tank can be achieved by using a smaller flow rate.
- The stratification of series connection is more than parallel connections.

REFERENCES

- Bong, K.C. NG., and H. BAO., 1993 , *Thermal Performance of a Flat Plate Heat Pipe Collector Array*, Solar Energy, vol. 50 no. 6 , pp 491-498 .

- Duffie , J. A., and Beckman,. W. A., 2006 , *Solar Engineering of Thermal Processes*, Solar energy, laboratory, University of Wisconsin-Madison .

- Herrero Martín, R., García Pinar,A. and Pérez García, J.,2011, *Experimental Heat Transfer Research in Enhanced Flat-Plate Solar Collectors*, World Renewable Energy Congress,Sweden,8-13 May.

- Khaled Z., A. G., Ramzi S., and Chakib K., 2012 , *Solar Thermal Systems Performances Versus Flat Plate Solar Collectors Connected in Series* , Engineering, 4, 881-893.

- - Kuang, R.Z., and L.Q. Yu., 2003, *Experimental Study on Solar Assisted Heat Pump System for Heat Supply* , Energy Conversion and Management, 44 , 1089–1098 .

- Maytham A. J., 2014, *Utilization of Air-Water Solar Collector System for Space Heating*, Master Thesis university of Technology.

- Myeong C. K., Yong H. K. , Sang H. L., and Wongee, C., 2006, *Numerical Analysis on The Thermal Performance of a Roof-Integrated Flat-Plate Solar Collector Assembly*, International Communications in Heat and Mass Transfer, 33 , 976–984.

- Peter J. L., 1979, *Solar Thermal Engineering Space Heating and Hot Water System*, New York, Chichester Brisbane Toronto .

- Rhett N., , 2013 , *The Water Wall – a Passive Solar Collector and Thermal Storage Device for Supplementary Radiant Heating* , Master Thesis , University of Nevada, Las Vegas December.

- Sinem E., 2011, *Assessment of Impact of Reservoirs Contaminated Bottom Sediments on Surface Water Quality by Sediment Water Interaction Model* , Master Thesis , the Graduate School of Engineering and Sciences .

- - Wang., and L.G. WU, 1990, *Analysis and Performance of Flat Plate Solar Collector Arrays*, Solar Energy vol.45, no.2, pp71-78 .

- Yi-Mei, L., Kung-Ming C., Keh-Chin C., and Tsong-Sheng L., 2012, *Performance of Thermosyphon Solar Water Heaters in Series* , Energies, 5, 3266-3278; doi:10.3390/en5093266 .

NOMENCLATURE

A_C=collector area, m^2.
b= time increments, s
$C_{P\ water}$=specific heat capacity of water, kJ/ kg.K .
G_T=incident solar radiation, W/m^2.
I=hourly solar radiation, J.
N=number of collectors.
n =for ith day of month
Q_U=useful energy, W.
q_u= useful energy per unit area,W/m^2.
qt=the useful energy with time (b)
Q_R=total solar radiation, W/m^2.
ta=ambient temperature, $^\circ$C.
T_{fin}=inlet fluid temperature, $^\circ$C.
T_{fout}=outlet fluid temperature, $^\circ$C.
T_m= mean fluid temperature, $^\circ$C.
T_P=absorber plate temperature, $^\circ$C.
T_S=storage tank temperature, $^\circ$C.
$\dot{m}_w$=water mass flow rate ,kg/s.
ρ_w=water density, kg/m^2.
η=collector efficiency.
η_i= instantaneous efficiency.

Table 1. The useful energy with time for different connection at flow rate (60ℓ/hr.).

Time	qu-ser.(W/m^2)	qu-Z- (W/m^2)	qu-I-(W/m^2)
8.00am	174.784	196.633	168.54
8.30am	243.45	230.969	218.48
9.00am	287.153	284.033	259.06
9.30am	340.217	315.246	318.362
10.00am	368.306	371.4274	358.94
10.30am	390.158	393.279	396.39
11.00am	415.127	424.4911	440.09
11.30am	399.51	433.854	455.7
12 noon	383.915	446.3387	477.54
12.30am	377.672	424.4911	446.33
1.00pm	337.03	390.158	412
1.30pm	305.879	349.581	349.58
2.00pm	265.304	312.125	324.61
2. 30pm	227.847	268.419	287.15
3.00pm	156.05	221.6	196.62
3.30pm	109.233	162.299	146.68
4.00pm	59.298	109.233	68.65
4.30pm	28.08	46.8	40.56
5.00pm	9.362	18.725	21.846

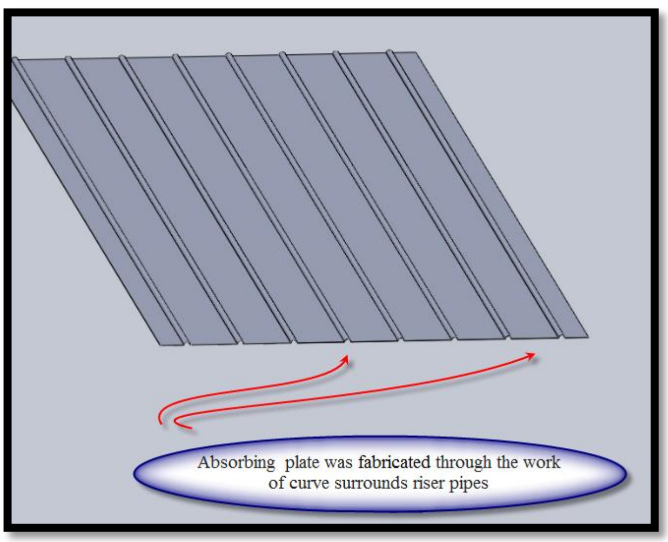


Figure 1. Absorber plate geometry.

Figure 2. A copper sheet welding on riser pipes**.**

Figure 3. Aluminum collector frame.

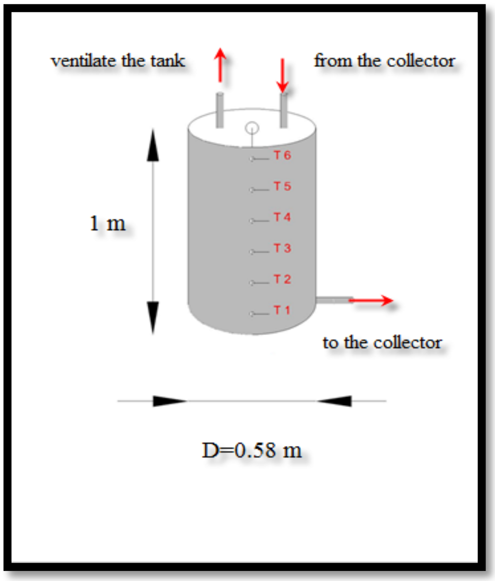


Figure 4-a. Position of thermocouple inside Storage tank

Figure 4-b. Water storage tank

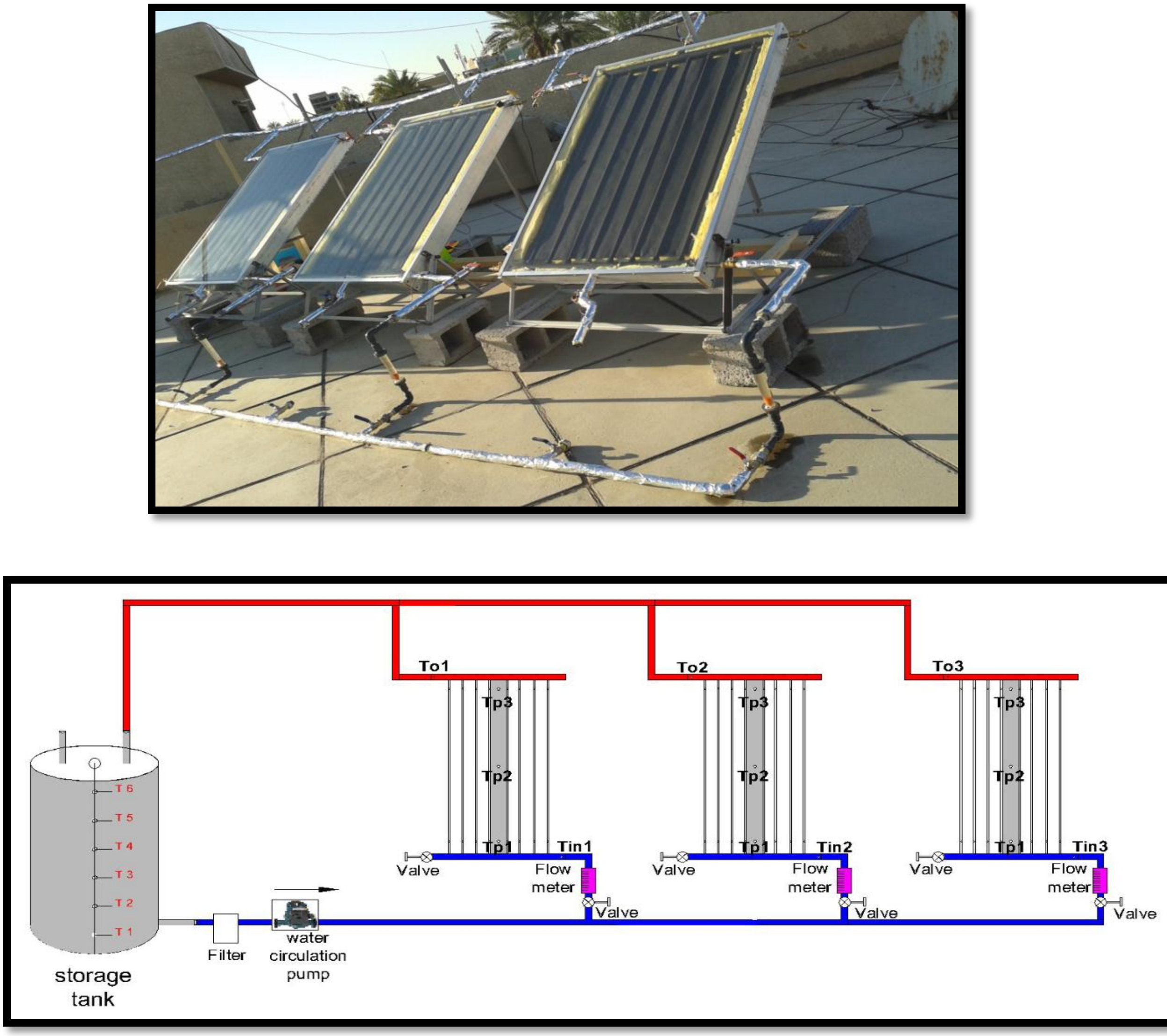
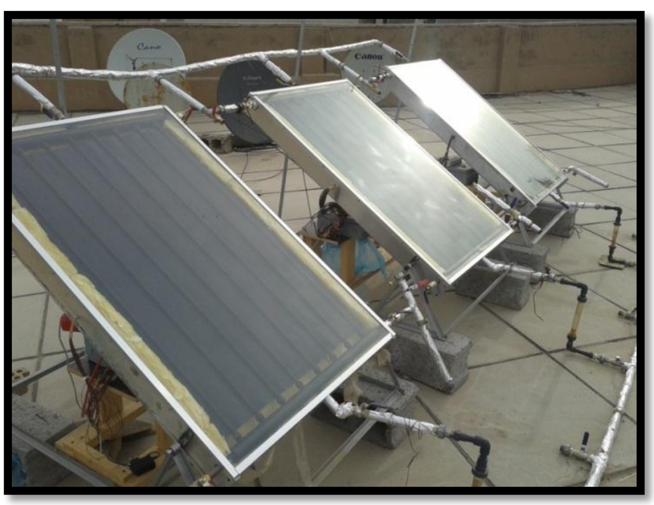


Figure 5. Three flat plate solar collector's connection in parallel mode (Z – Configuration).



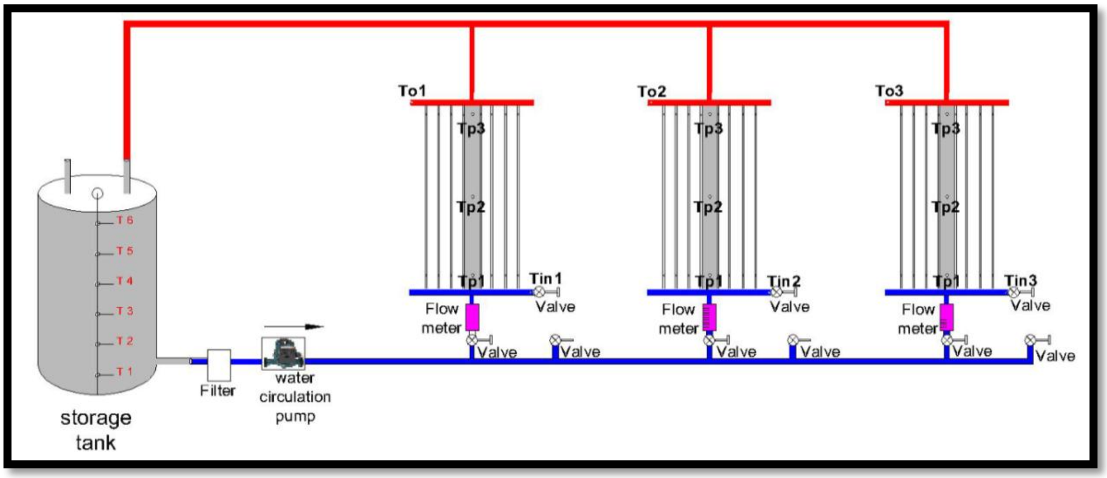
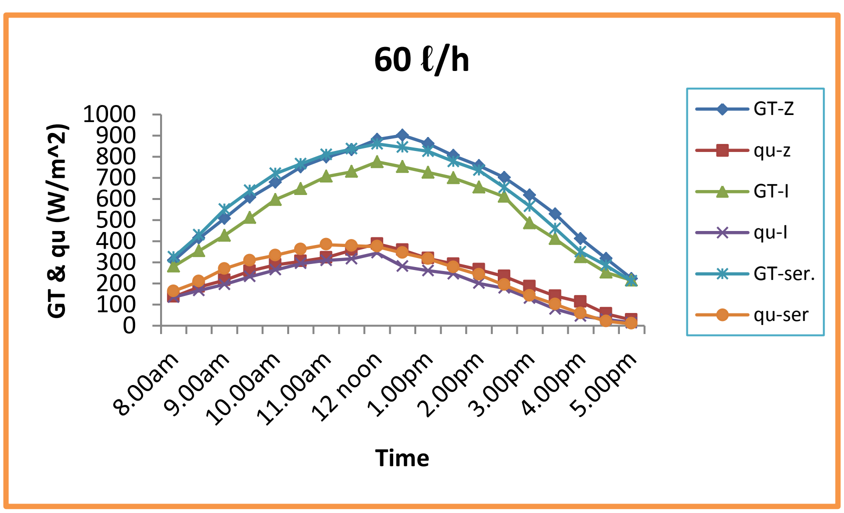


Figure 6. Three flat plate solar collector's connection in parallel mode (I – Configuration).

Figure 7. Three flat plate solar collector's connection in series**.**



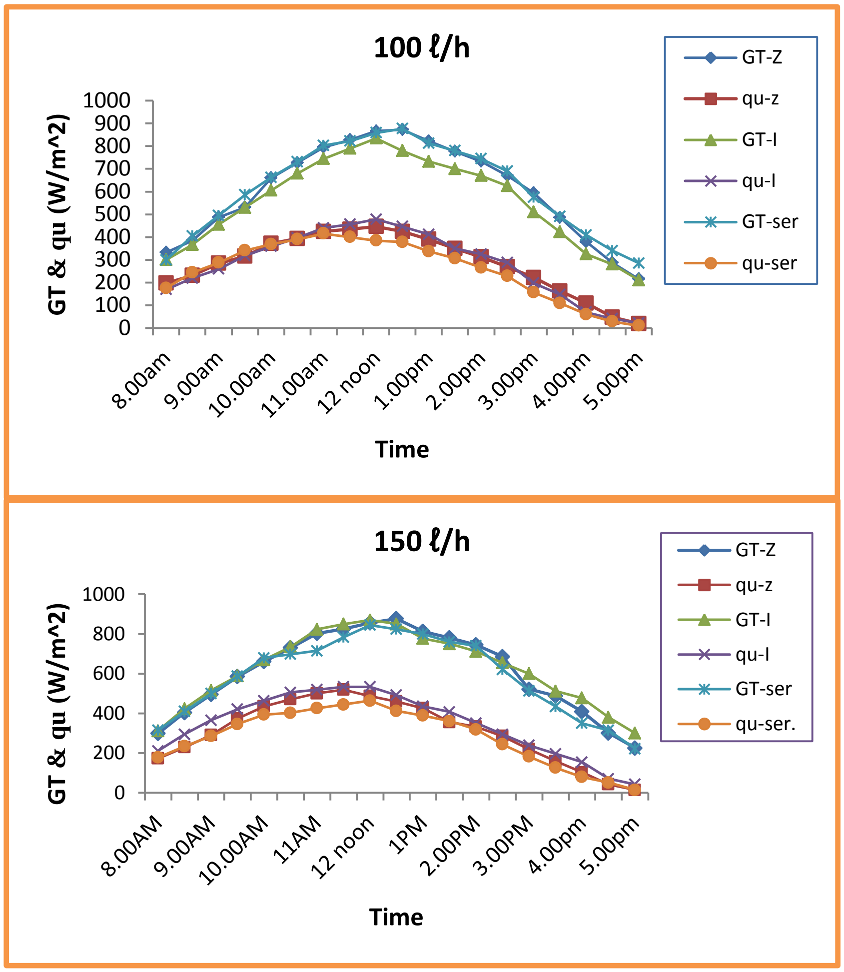


Figure 8. Relationship between the useful energy and solar radiation for different connections.

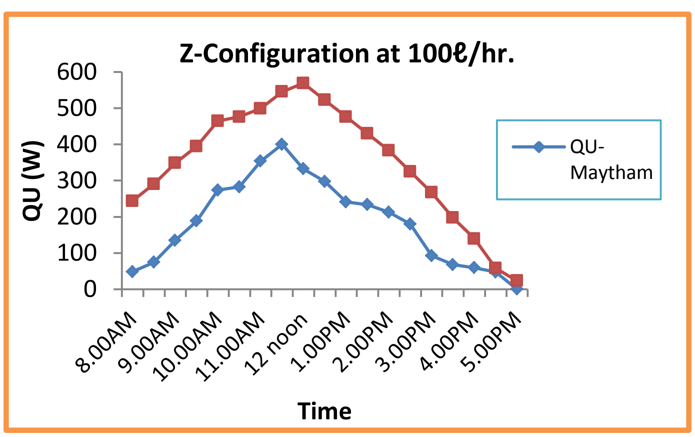


Figure 9. Comparison the behavior of useful energy between the present work and other work.

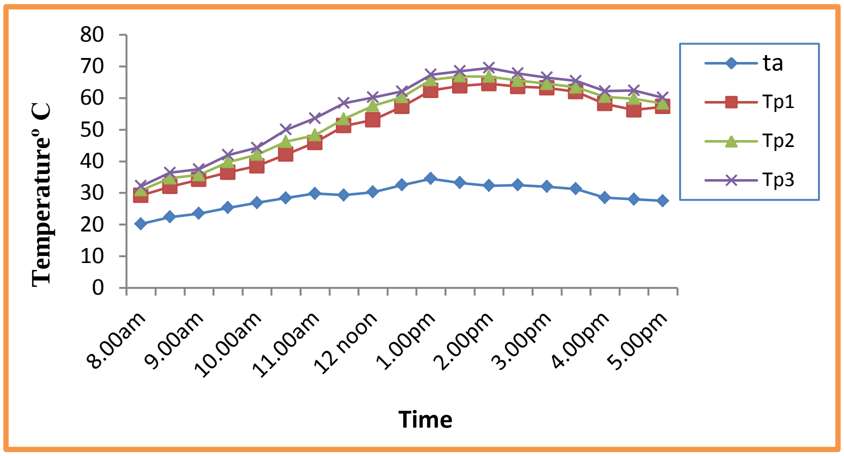


Figure 10. Absorber plate and ambient temperatures during day time at 100 ℓ/hr.

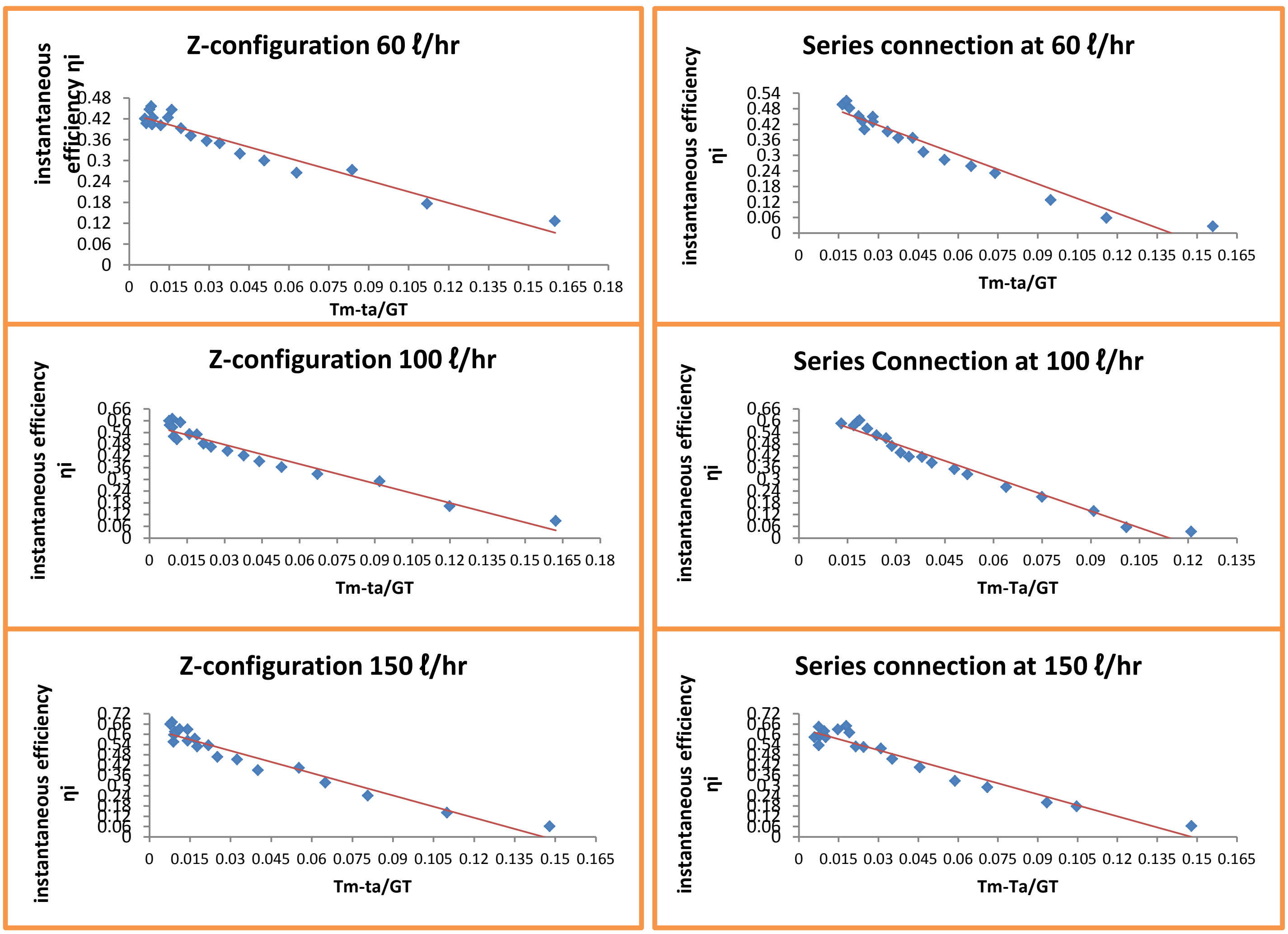


Figure 11. Performance test of series connection and parallel connection (Z-Configuration).

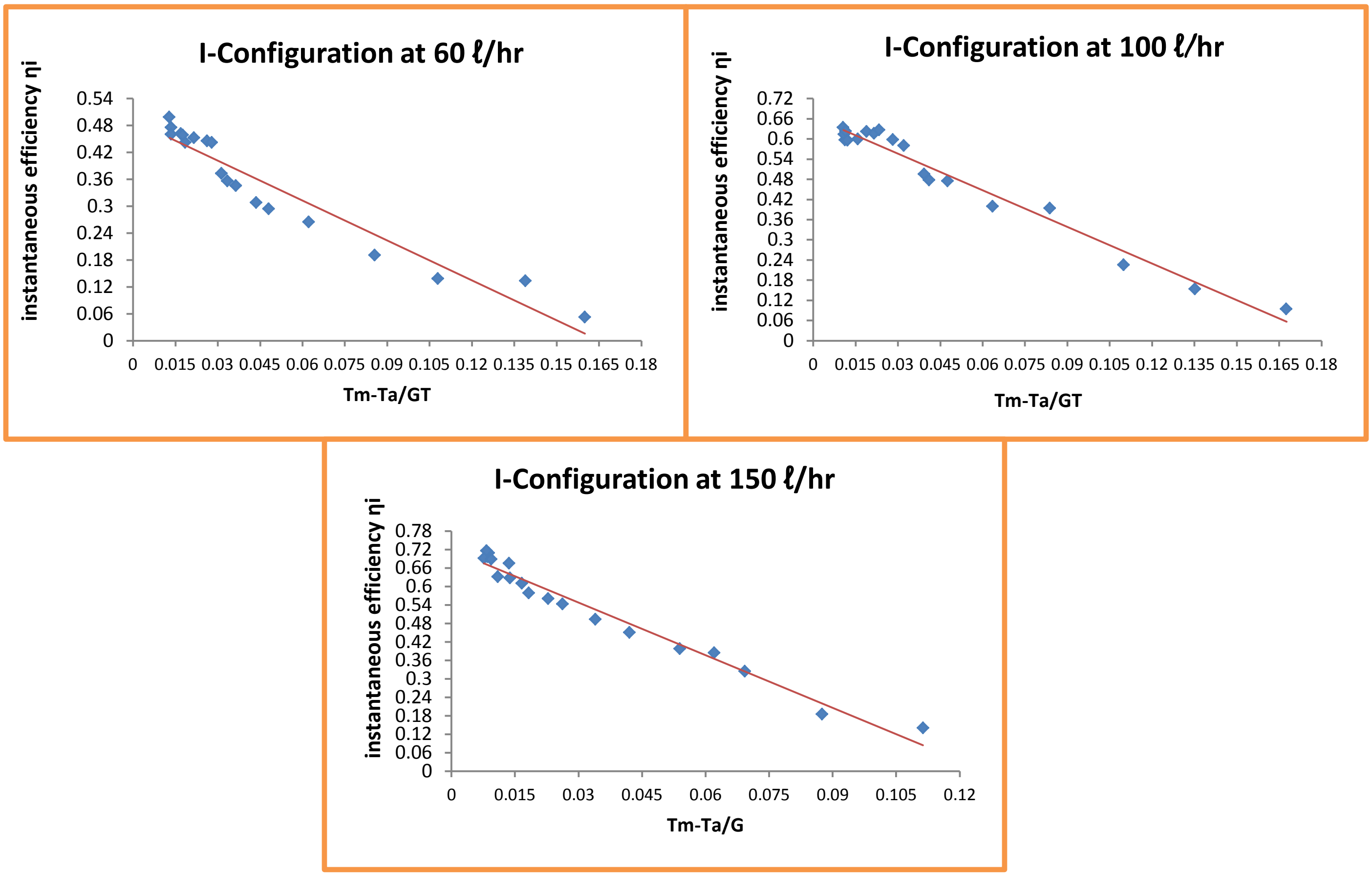


Figure 12. Performance test of I-configuration flat plate solar collectors array.

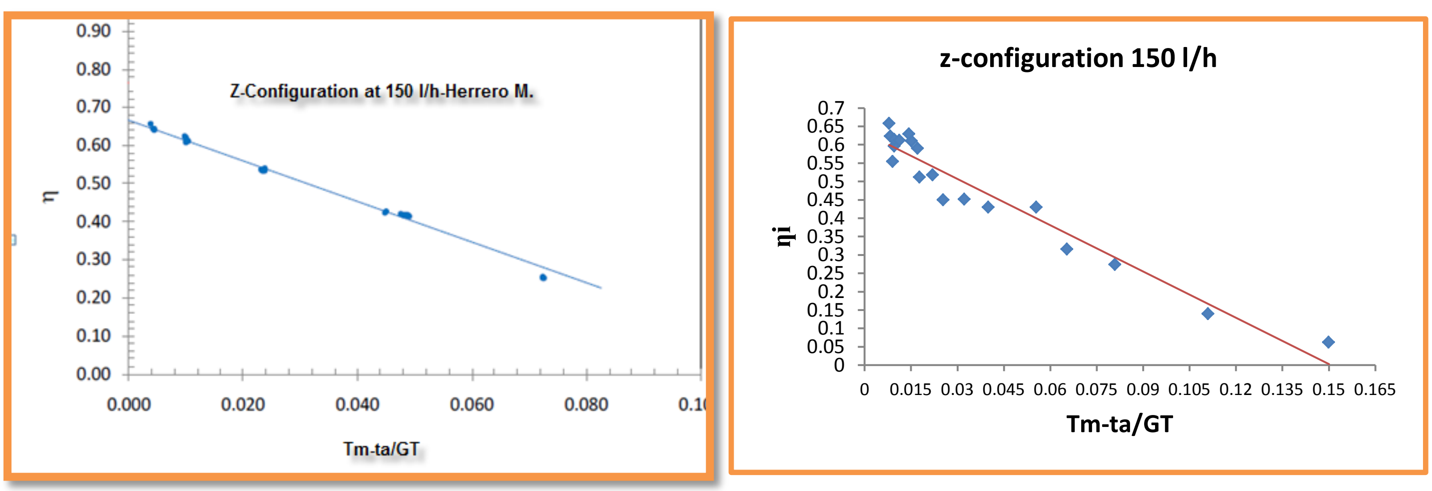


Figure .13 Comparisons the performance test at flow rate 150 ℓ/hr.

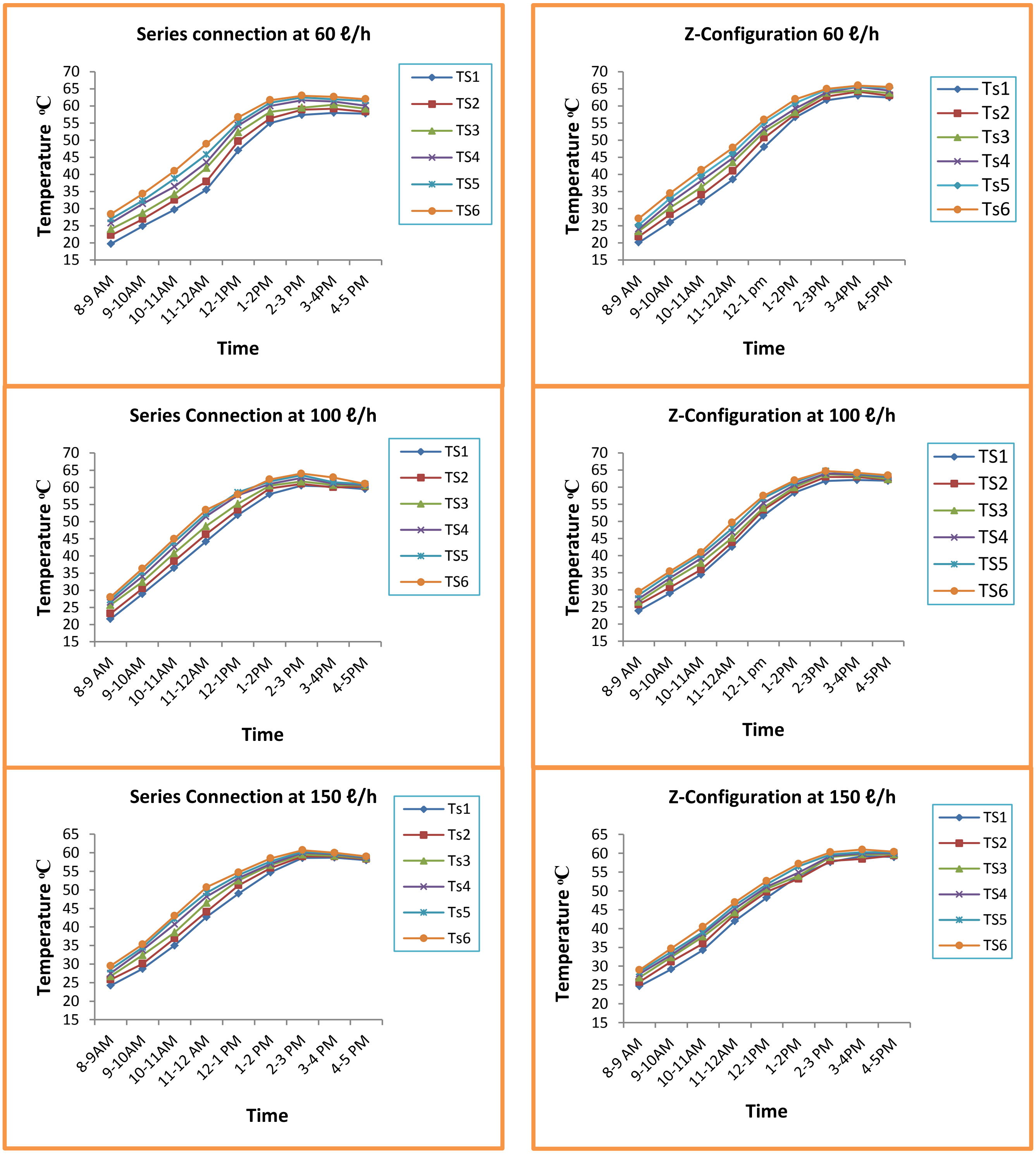


Figure 14. Stratification of storage tank of parallel (Z-Configuration) and series connections.

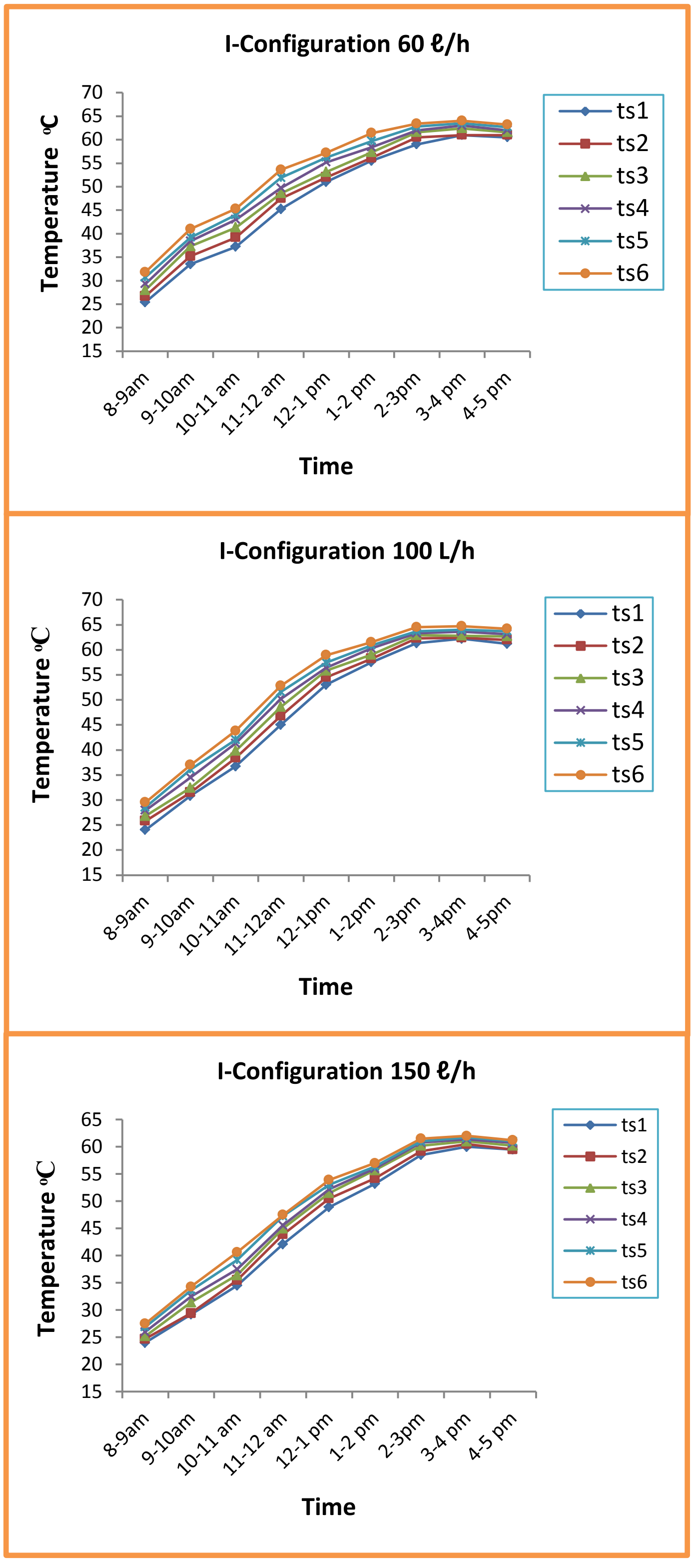


Figure 15 . Stratification of storage tank of parallel connection (I-Configuration).