

The Investigation of a New Solar Water Collector

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Abstract
A new type of solar water heater is proposed in this workand its thermal performanceis assessed theoretically and experimentally. The collector uses separated glass tube instead of integrated heat pipe. The actual area of the solar collector exhibition to solar radiation around (2.96 m^2), which included (20) glass tubes with a water storage tank 120 liter as main parts. The present work includes three aspects.Firstly, an experiment was conducted to test thermal performance of the new collector on November, 2014. After a daily work from 09:00 am to 16:00 pm the maximum collector efficiency could reach 66%, while the temperature of water storage tank increased by about 25 °C in the end.Secondly, a theoretical analysis on the energy balance for each component of the collector was made to understand the heat transfer process inside the collector.Thirdly, heat transfer model has been developed to calculate the collector efficiency, temperatures of water, the glass tube and the absorber plate, of which the theoretical results are somewhat different with the experimental data. Probably it is caused by the large heat loss in the experiment through the test devices.

الخلاصة:
تم خلال هذا البحث اقتراح نوع جديد من سخان الماء الشمسي. حيث استخدمت الانابيب الزجاجية المنفصلة بدلا من الانابيب الحرارية المتكاملة. وكانت المساحة الفعلية للمجمع الشمسي المعرض للإشعاع الشمسي حوالي ($2.96\ m^2$) و التي تتضمن 20 انبوب زجاجي مع خزان ماء سعة 120 لتر كأجزاء رئيسية.وشمل البحث ثلاثة محاور.
أولا، أجراء اختبار الأداء الحراري للمجمع الجديد في نوفمبر تشرين الثاني عام 2014. وبعد الاختبار اليومي من 9:00 صباحا حتى 16:00مساءا، ظهر أن أقصى كفاءة للمجمع يمكن ان تصل إلى 66٪، بينما درجة حرارة ماء الخزان قد زادت بنحو 25 °C في نهاية المطاف.
ثانيا، تم إجراء التحليل النظري على اتزان الطاقة لكل جزء من المجمع لفهم خطوات عملية انتقال الحرارة داخل المجمع.
ثالثا، تم تطوير نموذج انتقال الحرارة لحساب كفاءة المجمع، ودرجة حرارة المياه، و الانابيب الزجاجية ولوحة الامتصاص، والذي اظهر تباين نوعا ما بين النتائج النظرية والعملية. والتي لربما يعزى سببها الى الفقدان الكبيرللحرارة اثناء التجربة من خلال اجهزة الفحص.

Nomenclature

A	area, m^2
c_p	specific heat, $J/(kg\ K)$
d	distance between the glass tube and the absorber plate,m
g	gravitational acceleration, m/s^2
G	solar radiation absorbed by the absorber plate, W/m^2
h	heat transfer coefficient, $W/(m^2\ K)$
h_{lv}	latent heat of vaporization, J/kg
k	thermal conductivity, $W/(\ m\ K)$
L	length of collector, m
$\dot{m}$	mass flow rate, kg/s
m	mass, kg
n	time step
N_u	Nusselt number
q	heat transfer rate, W
Ra	Rayleigh number
p	pressure, Pa
t	time, s
T	temperature, °C
U	Overall heat transfer coefficient, $W/(m^2\ K)$
V_r	velocity, m/s
W	width of collector, m
z	number of glass tube

Greek symbols

Δ	temperature difference, K
α	absorptivity of the absorber plate
β	tilt angle of solar collector, °
ε	emissivity of the absorber plate
μ	viscosity, $N\ s/m^2$
η	solar heat collector efficiency
ρ	density, kg/m^3
	transmissivity
σ	Stephan Boltzmann constant, 5.68 * 10^{-8} $W/(\ m^2\ K)$

Subscripts

a	ambient
c	condenser
e	evaporator
g	glass
i	inlet
l	liqiud
o	outlet
p	absorber plate
sat	saturation
r	coppertube
v	vapor
w	water

1. Introduction:

Solar collectors have been in use for many years in almost every part of the world, mostly to answer the domestic hot water demands. Apart from this, there have also been solar collector applications for residential, livestock and greenhouse heating. Though the basic idea on solar energy storage has not changed, many interesting solar collectors have been tested and proposed. Some examples of these were; water filled oil barrels as solar collectors [1], a solar collector with a sand–mix concrete absorber with buried-in plastic hose [2], an air collector including rock particles as the absorber [3], and a metallic box solar collector [4].The solar water collector is still among the widely used devices to intercept solar insolation. Its main function is to absorb as much solar energy as possible and to transfer the retained heat to the working fluid flowing through it. The efficiency of such collectors has aroused the interest of many investigators [5, 6]. The main part of such a device is its absorber plate whose thermal performance has to be considered. This in turns requires information on the incident global solar radiation as an important input parameter. Several trials have been made to measure and predict the incident solar radiation using various parameters [7, 8]. The solar water collectors have been tested since the early 1970. Classical solar collectors were of the tube-in-fine flat plate types. Since new developments and innovations have result in more efficient collectors with the all glass tube and the heat pipe [9,10].

The use of solar energy for thermal applications constitutes today one of the most popular engineering applications in the world. According to the European Solar Thermal Energy Industry Federation [11], the average installed capacity in the Switzerland in 2006 was 27 kWth per 1000 capita, showing a spectacular growth of 47%. Cyprus with more than 530 kWth per 1000 capita is the distant leader while Austria with 225 and Greece with 208 are in second and third place. Currently, the most widespread solar application is for residential water heating. Today, systems for hot water production in single-family houses are dominant as they are proving economically feasible and viable [12]. The thermal behavior of a solar water heating system, however, constitutes a complex problem involving a number of interrelated parameters such as the solar radiation and other weather conditions, the water flow rate through the collector, the storage tank configuration, the effectiveness of the heat exchanger, and the thermal load. Based on the great number of such systems in operation today a number of researchers have examined the environmental impact of such systems and life cycle assessments have been performed [13]. An integrated collector/storage solar water heater was first patented in 1891 [14]. Due to its rather simple and concise structure, this type of system offers a value for money approach to permit the wide scale domestic adoption of solar water heating. Theoretical analyses of reflector/collector combinations [15] suggest that use of a concentrator improves significantly the system thermal efficiency. As suggested, concentrating reflector increases the solar energy collection of a cylindrical vessel, with a low surface area to volume ratio.

The water may freeze in cold days; a pump is needed to maintain the forced circulation; the heat loss due to the natural convection and radiation from the collector surface is considerably large; and the working life of the collector may be shortened due to the pipe corrosion. With the development of advanced heat transfer technology, heat pipes with high transfer rate which results of a continuous evaporation and condensation process of pure working fluid are now widely applied in the design of solar heat collectors. On the basis of applying heat pipes, numerous experiments have been conducted to optimize the thermal performance and the stability of the solar water heater. Nada et al. [16] designed a two-phase closed thermosyphon solar collector with a shell and tube heat exchanger. The influence of the cooling water mass flow rates, the inlet cooling water temperature and the number of the thermosyphon tubes on the thermal performance of the collector was experimentally studied. Mathiouslakis and Belessiotis[17]presented an investigation on a new type of solar heat collector employing a heat-pipe filled with ethanol, aimed to transfer heat from the collector to the water tank directly. A two-phase closed-loop thermosyphon was utilized with the condensation section placed in the water tank. The maximum instantaneous efficiency of the system reached 60%. Based on the similar solar water heater system, Esen [18] investigated the effect of adopting different working fluids on the thermal performance of the system, and used the integrated vacuum tube collector for solar cooker. As can be seen from the literature review above, there are two methods to improve the thermal performance of solar water heater. One is the optimization design of the structure of the solar water heater system; the other is the continuous search for new heat transfer elements. The solar collector systems introduced in the literature above have a row of integrate heat tubes in solar heat collector. Based on this anew solar heat collector with separated glass tube is proposed in this study experimentally and theoretically. The main advantages are high stability and leak avoidance between the water cooling side and the solar heating side. In order to investigate the thermal performance of new solar heat collector, an experiment was conducted on a clear day. Additionally, a transient heat transfer model was built based on the energy balance for each component of the collector and calculated in comparison with the experimental data.

2. Theoretical analysis:

The analysis is focused on three parts: the glass tube, the copper heat tube and the water to propose the transient heat transfer model of the solarwater heater employing the new collector. The energy balance for each component is illustrated in Figure. 1.To simplify the analysis, four assumptions are made as follows.

1. Ignoring the heat loss from the insulation.
2. Ignoring the thermal contact resistance in the process of heat transfer.

3. The temperature of the absorber plate and water in the tank is uniform.
4. The physical properties used in the calculation are constants

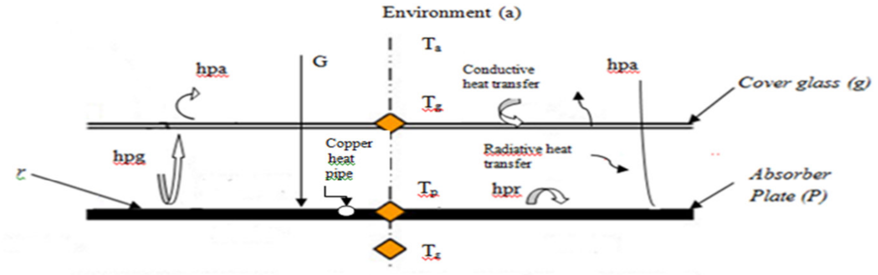

Figure. 1a

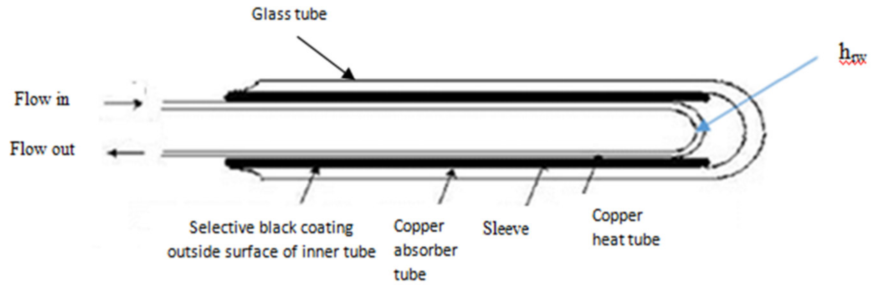

Figure. 1b

Figure. 1: Heat transfer model of each component of the new solar collector

The energy balance equations are described as follows.As shown in Fig. 1(a), the glass tube absorbs heat fromthe solar radiation and natural convection between thecopper absorber plate and the glass tube, while it loses heat dueto the convection of the ambient air. All heat transfer processesresult in the changing of the temperature of the glasstube.

$$(mc_p)\frac{dT_g}{dt} = A_g\alpha_g G - A_g \boldsymbol{h}_{ga}(T_g - T_a) + A_g \boldsymbol{h}_{pg}(T_p - T_g) \quad (1)$$

The energy balance equations are described as follows. As shown in Fig. 1(a), the copper absorber plate gets the solar radiation heat, while at the same time it transfers heat to the glass tube through natural convection, to the surrounding environment through radiation and to the copper heat tube through conduction. The conduction heat is equal to the heat transferred from the plate to the flowing water.

$$(mc_p)_p\frac{dT_p}{dt} = A_g\tau_g\alpha_g G - A_g \boldsymbol{h}_{pg}(T_p - T_g) - \varepsilon_p A_g \boldsymbol{h}_{p\sigma}(T_p^4 - T_a^4) - zA_{r,e}U_{r,e}^n\ (T_p - T_{w,i}) \quad (2)$$

The water in the storage tank obtains the latent heat released from the condensation of the vapor in the copper heat tube.

$$(mc_p)_p\frac{dT_w}{dt} = m_w c_{p,w}(T_{w,o} - T_{w,i}) = zA_{r,e}U_{r,e}^n\ (T_p - T_{w,i}) \quad (3)$$

Applying an explicit method of finite difference scheme, the Eqs.(1)–(3) were discredited to the form of Eqs. (4)–(6), respectively.

$$T_g^{n+1} = T_g^n + (t/(mc_p)_p)(A_g\alpha_g G^n - A_g h_{ga}^n(T_g^n - T_a^n) + A_g h_{pg}^n(T_p^n - T_g^n)) \quad (4)$$

$$T_p^{n+1} = T_p^n + \left(\frac{t}{(mc_p)_p}\right)\left(A_g\tau_g\alpha_p G^n - A_g h_{pg}^n(T_p^n - T_g^n) - \varepsilon_p A_g\sigma\left(T_p^{n^4} - T_a^{n^4}\right) - zA_{r,e}U_{r,e}^n(T_p^n - T_{w,i}^n)\right) \quad (5)$$

$$T_w^{n+1} = T_w^n + \frac{t}{(mc_p)_w} zA_{r,e}U_{r,e}^n(T_p^n - T_{w,i}^n) \quad (6)$$

The heat transfer coefficients (hga and hpg) in the equations were calculated according to the empirical correlations proposed by Watmuff et al. [19] and Hollands et al. [20].

$$\boldsymbol{h}_{ga} = 2.8 + 3\ V_w \quad (7)$$

$$N_u = \frac{h_{pg} d}{k_{air}} = 1 + 1.44\left[1 - \frac{1708\,(sin1.8\beta)^{1.6}}{Racos\beta}\right]\left[1 - \frac{1708}{Racos\beta}\right]^{+} + \left[\left(\frac{Rcos\beta}{5830}\right)^{\frac{1}{3}} - 1\right]^{+} \quad (8)$$

Vw is the wind velocity. The notation [ ]+ designates that the quantity in the square bracket is set equal to zero if negative. The heat transfer coefficient in the evaporator is based on thecorrelation proposed by Imura et al. [21]. It is difficult to deal with the transfer coefficient at the condenser because of the start-up process and its variation with the solar radiation. In this study, *hc* is calculated reasonably by a linear transformation of *he*. In the Eq. (10), *f* is a function of time. The experimental conditions is applied in the numerical simulation.

$$h_e = 0.32\left(\left(\rho_l^{0.65} k_l^{0.3} \left[g^{0.2} q^{0.4} C\right]_{(p,t)}^{0.7}\right)/\left(\rho_v^{0.25} h_{tv}^{0.4} \mu_l^{0.1}\right)\right) \left[(P_{sat}/P_a)\right]^{0.3} \quad (9)$$

$$h_c = f.h_e \quad (10)$$

3. Experimental part:

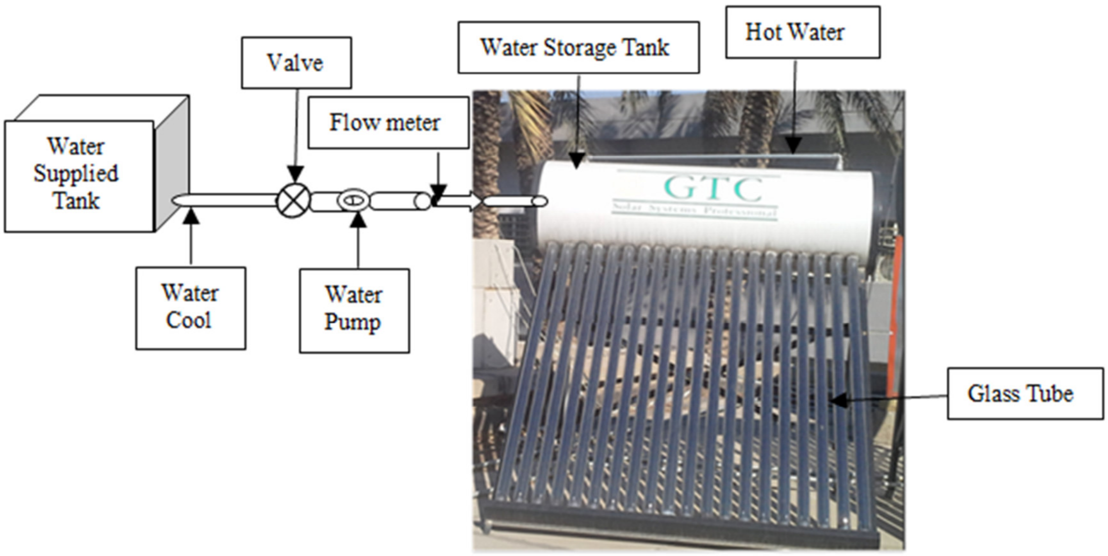

Figure.2: Experimental set-up of the new collector.

Figure. 2shows the basic parts of the solar collector used in this study. The system consists of anew solar collector, water storage tank, water pump, valve and flow meter. The new solar collector is comprised of a glass tube, copper heat tube, copper absorber plate, steel supporting structure, collector storag tank.The glass tube constructed from outer and inner tubes. made from extremely strong borosilicate glass. The outer tube has very low reflectivity and very high transmisivity thatradiation can pass through. The inner tube has a layer ofselective coating that maximizes absorption of solarenergy and minimizes the reflection, thereby locking theheat. On theinternal surface of the inner borosilicate glass tube thereis a copper absorber plate and copper tube which collects the radiation thatpasses through the glass layer. These absorber plate and tube ismostly of aluminum or copper as both of these metalshave a high heat reflectivity and transmitivity quotient. Itis also painted black so as to allow it to absorb maximum amount of solar radiation.Table. 1 shows the dimensions for the elements of the solar collector.

Table. 1: Dimensions for the elements of the solar collector

Element	Dimension
Collector length	140 cm
Collector width	140 cm
Diameter of glass tube	4.3 cm
Thickness of glass tube	0.7 cm
Absorber plate material	Copper
Tube material	Copper
Coating	Black paint

The glass tube system had 20 tubes each and mounted on steel supporting structure at angles of about 33.3° to the horizontal. Supplied water tank capacities was 1000 liter and for collector 120 liter. All temperature were measured using thermocouple and the solar radiation was measured by solar power meter.

4.1. Experimental procedure

Anew solar collector was tested during one month from 1 to 30 November 2014. The data measured were recorded from hour 9,00 to 1600 every 30 minute. Except the measuring of the data in figures (3, 4) for full day.A constant flow rate 0.7 Kg/s is used during all testperiod, the collector inlet temperature varied from ambient temperature to 60 ºC with test period. The supplied tank capacity was 1000 liter, the initial water temperature was 25ºC. Average water temperature (average of bottom, middle and top of the store), the absorber plate and the ambient was measured by using thermocouple. Solar radiation measurement was carried out by an energy sensor located at the surface the glass tube. In this study the measured of the collector performance is the collection efficiency defined as the ratio of useful heat gain over some specified time period to the incident solar energy over the same time period [22].

$$\eta = \frac{\int Q_u \, dt}{A \int G dt} (1 \qquad \textbf{(11)}$$

Where the energy gain $Q_u = m_w \, Cp_w \Delta T_w$ (12)

$$Q_u = m_w Cp_w \, (T_o - T_i) \qquad (13)$$

The thermal efficiency of the collector defined as the ratio of the amount of heat transfer to the water to the total amount of solar radiation received on the collector during the period of time is:

$$\eta = \frac{Q_u}{GA} \qquad (14)$$

$$\eta = \frac{m_w Cp_w (T_o - T_i)}{GA}, \qquad (15)$$

Te above equation was used to calculate the efficiencies of the collator using the data collated throughout the period of testing.

5. Results

Figure.3shows the variation of the water and ambient temperatures for a typicalfull day with high insulation. The water temperature reached to its maximum ofabout 60°C around midday with an hour time delay in comparison with the outside, decreasing then gradually as the day marched out in time, and it never decreased below 36°C till the morning of the next day. Also figure.(4) is illustrated the variation the solar radiation with the time of full clear day. The solar radiation is incident of the outer layer of the glass tube, the figure obviously explainsthe gradual rise and fall of the intensity of radiation. The area under the curve of this figure gives the value in Kwh/m^{2}day as radiation is only available from 6.10 in the morning to nearly 6 pm depending on the season.

The calculation value of collector efficiency for the period under investigation were also grouped together and analyzed numerically and experimentally. Figure.5 Show the variation of the efficiency of the solar collector with ΔT/G, according to this figure, the theoretical efficiency during the period is much higher than the experimental because the large heat loss in the experiment and the overestimate heat transfer coefficient additionally to affecting weather condition.The slope of linear fitted line in the figure is -7.498 W/m^2 ºC, while the slope in the experimental is much lower which implies that the heat loss from the experimental device is underestimated.

Figure.6 is shown the variation of the temperature of the water at the inlet and outlet of the flowing channel with working time. The initial inlet water temperature was 25 ºC and increased to 60 ºC during the working time. The water temperature stops increasing as the result of decline of the solar radiation after 16.00 pm.

Figure.7 is indicated the temperature of absorber plate aired as the result of the beginning of water circulation then the temperature begin growing as a result of solar radiation received on the collector during working time, where the absorber collects the radiation through the glass tube which have a high heat reflectivity and transmitivity properties.

6. Conclusion

This research indicated that a new type of solar collector provided that the absorption characteristic and efficiency of the collector improved by the design of solar collector with the separated glass tube. The experimental results showed that the collector efficiency reach 66%. By usinga new solar collector. The water temperature reached to its maximum of about 60°C. The present collector was able to keep the water temperature above 36°C during whole night to the morning of the next day. The collector efficiency shows the same tendency with the solar radiation. This new collector has a desired thermal performance and it can be well applied in the solar collector for green house water heating.

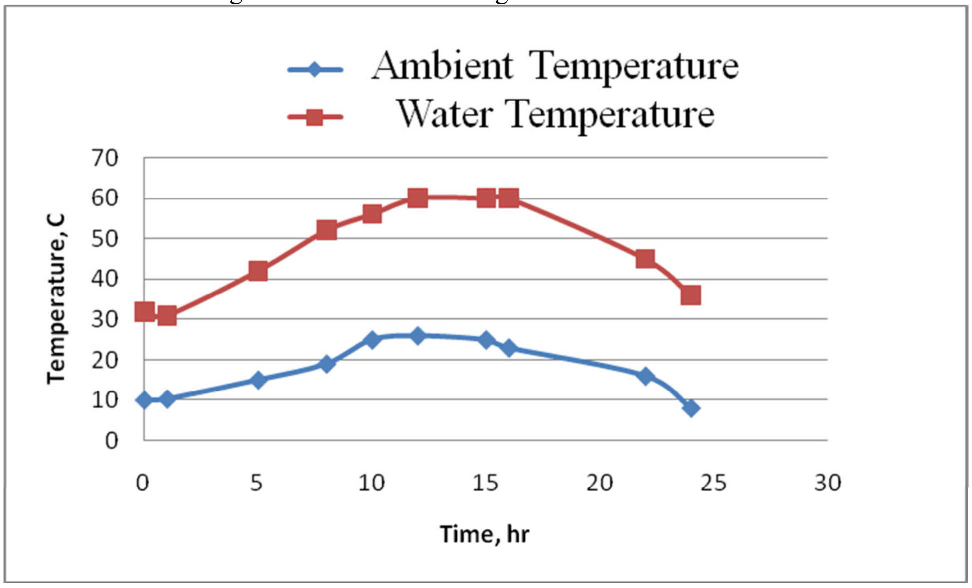

Figure.3 : Variation of ambient and water temperature with time for a full day

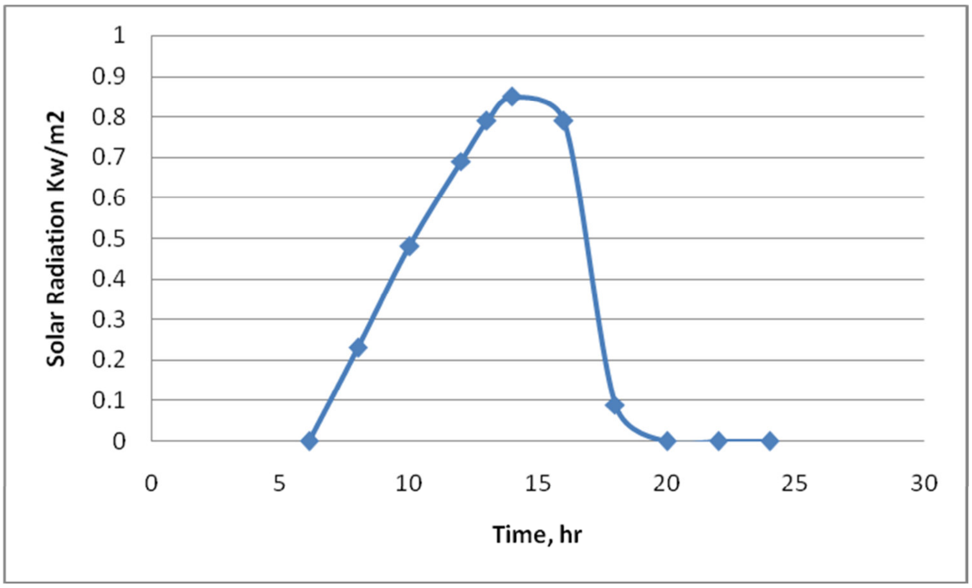

Figure.4: The variation of solar radiation with time for a full day

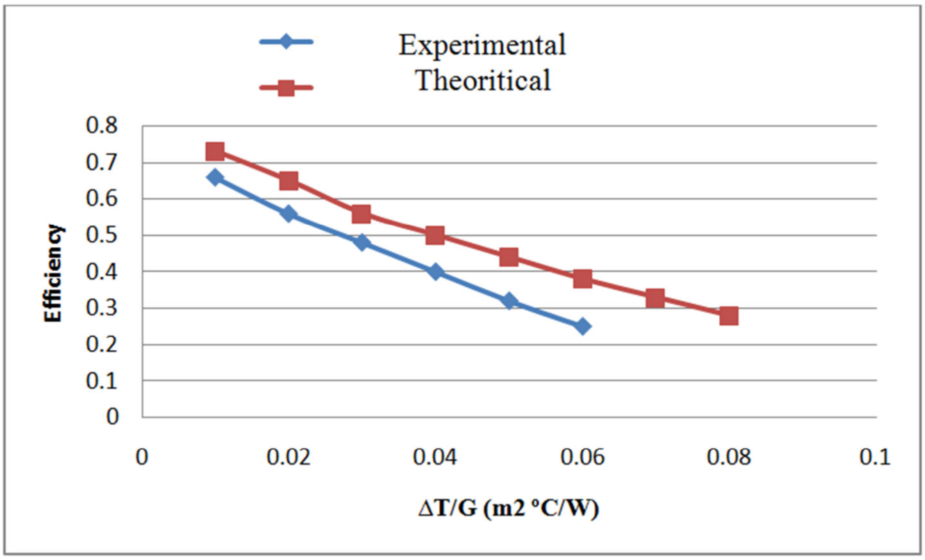

Figure.5: Theoretical and Experimental Collector Efficiency VS ΔT/G

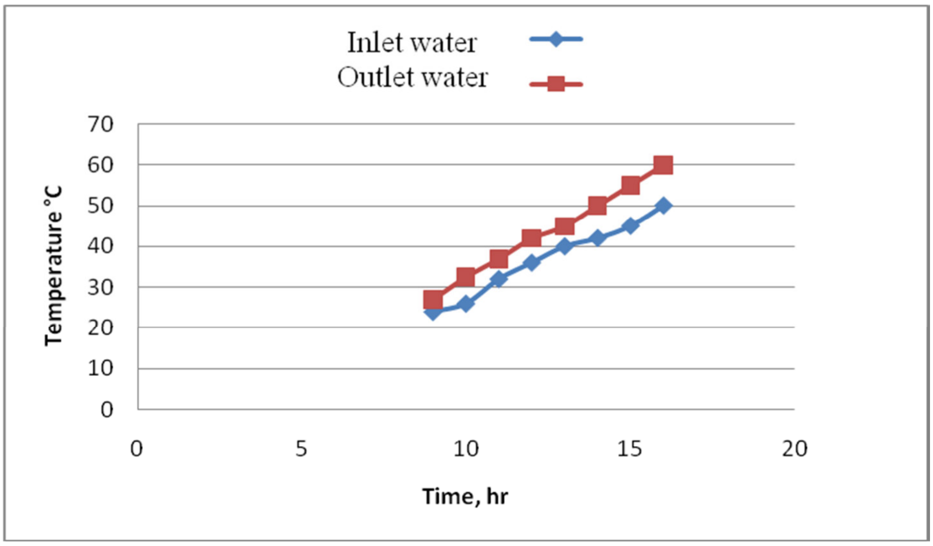

Figure.6: The Variation of the inlet and outlet water temperature with the working time

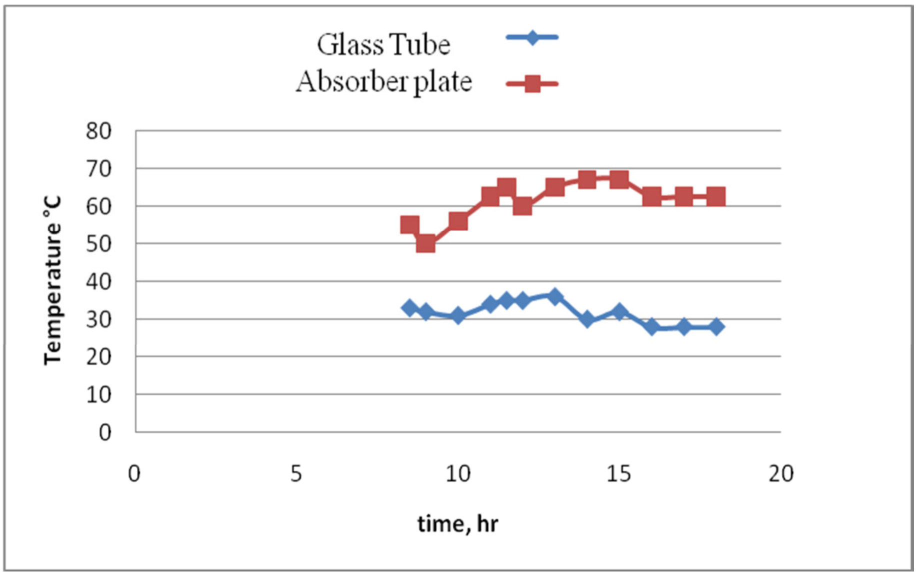

Figure.7: The Variation of temperature with the working time

7. References

[1] Reis A, Albuquerque P, Almeida F, Duarte J, Martins J, Pereira R. Water heating by means of solarenergy collecting oil barrels. In: Veziroglu TN, editor. Solar Collectors Storage, Alternative EnergySources IV, vol. 1. Ann Arbor (MI): Ann Arbour Science, 1982:101–11.
[2] Tiris M, Tiris C, Erdalli Y. Solar Water Heating Systems. Kocaeli: TUBITAK-MAM, 1997.
[3] Hamdan MA. Investigation of an inexpensive solar collector storage system. Energy ConverMgmt1998;39(5/6):415–20.
[4] Audi MS. Experimental study of a solar space heating model using Jordanian rocks for storage. Energy Convers Mgmt 1992;33(9):833–42.
[5] Chow SP, Harding GL. Effect of antireflection coating on the transimittance of glass tubular andplane double glazed covers for flat plate Collectors. Solar Energy 1985;34(2):183.
[6] Biga AJ, Rusa R. Estimating solar irradiance sums from sunshine and cloudiness observations. SolarEnergy 1980;25:265.
[7] Abbass Z. Salman, Roshen T. Ahmed. "The compration analysis of fixed pitch angel wind turbine generator ", National Renewable Energies Conference and Their Applications/ University of Technology, 2013
[8] Hartley LE, Martinez-Lozano JA, Utrillas MP, Tena F, Pedros R. The optimisation of the angle ofinclination of a solar collector to maximise the incident solar radition. Renewable Energy1999;17:291.
[9] Ong, K. S., “Experimental Performance Testing of Solar Water Heaters,” Int. Journal Low Carbon Technology (2011).
[10] Ma, L., Lu, Z., Zhang, J. and Liang, R., “Thermal Performanceof the Glass Tube Solar Collectorwith U-Tube,” Building and Environment, pp. 1959-1967 (2010).
[11] European Solar Thermal Energy Industry Federation (ESTIF), Solar ThermalMarkets in Europe (Trends and Market Statistics 2006). <http://www.estif.org/fileadmin/downloads/Solar_Thermal_Markets_in_Europe_2006.pdf>, June2007.
[12] C. Carboni, R. Montanari, Solar thermal systems: advantages in domesticintegration, Renewable Energy V33 (6) (2008) 1364–1373.
[13] F. Ardente, G. Beccali, M. Cellura, V. Lo Brano, Life cycle assessment of a solar thermal collector, Renewable Energy V30 (7) (2005) 1031–1054.
[14] C.M. Kemp, US Patent No. 451384, 1891.
[15] S.L. Grassie, N.R. Sheridan, The use of planar reflectors for increasing theenergy yield of flat-plate collectors, Solar Energy 19 (1977) 663–668.
[16] Nada, S.A., El-Ghetany, H.H., Hussein, H.M.S., 2004. Performance of atwo-phase closed thermosyphon solar collector with a shell and tubeheat exchanger. Applied Thermal Engineering 24, 1959–1968.
[17] Mathiouslakis, E., Belessiotis, V., 2002. A new heat-pipe type solardomestic hot water system. Solar Energy 72, 13–20.
[18] Esen, M., 2004. Thermal performance of a solar cooker integratedvacuum-tube collector with heat pipes containing different refrigerants.Solar Energy 76 (6), 751–757.
[19] Watmuff, J.H., Charters, W.W.S., Proctor, D., 1977. Solar and windinduced external coefficients for solar collectors. COMPLES 2, 56.
[20] Hollands, K.G.T., Unny, T.E., Raithby, G.R., Konicek, L., 1976. Freeconvective heat transfer across inclined air layers. Jounal of HeatTransfer 98, 189–193.
[21] Imura, H., Kusada, H., Oyata, J., Miyazaki, T., Sakamoto, N., 1991. Heattransfer in two-phase closed-type thermosyphons. Transactions ofJapan Society of Mechanical Engineers 22, 485–493.
[22] J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, John Wiley, New York, 1991.