Experimental and Theoretical Study of a Parabolic Trough Solar Collector

Tadahmun Ahmed Yassen
Mechanical Engineering Department
Collage of Engineering - University of Tikrit
Email: tadamun_77@yahoo.com

Received on : 11/11/2010 ***Accepted on :3/4/2012***

ABSTRACT

An experimental and theoretical study has been conducted to determine the thermal efficiency of a parabolic trough solar collector. The experiments have been performed during winter and summer at Tikrit-Iraq. The solar radiation of Tikrit University was calculated theoretically and a theoretical study was performed by using FORTRAN 90 program. The dimensions and specifications of the collector were entered to the program to determine the theoretical thermal efficiency. It has been found the experimental thermal efficiency of collector is less than the theoretical one in percentage between (7-15) .So the increase in water mass flow rate leads to an increase in the thermal efficiency, and there is no significant change in thermal efficiency when the water mass flow rate becomes more than forty kilograms per hour.

Key words: solar collector, parabolic trough, efficiency

1. INTRODUCTION

Solar energy is a permanent, none polluting and low running cost source of energy. Flat plate collectors were used for low temperature applications. Many industrial applications require high order energy levels in temperature ranges more than 100°C, which can be obtained by using concentrators. A concentrator is used instead of flat plate collectors at high temperatures due to its higher efficiency which referred to small area available for heat losses. Solar concentrators increase the amount of incident energy on the absorber surface as compared to that the concentrator aperture. The increase is achieved by using of reflecting or refracting surfaces which concentrate the incident radiation on to a suitable absorber/receiver.

In 1985 Faik A. Hamad [1] studies experimentally the parabolic trough collector consists of a reflector and absorber. The reflector 1m in length and 1m in width and the diameter of the absorber is 0.0125 m. The researcher found that the collector performance depends mainly on water mass flow rate, and there was no significant change when the mass flow rate becomes more than ten kilograms per hour.

In 1994 Vernon E. Dudley and Gregory J. Kolb in Sandia National Laboratory [2] study theoretically and experimentally the parabolic trough solar collector to determine the collector efficiency and thermal losses with two types of receiver selective coatings combined with three different receiver configurations; glass envelope with either vacuum or air in the receiver annulus, and glass envelope removed from the receiver. The researchers reach to decreased performance when the cermet selective coating, and progressively degraded as air was introduced into the vacuum annulus, and when the glass envelope was removed from receiver.

In 2007 Amirtham .V. Arasu and Samuel .T. Sornakumar [3] using a computer simulation program to modeling a parabolic trough collector with hot water generation system with a well-mixed type storage tank. This is followed by an experimental verification of the model and an analysis of the experimental results. The researchers reach to the experimental thermal efficiency less than the theoretical thermal efficiency by six percent.
Numerical simulation of a parabolic trough solar collector was performed by O. Garcia-Valladares a, , N. Velazquez b in 2009 [4]. The researchers compared between the simulation and the experimental study of Sandia National Laboratory and they concluded that the theoretical efficiency of simulation is larger than actual efficiency of Sandia by about six percent.
The aim of this research is to design the parabolic solar collector and test it in Tikrit city and to assess the efficiency of this type of collectors in Tikrit city.
The experimental results are to be compared with the theoretical results.

3. THEORY

3.1 Calculation of Solar Radiation

The calculation of the total incident solar radiation on an exposed surface involves the determination of the beam and diffuse radiation, which are computed after estimating the solar time and position. As the sun radiation passes through the atmosphere it is attenuated in proportion to the length of its path according to an extinction coefficient B, to produce the normal radiance at the earth surface [9]:

$$I_{DN} = A_1 * \exp(-\frac{P_L}{P_o} * \frac{B}{\sin(\alpha)}) \qquad (1)$$

Where,

$\frac{P_L}{P_o}$ is the pressure ratio at location concerned relative to the standard atmospheric pressure given as:

$$\frac{P_L}{P_o} = \exp(-0.0001184 * H_{alt}) \qquad (2)$$

Where, H_{alt} is the altitude in meters above sea level.

The values of extraterrestrial solar intensity A_1, the atmospheric extinction coefficient B, and sky-diffused factor, C_1, were estimated by Joudi (1988) [10] for any day of the month by the following equations:

$$\mathrm{A}_1 = 1158 * [1 + 0.066 * \cos(360 * \mathrm{ND}/370)] \qquad (3)$$

$$\begin{aligned} \mathrm{B} &= 0.175 * [1 - 0.2 * \cos(0.93 * \mathrm{ND})] \\ &- 0.0045 * [1 - \cos(1.86 * ND)] \end{aligned} \qquad (4)$$

$$\begin{aligned} C_1 &= 0.0965*\left[1 - 0.42*\cos((360/370)*\mathrm{ND})\right] \\ &- 0.0075*\left[1-\cos(1.95*ND)\right] \end{aligned} \tag{5}$$

Where, ND is the number of day in the year.

The sun altitude angle α and declination angle δ are given by (Lunde,1980) [10] as:

$$\alpha = \sin^{-1}(\cos\phi * \cos\delta * \cos\omega + \sin\delta * \sin\phi) \tag{6}$$

$$\delta = 23.45*\sin\left[360*(\mathrm{ND}-80)/370\right] \tag{7}$$

Where,

ϕ is the latitude angle. (equal to 34°21\` for Tikrit city).

ω is the hour angle or solar time angle which is defined as the angle position away from solar noon caused by earth's rotation. This angle is expressed in degree as:

$$\omega = 15*\left[Ast - 12\right] \tag{8}$$

Where Ast is the solar time. It is necessary to convert standard time to solar time by applying two corrections. First, there is a constant correction for the difference in longitude between the observer's meridian location and the meridian on which the local stander time is based; the sun takes four minutes to transverse 1° of longitude. The second correction is from the equation of time, which takes into account the perturbations in the earth's rate of radiation, which affect the time the sun crosses the observer's meridian. Solar time is related to standard time by:

$$\text{Solar time} = \text{Standard time} + E/60 - (L_{st} - L_{loc})/15 \tag{9}$$

Where:

L_{st} is the standard meridian of local time zone for Iraq (it is 45°).
L_{loc} is the longitude location concerned (equal to 45° 45\` for Tikrit city).

Standard time is the local time in hours.

E is the equation of time, which be calculated as [11] :

$$E = \sum_{K=0}^{K=5}\left[A_K \cos\left(\frac{2*\pi*K*N_n}{365.25}\right) + B_K \sin\left(\frac{2*\pi*K*N_n}{365.25}\right)\right] \tag{10}$$

Where,

N_n is the number of the day in a 4-year cycle, with N_n =1 being January 1st of the leap year and N_n=1461 corresponding to December 31 of the 4th year of cycle.

A_k, B_k are constant given in **table (3)**.

The beam irradiance can be computed as:

$$I_b = I_{DN} * \cos \theta_1 \tag{11}$$

The general definition of the incident angle θ_1 for any surface orientation can be expressed as [12]:

$$\begin{aligned}\cos\theta_1 &= \sin\delta * \sin\phi * \cos\beta - \sin\delta * \cos\phi * \sin\beta * \cos\gamma + \\ &\cos\delta * \cos\beta * \cos\phi * \cos\omega + \cos\delta * \sin\phi * \sin\beta * \cos\gamma * \\ &\cos\omega + \cos\delta * \sin\beta * \sin\gamma * \sin\omega\end{aligned} \tag{12}$$

Where:

γ is the surface azimuth angle. That is, the deviation of projection on a horizontal plane of the normal to the surface from local meridian with zero due south.

β slop of the collector.

β=23° in summer

β=45 in winter

The diffuse irradiance on the tilted collector is given by (Lunde,1980) [10]:

$$I_d = I_{DN} * \left[C_1 * \frac{(1+\cos\beta)}{2} + s*(C_1 + \sin\alpha) * \frac{(1-\cos\beta)}{2} \right] \tag{13}$$

Where:

s is the reflectivity of ordinary ground taken as 0.2.

Finally, the total incident solar radiation is the sum of the beam and diffuse intensities;

$$I_t = I_d + I_b \tag{14}$$

3.2 Calculation of Thermal Efficiency

The theoretical useful energy from parabolic trough solar collector calculated by equation writing as [5]:

$$Q_{u,th} = A_{ap} F_R \left[H_{ab} - \frac{A_{r,ext}}{A_{ap}} U_l \left(T_{f,i} - T_{amb} \right) \right] \tag{15}$$

$$A_{r,ext} = \pi D_{r,ext} L \tag{15a}$$

$$A_{ap} = \left(W - D_{r,ext} \right) L \tag{15b}$$

$$H_{ab} = I_b \alpha \rho \qquad (15C)$$

Where:

$\rho =$ reflectivity of the reflector

The overall heat loss coefficient is one of the most important parameters and can be found out through the following equation [5]:

$$U_l = h_w + h_{r,r-a} \qquad (16)$$

The convective heat transfer coefficient h_w between receiver and ambient air due to the wind can be calculated as [6].

$$h_w = \frac{Nu_a k_a}{D_{r,ext}} \qquad (16a)$$

$Nu_a=0.4+0.54 * Re_a^{0.53}$ for $0.1< Re_a < 1000$ (16a1)

$Nu_a= 0.3*Re_a^{0.6}$ for $1000 < Re_a < 50,000$ (16a2)

$$Re_a = \frac{VD_{r,ext}}{\upsilon_a}$$

The radiation heat transfer coefficient between absorber tube and ambient can be writing in equation as [5]:

$$h_{r,r-a} = \varepsilon\sigma(T_r + T_a)\left(T_r^2 + T_a^2\right) \qquad (17)$$

The temperature of the absorber surface can be calculated from the written equation as[13]:

$$T_r = T_{f,m} + \frac{MC_P\left(T_{f,o} - T_{f,i}\right)}{h_{c,i}\pi D_{r,ext}L} \qquad (18)$$

$$T_{f,m} = \frac{T_{f,i} + T_{f,o}}{2} \qquad (19)$$

$$T_{f,o} = T_{f,i} + \frac{Q_u}{MC_p} \qquad (20)$$

The heat removal efficiency factor is given as [5]:

$$F_R = \frac{MC_p}{A_{r,\text{int}}U_l}\left[1-\exp\left(-\frac{A_{r,\text{int}}U_l F^-}{MC_p}\right)\right] \tag{21}$$

For a tubular absorber with inside diameter $D_{r,\text{int}}$ and outside diameter $D_{r,ext}$ having $h_{c,i}$ the convective heat transfer coefficient between absorber and the fluid, the collector efficiency factor is given as [5]:

$$F^- = \frac{1/U_l}{\frac{1}{U_l}+\frac{D_{r,ext}}{h_{c,i}D_{r,\text{int}}}+\frac{D_{r,ext}\ln\left(D_{r,ext}/D_{r,\text{int}}\right)}{2k_r}} \tag{22}$$

The convective heat transfer coefficient is given as [7]:

$$h_{c,i} = \frac{k_w}{D_{r,\text{int}}}\left[3.6+\frac{0.0668\left(D_{r,\text{int}}/L\right)\text{Re}_w\,\text{Pr}_w}{1+0.04\left[\left(\frac{D_{r,\text{int}}}{L}\right)\text{Re}_w\,\text{Pr}_w\right]^{2/3}}\right] \tag{23}$$

Where

$$\text{Re}_w = \frac{u_w D_{r,\text{int}}}{\upsilon_w} \qquad u_w = \frac{M}{\rho_w A_{c,r,\text{int}}} \qquad A_{c,r,\text{int}} = \frac{\pi D_{r,\text{int}}^{\;2}}{4}$$

The actual useful energy obtained from parabolic trough solar collector is given as:

$$Q_{u,\exp} = MC_P\left(T_{f,o}-T_{f,i}\right) \tag{24}$$

The theoretical thermal efficiency is writing as:

$$\eta_{th} = \frac{Q_{u,th}}{I_b A_a} \tag{25}$$

The experimental thermal efficiency is given as:

$$\eta_{\exp} = \frac{Q_{u,\exp}}{I_b A_a} \tag{26}$$

4. DESIGN AND MANUFACTURING SIDES

The solar collector which consists of a parabolic section, reflector and absorber tube, is installed in the focus line of the surface reflector. A parabolic arc was drawn using AutoCAD and the equation ($y=x^2/4F$). Assuming that the length of focus (F = 0.25 m). Length of that parabolic arc was extracted from the drawing as illustrated in **Fig. (2)** . The arc width(W) is calculated using equation of parabolic arc.

Since the arc length (1.1473m), the reflector width (w=1m) and the focal length are known. Therefore a special rolling device has been used to deflect a galvanized steel plate of length (L=1.9m). Referring to **Fig.(3)**, this plate is bended in a curved shape of a parabolic trough. And then covered by a very thin sheet of bright aluminum of reflectivity value (ρ=0.85[5]). The whole arrangements are fitted on a steel frame. This frame allows the reflector to be adjusted and varying its slope, (β). Then a galvanized tube has been selected as a heat collector. This tube has an internal diameter ($D_{r,int}$=0.026m) , external diameter ($D_{r,ext}$=0.03m), absorptivity (α=0.9) [5], emissivity (ε_r=0.9) [5] and conductivity (K_r=54W/m.°c) [5]. This tube is painted with a black color and fixed in the reflector focal zone, in order to receive the solar rays from the reflector.

5. TESTS OF THE MANUFACTURED COLLECTOR

In winter, the solar collector was tested in two clear sky days during January in 2010 (16,24 / 1 / 2010); whereas in the summer, testing was done during two clear sky days on June in 2009 (11,21 / 6 / 2009) located at roof of building of Department of Mechanical Engineering in the Tikrit University. Readings were taken from 8 AM until 4 PM. Temperature of the water inlet and outlet of the absorber and ambient temperature was measured using a calibrated thermocouple of type K connected with a digital thermometer. The absorber was drilled at inlet and outlet to enter thermocouples. Wind speed was measured using Anemometer. The mass flow rate (M) has been measured as follow:

Since mass flow rate = mass/time= (Volume/density)/Time

Volume - has been measured using a scale vessel.

Time - has been counted using a stopwatch.

then mass=Volume (measured)/density

therefore mass flow rate could be counted from the previous measured parameters.

6. RESULTS AND DISCUSSION

Fig.(4) shows change of the thermal efficiency of the solar collector with daylight hours during the days mentioned above. Consideration of the figure explains that the rise of mass flow rate leads to high efficiency (40-65) % for the flow rate values (20.23-100) kg / hr.Furthermore; as well as the figure shows that the minimum efficiency is reached at 8 AM and then rises until mid-day at twelve o'clock AM. Then it begins to descend down up to 4PM.

Fig.(5) shows the comparison between the experimental results of the thermal efficiency and the theoretical results of the thermal efficiency as was calculated for the dimensions and specifications of the device manufacturer by a program written in FORTRAN 90 and as illustrated in the flowchart in **Fig.(9)**. **Fig.(5)** illustrate that the theoretical thermal efficiency is nearly constant during the day hours whereas experimental thermal efficiency increases from 8 AM to noon a maximum value and then descends until 4 PM, the figure shows that the experimental thermal efficiency is (7-15)% less than the theoretical thermal efficiency.

Fig.(6) shows a comparison between the experimental and theoretical useful energy. It can be clearly observed that the experimental is less than the theoretical one in about (60- 80 W/m^2). Also it shows that the useful energy depends on the solar radiation.

The variation of collector efficiency against water mass flow rate is shown in **Fig.(7)**. The efficiency starts from zero when the mass flow rate is zero because the heat removal factor is zero, and it increases quickly till it reaches about (62%) at mass flow rate of 40 kg/hr. That is, the increase of mass flow rate will decrease the absorber tube temperature so that the heat losses decreases and the heat removal factor is improved. The efficiency reaches a maximum at 40 kg / hr mass flow above which no more efficiency increase is observed. These two effects will result in improvement in collector efficiency to a certain value. So the effect becomes unremarkable.

Fig.(8) shows the comparison between the experimental results of the manufactured device and the experimental results of different references. **Table(2)** shows comparison between the intensity of the solar beam, ambient temperature, temperature of the inlet water, mass flow rate and the projected area as presented in the present work and in references [1] and [8]. The figure shows that there is an agreement in the results between the present research and reference [1].

7. CONCLUSIONS

1. The actual thermal efficiency of concentrator is less than the theoretical thermal efficiency in (7-15) percent.
2. No significant change in efficiency when the water mass flow rate becomes more than forty kilograms per hour.
3. The thermal efficiency of collector in winter is more than the thermal efficiency in summer by (2-5) percent.

4. The useful energy gained from collector in summer is (20-60)W/m^2 more than the useful energy gained from collector in winter

8. REFERENCES

[1]. Faik A. Hamad, "The Performance Of Cylindrical Parabolic Solar Concentrator", Solar Energy Res. Vol. 5, No. 2, P.P. (1-19), Basrah, Iraq, 1987.

[2]. V.E. Dudley, G.J. Kolb, A.R. Mahoney, T.R. Mancini, C.W. Matthews, M. Sloan, D. Kearney, Test results: SEGS LS-2 solar collector, Report of Sandia National Laboratories (SANDIA-94-1884), 1994.

[3]. A. Valan Arasu, S. T. Sornakumar, "Theoretical Analysis And Experimental Verification of Parabolic Trough Solar Collector With Hot Water Generation System"، THERMAL SCIENCE: Vol. 11, No. 1, pp. 119-126, 2007.

[4]. O. Garcia-Valladares a,*, N. Velazquez b, "Numerical simulation of parabolic trough solar collector: Improvement using counter flow concentric circular heat exchangers", International Journal of Heat and Mass Transfer 52 (2009) 597–609.

[5]. H. P. Gary and J. Prakash, "Solar Energy Fundamentals and Applications", New Delhe,www.Tata McGraw-Hill.Com, 2005.

[6]. J. A. Duffie and A. Beckman, "Solar Engineering of Thermal Processes", John Wiley & Sons Inc., 2nd Edition, 1991.

[7]. J. P. Holman, "Heat Transfer", McGraw-Hill, Fourth Edition, 1976.

[8]. Ahmed S. Hegazy and Mohamed M. ElMadany, "Design And Testing Of A Solar Parabolic Trough Collector With Its Tracking System For Salt-Water Desalination In Arid Areas Of Saudi Arabia", Proceedings Of The 7th Saudi Engineering Conference (SEC7), 2007.

[9]. Lunde, P.J.; "Solar thermal engineering-Space heating and hot water system", John Wiley and sons, New York, 1980.

[10]. Joudi, K.A.; "Some aspects of solar irradiance calculation, Proceeding of the third Arab international solar water energy conversion, edited by N.I. Al-Hamdani, Naman, S.A., Solar energy research center, Baghdad, 1988.

[11]. Lamm, L.O.; "A new expression for the equation of time", Solar energy, Vol.26, p.456, 1981.

[12]. Duffie, J. and Beckman, W., "Solar energy thermal processes", John Wiley and Sons, New York, 1980.

[13]. G.D. Rai , "Solar Energy Utilization", Delhi-110006(India), Fifth Edition, 1976.

9. NOMENCLATURE

A_{ap} aperture area [m^2]
$A_{c,r,int}$ cross sectional area of receiver due to internal diameter [m^2]
$A_{r,ext}$ external surface area of receiver [m^2]
$A_{r,int}$ internal surface area of receiver [m^2]
C_P specific heat of water [J/kg. °C]
C concentration ratio [dimensionless]
$D_{r,ext}$ external diameter of receiver [m]
$D_{r,int}$ internal diameter of receiver [m]
F^{-} efficiency factor of collector [dimensionless]
F_R heat removal factor of collector [dimensionless]
H_{ab} absorbed radiation [W/m^2]

$h_{c,i}$ convective heat transfer coefficient between receiver and fluid [$W/m^2.°C$]
$h_{r,r-a}$ radiation heat transfer coefficient between receiver and ambient [$W/m^2.°C$]
h_w convective heat transfer coefficient between receiver and ambient [$W/m^2.°C$]
I_b beam solar radiation [W/m^2]
K_a conductivity of air [W/m.°C]
K_r conductivity of receiver [W/m.°C]
K_w conductivity of water [W/m.°C]
L collector length [m]
M mass flow rate [Kg/hr]
Nu_a Nusselt number of air [dimensionless]
$Q_{u,exp}$ experimental useful energy [W]
$Q_{u,th}$ theoretical useful energy [W]
Re_a Reynolds number of air [dimensionless]
Re_w Reynolds number of water [dimensionless]
T_{amb} ambient temperature [°C]
T_r receiver temperature [°C]
$T_{f,i}$ inlet fluid temperature [°C]
$T_{f,m}$ mean fluid temperature [°C]
$T_{f,o}$ outlet fluid temperature [°C]
U_l overall heat loss coefficient [$W/m^2.°C$]
u_w water velocity [m/s]
V wind velocity [m/s]
W collector width [m]

Greek symbols
α absorptance [dimensionless]
Ø aperture angle [rad]
η_{exp} actual thermal efficiency [dimensionless]
η_{th} theoretical thermal efficiency [dimensionless]
υ_a kinematic viscosity of air [m^2/s]
υ_w kinematic viscosity of water [m^2/s]
ρ reflectivity [dimensionless]
σ Stefan–Boltzman constant [5.6697×10^8 W/(m^2 K^4)]

Table (1): Parabolic trough collector specification.

F (m)	Ø (°)	W (m)	A_{ap} (m^2)	L (m)	C	$D_{r,ext}$ (m)	$D_{r,int}$ (m)	ρ	ε_r	K_r (w/m.°c)
0.25	90	1	1.9	1.9	10.3	0.03	0.026	0.85	0.9	54

Table(2): comparison between many parameters for present actual work and references.

	Solar radiation range (w/m^2)	Inlet temp. range(°C)	Ambient temp. range(°C)	Aperture area(m^2)	Flow rate(kg/hr)
Present work	240-950	19-26	12-18	1.9	20.23
Refrence [1]	400-900	20-25	15-20	1	20
Refrence [8]	200-860	23-30	15-18	5.4	290

Table (3): A_k and B_k coefficients for equation (10).

K	A_K	B_K
0	$2.0870*10^{-4}$	0
1	$9.2869*10^{-3}$	$-1.2229 * 10^{-1}$
2	$-5.2258 * 10^{-2}$	$-1.2698*10^{-1}$
3	$-2.1867*10^{-3}$	$-2.9823 * 10^{-3}$
4	$-2.1867 * 10^{-3}$	$-2.9823 * 10^{-3}$
5	$-1.51 * 10$	$-2.3463 * 10^{-4}$

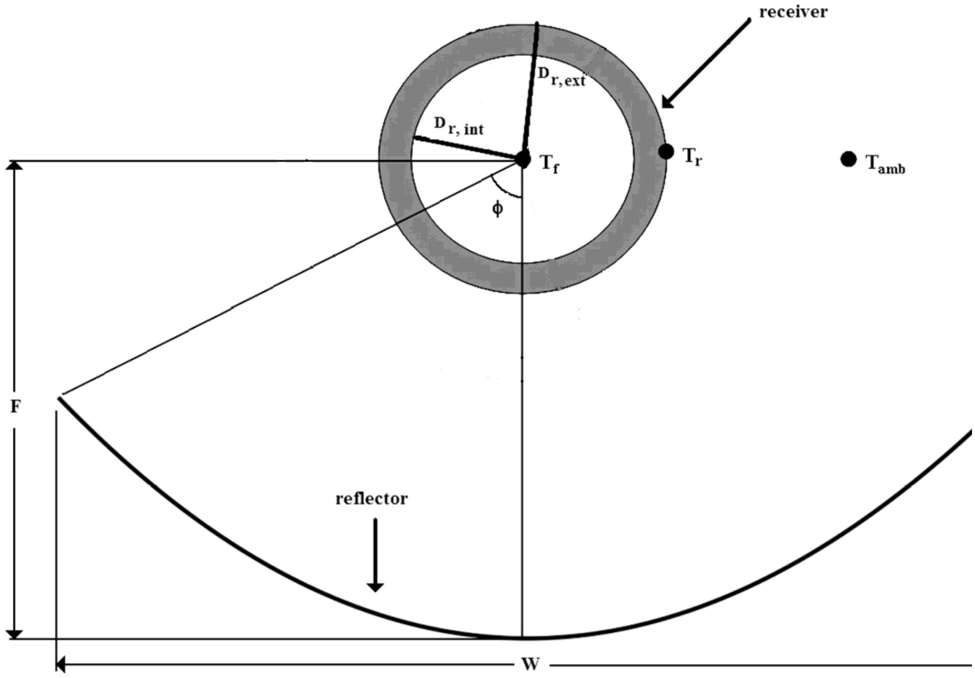


Figure (1): front cross section view of collector.

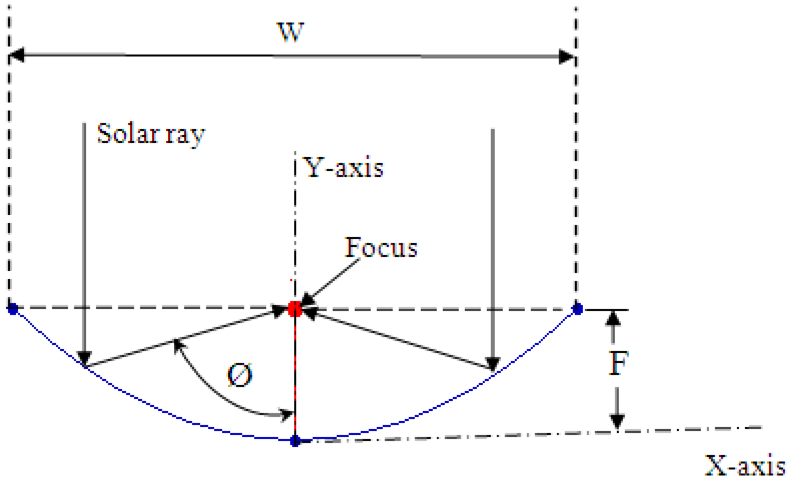


Figure (2): drawing the arc of the reflector.

Figure (3): photograph of the collector.

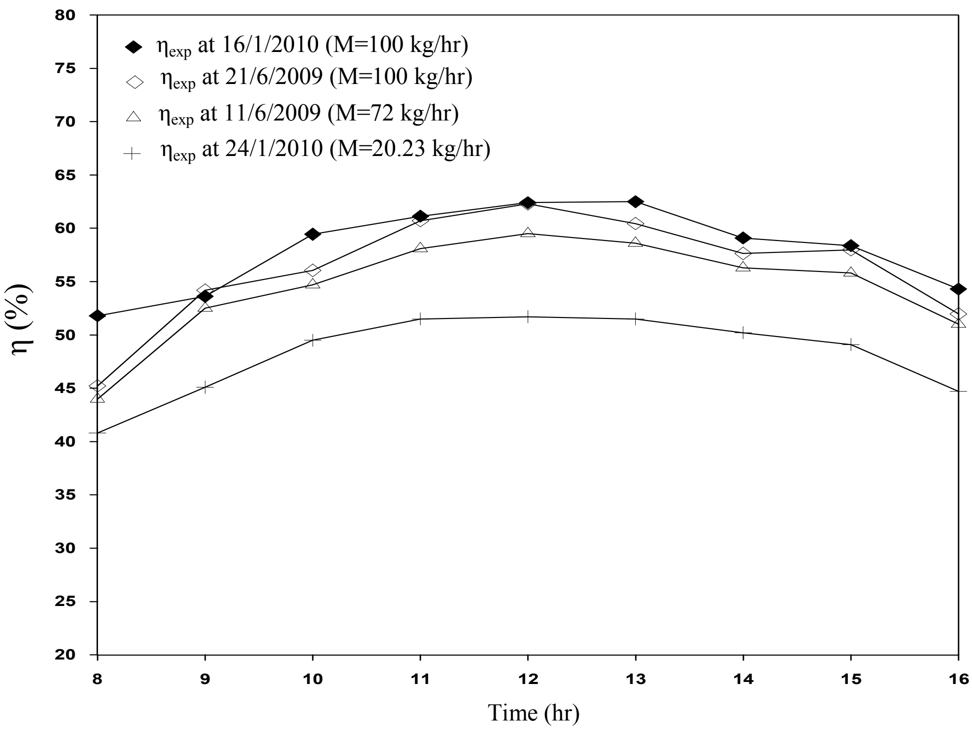
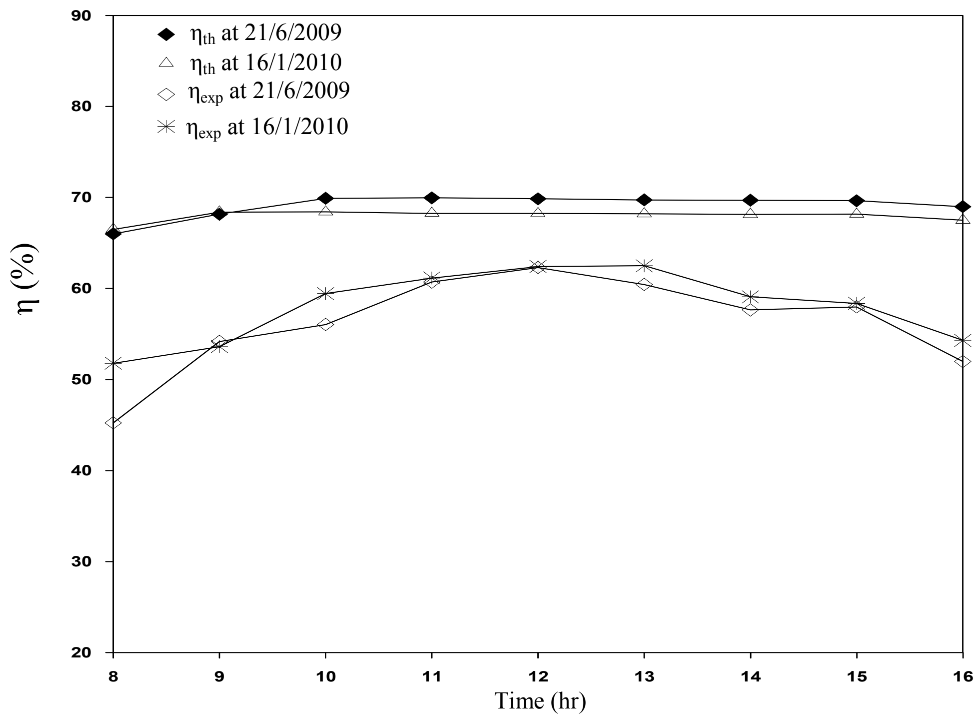
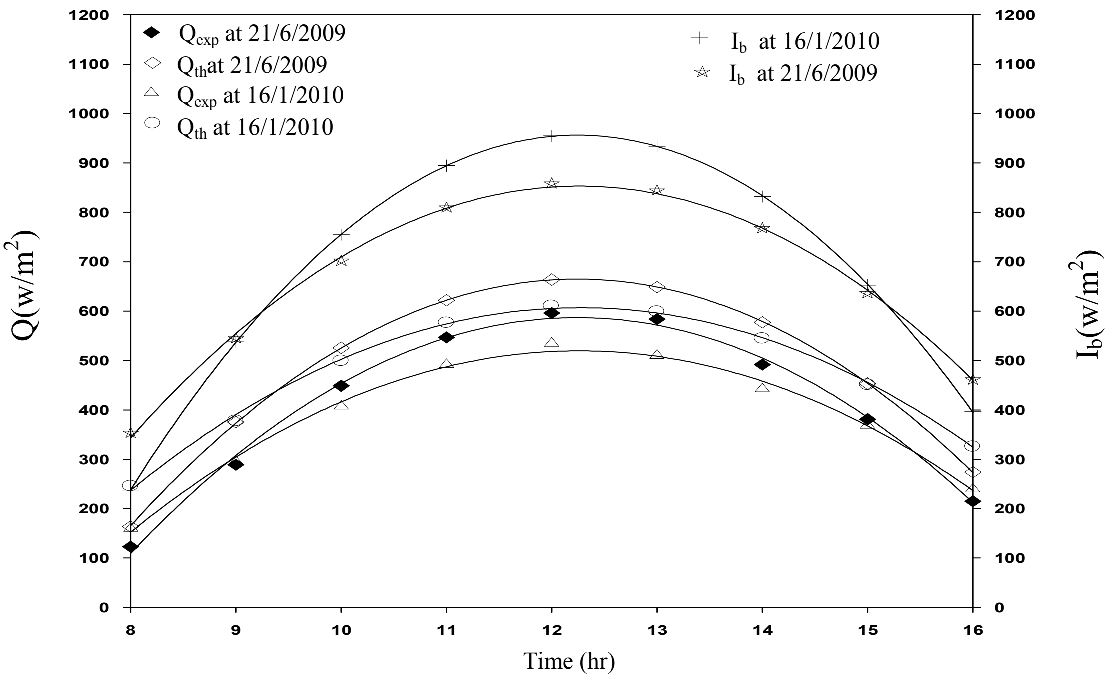


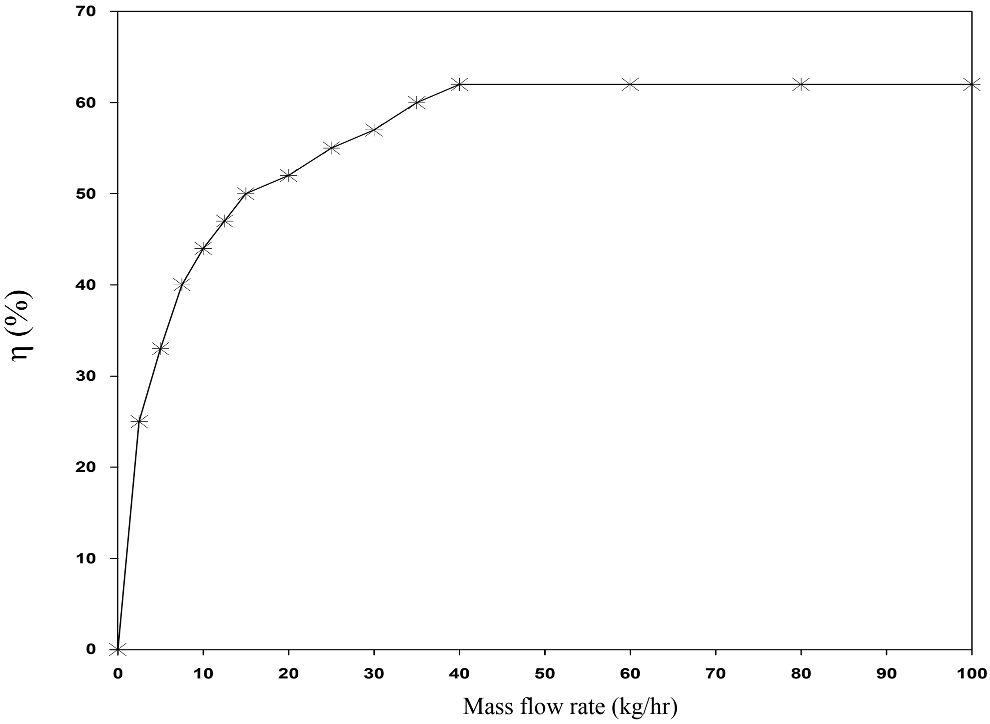
Figure (4): variation of experimental thermal efficiency with hours of winter and summer days.



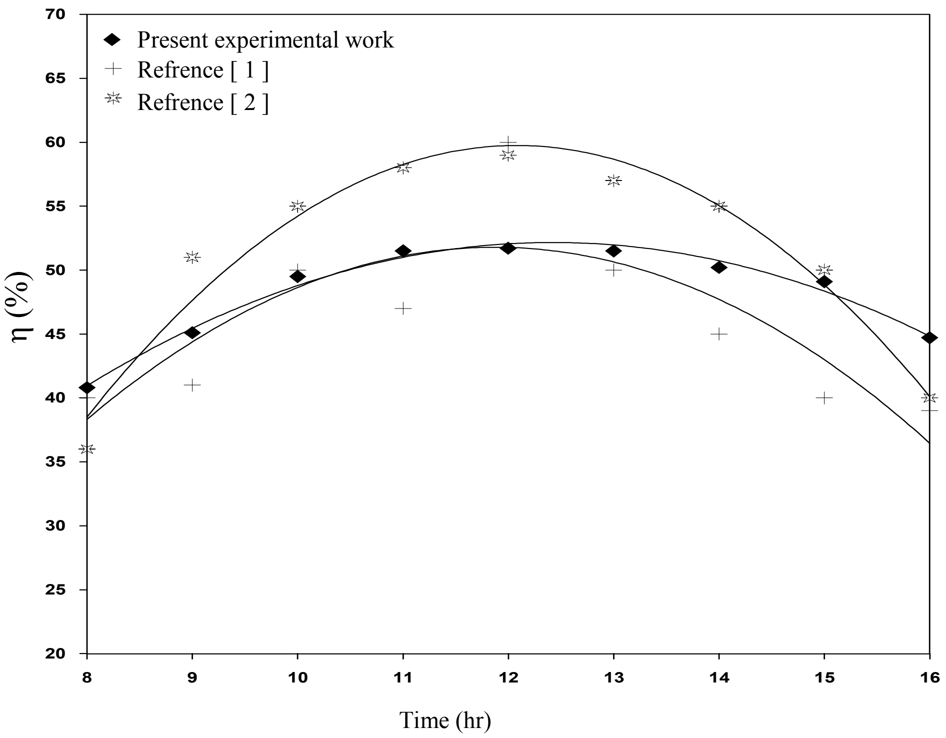
Figure(5): comparison between experimental and theoretical results of the thermal efficiency during selected winter and summer days.



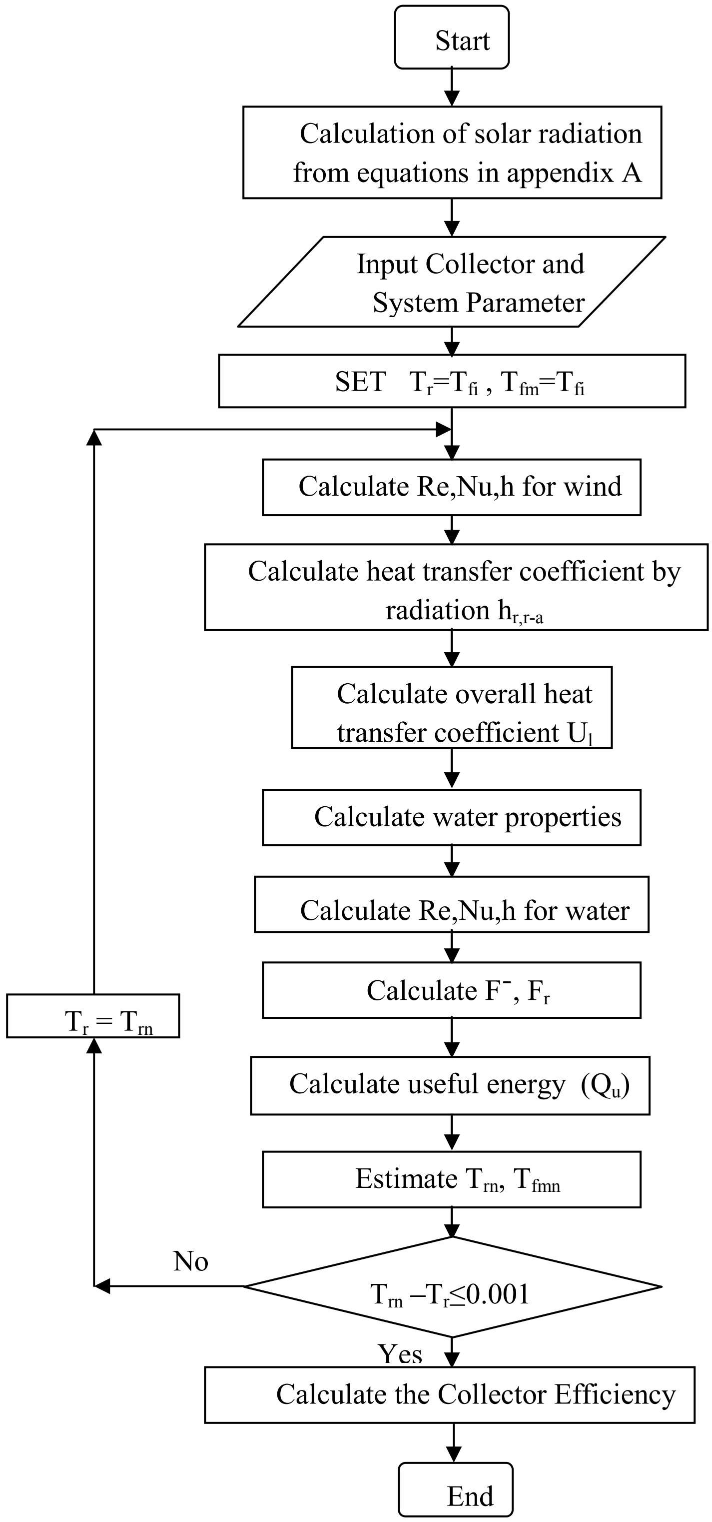
Figure(6): variation of collected useful energy and solar radiation with hours of day.



Figure(7): variation of thermal efficiency of collector with mass flow rate.



Figure(8): comparison between thermal experimental efficiency of present work with other references.



Figure(9): flow chart to calculate theoretical thermal efficiency of parabolic trough collector.

دراسة عملية ونظرية لمجمع شمسي ذي القطع المكافىء

م.م. تضامن احمد ياسين

قسم الهندسة الميكانيكية – كلية الهندسة

جامعة تكريت

الخلاصــة:

درس عمليا ونظريا مجمع شمسي ذي القطع المكافىء لحساب الكفاءة الحرارية. انجزت الدراسة العملية خلال فصل الصيف والشتاء في مدينة تكريت في العراق. الاشعاع الشمسي لمدينة تكريت حسب نظريا. الدراسة النظرية انجزت باستخدام برنامج الفورتران 90 .مواصفات وابعاد المجمع ادخلت الى البرنامج لحساب الكفاءة الحرارية النظرية. وجد ان الكفاءة الحرارية العملية للمجمع اقل من الكفاءة الحرارية النظرية بنسبة تتراوح ما بين (7–15) بالمئة، كذلك وجد ان الزيادة بتدفق الكتلي للماء تقود الى الزيادة بالكفاءة الحرارية ولا يوجد تغير بالكفاءة الحرارية عندما يزيد التدفق الكتلي للماء عن اربعين كيلوا غرام بالساعة.