Field Study of Novel Storage Tank of Solar Water Heating System

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ABSTRACT

In this paper thermo-hydrodynamic characteristics were investigated experimentally for a new type shell-helical coiled tube heat exchanger used as a storage tank of closed loop solar water heater system. Triple concentric helical coils were made of copper tubes of (12.5mm OD and 10mm ID) with coils diameter of (207, 152.2, 97mm) for outer, middle and inner coils respectively. The experiments were carried out during a clear sky days of (March and April 2012). The parameters studied in this work are: history of average temperature of shell side of the storage tank, collector heat gain, heat rejected from coils to shell side of the storage tank, collector efficiency, thermal effectiveness of the heat exchanger (storage tank), and pressure drop. These parameters were studied at four different circulating mass flow rates of (1.8, 3, 6, 9 l/min) and for two consuming modes of supply water namely no withdrawal, and continuous withdrawal of (1 l/min). The results show that stratification temperature in the storage tank is increased for no withdrawal compared with water withdrawal, also the shell side average temperature increases with increased solar time. Collector efficiency is increased with increasing circulation flow rates, also increases with water withdrawn from storage tank. The pressure drop decreases with the increase of solar radiation .

KEYWORDS: solar hot water system; storage tank; heat exchanger; helical coil tube; pressure drop; effectiveness.

دراسة ميدانية لخزان جديد مستخدم في منظومة شمسية لتسخين الماء

أ.م.د. كريمة أسماعيل عموري جنان شاكر شيرزة

الخلاصة

في هذا البحث تم التحقق من المواصفات الحرارية والهيدروديناميكية عمليا لمبادل حراري جديد نوع قشرة-أنبوب ملتف حلزونيا مستخدم كخزان لمنظومة شمسية لتسخين الماء. صنعت ثلاثة ملفات حلزونية متمركزة من أنبوب نحاس ذو قطر خارجي =12.5 ملم وقطر داخلي=10ملم وبقطر ملف خارجي، وسطي، وداخلي (207، 152.2، و 97ملم) على التوالي. أجريت التجارب في أيام صحوة خلال شهري آذار ونيسان من سنة 2012. درست المتغيرات التالية: توزيع معدل درجة الحرارة في ماء قشرة الخزان، الكسب الحراري للمجمع الشمسي، الحرارة المنتقلة من ماء الملف الى ماء القشرة، كفاءة المجمع، الفعالية الحرارية للمبادل الحراري، وهبوط الضغط. تم دراسة هذه المتغيرات عند اربع قيم لمعدل جريان ماء التدوير (1.8، 3، 6، و 9 لتر/دقيقة) ولنموذجي صرف من ماء التجهيز للمستهلك وهما نموذج عدم سحب الماء، والآخر صرف الماء بمعدل 1لتر/دقيقة وبصورة مستمرة. بينت النتائج وجود تراصف حراري أقوى في الخزان في حالة عدم السحب مقارنة بحالة السحب، وان معدل درجة حرارة ماء

الخزان تتزايد مع تقدم ساعات النهار. تتزايد كفاءة المجمع الشمسي مع زيادة معدل جريان ماء التدوير، وتزداد في حالة سحب الماء من الخزان عما هو عليه في حالة عدم السحب. يقل هبوط ضغط ماء التدوير مع زيادة قيمة الأشعاع الشمسي عمليا ونظريا".

الكلمات الرئيسية: منظومة شمسية لتسخين الماء، خزان،مبادل حراري،أنبوب ملتف حلزونيا، هبوط الضغط، فعالية.

INTRODUCTION:

Heat exchangers are used in a wide engineering applications including power plants, nuclear reactors, refrigeration and air conditioning systems, automotive industries, heat recovery systems, chemical processing, and food industries. Heat transfer enhancement enables the size of the heat exchanger to be considerably decreased. The previously used enhancement techniques can be divided into two groups: active and passive techniques. The active techniques require external forces like fluid vibration, electric field, and surface vibration. The passive techniques require special surface geometries or fluid additives like various tube inserts. Several studies have indicated that helically coiled tubes are superior to straight tubes when employed in heat transfer applications. The centrifugal force due to the curvature of the tube results in the secondary flow development which enhances the heat transfer rate.

Seban and Mclaughlin (1962) presented friction and heat transfer results for the laminar flow of oil and the turbulent flow of water in tube coils having ratios of coil diameter to tube diameter of 17 and 104, for Reynolds number ranged from 12 to 65000.**Rogers and Mayhew (1964)** reported and compared experimental results for forced convection heat transfer and friction factors, obtained for water flowing through steam heated coils. Existing equations for isothermal friction factors in smooth coils are deemed satisfactory. Non-isothermal friction factors and heat-transfer coefficients can be estimated from proposed equations for design purposes, but results cannot yet claim the same validity as those for straight pipes..**Ali (1994)** obtained average outside heat transfer coefficients for turbulent heat transfer from vertical helical coils submersed in water. Water was pumped through the coil and the inside heat transfer coefficients were calculated based on the Nusselt number correlation of **Rogers and Mayhew**. Outside heat transfer coefficients were calculated based on the thermal resistance method for cylindrical tubes. **Kharat, et.al. (2009)** developed a correlation for heat transfer coefficient for flow between concentric helical coils. A Correlation is found to result in large discrepancies with the increase in gap between the concentric coils when compared with the experimental results. They are used experimental data and CFD simulations using Fluent 6.3.26 to develop improved heat transfer coefficient correlation for the flue gas side of heat exchanger. **Salimpour (2009)** investigated experimentally the heat transfer coefficients of shell and helically coiled tube heat exchangers. Three heat exchangers are tested with different coil pitches for both parallel and counter-flow configurations. The inlet and outlet temperatures of tube side and shell-side fluids, flow rate are measured. It was found that the shell side heat transfer coefficients of the coils with the larger pitches are higher than those for smaller pitches. Empirical correlations were proposed for shell-side and tube-side. His results were compared with previously existing correlations for other boundary conditions and a reasonable agreement was observed. **Jayakumar et. al. (2010)** adopted CFD simulation package FLUENT version 6.3 for vertically oriented helical coils by varying coil parameters such as (i) pitch circle diameter, (ii) tube pitch and (iii) pipe diameter and their influence on heat transfer. Correlations are developed of local Nusselt number as a function of angular location of the point. **Ghorbani et.al. (2010)** investigated experimentally the mixed convection heat transfer in a coil-shell heat exchanger for various Reynolds number, Rayleigh numbers, various tube-to-coil diameter ratios and dimensionless coil pitch.

The objective of this work is to investigate experimentally the thermal and hydrodynamic characteristics of a new type of shell-helical coiled tube heat exchanger used as a storage tank of forced closed loop solar water heater system for Baghdad climate conditions. The outdoor tests are performed under different circulation flow rates to establish the, thermal stratification within the shell side of the storage tank, collector efficiency, storage tank effectiveness, and pressure drop of the helical coiled tubes. Up to our knowledge there is no previous reported study dealing with this type of work.

EXPERIMENTAL SETUP

Fig.(1) shows a schematic diagram of the experimental set-up. A closed loop forced circulation solar hot water system is formed of two flat plate solar collectors, of single glass cover, south oriented, (each of dimensions 1.92m*0.85m) are used to provide hot water stream to a storage tank formed of shell-triple concentric helical coiled tubes. A cold supply water stream (flowing in the shell-side of the storage tank of 120 liter capacity) cools the hot circulating water flowing inside the helical coiled tube. The heat exchanger includes a copper coiled tube and an insulated shell. The specifications of the heat exchanger are depicted in Table (1). This design has been adopted based on the capacity of the storage tank. A centrifugal water pump type Vicounte PKM60 of (0.5HP) power, is used to circulate water within the closed cycle. Five valves are used to control the flow rate of hot water and supply coolant water. The experimental set-up is a well instrumented, fourteen calibrated thermocouples (type K) are located at different positions of the test rig as shown in Fig.(1). All thermocouples are connected to two 12-Channels thermometers (type k temperature reader with SD Card Data-Logger - Model BTM-4208SD-Lutron Company). A flow meter type Z-4002 float type of range (1.8 to 18 l/min) is used of (0.3 l/min) resolution. The pressure drop of water flowing in the helical coiled tubes is measured by using a Borden gage of range (0 to 160 mbar) and 5 mbar resolutions. The global solar radiation has been taken from the Ministry of Science and Technology in Baghdad city 33.3^o north.

THEORY

The thermo-physical properties of the hot water for the coil side or for the shell side are taken at the water bulk temperature of that side for each reading (the experimental readings were taken every 30 minutes). Heat rejected from the coil Q_c to the shell side is calculated as:

$$Q_c = \dot{m} c_p (T_{ci} - T_{co}) \qquad (1)$$

where Q_c is the heat rejected from the coils (W), is the flow rate (kg/s) ,T_{ci} is the coil inlet temperature (K),T_{co} is the coil outlet temperature (K), and c_p is water specific heat (J/kg.K).

The hot water mass flow rate $\dot{m}$ is obtained from flow-meter reading $\dot{V}$ as:

$$\dot{m} = \rho * \dot{V} \qquad (2)$$

The collector heat gain can be calculated from

$$Q_{coll.} = \dot{m} c_p (T_{coll.o} - T_{coll.i}) \qquad (3)$$

The effectiveness of the storage tank can be expressed as:

for no withdrawal

$$\varepsilon = \frac{(T_{c,i} - T_{c,o})}{(T_{c,i} - T_{tank\,avg})} \quad (4)$$

for water withdrawal **Ghorbani (2010)**

$$\acute{\varepsilon} = \frac{(T_{c,i} - T_{c,o})}{(T_{c,i} - T_{s,i})} \quad (5)$$

The collector efficiency is calculated as:

$$\eta = \frac{\dot{m} C_p \Delta T}{AI} \quad (6)$$

where

$\dot{m}$ is circulating mass flow rate of water (kg/s)

ΔT is collector outlet and inlet temperature difference (K)

A is area of collectors (m^2)

I is incident solar radiation (W/m^2)

RESULTS AND DISCUSSION

Figure (2) illustrates the incident solar radiation on the collector plane, the ambient temperature and wind speed on 19-3-2012 (clear sky day). The ambient temperature rises as the solar radiation rise, the maximum values indicated after solar noon was 20.6^{o}C at 3:00PM with no considerable variation in wind speed. The global solar radiation was 230 W/m^2 and 615 W/m^2 at 8:00, 12:00 respectively.

The collector inlet and outlet temperature for different circulation flow rates are shown in Fig.s (3.a-b-c-d) and (4 a-b-c-d) for no water withdrawn and water withdrawn of 1 l/min respectively. Water drawn modes are selected according to **Agbo(2006)**. The temperature difference decreases as circulating flow rate increases. When solar radiation increases with time the temperature difference increases with time also. It is clear that higher temperature difference is obtained when the storage tank is under water withdrawal. Quantitatively at the solar noon the temperature differences were (13.65 ^{o}C at 1.8 l/min and 3.65 ^{o}C at 9 l/min) for water withdrawal, while for no water withdrawn they were (10.3 ^{o}C at 1.8 l/min and 2.85 ^{o}C at 9 l/min).

Figures (5a-b-c-d) and Fig (6 a-b-c-d) show the stratification phenomena in the storage tank for no withdrawal and water withdrawal of (1 l/min) respectively. It is clear that the temperature of the storage tank increases with increasing solar radiation. Fig.(5) shows inconsiderable variation in the temperature along the storage tank height for different circulating flow rates when no water withdrawn from the tank. The water temperature within the storage tank decreases when supply water is withdrawn compared with that of no water withdrawn as shown in Fig.(6). It is clear that a considerable variation in water temperature along storage tank height for different circulating flow rates.

Figures (7 a-b-c-d) and Figure (8 a-b-c-d) illustrate the influence of circulation flow rate on useful heat gain by the collector (Q_{gain}) and the heat rejected from the helical coil side to the shell side of the storage tank (Q_{coil}). Both of (Q_{gain}) and (Q_{coil}) increases with the increase of the circulation flow rate in a similar behavior, knotting that the useful heat gain is higher than coil heat rejected to the shell side since part of the heat is lost to the ambient. For case I the values of (Q_{gain}) and (Q_{coil}) are (1276, 1376, 1509, and 1770 W) and (1251, 1325, 1447, and 1739 W) respectively at 12:00AM for circulating flow rates of (1.8, 3, 6, and 9) respectively. The effect of circulation flow rate on (Q_{gain}) and (Q_{coil}) is found higher fo case II than that for case I (no withdrawal).

Figures (9 and 10) demonstrate the collector efficiency for different circulation flow rates and for no withdrawal and withdrawal of (1 l/min) respectively. The increase of the circulation mass flow rate leads to increase Reynolds No. which increases Nusselt No. and heat transfer coefficient so higher heat gain can be obtained. The collector efficiency reaches (52.7%, 55.3%, 69%, and 71.6%) at 12:00 PM for mass flow rates of (1.8, 3, 6, and 9 l/min) respectively for no water withdrawal. Higher collector efficiencies are found for water withdrawal namely (93.3%, 91.5%, 87.8% and 74.5%) at 12:00 PM for mass flow rates of (1.8, 3, 6, 9 l/min) respectively, since colder water enters the shell side and the distribution of the triple helical coils within the shell assist to reject more heat to it so colder circulating water will return to the collector. The triple concentric helical coil used in this work enhances the flat plate collector efficiency especially at 9 l/min and for water drawn off from the storage tank. the collector efficiency reaches 93% during the day hours as noticed from Fig. (10). This is because the good thermal performance of this coil in transforming heat from coil side to shell side. The compact size of the storage tank used in this work is another advantage of this design of heat exchanger.

The storage tank effectiveness follows the incident solar radiation as shown in Fig.(11) when there is no withdrawal, while it is decreased with time when there is water withdrawal as presented in Fig.(12). It clear that the effectiveness rises with decreasing the circulation flow rate, since an increase of circulating flow rate decreases its' temperature difference across the storage tank thence decreases its' effectiveness. Also as solar radiation increases, the temperature difference $(T_{c,i} - T_{s,i})$ is increases which causes a decrease in effectiveness with time. The effectiveness was (0.8, 0.56, 0.35, and 0.23) at (9:00A.M) and (0.38, 0.25, 0.14, and 0.1) at (14:00PM) for circulation flow rates of (1.8, 3, 6, and 9 l/min) respectively.

The hourly pressure drop decreases as indicated in Fig.s (13 and 14) since the properties of water (density and viscosity) are reduced with the increase of its temperature. It is clear that increasing circulating flow rate increases the pressure drop. Pressure drop reaches (1, 2.2, 5.3, and 9.2kPa) at (12:00 PM) for circulation flow rates of (1.8, 3, 6, 9 l/min) respectively. A tiny deviation of the measured pressure drop is observed between with and with no water withdrawal, especially for circulating flow rates of (1.8, and 3 l/min). Since there is a rare work matches the parameters studied in this study, the heat gain to heat input ratio at (3 l/min) circulating flow rate of the present work is compared with the results of Mondol et al. for single coil-shell storage tank (119.6 liter) at (2.4 l/min) circulating flow rate as shown in Fig. 15., the triple concentric coiled tube is more efficient than the single coil tube.

CONCLUSIONS

The following conclusions can be extracted from the previous discussion of the results obtained through this work:

1. A weak variation of temperature difference between collector inlet and outlet temperature during the test day for higher values of circulating flow rates.
2. The circulation rate is a significant parametric effect on the useful heat gain of the collector. Higher values of collector heat gain can be obtained when there is water withdrawal from storage tank
3. The efficiency of the collector increases with the increase of circulation mass flow rate. Higher values of collector efficiency are obtained when water is withdrawn from the storage tank.
4. Effectiveness of heat exchanger is increased when circulation

flow rate is decreased. The heat exchanger effectiveness follows the solar radiation for no water withdrawal while it is decreased with time for water withdrawal .

5. The hourly pressure drop is decreased When Dean number increases.

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NOMENCLATURE

symbol	Description	symbol	Description
A	surface area (m^2)	$\dot{m}$	mass flow rate (kg/s)
C_p	specific heat (KJ/kg K)	N	number of coil turns
D_c	helical coil diameter (m)	P	coil pitch (m)
d	outside tube diameter (m)	Q	heat transfer (W)
I	solar radiation (W/m^2)	T	temperature (^oC)
L_c	coil length (m)	$\dot{V}$	volumetric flow rate, m^3/s
Greek symbols			
ε	effectiveness	ρ	mass density (kg/m^3)
η	collector efficiency	ΔT	temperature difference (^oC)
Subscript			
c,	coil	o	outlet
coll.	collector	s,i	inlet of supply water
i	inlet	tank,avg.	tank average

Table (1): Geometrical characteristics of the triple concentric coils

Item	Outer Coil	Middle Coil	Inner
Coil diameter, tube-center-to-tube-center D_c, (mm)	207	152.5	97
tube outside diameter d, (mm)	12.5	12.5	12.5
tube inside diameter di , (mm)	10	10	10
Axial length of helical coil L_c , (m)	14.95	14.85	14.04
Number of turns in helical coil, N	23	31	46
Curvature ratio , d_i/D_c	0.048	0.066	0.1031
Coil pitch p, (mm)	20	15	10
Coil height (mm)	460	465	460

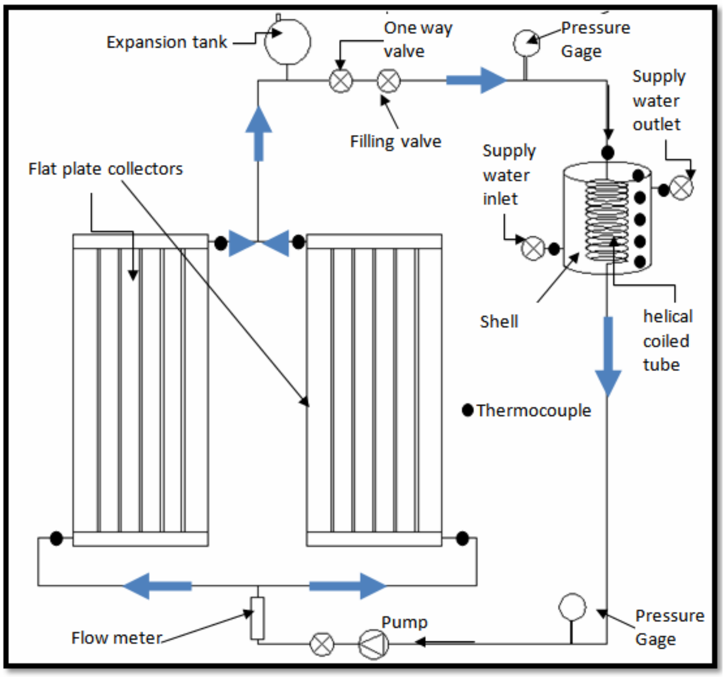


Fig.(1): Schematic Diagram of the Experimental rig (Solar Water Heating System)

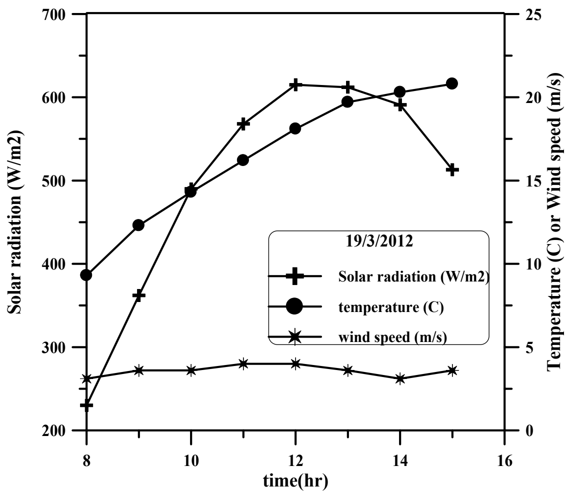


Fig.(2): Hourly Variation of Solar Radiation , Ambient Temperature, and Wind Speed.

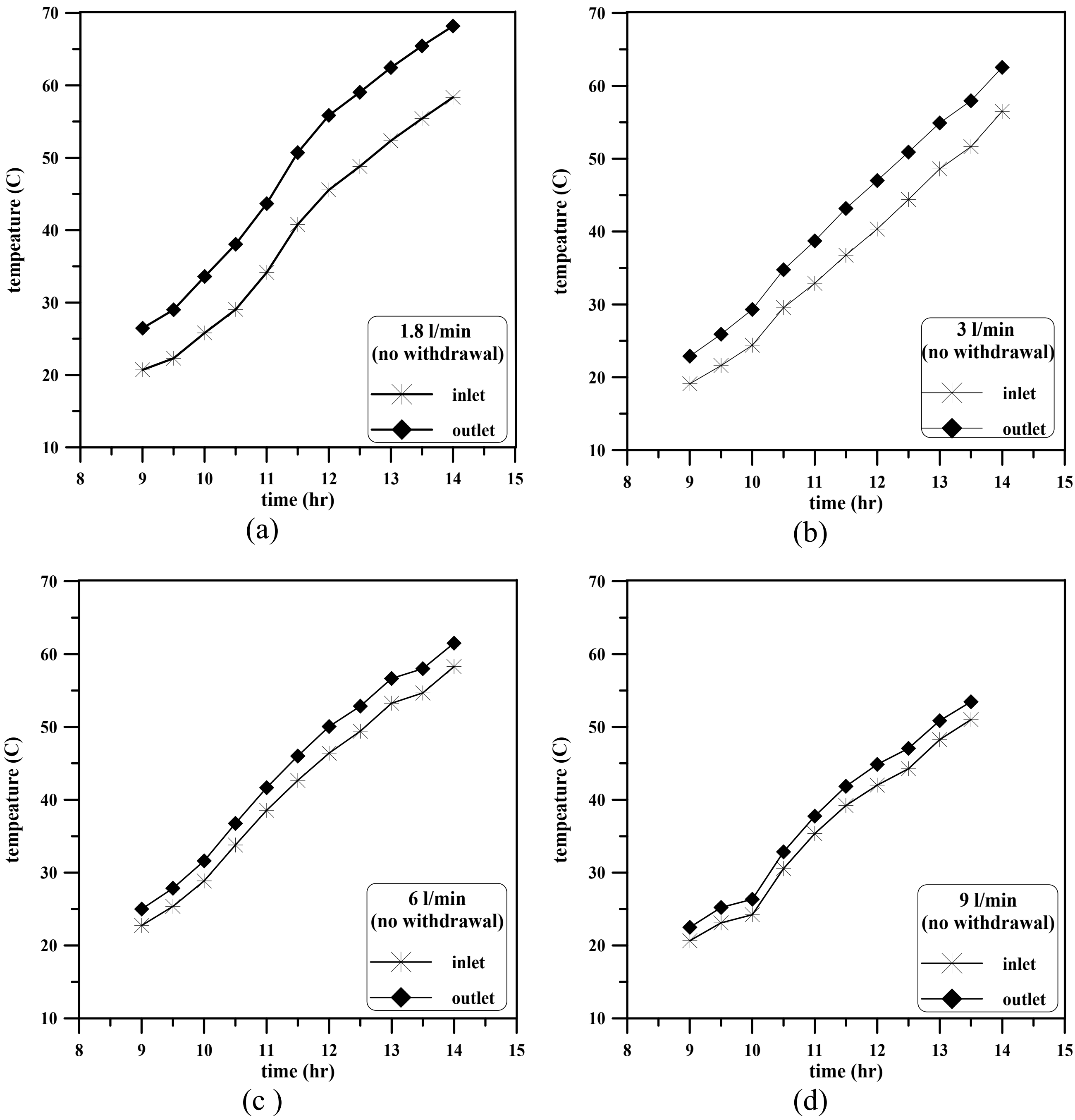
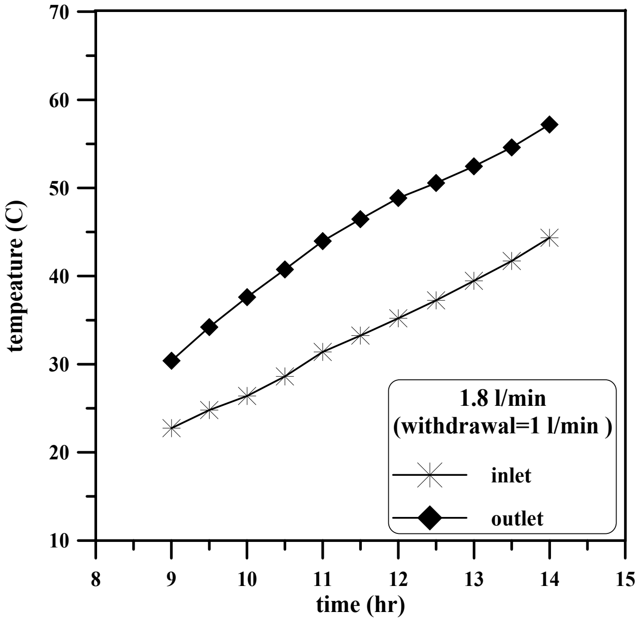
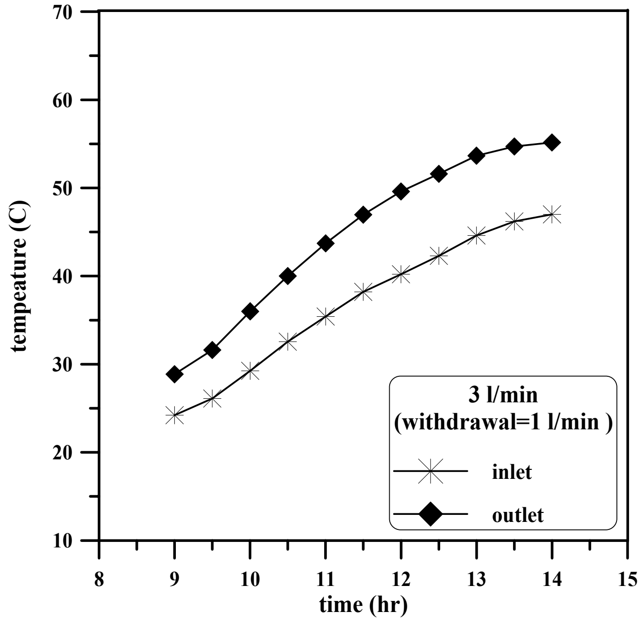


Fig.(3): Hourly Variation of Collector Inlet and Outlet Temperature for no Withdrawal. a)1.8 l/min, b)3 l/min, c)6 l/min, d)9 l/min



(a)



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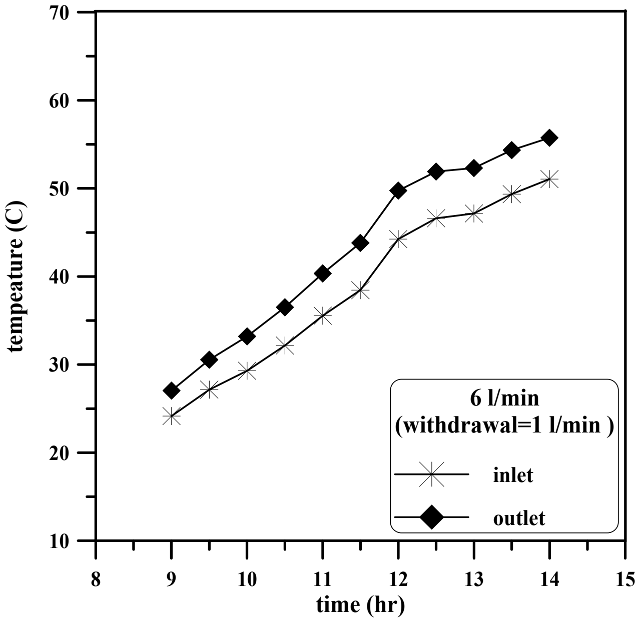

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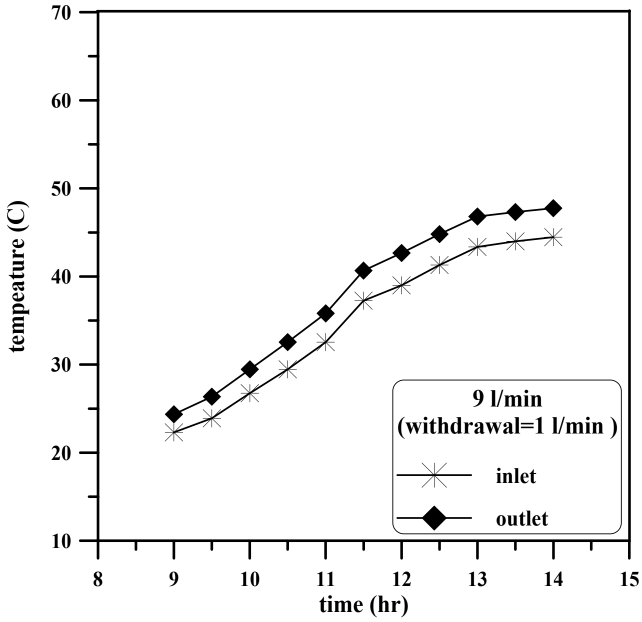

(d)

Fig.(4): Hourly Variation of Collector Inlet and Outlet Temperature for Water Withdrawal of (1 liter/min). a)1.8 l/min, b)3 l/min, c)6 l/min, d)9 l/min

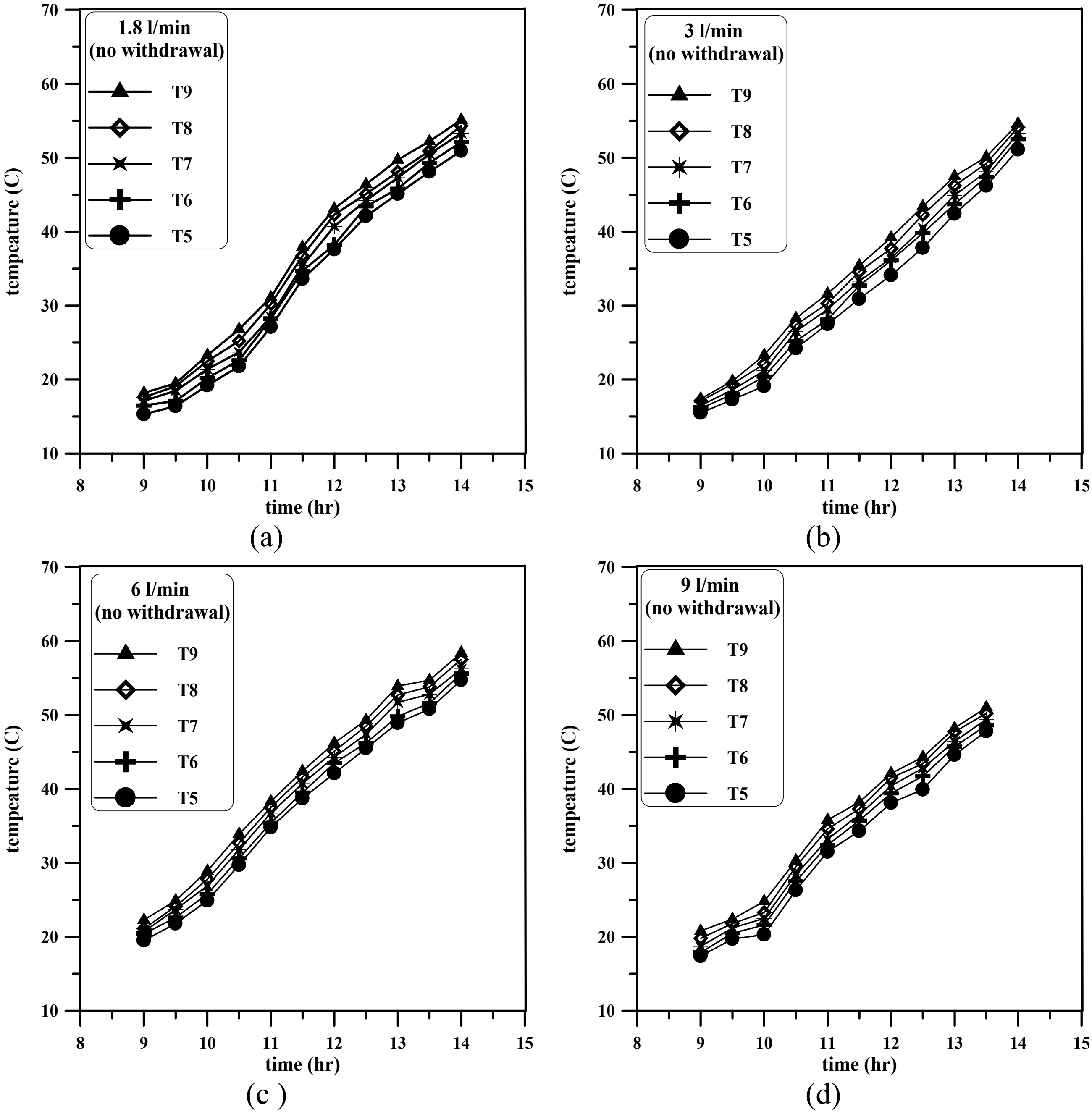

Fig.(5): Variation of Hourly Stratification in the Storage Tank with no Withdrawal. a)1.8 l/min, b)3 l/min, c)6 l/min, d)9 l/min

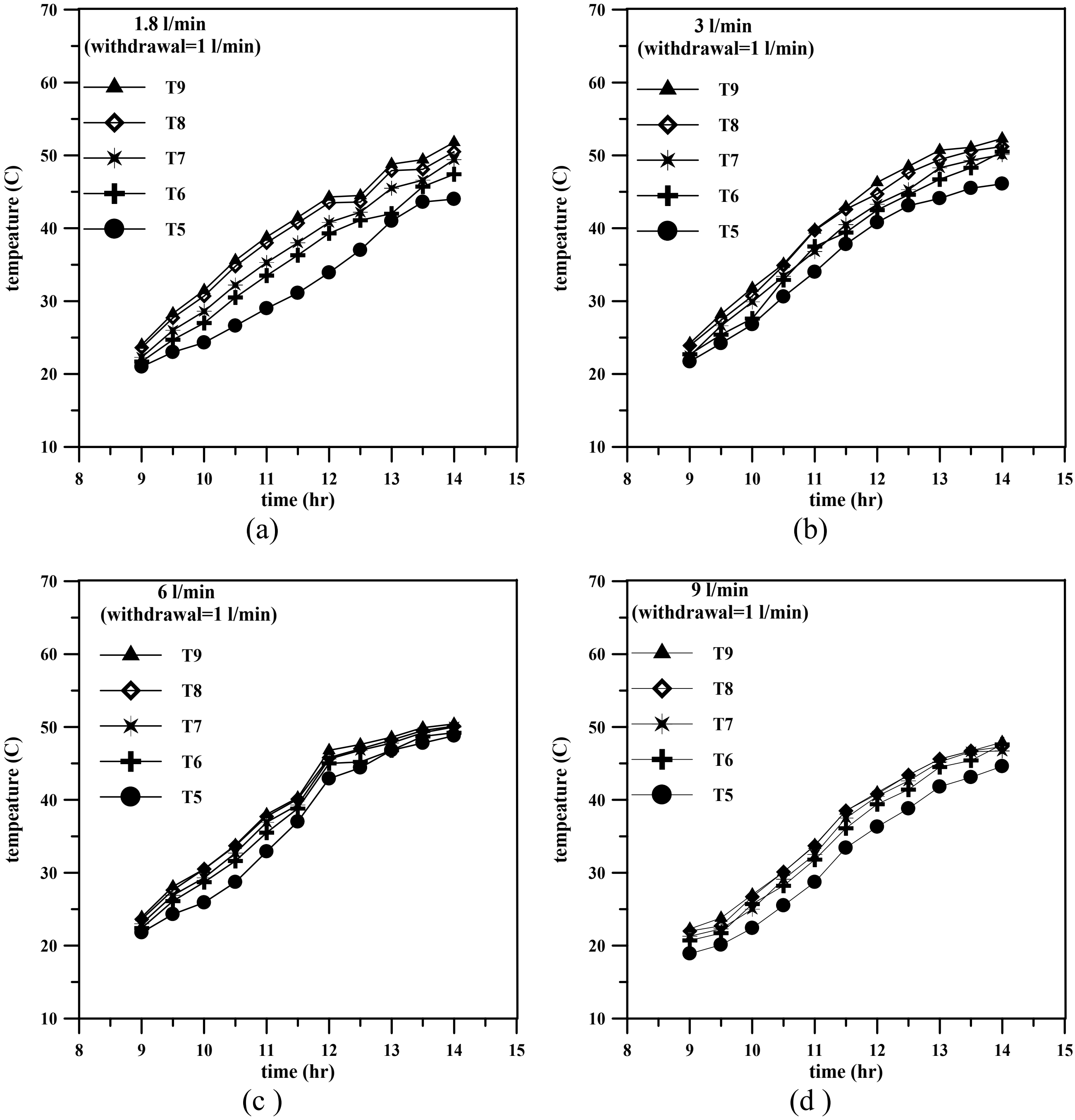

Fig.(6): Hourly Variation of Thermal Stratification in the Storage Tank for Withdrawal = 1 l/min. a)1.8 l/min, b)3 l/min, c)6 l/min, d)9 l/min

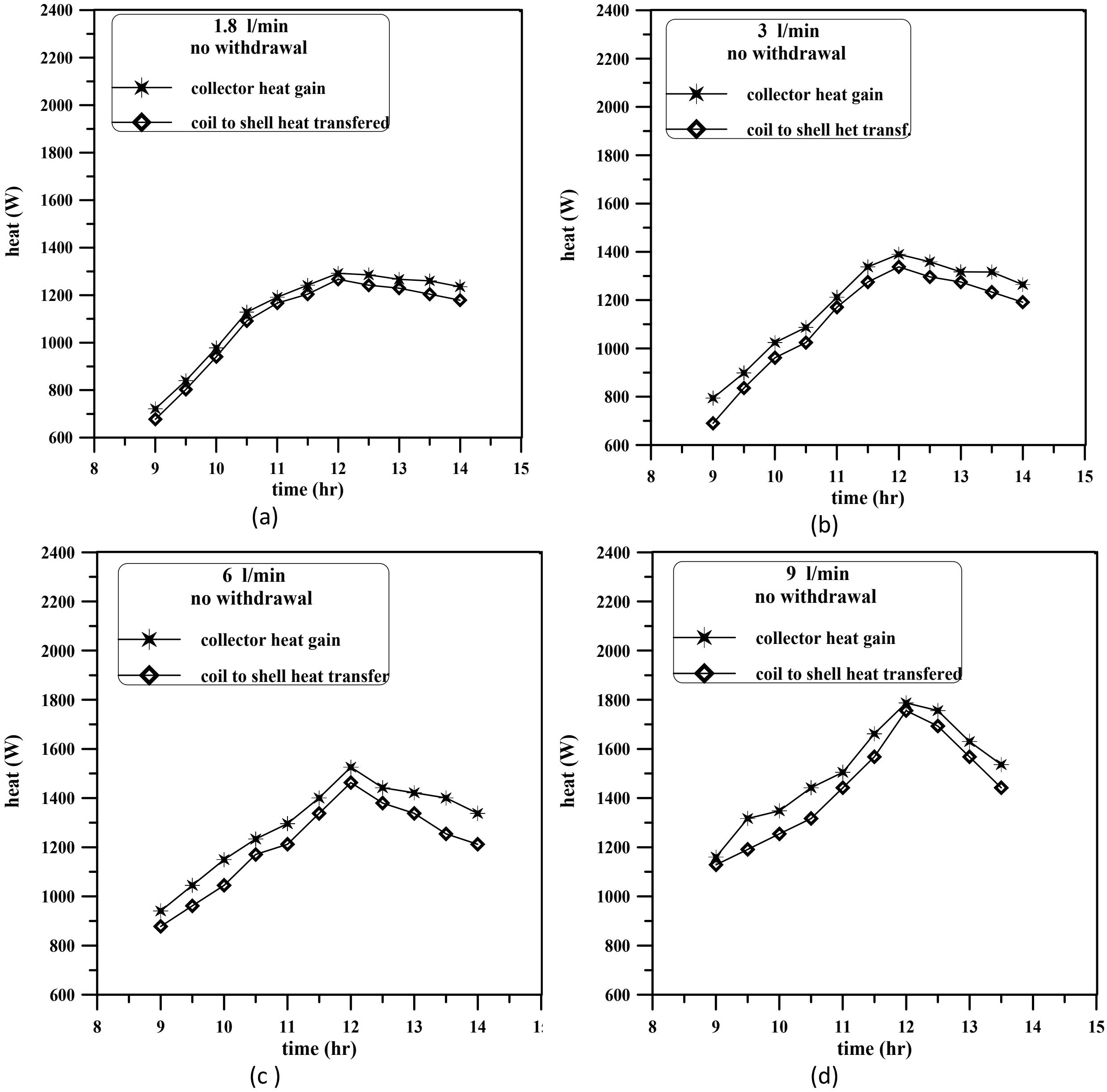

Fig.(7): Variation of Hourly Collector Heat Gain and Coil Heat Rejected for no Withdrawal. a)1.8 l/min, b)3 l/min, c)6 l/min, d)9 l/min

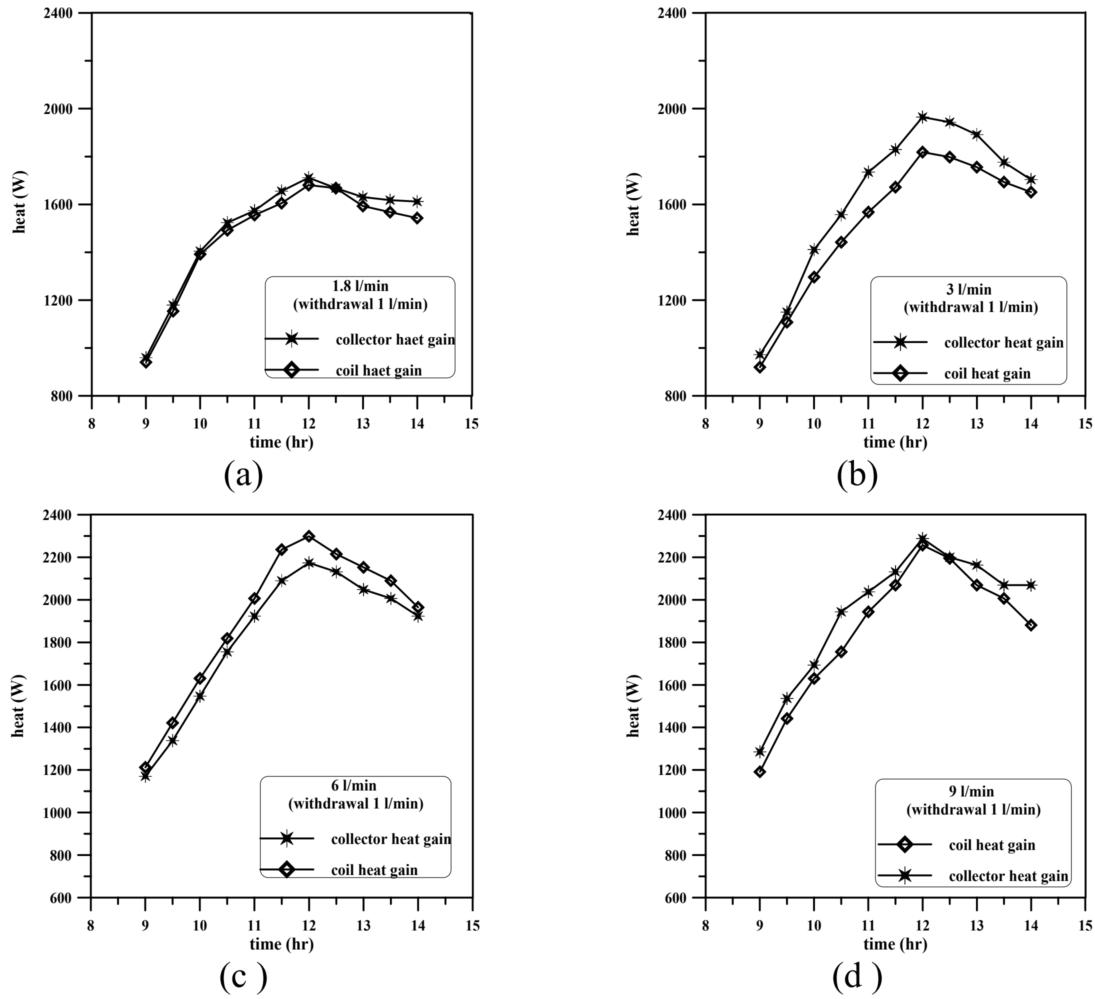

Fig.(8): Variation of Hourly Collector Heat Gain and Coil Heat Rejected for supply water Withdrawal=1 l/min. a)1.8 l/min, b)3 l/min, c)6 l/min, d)9 l/min

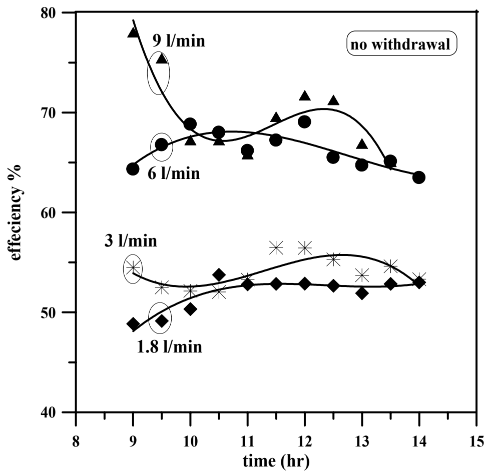

Fig.(9): Hourly Variation of Collector Efficiency for Different Circulation Flow Rates for no withdrawal

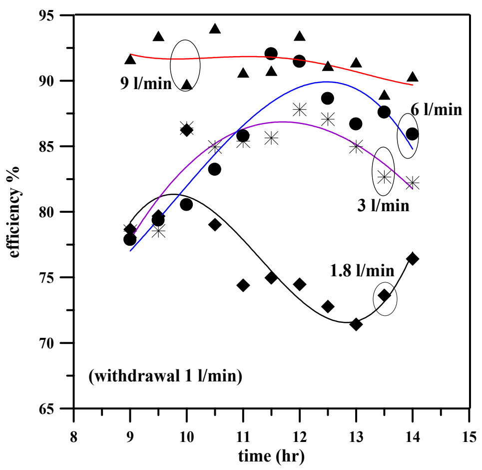

Fig.(10): Hourly Variation of Collector Efficiency for Different Circulation Flow Rates for withdrawal=1 l/min

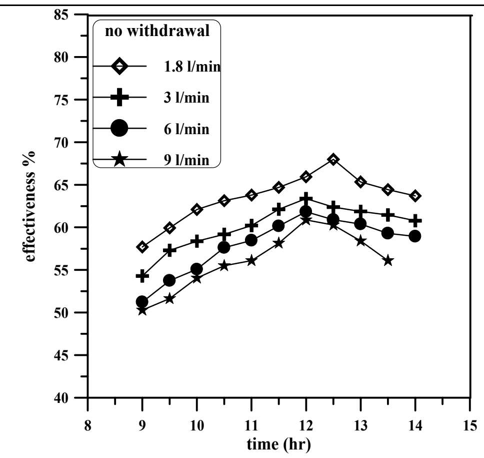

Fig.(11): Hourly Variation of Storage Tank Effectiveness for Different Circulation Flow Rates for no Withdrawal

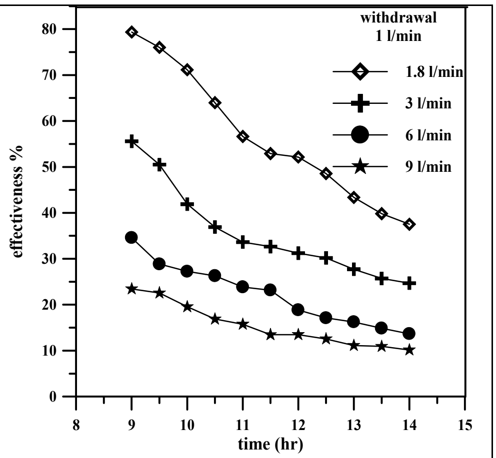

Fig.(12): Hourly Variation of Storage T Effectiveness for Different Circulation Rates for withdrawal=1 l/min

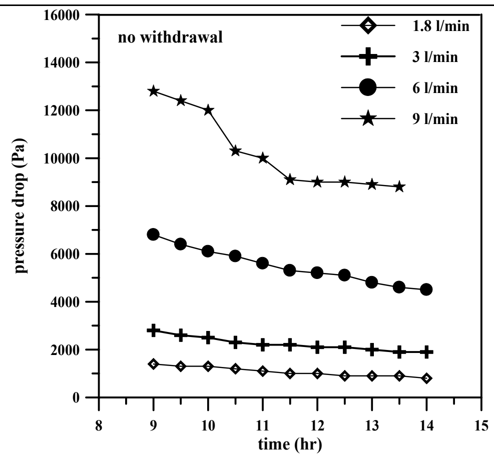

Fig.(13): Hourly Variation of Measured Pressure Drop Across Helical Coiled Tube. for no Withdrawal

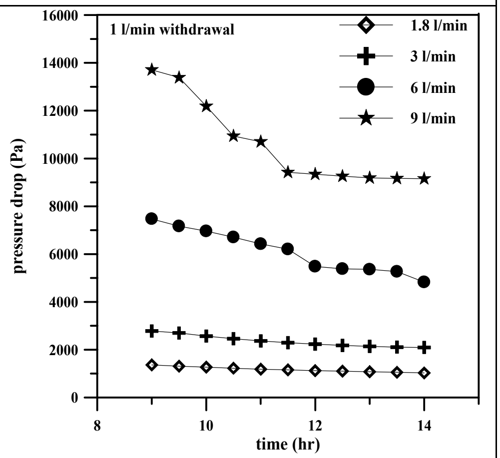

Fig.(14): Hourly Variation of Measured Pressure Drop Across Helical Coiled Tube. for Withdrawal =1 l/min

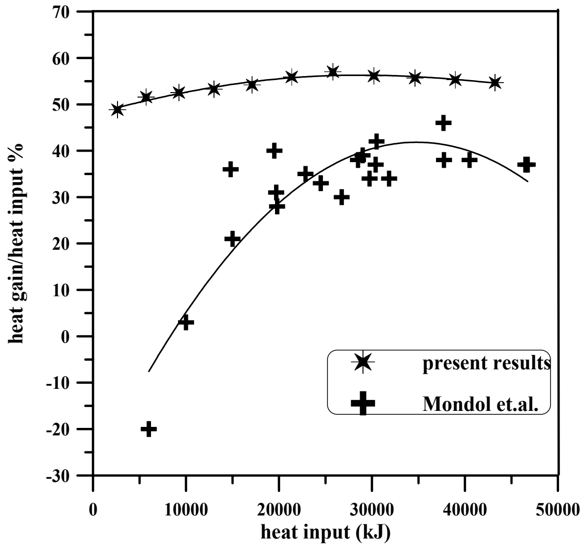

Fig. 15. Comparison of the percentage heat transfer of the present work with previously reported results.