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ENGINEERING FACTORS AFFECTING THE OUTLET WATER TEMPERATURE OF SOLAR WATER HEATER

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ABSTRACT

The application of solar energy as a clean renewable source of energy in agricultural purposes has the major interest worldwide especially in countries with a high solar insolation. The aim of this study was to investigate the effect of some factors ; solar radiation incident, water flow rate, water inlet temperature, ambient air temperature and absorber plate temperature on outlet temperatur of the operating fluid. A solar heating system icludes a solar collector has an area of 2 m^2, an insulated storage tank, a heat exchanger, a fluid distribution system and a control system was constructed and installed in Densosher village, El-Mehalla ElKobra, Gharbia Governorate at a latitude angle of 30.9 N^o. The collected data for this research restricted between 15 August and 25 September 2010. The statistical analysis, forward stepwise regression, revealed that the water inlet and the absorber plate temperatures had the major effect on the water outlet temperature as compared with the other parameters.

INTRODUCTION

Flat plate solar collectors used in many applications; heating, cooling, strelization root media. The solar energy absorbed by the plate is transferred to the operating fluid in the collector tubes. To optimize the absorption of the solar radiation which depends on the temperature level required for the specific application and the climatic conditions of the site of installation.

One of the factors is the outlet temperature from solar collector which determined the application what used. The factors which affect the outlet temperature can be classified into two categories; control factors and the environmental factors.

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The control factors are the parameters which can be specified freely by a designer such as: inlet fluid temperature and difference between inlet and outlet fluid temperature. The environmental factors are the parameters that are not under a designer's control such as: solar radiation and ambient air temperature. Considerable effort has been expended over the years to improve and increase thermal efficiency and the output temperatures of flat plate solar collectors. This effort has been made with several goals in mind. One is to store heat more efficiently for use during nights and cloudy days when stored as latent heat, a high temperature contains more calories per gram of matter. A second goal is to increase the temperature so that other tasks than simply providing hot water are possible, (**Meinel and Meinel, 1979).**

Abdellatif (1985) employed a solar panel for heating water at 51^{o} N latitude angle (Wye, England) in order to utilize the stored solar energy in the storage tank for solution heating in Nutrient Film Technique lettuce production inside a greenhouse. The results revealed that, the solar energy system provided 29.3%, 58.7% and 72.8% for winter, spring and summer crops, respectively. Most solar energy systems are capital intensive; therefore care has to be taken with system design to achieve the optimum configuration. General solar system design procedures have often been resulted from experience gained in the construction and operation of several systems. However, this has normally taken a number of years to develop an acceptable method. The solar energy for agricultural applications is strongly dependent upon the development of solar energy systems that have optimum performance, good reliability, and economic characteristics**.**Any blackened flat plate exposed to strong solar radiation will absorb energy and its temperature will rise above that of its surroundings. When the fluid is circulated through suitable paths formed in the plate or allowed to run over the surface of the plate; some of the absorbed energy will be transferred to the fluid as a useful heat gain. The rest of the absorbed energy will be dissipated to the surroundings through radiation, convection, and conduction heat transfers. The thermal performance of solar water heaters is influenced by the mass flow rate of water which is circulated through the solar system **(George et al., 1980; Jesch and Braun, 1984; and Fanney and**

Klein, 1988). Operating and environmental parameters affecting the thermal performance of flat plate solar collectors were also investigated by **Abdellatif et al. (1990).** The specific conclusions they obtained were 1) As the water volume inside the solar collector per unit area of absorber black plate increased, the heat transfer rate was increased and rate of absorbed thermal energy converted into useful heat gain to storage was thus increased. 2) As the length of the water column passing through the solar collector reduced, the operating temperature was reduced making the heat transfer between the water and absorber plate more efficient. **3)** As the solar collector situated inside the polyethylene shade was sheltered from the effect of wind, the thermal performance of the solar system was more efficient than the other system located outside.**Li and Wang (2002)** proposed a new flat plate solar hybrid system for heating and cooling. They reported that this new hybrid machine will be of high efficiency of solar energy conversion, and a good choice for the utilization of solar energy with solar irradiance intensity of 18-22 MJ/m^2 (5-6.1 kWh/day).**Kalogirou (2003)** mentioned that flat plate collectors are usually permanently fixed in position and require no tracking of the sun. The collectors should be oriented directly towards the equator, facing south in the northern hemisphere and north in the southern. The optimum tilt angle of the collector is equal to the latitude of the location with angle variations of 10-15° more or less depending on the application. **Abdellatif et al. (2006a,b)** compared two similar solar water heaters of flat plate type under clear sky conditions to investigate the effect of orientation and tilt angles, and water inlet temperature on the thermal performance. They revealed that, the solar water heater which was oriented and tilted to track the sun's rays once each half hour from sunrise to sunset was an average 20.98 % more efficient than a startionary non-tracking solar heater. The obtained results also showed that, the water inlet temperature was directly proportional to the solar energy system heat losses and consequently it was inversely proportional to the overall thermal efficiency. As the water inlet temperature increased; firstly, the operating temperature of the absorber plate increased above the ambient air temperature surrounding the solar panel and thus heat losses increased; secondly, the difference in temperature between the absorber plate and the water reduced, making the heat transfer less efficient. For these reasons the daily average heat transfer efficiencies for the two solar panels using two different water inlet temperatures (29.5 and 18.8° C) were 81.12 % and 91.47%, consequently 18.88 % and 8.53% of the absorbed solar energy were lost, respectively. **Sozen et al. (2008)** used the flat-plate solar collectors to heat water by circulating fluid to a temperature considerably less than that of the boiling point of water and are best suited to applications where the required temperature is 30-70°C. Integral closed circuit (pressurized) stainless steel storage tank with natural thermo-siphon system. A closed circuit solar water heater system is a system where the storage tanks' water is circulated directly from the storage tank through the solar collector. They also indicated that calculation of performance of the solar thermal collector is very complex and based on different working angles and parameters. These angles such as: altitude, azimuth, solar declination, incidence and collector tilt angles. Also, they added that the efficiency of flat-plate solar collector depends on many parameters including mean ambient temperature, date, time and solar radiation.**Nuntaphan et al. (2009)** used a collector area about 4 m^2 and volume of water in the storage tank ranged between 100 and 300 Liter with the mass flow rate between 6 and 12 l/ min. They found that a single solar collector can produce approximately 48-56°C hot water with an average solar radiation of 600-700 W/ m^2 at a mass flow rate of 0.2 kg/s. Their results further showed that the higher water volume exhibited the lower water temperature and the mass flow rate of water had no effect on the water temperature under these conditions. From the previous litterature, there are many factors affecting outlet fluid temperature. Therefore, the objectives of this research are to:

1- Study the factors which affect the outlet fluid temperature such as: solar radiation, water flow rate, water inlet temperature, ambient air temperature and absorber plate temperature.

2- Determine the mathematical relationships between these parametersu using SAS static programme.

MATERIALS AND METHODS

The solar energy system was designed and constructed in a private workshop, and installed on the roof of house at Denosher village, El-Mehalla El-Kobra, El-Ghrabia Governorate (latitude angle of 30.9 ^{o}N) as shown in Fig.(1). The experiments were carried outf from 15th August until 25th September 2010. The solar energy system include a solar collector, an insulated heat storage tank, a heat exchanger, a fluid distribution system and a control system. The solar collector consisted of five components (collector box, absorber plate, copper pipes, insulation material, and glass cover), as mentioned by **Darwesh (2010).** Three different volumes of water (40, 150 and 240 liters) and three different mass flow rates (0.033, 0.125 and 0.200 kg/s) were used during the experimental period. This volumes depended upon the number of circulation rate per hour through solar collector according the following equation balance:

$$\frac{(\dot{m}_1 \times t)}{m_1} = \frac{(\dot{m}_2 \times t)}{m_2} = \frac{(\dot{m}_3 \times t)}{m_3} = N \qquad (1)$$

Where:-

$\dot{m}$ = mass flow rate ($\dot{m}_1$ = 0.033, $\dot{m}_2$ = 0.125, $\dot{m}_3$ = 0.200 kg/s) of operating fluid

t = time (s)

m = mass of water in the storage tank (m_1 =40, m_2 =150, m_3 = 240 liters)

N= the mass unit of water which circulates in the solar collector, dimensionless

Instrumentation

1. Temperature: two data loggers each having eight channels were used to meausre different temperatures. Each data logger has a keyboard, a monitor, a programmed card and controllers. The two data-loggers were connected with fourteen sensors (therimstors type) to measure the temperature at selected positions in the solar energy system as demonstrated in Fig.(2). The data were updated by a scan of all the sensors every to second, and the mean of 600 scans was reached each on a computer.

2.Solar radiation: A pyranometer, Kipp and Zohne, Holand was used to measure the solar radiation flux incident on a horizontal surface. The device has an output of approximately 0.5 mV per 100 W/m^2. The expected solar radiation was in the range of 0 -1100 W/m^2. The solarimeter was connected to a voltammeter device to measure the solar radiation flux incident on any surface in W/m^2, as illustrated in Fig. (3).

The experiments were carried out to study the effect of some operating parameters on the water outlet temperature of the solar collector. Four sunny days were selected for each flow rate. Each experimental day started from 9 am till 4 pm.

Temperature Measurements

The temperatures at different locations of solar energy systems were measured and recorded as shown in Figs. (1 and 4). These measurements include: glass cover, absorber plate, outlet, inlet of water and storage tank. Some points took three sensors according to the nature and importance of this part. Three sensors were used to the absorber plate temperature, and the average of three temperatures was taken in the calculations.

Solar collector measurements:

To measure factors which affecting outlet water temperature should be calculated some values as following:

- Avilable solar energy (Q): which could be calculated as a function of solar radiation flux incident (R) and solar heater surface area (A_C) as follows:

  $Q = RA_C$, W...(2)

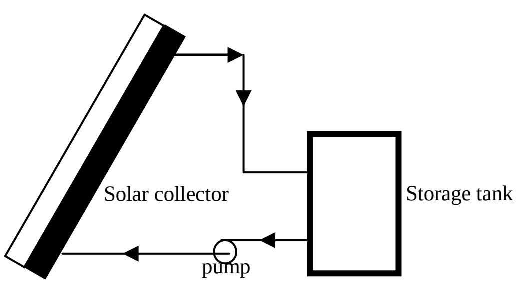

Fig. (1): Schematic diagram of the solar energy system using the forced how system

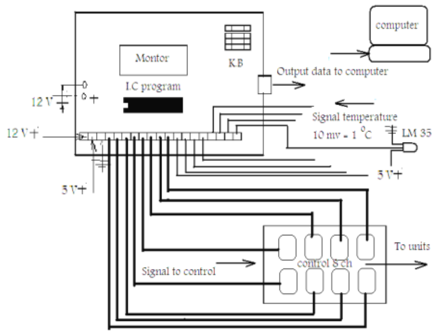

Fig.(2):Schematic diagram of each data logger with the computer.

Fig. (3): The pyranometer device and digital voltammeter used to measure the solar radiation flux incident.

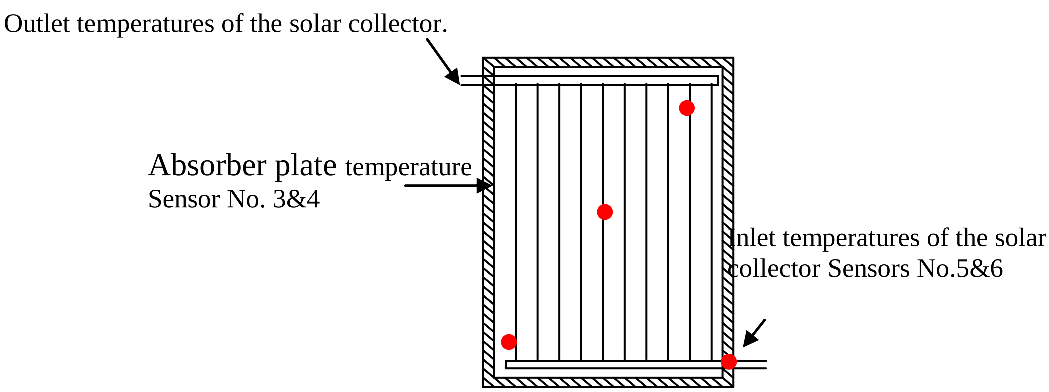

Fig. (4): Distribution of sensors on the solar collectors.

The useful heat gain (Q_C): which represents the rate of extraction of heat from the collector may be measured by means of the amount of heat carried away in fluid passed through it, as follows

$Q_C = m\, C_P\, (T_{fo} - T_{fi})$, W...(3)

Where:

m =	mass flow rate of fluid,	kg/s
C_P =	specific heat of fluid,	J/kg/°C
T_{fo} =	outlet temperature of fluid,	°C
T_{fi} =	inlet temperature of fluid,	°C

Overall thermal efficiency (η_o): which defined as the ratio of the useful energy gain (Q_C) to the incident solar energy over a particular time period as follows:

$$\eta_o = \frac{Q_C}{Q} \times 100 \quad ....(4)$$

Temperature rise (D_T): which equal the different between fluid inlet temperature (T_{fi}) and the ambient air temperature (T_a) divided by solar energy flux incident, can be determined from the following equation:

$$D_T = \frac{(T_{fi} - T_a)}{R} \quad , \quad m^2\,.°C/W.............. ....(5)$$

Statistical analysis:

The recorded data were statistically analyzed using the SAS statistical Package Version 8.2 with the procedure of regression. The Forward, backward and mixed multiple regression models were applied to determine the best model for demonstrating the relationship between the outlet water temperature as a function of the solar radiation flux incident on the absorber plate, inlet water and ambient air temperatures.

RESULTS AND DISCUSSION

The mean values for the four days were calculated for different mass flow rates to investigate the relationship between all variables studied in this resarch. The obtained data are listed and summerized in Table (1) and depicted in Figs.5, 6,7 and 8 for the three different mass flow rates, respectively. The results of the regression analysis are shown Fig.9 .

Table (1). Hourly average solar radiation flux incident (R), absorber plat (T_P), ambient air (T_a), inlet water (T_{fi}), outlet water (T_{fo}) temperatures, difference between outlet and inlet water temperatures (dT) for the three different mass flow rates, normalized temperature rise (D_T) and overall thermal efficiency, (η_o). m².°C/W

Time	R, W/m²	T_P, °C	Ta, °C	T_{fi}, °C	T_{fo}, °C	dT, °C	DT, m².°C/ W×10⁻²	η_o, %
Mass flow rate, 0.033 kg/s								
9	657.0	68.0	29.9	50.0	55.9	5.9	3.059361	70.55
10	785.5	77.1	32.5	55.9	62.2	6.3	2.978994	70.09
11	896.8	86.3	33.8	62.1	70.7	8.6	3.155665	71.04
12	893.3	94.0	34.9	70.7	79.1	8.4	4.007612	70.25
13	841.6	101.8	32.7	79.0	87.2	8.3	5.501426	68.82
14	723.4	108.6	33.1	87.2	94.9	7.7	7.478573	63.60
15	512.4	110.3	31.8	94.9	100.5	5.6	12.3146	55.90
16	337.0	107.8	27.4	100.5	103.2	2.7	21.69139	41.84
Mass flow rate, 0.125 kg/s								
9	662.0	65.3	24.9	50.0	51.4	1.4	3.791541	62.86
10	797.8	69.8	26.5	51.4	53.3	1.9	3.121083	65.14
11	969.7	75.8	26.0	53.2	55.6	2.4	2.804991	66.23
12	995.7	77.9	25.9	55.5	58.0	2.4	2.972783	66.43
13	896.8	78.5	24.9	57.9	60.1	2.2	3.67975	63.38
14	747.9	77.3	24.3	60.1	61.9	1.9	4.786636	63.72
15	504.8	73.4	22.6	61.9	63.0	1.1	7.785261	49.03
16	347.7	69.1	21.2	62.9	63.3	0.4	11.9931	32.32
Mass flow rate, 0.200 kg/s								
9	628.4	64.0	26.3	50.0	51.1	1.1	3.771483	86.88
10	762.8	68.1	27.7	51.0	52.3	1.3	3.054536	90.08
11	908.1	73.7	27.5	52.3	53.9	1.6	2.730977	92.41
12	924.8	75.6	26.8	53.9	55.5	1.6	2.930363	91.00
13	836.3	74.9	27.4	55.4	56.9	1.5	3.348081	90.25
14	660.3	71.6	27.4	56.9	58.0	1.2	4.467666	79.97
15	505.3	69.9	26.2	58.0	58.9	0.9	6.293291	67.39
16	299.3	65.3	23.3	58.8	59.3	0.5	11.86101	44.24

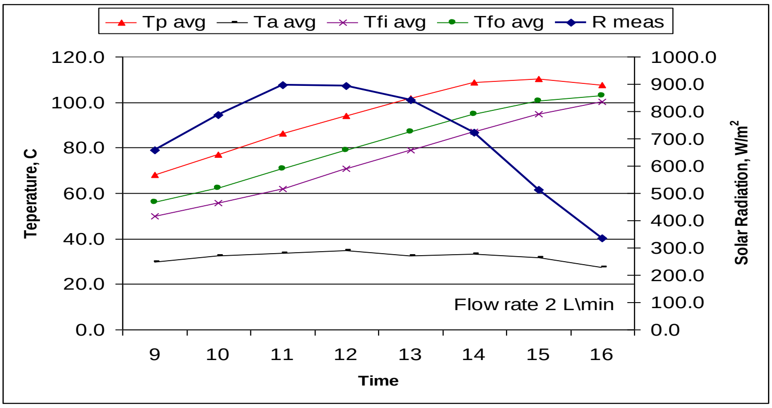

Fig.(5): Hourly average temperatures and solar radiation incident for the mass flow rate 0.033 kg/s throughout the day.

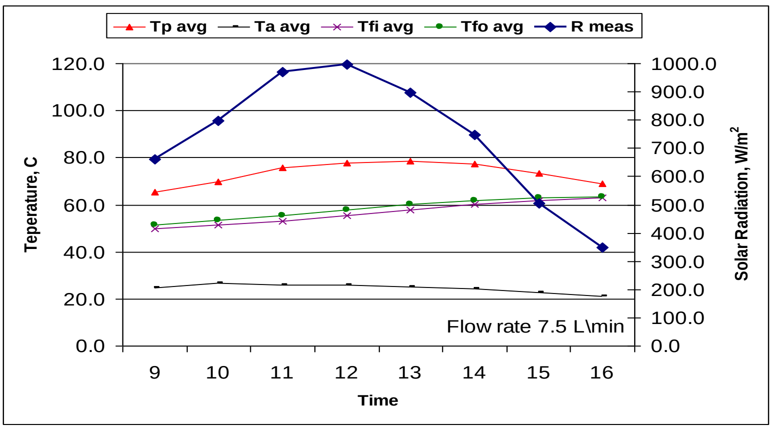

Fig.(6): Hourly average temperatures and solar radiation incident for the mass flow rate 0.125 kg/s throughout the day.

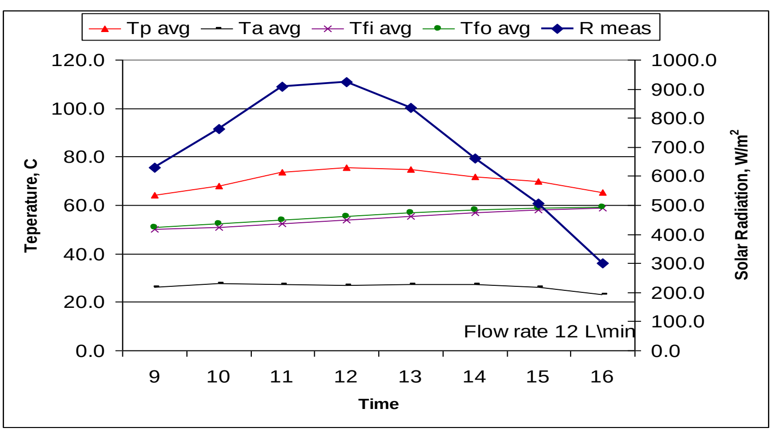

Fig.(7): Hourly average temperatures and solar radiation incident for the mass flow rate 0.200 kg/s throughout the day.

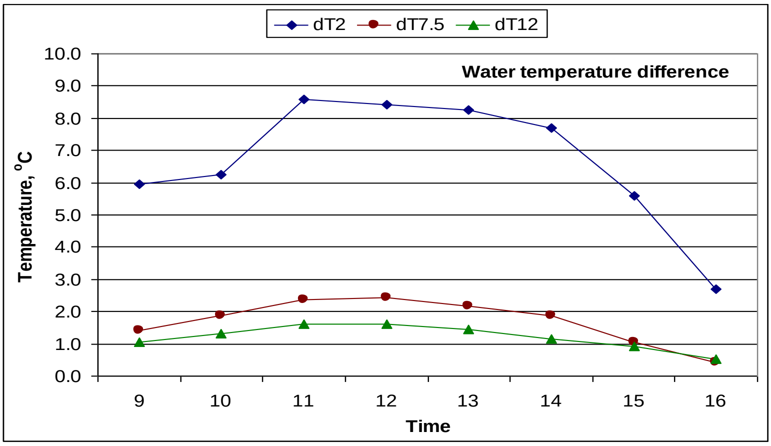

Fig.(8): The average temperature differences between the water outlet and inlet temperature for three flow rates throughout the day.

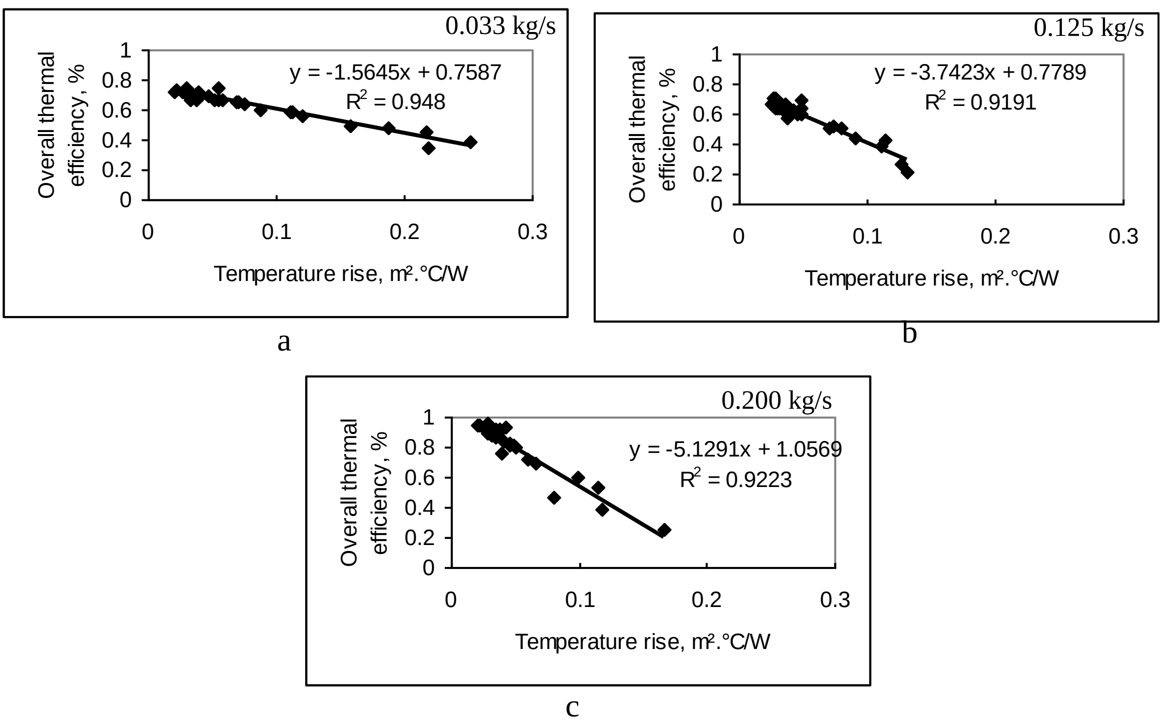

Fig. (9 a, b, c): Overall thermal efficiency against temperature rise for different mass flow rates.

The hourly average solar radiation shown in Fig. (5) and Table (1) for the mass flow rate of 0.033 kg/s was 657 W/m^2, and increased gradually until reached 893.3 W/m^2 at noon. Then it declined till reached 337 W/m^2 at 4 pm. While, the absorber plat temperature at 9 am was 68 ^{o}C and gradually increased until reached its maximum temperature (110.3 ^{o}C) at 3 pm then decreased. The outlet water temperature at 9 am was 55.9 ^{o}C, and staidly increased till the end of the daylight (109.3 ^{o}C).It was observed that, the outlet water temperature almost in parallel with the inlet water temperature.

The data depicted in Fig. (6) and listed in Table (1) for the mass flow rate of 0.125 kg/s revealed that the hourly average solar radiation incident was 660 W/m^2, and increased gradually until reached 896.8 W/m^2 at noon. Then it decline till reached 347.7 W/m^2 at 4 pm. While, The absorber plat temperature at 9 am was 65.3 ^{o}C and increased gradually until reached its maximum temperature 78.5 ^{o}C at noon then decreased. The outlet water temperature at 9 am was 51.4 ^{o}C and staidly increased till the end of the day-light 63.3 ^{o}C .

The data for the mass flow rate of 0.200 kg/s are presented in Table (1) and Fig. (7). It is clear that the average solar radiation incident increased from 628.2 to 924.8 W/m^2 at noon then decreased throughout the rest of the day. However, the absorber plate temperature raised from 64 to 75.7 ^{o}C also at noon then decreased untill the end of the day. While, the water outlet temperature increased gradually from 51.1 to 59.3 ^{o}C at the end of the day.

It is obviously showed that the mass flow rate of 0.200 kg/s gained the most of the solar radiation flux incident on the absorber plate, than that of the other flow rates. The difference between outlet and inlet water temperature is shown in Table (1) and Figure (8). It was observed that increasing the flow rate led to minimize the difference between outlet and inlet water temperature.

The overall efficiency of the solar collector is a combination of absorption and heat transfer efficiencies. For the duration of the experimental work, the daily average overall thermal efficiency for 15 August and 25 September 2010 for 0.033, 0.125 and 0.200 kg/s was 64.01, 58.63 and 80.27%, respectively. The overall thermal efficiency of the solar collector (η_o) was plotted as a function of the temperature rise D_T to examine their relationships with different mass flow rates as shown in (Fig.9). The overall thermal performance of the solar collector can be represented as:-

$$\eta_o = F_R (\tau\alpha) - U_o F_R \left[\frac{T_{fi} - T_{fo}}{R}\right] \text{..........} (6)$$

$$\eta_o = F_R (\tau\alpha) - U_o F_R (D_T) \text{..........} (7)$$

$$\eta_o = a - b (D_T) \text{..........} (8)$$

Equation (6) is certainly the numerical representation of equations (9), (10) and (11). The y-intercept (a) is represent and equal to the product of the heat removal factor (F_R), transmittance of the glass cover (τ), and absorptance of the absorber black plate (α). The slope (b) is symbolize and equal the product of the heat removal factor and overall heat transfer coefficient (U_o). The plot of overall thermal efficiency against temperature rise during the experimental work was straight line with y-intercept $F_R (\tau\alpha)$ and slope ($-F_R U_o$). The regression analysis also clarified that the highest R^2 was recorded with 0.033 kg/s mass flow rate but the overall thermal efficiency was low. This may have been a result of the higher outlet water temperature with this treatment.

Regression analysis revealed a high significant linear relationship between temperature rise and overall thermal efficiency atdifferent mass flow rates as follows:-

$$\eta_o = 0.7587 - 1.5645 \text{ X at } \dot{m}_1 = 0.033 \text{ kg/s..........} (9)$$

$$\eta_o = 0.7789 - 3.7423 \text{ X at } \dot{m}_2 = 0.125 \text{ kg/s..........} (10)$$

$$\eta_o = 1.0569 - 5.1291 \text{ X at } \dot{m}_3 = 0.200 \text{ kg/s..........} (11)$$

The multiple regression analysis for the data (forward, backward and mixed regression analysis was performed to drive a relationship between the outlet water temperature and the other measured factors; solar radiation incident, absorber plate, ambient air and inlet water temperatures for the three flow rates. The output result of the forward regression analysis pointed out by evaluating the data by its effect on the model, it firstly got out the best 1-variable model with entering the inlet water temperature and the corresponding R^2 value was 0.974 with single liner regression equation:

T_{fo} = 1.0899 T_{fi} - 2.38356...(12)

The best 2-variable model when the absorber plate temperature entered to the previous one. The R^2 was 0.986 with the multiple regression equation:

Tfo = 0.819 T_{fi} + 0.288 T_p – 8.455..(13)

The best 3-variable model was achieved when the ambient air temperature entered the model. It increased the coefficient of determination R^2 to value of 0.9898. The regression equation was:

T_{fo} = 0.884 T_{fi} + 0.192 T_p + 0.2505 T_a – 11.76............................(14)

The analysis revealed that when the all variables were entered in the model, the coefficient of determionation (R^2) was 0.9902 with a regression equation of:

Tfo = -0.0035 R + 0.2989 T_p + 0.443 T_a + 0.767 T_{fi} – 10.316.....(15)

The multiple regression analysis showed the all possible combination could be taken from all variable and are showed in Table (2).

Table (2): The multiple regression analysis for all possible combination taken from all varaibles

No. of variable in Model	**R-Square**	**Variables in Model**
1	0.9743	T_{fi}
1	0.8957	T_p
1	0.1692	T_a
1	0.0645	R
2	0.9861	T_p ,T_{fi}
2	0.9860	T_a ,T_{fi}
2	0.9821	R, T_{fi}
2	0.9770	R, T_p
2	0.8985	T_p, T_a
2	0.3173	R, T_a
3	0.9898	T_p, T_a, T_{fi}
3	0.9881	R, T_a, T_{fi}
3	0.9867	R, T_p ,T_{fi}
3	0.9782	R, T_p, T_a
4	0.9902	R, T_p, T_a ,T_{fi}

CONCLUSION

The obtained data of this experimental work can be summarized and concluded as follows:

1- The 0.033 kg/s mass flow rate produced the highest outlet water temperature103.2 °C, while 0.125 and 0.200 kg/s produced 63.3 and 59.3 °C, respectively.

2- The results of the regression analysis indicated that, under the experimental conditions, it is possible predict the outlet water temperature by measuring both the inlet and the absorber plate temperatures.

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الملخص العربى

دراسة لبعض العوامل المؤثرة على درجة حرارة المياه الخارجة من المجمع الشمسى

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تستخدم الطاقة الشمسية كمصدر نظيف للطاقة المتجددة في الأغراض الزراعة في معظم دول العالم الكبرى وخاصة في البلدان ذات الطاقة الشمسية العالية. ويتضمن النظام الشمسي المستخدم مجمع للطاقة الشمسية تبلغ مساحته ٢ متر مربع ومبادل حراري ، السائل المار مياه ونظام تحكم. أجريت الدراسة في قرية دنوشر بالمحلة الكبرى بمحافظة الغربية عند خط عرض ٣٠.٩° شمالا في الفترة من ١٥ أغسطس حتى ٢٥ سبتمبر ٢٠١٠ .

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وكان الهدف من هذه الدراسة هي دراسة تـأثير بعض العوامل عند تثبيت درجة حرارة دخول المائع في بداية التشغيل مثل : الإشعاع الشمسي الساقط ، ومعدل تدفق المياه ودرجة حرارة الهواء المحيط و درجة حرارة السطح الماص للمجمع على درجة حرارة خروج الماء من المجمع .

حيث تم تثبيت درجة حرارة دخول المياه عند درجة حرارة 50 °C وذلك تحت ثلاث معدلات تدفق هي :- 0.033, 0.125 and 0.200 kg/s.

وكانت أهم النتائج المتحصل عليها هي:-

١- أمكن الحصول علي أعلي درجة حرارة للمائع عند خروجه من المجمع الشمسي عند معدل تدفق قدره 0.033 kg/s حيث كانت درجة الحرارة 103.2 °C بينما كان الفاقد في الطاقة الحرارية كبيرا حيث بلغت الكفاءة الحرارية للنظام ٦٤.٠١% عند نفس معدل التدفق.

٢- أن تحليل الانحدار الإحصائي أوضح أن درجة حرارة دخول المياه ودرجات الحرارة للسطح الماص كان لهما الأثر الأكبر على درجة حرارة خروج المياه من المجمع أكثر من العوامل الأخرى. وكانت المعادلة المتحصل عليها هي:-

$$Tfo = -0.0035\ R + 0.2989\ T_p + 0.443\ T_a + 0.767\ T_{fi} - 10.316$$