Theoretical and Experimental Study of The Effect of Concentration Ratio on CTPTC Performance

Ahmed Hasan Ahmed[1], Hussain S. Akbar[2], Ahmad S.Mohamad[2], Raid W. Daoud[1], Zaid H. Ali[1]
Ahmedhassan_hwj@ntu.edu.iq[1], raid_hwj@ntu.edu.iq[4], zaidali_hwj@ntu.edu.iq[5]

1.Northern Technical University, Iraq, 2.Kirkuk University, Physics Dept., Iraq.
Corresponding author: Ahmed Hasan Ahmed, e-mail: Ahmedhassan_hwj@ntu.edu.iq.
Co-authors: RWD: raid_hwj@ntu.edu.iq, ZHA: zaidali_hwj@ntu.edu.iq
Received: 12-08-2021, Accepted: 01-09-2021, Published online: 15-09-2021

Abstract: A Theoretical and practical study was conducted to analyze the performance of a closed type parabolic trough collector CTPTC. The study was conducted in northern Iraq at longitude 43°.53 and latitude 35º.25. Use water as a working fluid at a mass flow rate of 0.00083,0.0011 ,0.00166 ,0.00138 Kg/sec, with a concentration ratio of 10, 14 and 22. The maximum value of experimental efficiency of 42% in the summer and 29% in the Winter. The theoretical study was conducted according to ASHRAE 93-1986 (RA-91). The hypothetical results show that theoretical efficiency starts at 30% and increases relatively with increasing mass flow and decreases with temperature and the concentration ratio to reach a maximum value of 50%in the summer and a maximum value of 68% in the Winter.

Keywords: solar energy, solar collector, concentration ratio, CTPTC.

Nomenclature

Symbol	Description	Unit
I_T	Total solar radiation	w/m^2
A_a	Area collector	m^2
$A_{r,i}$	Inside tube area	m^2
C	Concentration ratio	-
cp_f	Specific heat of the fluid	J/kg.k
cp_r	Specific heat of absorber	J/kg.k
$D_{r,o}$	The outside diameter of the absorber	m
$D_{r,i}$	Inside diameter of the absorber	m
F'	Collector efficiency factor	-
F_R	Heat removal factor	-
$h_{c,i}$	Inside convection heat transfer coefficient	$w/m^2°C$
$h_{rad,r-sky}$	Radiation heat transfer coefficient	$w/m^2°C$
h_w	Air convection heat transfer coefficient	$w/m^2°C$
I_b	Vertical solar radiation intensity	w/m^2
K_f	Thermal conductivity of a fluid	$w/m°C$
K_r	Thermal conductivity of absorber	$w/m°C$
L	Collector length	m
$\dot{m}$	A mass flow rate of fluid	kg/sec
S	Absorber solar radiation	w/m^2
T_a	Air temperature	°C
T_{amb}	Ambient temperature	°C
$T_{f,i}$	Inside tube temperature	°C
$T_{f,o}$	Outside tube temperature	°C
T_r	Absorber tube temperature	°C
T_{sky}	Sky temperature	°C
W	Width of collector	m
$P_{r,f}$	Prandtl number	-
R_{ef}	Reynolds number	-
η_{EXP}	Experimental efficiency	-
η_o	Optical efficiency	-
η_{th}	Theoretical efficiency	-
ε_r	Tube absorbers	-
σ	Stephan Poltesman constant	w/m^2K^4
γ	Interception Factor	-
ρ_a	Surface reflector	-
T	Permeably	-

Introduction

The energy crisis has become one of the most critical problems the world faces recently due to the huge and continuous increase in energy consumption corresponding to its limited traditional energy reserves [1]. Increased deployment of concentrating solar collectors for hot water and process heat supply suggests growing acceptance of the technology and a maturing attitude towards this 'green' source of energy. The increase in the fuel prices and environmental problems caused by resources of conventional fuel. Therefore, the researchers try to think about developing new and replaced resources. So the looked at the renewable energy, on top of it, is solar energy to face the problem of depleting traditional fuel and replacing it with renewable, non-depleted and polluted energy [2-4]. An experimental study to developing electrical technology produced from the solar thermal technology in china by building a collective tank type (PTCS)to generate thermal energy. Its performance has been studied using industrial oil flued to transfer heat at different rates thy found that the solar collector efficiency of the parabola is between (40% -60%)[5]. A theoretical and practical study to estimate the efficiency of the PTC under different conditions to analyze the performance of the solar collector. they found out that this kind of collectors considered the best due to the least in heat losses, which make its performance good under different condition[6]. (Dr .subhi S. Mahammed et al.) 2012, studied the theory of solar collector with a double reflector as a parabola, the outcome of the theoretical efficiency of the solar collector is (60 – 67°C), when the mass flow is between (0.02 -0.03)kg/s, with a concentration rate (3.8) without a solar tracking system. The researchers concluded that the increase in the solar radiation leads to an increase in the energy gained from it[7]. A theoretical and practical study to know the efficiency of PTC, once using water and oil as a working fluid to make the comparison between them studying. The results showed that the solar collector efficiency using water like fluid is better than the efficiency at some solar collectors when using converter oil as a fluid in the same climate condition and at the same rate of the mass flow rate [8]. A PTC design and manufacturing using two types of suction pipes, the first are made of copper, and the second is made of copper inserted in a glass pipe tube vacuumed from the air. Four values are tested of the rate of water mass flow rate (0.08,0.06 , 0.04,0.02 kg/sec). The results showed that the highest practical efficiency of the system is (57,65%) at noon in June at a mass flow rate of 0.08 kg /sec while the thermal loss in the tank is increased by the difference between the water temperature in the tank and the external temperature [9].

Characteristics Of The Solar Collector

The PTC is mainly made up of five main components: mirrors, a supporting structure, a receiver, working fluid, and a tracking system. Each component is designed to fulfill a specific purpose and is fabricated using materials based on its functions and desired properties [10-14]. Figure 1 shows a detailed plan of the CTPTC used in research and its features explained in table (1), consist of two parts, the base and the movable part. The solar collector used is a galvanized metal plate covered by a piece of mirrors with high reflection. The chosen suction pipe is made of aluminium rust resistance; the tube is shaped as a coil around a supporting pipe made of iron for a length of (0.6 m) to control the concentration ratio. Three supporting pipes are used with dimensions(0.0254, 0.0508, 0.0762 m) to control the demanded concentration ratio. The pipe is painted black to increase its absorption and reducing reflection, using water as a working fluid.

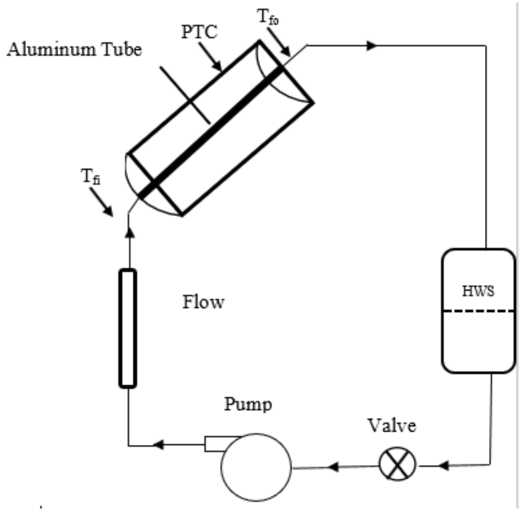

Figure 1. Solar collector with its main contents.

Table 1: Characteristic of the close type parabolic trough collector

Symbol	value	symbol	value
Aperture Length	0.6m	supporting pipe diameter	(0.0254, 0.0508, 0.0762m)
Aperture Width	0.97m	pump	40W
Aperture Area	0.582m^2	Tracking pattern	2-Dim

Length of absorber	0.6m	Concentrating Ratio	$\mathbf{10,14,22}$
Rim Angle	90°	(γ)	0.995
Focal length	0.24m	(ρ)	0.95
$(D_{r,i})$	0.008m	Perembity*reflectivity	0.99
(Dr,o)	0.0095 m	Specific heat of material	$\mathbf{900J/kg.k}$
Length of coil (m)	7.66,12.05,16.43	Specific heat of fluid	$\mathbf{4.18J/kg.k}$

Methodology

Calculating the theoretical and practical efficiency that study carried out according to Ashrea standard(ASHRAE 93 -1986). while stabilization condition is to be supposed daring test, the state of the fluid in the suction pipe is unchanged. Still, it remains as one state, neglecting the change in the external surface heat of the suction pipe, stabilizing the fluid pressure in the suction pipe, neglecting the heat loss by conduction along the suction pipe. The temperature of the liquid, wind velocity, solar radiation, and the temperature has been taken instantly.

The optical efficiency of the collector is calculated from the following equation [15].

$$\eta_o = \frac{S}{I_h} \tag{1}$$

The absorber solar radiation by the suction pipe can be calculated from the following equation [16, 17].

$$s = I_b\left(\rho_a \tau \alpha_r \gamma\right) \tag{2}$$

The calculation of the overall heat transfer coefficient is according to the following equation [1]:

h_w is calculated as the following equation [1]:

The radiation heat transfer coefficient from the suction pipe to the external surrounding is calculated as [1]:

The calculation of the overall heat transfer coefficient is according to the following equation [2]:

$$U_L = h_w + h_{rad,r-sky} \tag{3}$$

h_w is calculated as the following equation [2]:

$$h_w = 5.7 + 3.8V \tag{4}$$

The radiation heat transfer coefficient from the suction pipe to the external surrounding is calculated as follows [2]:

$$h_{rad,r-sky} = \varepsilon_r.\sigma\left(T_r + T_{sky}\right)\left(T_r^2 + T_{sky}^2\right) \tag{5}$$

T_{sky} calculated as the following equation :

$$T_{sky} = 0.055T_a^{1.5} \tag{6}$$

The absorbent temperature is calculated as follows:

$$T_r = T_{m,f} + \frac{\dot{m}cp_r\left(T_{f,o}-T_{f,i}\right)}{h_{c,i}.A_{r,i}} \tag{7}$$

The average temperature is determined as follows:

$$T_{f,m} = T_{f,i} + \frac{Q_u}{A_{r,i}.U_L.f_r}\left(1 - \frac{f_r}{f'}\right) \tag{8}$$

The useful energy is computed according to the following equation:

$$Q_u = A_a.f_r\left[s - \frac{A_r}{A_a}U_L\left(T_{f,i} - T_{amb}\right)\right] \tag{9}$$

The output pipe temperature shall be calculated as [2]:

$$T_{f,o} = T_{f,i} + \frac{Q_u}{\dot{m}\,cp} \tag{10}$$

The convection Heat transforming coefficient in the suction pipe is calculated from the following equation:

$$h_{c,i} = \frac{K_f}{D_{r,i}}\left[3.6 + \frac{0.668\left(\frac{D_{r,i}}{L}\right)R_{e,f}.P_{r,f}}{1+0.04\left[\left(\frac{D_{r,i}}{L}\right)R_{e,f}.P_{r,f}\right]^{2/3}}\right] \tag{11}$$

Renolds number is calculated as belw [24,25]:

$$R_{e,f} = \frac{4\dot{m}}{\pi\rho_f.v_f.D_{r,i}} \tag{12}$$

The solar collector factor is calculated according to the following equation [2]:

$$F' = \frac{1/U_L}{\frac{1}{U_L} + \frac{D_{r,o}}{h_{c,i}.D_{r,i}} + \frac{D_{r,o}\ln\left(D_{r,o}/D_{r,i}\right)}{2K_r}} \tag{13}$$

The heat removal factor is determined as follows [1] :

$$F_R = \frac{\dot{m}_f cp_f}{A_r.U_L}\left[1 - \exp\left(\frac{-A_{r,i}.U_L F'}{\dot{m}_f.cp_f}\right)\right] \tag{14}$$

The thermal efficiency of the solar collector is calculated by the following equation [14]:

$$\eta_{th} = F_R\left[\eta_o - \frac{U_L\left(T_{f,i}-T_{amb}\right)}{I_b.C}\right] \tag{15}$$

Results and Discussion

Practical tests have been carried out to identify the efficiency of the CTPTC in the climate of Kirkuk at different times. The experimental test started in the early morning and ends at dusk, the fluid used to transform heat is water. The study is carried out to show the Effect of the concentration ratio on the performance of the CTPTC. Three values of concentration ratio are chosen (10,14 and 24). Four quantities of mass flowrate are chosen (0.00083, 0.0011, 0.00138 , and 0.00166 kg /sec) respectively . Figure (2) explains the distribution of solar radiation intensity for the different days during the year. The highest value of radiation intensity on August 4th is: $1000\ w/m^2$ while the highest value on January 17th is 700 w/m^2. The figure aims to observe the behaviour of solar radiation during the seasons. Then the Effect of the intensity of the solar radiation on the efficiency.

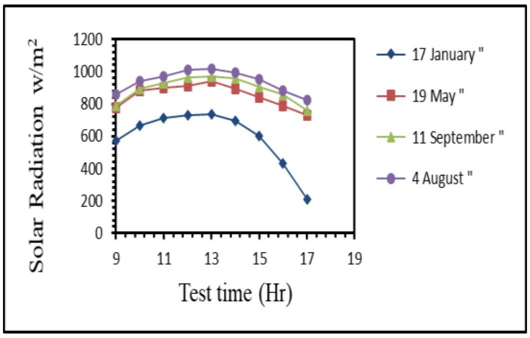

Figure 2. the variation of solar radiation through seasons.

Figures 3,4,5 and 6 are represent the change in the practical efficiency during a time compared to the theoretical efficiency. The concentration ratio beings with the lowest value of 10 and ends with the highest value of 22, and the mass flowrate beings with the lowest value of 0.00083 kg /sec and ends with the highest value 0.00166 kg /sec. The results show that the practical efficiency in Winter is decreased gradually from (25-21%) concerning concentration ratio. Also, it is increase gradually from (21-32%) concerning mass flowrate shows that it reaches the lowest value for theoretical by 20%, at the lowest mass flow rate and the concentration ratio (22), to increase gradually with the increase of the mass flow, reaching its peak at the highest value 33%. The highest value of the theoretical efficiency is 50% at the lowest flow and increased relatively to 63% at the highest flow rate for the same concentration ratio. In comparison, the highest value of the theoretical efficiency is 35% at the lowest concentration ratio and increased relatively to 52% at the highest concentration ratio for the same mass flow rate. The difference between the theoretical efficiencies in Winter for the same concentration and varying mass flow rate not exceeding 7%. These results correspond to references [14, 22].

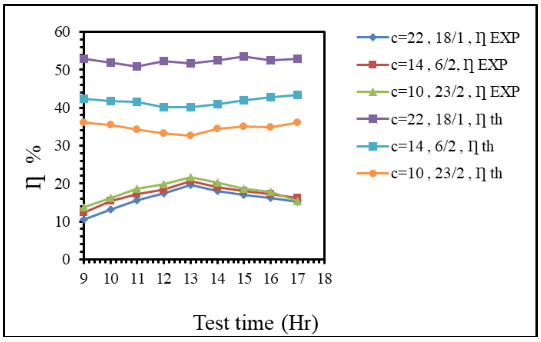

Figure 3. the variation of efficiency concerning time for mass flowrate 0.00083Kg/sec

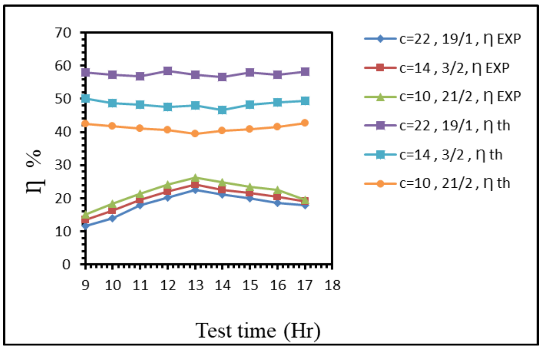

Figure 4. the variation of efficiency concerning time for mass flowrate 0.0011Kg/sec

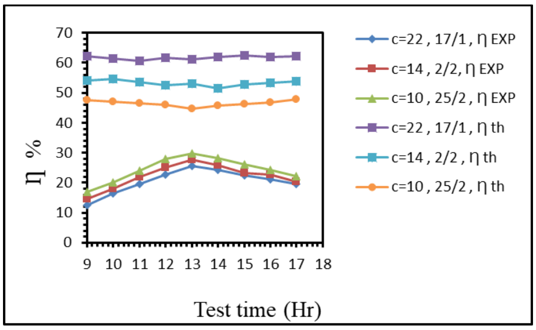

Figure 5. the variation of efficiency concerning time for mass flowrate 0.00138Kg/sec

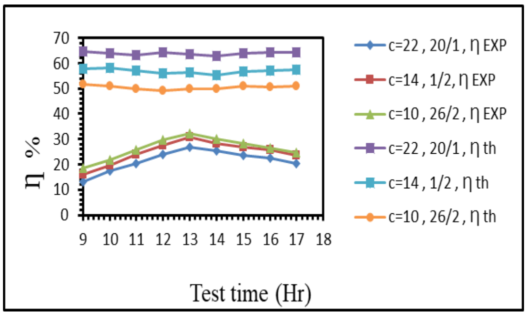

Figure 6. the variation of efficiency concerning time for mass flowrate 0.00166Kg/sec

Figures (7, 8, 9, 10)show the change in the practical efficiency over time compared to the theoretical efficiency in spring at varying concentration values. A mass flowrate begins at the lowest value 0.00083 kg /sec and ends with the highest value 0.00166 kg/sec. The results show that the experimental efficiency in spring exceeds the practical efficiency in Winter as (6 -10 %). In spring, it is clear that in spring reaches its highest value 37%, and in Winter, 32%, at the same mass flow rate and concentration ratio. On the other hand, the highest value of the theoretical efficiency is 52%at the lowest flow rate and gradually increases to 64% at the highest flow rate for the maximum concentration ratio. Thus, the difference between the hypothetical value of the efficiencies in Spring and Winter for the same concentration ratio of the whole quantities of the mass flow exceeds 15%. The thermal performance of the collector is consistent with [13,23,24].

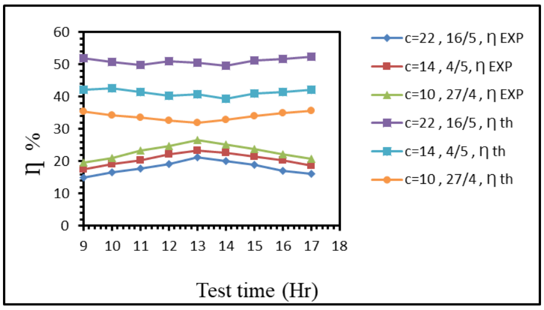

Figure 7. the variation of efficiency concerning time for mass flowrate 0.00083Kg/sec.

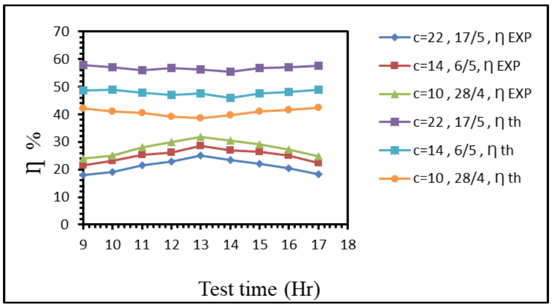

Figure 8. the variation of efficiency concerning time for mass flowrate 0.0011Kg/sec

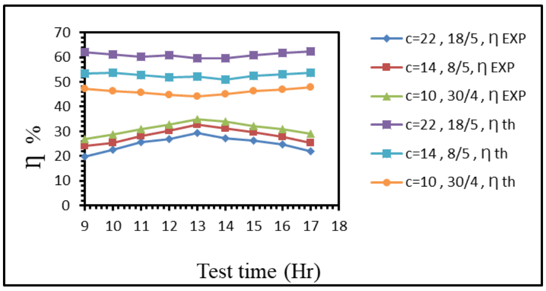

Figure 9. the variation of efficiency concerning time for mass flowrate 0.00138Kg/sec

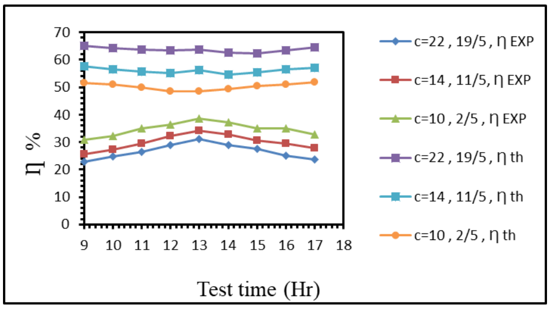

Figure 10. the variation of efficiency concerning time for mass flowrate 0.00166Kg/sec

Figures 11, 12, 13 and 14 represent the change in practical efficiency over time compared to theoretical efficiency at concentration starts from (10), and a mass flowrate starts at the lowest value of 0.00083 kg /sec. The results show that the practical efficiency in summer exceeding the practical efficiency in Winter and spring by approximately (10 -15%). This seems clear that it reaches its highest value in Summer 27%, and in Winter 18% at the lowest flow and concentration ratio (10), to increase gradually with the increase of the mass flow quantity, to reach its highest value 42% in Summer, and 29% in Winter. On the other hand, the highest value of the theoretical efficiency is about 35% at the lowest mass flowrate and increase relatedly to 63% at the highest flow rate and concentration ratio where's the difference between the theoretical efficiency in spring and Summer for the same concentration ratio of the total mass flow not exceeding 2% [13,25,26]. Those results are consistent with references [1, 22].

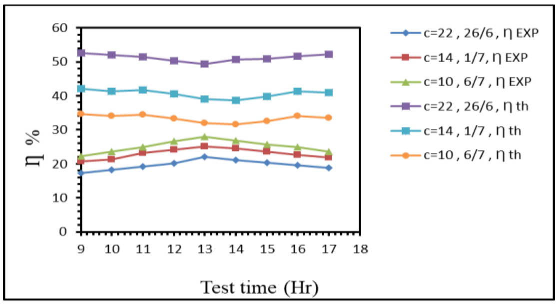

Figure 11. the variation of efficiency concerning time for mass flowrate 0.00083Kg/sec

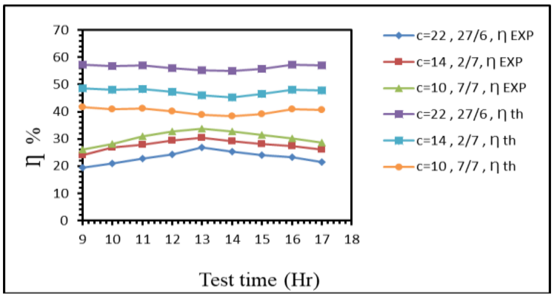

Figure 12. the variation of efficiency concerning time for mass flowrate 0.0011Kg/sec

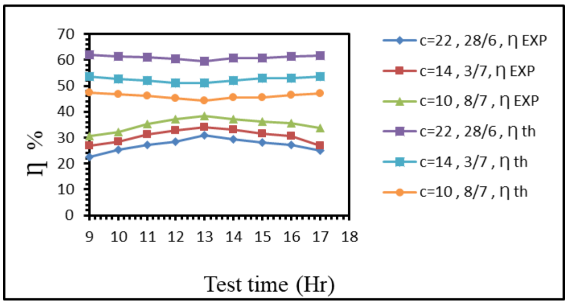

Figure 13. the variation of efficiency concerning time for mass flowrate 0.00138Kg/sec

Figures 15,16,17 and 18 represent the change in efficiency with time for the autumn season, as it starts at the lowest mass flow and different concentration ratios. This is due to the similarity in temperature. It is mentioned for different daytime in Winter, spring, and Summer. According to Ashri model and practical study, the theoretical study proves that the efficiency has a direct proportion with the mass flow quantity for the all concentration ratio.

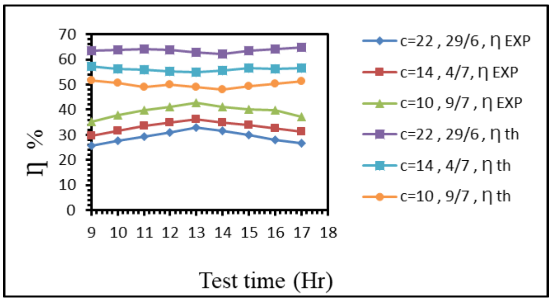

Figure 14. the variation of efficiency concerning time for mass flowrate 0.00166Kg/sec

This belongs to the increase in the amount of water flow in the collector, which helps draw the highest amount of heat from the solar collector. Therefore, it witnesses an improvement in inefficiency. This is not a contradiction with the basic principle of heat transfer, like heat transfer from the surface of the suction pipe to the fluid by convection. Indeed, the increase in flow mass and the increase in velocity, increasing in Renolds number, as the other variables are fixed, leads to an increase in the convection heat transfer coefficient, so this explains everything. The impact concentration ratio on the theoretical efficiency is increased when the concentration ratio increase, therefore the efficiency rises, whereas the positive relation despite the temperature and radiation intensity. Therefore, there is efficiency at noon; its lowest value is recorded for the whole season. This is not contradictory with the principle of solar collector operation, whereas the losses of the apparatus increase when the temperature of the collector increased. This behavior is similar to [9,27,28].

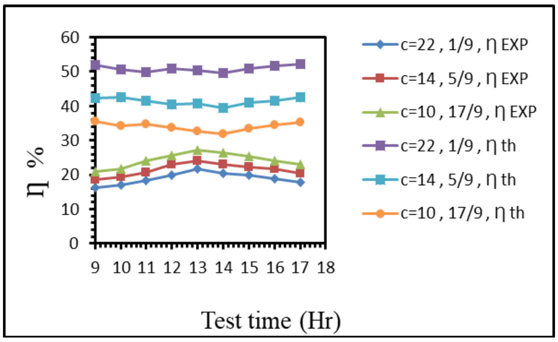

Figure 15. the variation of efficiency concerning time for mass flowrate 0.000183Kg/sec

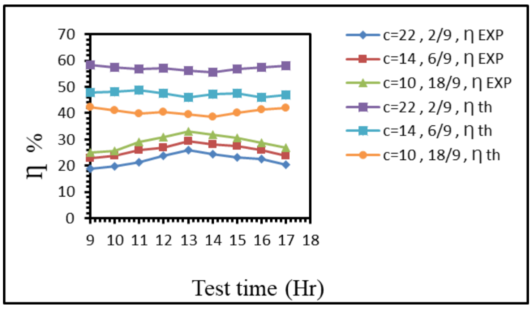

Figure 16. the variation of efficiency concerning time for mass flowrate 0.0011Kg/sec

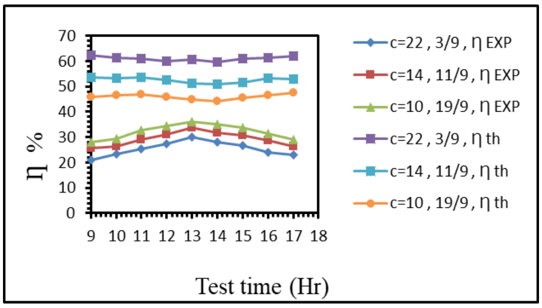

Figure 17. the variation of efficiency concerning time for mass flowrate 0.00138Kg/sec

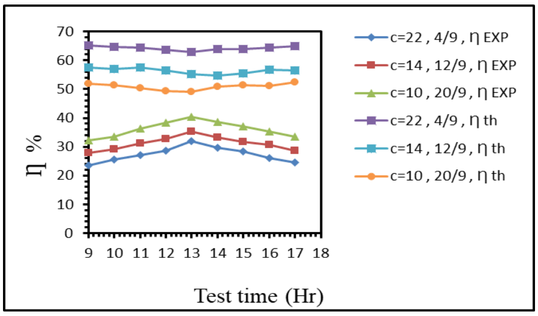

Figure 18. the variation of efficiency concerning time for mass flowrate 0.00166Kg/sec

References

[1] O. K. Ahmed and A. Ahmed Hassen, Principle of Renewable energies, First edit. Baghdad: Foundation of technical education, 2011.

[2] Z. Şen, Solar energy fundamentals and modelling techniques: Atmosphere, environment, climate change and renewable energy. 2008.

[3] A. Maczulak, Renewable Energy Sources Watt Committee Report Number 22. 2010.

[4] G. Harper, Solar Energy Projects for the Evil Genius. 2007.

[5] LIU QiBin1, WANG YaLong1,2, GAO ZhiChao1,2, SUI Jun1*, JIN HongGuang1 & LI HePing3," Experimental investigation on a parabolic trough solar collector for thermal power generation", January (2010) Vol. 53 No.1: 52–56.

[6] Muhammad M. Rahman, Heat transfer analysis of parabolic trough solar receiver, Applied Energy 88(2011) 5097-5110.

[7] Dr Subhi S. Mahammed, Theoretical Study of the Compound Parabolic Trough Solar Collector. Tikrit Journal of Engineering Science, Vol.19/ No.2/ June 2012 (1-9).

[8] Ahmed T. Ahmed, A theoretical and practical study of a horizontal parabola trough collector using a tracking system, M.Sc, University of Tikrit College of Engineering, 2014

[9] Hussam S Diab, Study and analysis of a parabola-type solar system using simulation, scientific method and automatic tracking, M.Sc, University of Tikrit College of Engineering, 2015

[10] Atkinson C, Sansom C, Almond H, Shaw C. Coating for concentrating solar systems – A review. Renew Sust Energ Rev. 2015;45:113–22.

[11] Arancibia-Bulnes C, Peña-Cruz M, Mutuberría A, Díaz- Uribe R, Sánchez-González M. A survey of methods for the evaluation of reflective solar concentration optics. Renew Sust Energ Rev. 2017;69:673–84.

[12] Fernández-García A, Sutter F, Martínez-Arcos L, Valenzuela L, Sansom C. Advanced mirror concepts for concentrating solar thermal systems. In: Blanco M, Ramirez SL, editor. Advances in concentrating solar thermal research and technology. Cambridge (MA, USA): Woodhead Publishing Elsevier; 2017. p. 29–43.

[13] Fernández-García A, Sutter F, Montecchi M, Sallaberry F, Heimsath A, Heras C, et al. SolarPaces Guidelines: Parameters and methods to evaluate the solar reflectance properties of reflector materials for concentrating solar power technology (Version 3). Almeria, Spain; 2018. [cited 2020 Aug 19]. Available from: http://www.solarpaces.org/wp-content/uploads/ 20180320_SolarPACES-Reflectance-Guidelines-V3.pdf.

[14] Zhu G, Kearny D, Mehos M. On characterization and measurement of average solar field mirror reflectance in utilityscale concentrating solar power plants. Sol Energy. 2014;99:185–202.

[15] Michael John Brooks, Performance Of a Parabolic Trough Solar Collector, Thesis for The Degree of Master of Science in Engineering, University of Stellenbosch, 2005.

[16] Lamprecht A. J. Efficiency Improvement of Parabolic Trough Solar Collector Mechanical Project 478, University of Stellenbosch, (2000).

[17] Jacobson, E., Ketjoy, N., Nathakaranakule, S. and Rakwichian, W. "Solar parabolic trough simulation and application for a hybrid power plant in Thailand", 32 (2006) No. 2, 187-199.

[18] Garcia O. and Velazquez N., "Numerical Simulation of Parabolic Trough Solar Collector: Improvement using Counter Flow Concentric Circular Heat Exchangers", Journal of Heat and Mass Transfer 52 (2009) 597–609.

[19] A. Duffie and A. Beckman, Solar Engineering of Thermal Processes, (John Wiley & Sons Inc, 2006), pp 244-247.

[20] Thepa S., Kitikara K., Hirunlabh J. and Khedari J. "Improving Indoor Conditions of a Thai-Style Mushroom House by Means of an Evaporative Cooler and Continuous", Renewable Energy 17, (1999) 359-369.

[21] F. P. Incropera and D. P. DeWitt, Fundamentals of Heat and Mass Transfer, 5th ed. (Wiley, USA, 2002)

[22] N. El Gharbi, H. Derbal, S. Bouaichaoui, and N. Said, "A comparative study between parabolic trough collector and linear Fresnel reflector technologies," Energy Procedia, vol. 6, pp. 565–572, 2011.

[23] G. Kumaresan, R. Sridhar, and R. Velraj, "Performance studies of a solar parabolic trough collector with a thermal energy storage system," Energy, vol. 47, no. 1, pp. 395–402, 2012.

[24] T. A. Yassen, "Experimental and Theoretical Study of a Parabolic Trough Solar Collector," Anbar J. Eng. Sci., vol. 5, no. 1, pp. 109–125, 2012.

[25] M. Brooks, I. Mills, and T. Harms, "Design, construction and testing of a parabolic trough solar collector for a developing-country application," Proc. ISES Sol. World Congr. Orlando, FL, 2005.

[26] O. A. Jaramillo, E. Venegas-Reyes, J. O. Aguilar, R. Castrejón-García, and F. Sosa-Montemayor, "Parabolic trough concentrators for low enthalpy processes," Renew. Energy, vol. 60, pp. 529–539, 2013.

[27] J. Al Asfar, O. Ayadi, and A. Al Salaymeh, "Design and Performance Assessment of a Parabolic Trough CollectorJamil," Jordan J. Mech. Ind. Eng., vol. 8, no. 1, pp. 1–5, 2014.

[28] A. V. Arasu and S. T. Sornakumar, "Performance characteristics of the solar parabolic trough collector with hot water generation system," Therm. Sci., vol. 10, no. 2, pp. 117–167, 2006.