J. Biomedical Science and Engineering, 2015, 8, 370-379
Published Online June 2015 in SciRes. http://www.scirp.org/journal/jbise
http://dx.doi.org/10.4236/jbise.2015.86035

Manufacturing and Thermal Performance Test of (Compound) Solar Collector in Damascus City

Mohamad Sadek Jouhari[1*], Sinjar Touhmeh[2], Nadeem Moukhayber[1]

[1]Department of Mechanics, Faculty of Mechanical and Electrical Engineering, Damascus University, Damascus, Syria
[2]National Energy Research Centre, Damascus, Syria
Email: [*]sadekjouhari@gmail.com

Received 7 May 2015; accepted 9 June 2015; published 12 June 2015

Abstract

Solar water collectors that uses for domestic and industrial applications within temperature up to, are classified under two main types: Flat Plate collector (FP), and Evacuated Tube collector (ET). Thermal performance test results showed that each type have different thermal features. Comparison between (FP & ET) collectors showed that they could take advantages of different thermal features of two types when they work in the same climatic conditions and overlap of these thermal features when they work in different operational conditions. They can take advantage of these features through (compound) solar collector. Compound solar water Collector (CO) composed of a part of flat plate collector shape (FP), and a part of evacuated tube collector shape (ET). Booth have equal reference area, and connected together to be as one Solar collector (CO). Water entered first flat part (FP), then evacuated tube part (ET) then to tank or end-use. In this paper, present design and manufacturing as well the thermal performance test of (compound) solar collector, according to Standard Specification of tests, was EN12975:2001. Mechanical test for (CO) collector conducted successfully according to durability, reliability, and safety requirements. In addition, thermal performance was tested in steady state at the climatic conditions of Damascus city, and concluded the thermal performance of (FP & ET) that constitute (CO) collector. The results showed enhancement of thermal performance.

Keywords

Solar Collector, Compound Collector, Evacuated Tube Collector, Flat Plate Collector

[*]Corresponding author.

How to cite this paper: Jouhari, M.S., Touhmeh, S. and Moukhayber, N. (2015) Manufacturing and Thermal Performance Test of (Compound) Solar Collector in Damascus City. *J. Biomedical Science and Engineering*, **8**, 370-379.
http://dx.doi.org/10.4236/jbise.2015.86035

1. Introduction

Solar water collectors are classified into two types: Flat Plate collectors (FP) and Evacuated Tube Collector (ET); each has different technical and thermal specifications, usually basic comparison between them on the design, cost, and the thermal performance. Researches on solar collectors aimed to increase the energy that can be exploited from solar radiation and convert it to the maximum useful thermal energy and improve its thermal performance. Many researches are done to develop designs and structures for solar collectors to improve their specifications and develop new and hybrid types. They are classified into three main parts:

First part: Researches to develop engineering design of each components of the collector in different designs, materials, dimensions, layers, heat transfer fluid, and the development of new hybrid types used for different applications. Researches regarding (ET), (hybrid) collectors, and (CO) collector remain in constant evolution.

Second part: Researches to study the appropriate oriented, tilt angles, incidence angle, and tracing the sun.

Third part: Researches concerned with the optimal use of solar energy gained, thermal storage, and development of the operating methods, thermal insulation, and control strategy of the pump, flow rate, and control operating temperatures. The Compound Collector (CO), which is the research topic, is about trying to take advantage of the different thermal features of (FP) and (ET) where it is designed, manufactured and tested on thermal performance under Damascus city climate.

2. Review

(FP) collector known since the beginning of the twentieth century, Hottel and Willier developed it and modeled it mathematically in the fifties of the twentieth century, a lot of improvements carried on it to enhancement of thermal performance, Hottel and Woertz, 1942 conducted the first test of the thermal performance of (FP) collector and concluded the mathematical model. The (ET) collector known first by Speyer, 1965 and developed rapidly [1]. Fouad Kamel Abdalla, 2005 [2] studied and experimented a hybrid collector (ET & FP), he put the (FP) collector above the (ET) collector to work as a top complex to it and studied the curves of thermal performance of the new hybrid collector, and compare it with the tubular and flat collectors, concluded that the energy gained improved in the hybrid collector, and the efficiency curve is located between the (ET) collector and the (FP) collector. E. Zambolin *et al.*, 2010 [3] make an experimental study to the thermal performance of (FP & ET) collectors in steady-state, quasi-dynamic , and daily work condition, he founded that the optical efficiency of the (FP) is higher than the (ET) but the leaning of the efficiency curve for (ET) is less while the efficiency curve of the (FP) collapse due to heat loss at high temperatures, while the (ET) has the advantage of continuous efficiency curve with less leaning because of the vacuum space between the evacuated glass tubes leading to the reduction of thermal loss. Munish Kainth, 2014 [4] make a reference study for the techniques used in (FP) and its different types , designs and its development in the last ten years. Zhangyuan Wang *et al.*, 2015 [5] showed the future direction for the development of solar collectors and reviewed new types to improve thermal performance and reduce cost. Sadek Jouhari *et al.*, 2014 [6] make an experimental study of thermal performance in steady-state condition for (FP & ET) collectors, which have same reference area under the climatic conditions of the city of Damascus, Founded that each type of collectors (FP & ET) has different thermal features when working under the same climatic conditions, The advantages of the thermal features of the two types together and overlapped in various operating conditions could be taken in a new hybrid type called (compound) collector.

3. Thermal Performance Equations

To estimate thermal performance of the solar collector will be used basic equations in steady-state condition According to Standard Specification of Tests EN12975-2:2001 [7].

Useful gain power from collector:

$$Q_u = \dot{m} C_p \Delta T \tag{1}$$

Portable power with solar radiation received by the collector:

$$Q_u = A_a \cdot G \cdot \eta \tag{2}$$

Mean temperature of heat fluid collector:

$$T_m = T_i + \frac{\Delta T}{2} \tag{3}$$

Temperature difference between fluid outlet and inlet to collector:

$$\Delta T = T_e - T_i \tag{4}$$

Reduce temperature difference:

$$T_m^* = \frac{T_m - T_a}{G} \tag{5}$$

Instantaneous efficiency for collector:

$$\eta = \eta_0 - a_1 \cdot T_m^* - a_2 \cdot G\left(T_m^*\right)^2 \tag{6}$$

Compensation between equations, (5) and (6):

$$\eta = \eta_0 - a_1 \frac{T_m - T_a}{G} - a_2 \cdot G\left(\frac{T_m - T_a}{G}\right)^2 \tag{7}$$

Compensation between equations, (1), (2) and (7), Useful gain power from collector:

$$Q_u = A \cdot G\left[\eta_0 - a_1 \frac{T_m - T_a}{G} - a_2 \cdot G\left(\frac{T_m - T_a}{G}\right)^2\right] \tag{8}$$

Thermal performance curves of solar collectors plotted by using the previous equations after conducting experiments in steady-state condition. Normally a second-order curve shall be used which can be achieved by least squares regression.

4. Design and Manufacture of (Compound) Collector (CO)

(CO) is a solar thermal collector for heating water which is composed of two parts connected together in series. First part is a flat collector (FP), and second part is an evacuated tube collector (ET) of the type (U-pipe). Water enters the bottom of (FP) and exit the top of (ET). Reference area for the two collectors are equal, which are: Aperture area A_a, Absorber surface area exposed to solar radiation A_A, and Gross area A_G [8]. The Design and the manufacturing are as follows:

4.1. Flat Collector Part

Frame made from bronze color painted pure Aluminum, Oxidized at high temperatures to prevent the influence of atmospheric conditions, the rear surface made from heat coated galvanized tin, thermal insulation made from glass wool, number 6 longitudinal pipe network made of red copper (ASTM B88 TUBE). The complex tube welded with each other by silver welding. Absorber plate made from red Copper composed in rolling Mills, Copper piping network fixed on the copper absorber plate by intermitting welding strikes secure full contact between the pipes and the absorber plate, absorber coating is Pitch black from carbonaceous and semi-charcoal material. Cover is a glass plate dimensions fit with the collector and the frame with high transparency. The frame made frame not affected by atmospheric conditions, tighten the glass plate with the body of the collector. Exits and entrances Pipe both sides are made of galvanized steel (ASME B 36), welded to the copper pipeline network complex.

4.2. Evacuated Tube Part

Consists of seven Evacuated glass [9] with red Copper U-pipe, connect to two upper complex Copper (ASTM B88 TUBE). Each Copper U-pipe put inside glass tube surrounded by thin sheet made from Aluminum to increase the thermal conductivity. The Copper pipe and the Aluminum sheets fixed within an evacuated glass type Tree target vacuum tube. The selective coating three-layer: CU/SS-ALN (H)/SS-ALN (L)/ALN. Water enters to copper complex at the top of the collector and the U-pipes distributed from it, the hot water goes out to another copper complex at the top of collector, two complexes are parallel within a casing surrounded by foam thermal insulation Poly Rithan. Behind the glass tubes, three Stainless Steel reflectors placed.

4.3. Final Shape of (CO) Collector

Figure 1 shows the Engineering design of innovative (compound) solar collector.
Table 1 shows basic Dimensional design for (FP), (ET) and (CO) collector's parts.

5. Tests Methodology

Mechanical tests conducted successfully for (CO) collector, according to durability, reliability, and safety requirements [10]. Thermal performance for (FP) and (ET) parts which compose (CO) tested separately at same time under climatic conditions of Damascus city in steady-state condition according to [6] [7]. Then two parts connected to compose (CO) collector which tested by the same test platform in steady-state conditions [7] [11]. **Figure 2** shows (CO) collector on the test platform. Climatic conditions of test area "Damascus city" are: Latitude: 33.29 [N˚] Longitude: 36.14 [E˚], Altitude: 729 [m], Number of days of sunshine per year: 330 [day], Number of hours of sunshine per year: 3000 [hour]. The average daily rate on a horizontal surface throughout the year in "Damascus city" about 2200 [kWh/m^2] per year. Thermal performance test done during 15-3-2014 to 15-4-2014. **Figure 3** shows weather station data during a test day.

6. Tests Results

Thermal behavior of (CO) collector are similar to thermal behavior of any other collector in terms of values of thermal constants (η_0, a_1, a_2), and affection by reference area, tilt angle (**Table 2**). Productive power decreased with temperature difference $(T_m - T_a)$ (**Table 3** and **Figure 4**). General shape of thermal performance curves of (CO) collector is similar to overall shape of (FP) and (ET) collector's curves.

(CO) collector Instantaneous efficiency decrease by increase the reduce temperature (T^*) (**Figure 5**).

Moreover, the efficiency influenced by solar irradiance value (**Figure 6**).

Figure 7 shows Instantaneous efficiency curves of three collectors Plotted with reduce temperature (T^*). At the Intersection point of (ET) and (FP) curves when (T^* = 0.035) value of the efficiency of each $(\eta = 0.52)$

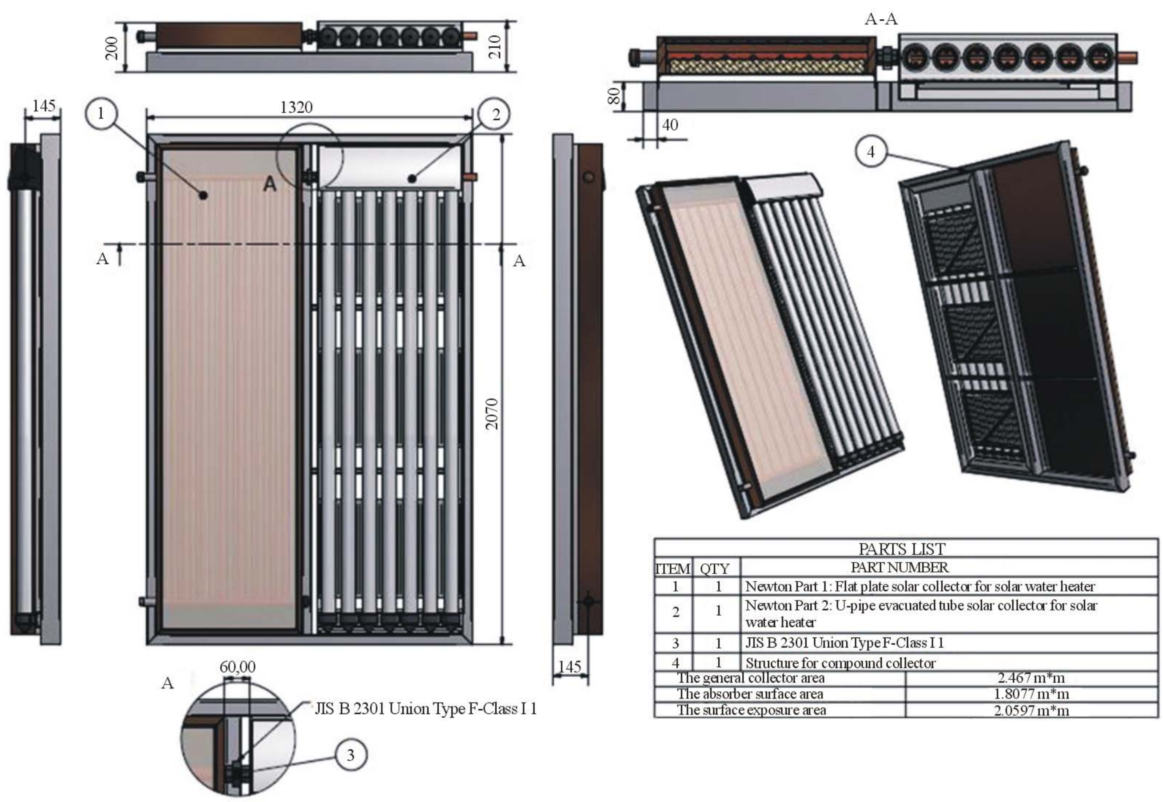

Figure 1. Engineering design of innovative (compound) solar collector creative by researcher [1].

Table 1. Basic dimensional design for (FP), (ET) and (CO) collector's parts.

Part Name		Collector	Measurements	Units
Thermal insulation	Thickness	FP	35	[mm]
		ET	50	
	Density	FP	38 - 40	[Kg/m^3]
		ET	30	
	Thermal conductivity factor	FP	0.045	[W/m·K]
		ET	0.025	
Copper pipe	Internal diameter	FP	11.3	[mm]
		ET	8.3	
	Outer diameter	FP	12.7	[mm]
		ET	9.5	
Copper complex tube	Internal diameter	FP & ET	26	[mm]
	Outer diameter	FP & ET	28.5	[mm]
Absorber	Plate Thickness	FP	0.4	[mm]
	Absorptance α_p	FP	0.92	[-]
		ET	0.937	
	Emittance ε_p	FP	0.92	[-]
		ET	0.06	
	Reflectivity ρ_p	FP	0.08	[-]
		ET	0.063	
Glass	Cover thickness	FP	40	[mm]
	Transmittance τ_g	FP	0.9	[-]
		ET	0.91	
	Reflectivity ρ_g	FP	0.08	[-]
		ET	0.07	
	Absorptance α_g	FP & ET	0.02	[-]
	Emittance ε_g	FP	0.88	[-]
		ET	0.02	
Galvanized steel exits and entrances pipe	Internal diameter	FP & ET	25.4	[mm]
	Outer diameter	FP & ET	33	[mm]
Aluminum sheet	Thickness	ET	1	[mm]
	Length		1000	
Stainless steel reflector	Width	ET	580	[mm]
	Height		400	
	Thickness		1	
Glass Evacuated tube	Length	ET	1800	[mm]
	Internal diameter		47	
	Outer diameter		58	
FP & ET Collectors	Height	FP & ET	1990	[mm]
	Width	FP & ET	590	[mm]
	Gross area A_G	FP & ET	1.174	[m^2]
	Aperture area A_a	FP	1.043	[m^2]
		ET	1.01675	
	Absorbent surface area A_A	FP	0.903	[m^2]
		ET	0.9039	
CO Collector	Height	CO	1990	[mm]
	*Gross height with frame	CO	2070	[mm]
	Width with joint between two parts	CO	1240	[mm]
	Gross width with frame	CO	1320	[mm]
	**Gross area A_G	CO	2.467	[m^2]
	Aperture area A_a	CO	2.0597	[m^2]
	Absorbent surface area A_A	CO	1.8077	[m^2]

*Two collectors parts (FP & ET), fixed on one Aluminum frame (ISO 4019). **(CO) collector Gross area including the joint between the two parts (FP & ET), (JIS B 2301).

Figure 2. (compound) collector on test platform.

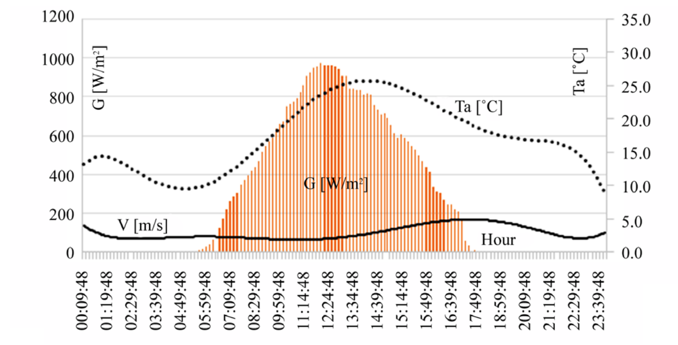

Figure 3. Weather station data during a test day.

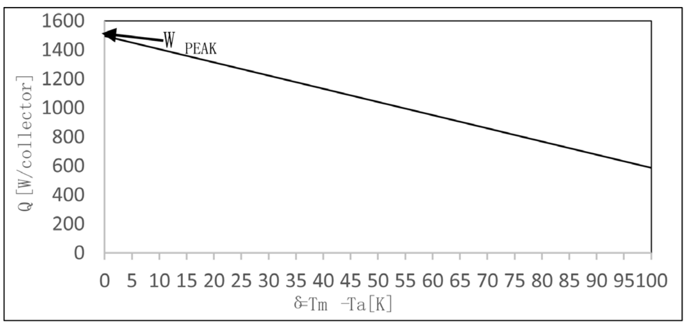

Figure 4. Productive and weak power curve for (CO) at: G = 1000 [W/m^2], Tilt 45 [˚]. Plotted with ($T_m - T_a$).

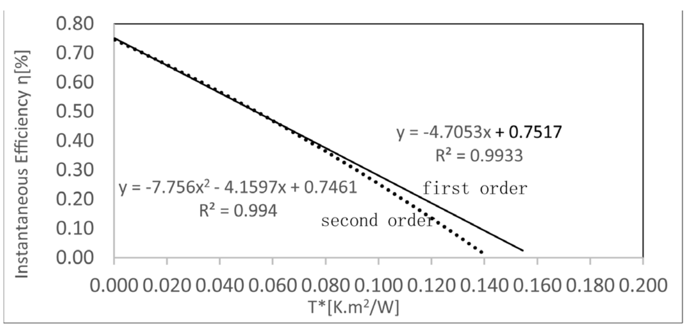

Figure 5. Instantaneous efficiency curve for (CO), at Tilt 45 [˚]. Second and first order. Plotted with (T^*).

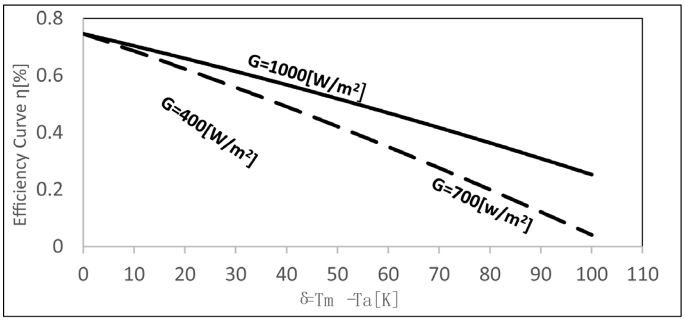

Figure 6. Efficiency curve for (CO), at Tilt 45 [˚] ,G = 400,700,1000 [W/m^2]. Plotted with (T_m − T_a).

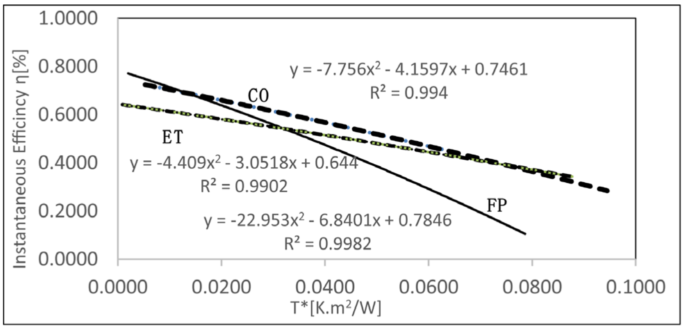

Figure 7. Instantaneous efficiency curves of the three collectors plotted with reduce temperature (T^*).

Table 2. Thermal constants for (FP), (ET), and (CO) collectors, at aperture area, tilt 45 [˚].

Curve type	FP	ET	CO
Second order	$\eta_0 = 0.7846$	$\eta_0 = 0.644$	$\eta_0 = 0.7461$
	$a_1 = 6.8401$	$A_1 = 3.0518$	$a_1 = 4.1597$
	$a_2 = 0.022953$	$A_2 = 0.004409$	$a_2 = 0.007756$
First order	$\eta_0 = 0.8047$	$\eta_0 = 0.6484$	$\eta_0 = 0.7517$
	$a_1 = 8.6763$	$a_1 = 3.4392$	$a_1 = 4.7053$

Table 3. Productive power of (FP), (ET), and (CO) collectors, at aperture area, tilt 45 [˚].

Productive power Q_u [W/collector]					
$T_m - T_a$	400	700	1000	G [W/m^2]	W_{peak} power
	313.8	549.2	784.6	FP	784.6
0	257.6	450.8	644	ET	644
	596.9	1044.5	1492.2	CO	1492.2
	243.1	478.5	713.9	FP	
10	226.6	419.8	613	ET	
	512	959.8	1407.4	CO	
	88	323.3	558.7	FP	
30	162	335.2	548.4	ET	
	333.3	781	1228.6	CO	
	–85.5	149.8	385.2	FP	
50	94	287.2	480.4	ET	
	142	589.9	1037.4	CO	

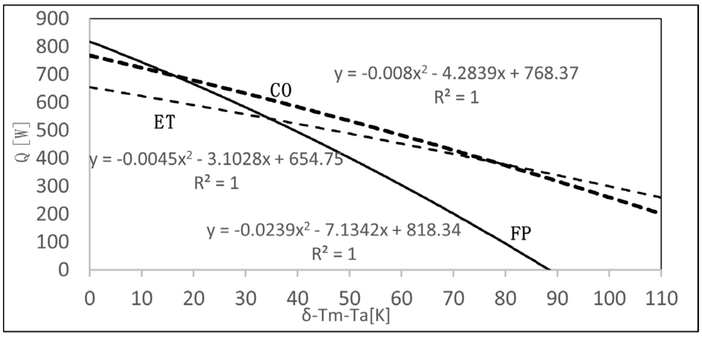

Figure 8. Productive power curve for (FP), (ET) and (CO) at: $G = 1000$ [W/m^2], Tilt 45 [˚]. Plotted with ($T_m - T_a$).

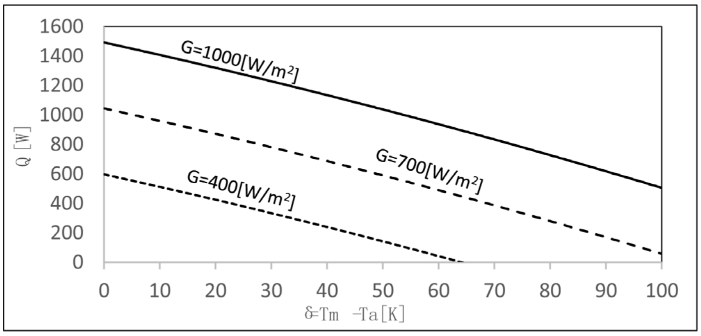

Figure 9. Productive power curve for (CO) collector at: $G = 400,700,1000$ [W/m^2], Tilt 45 [˚]. Plotted with ($T_m - T_a$).

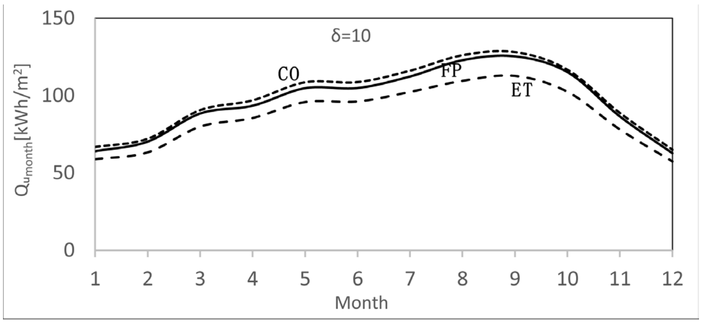

Figure 10. Energy produced curves for three collectors plotted with months when ($\delta = T_m - T_a = 10$).

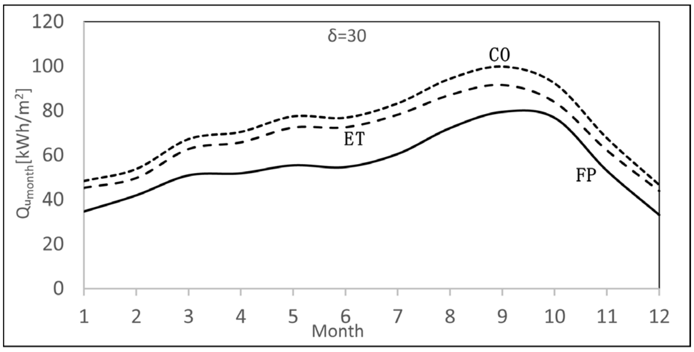

Figure 11. Energy produced curves for three collectors plotted with months when ($\delta = T_m - T_a = 30$).

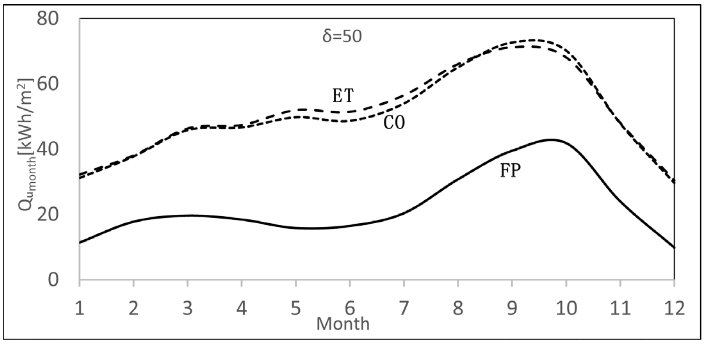

Figure 12. Energy produced curves for three collectors plotted with months when ($\delta = T_m - T_a = 50$).

where the efficiency of (CO) collector at the same point $(\eta = 0.61)$, which mean an increase of 17% of (CO) collector at this point. **Figure 8** shows Productive power Curve three collectors at G = 1000 [W/m^2], Tilt 45 [˚]. Plotted with $(T_m - T_a)$. At the Intersection point of (ET) with (FP) curves when ($T_m - T_a$ = 35 [˚C]), the value of gained power for each (550 [W]), while for (CO) collector the value at the same point is (610 [W]), which mean an increase of 11% for (CO) collector at this point. **Figure 9** shows Productive power of (CO) collector influenced by solar irradiance value at: G = 400; 700; 1000 [W/m^2], Tilt 45 [˚]. Plotted with $(T_m - T_a)$.

Figure 10 shows Productive energy for three collectors plotted with months of the year, $(\delta = T_m - T_a = 10)$.

Figure 11 shows Productive energy for three collectors plotted with months of the year, $(\delta = T_m - T_a = 30)$.

Figure 12 shows Productive energy for three collectors plotted with months of the year, $(\delta = T_m - T_a = 50)$.

Notes, (CO) collector behaviors converge with (FP) collector at $(\delta = 10)$, converge with (ET) collector at $(\delta = 50)$.

7. Conclusion

Thermal performance of the compound solar collector was improved compared with thermal performance of flat and evacuated collectors which the compound collector consists of them, and where the compound solar collector benefited from the thermal characteristics of each of them at the same climatic conditions and overlap thermal characteristics of each of them at different operating conditions. Each (FP & ET) collector alone showed significant thermal enhancement from each other in some climatic conditions and terms of operating; (CO) collector combines the benefits of them. The (CO) collector fits the climate conditions in Damascus city [11].

References

[1] Duffie, J. and Beckman, W. (2000) Solar Engineering of Thermal Processes. 3nd Edition, John Wiley & Sonce, INC, New York City.

[2] Abdalla, F.K. (2005) Modeling and Assessment of an Experimental Combined Evacuated-Tubes-Direct-Flat-Plate Solar Heater, Advanced Energy Centre, Bryndwr, Christchurch, New Zealand.

[3] Zambolin, E., *et al.* (2010) Experimental Analysis of Thermal Performance of Flat Plate and Evacuated Tube Solar Collectors in Stationary Standard and Daily Conditions. *Solar Energy*, **84**, 1382-1396. http://dx.doi.org/10.1016/j.solener.2010.04.020

[4] Munish, K. (2014) Latest Evolutions in Flat Plate Solar Collectors Technology. *International Journal of Mechanical Engineering*, **1**.

[5] Wang, Z., *et al.* (2015) Solar Water Heating: From Theory, Application, Marketing and Research. *Renewable and Sustainable Energy Reviews*, **41**, 68-84. http://dx.doi.org/10.1016/j.rser.2014.08.026

[6] Jouhari, M.S., *et al.* (2014) Thermal Performance test of Two Types of Solar Collectors and Compare Them Under Climatic Conditions of the City of Damascus. Damascus University, *Journal for Engineering Science*. Paper Approved for Publishing (1574), 14-9-2014.

[7] EN12975-2 (2001) Thermal Solar Systems and Components, Solar Collector Part 2: Test Methods.

[8] IS/ISO 9488 (1999) Solar Energy—Vocabulary. Bureau of Indian Standard, April 2010.

[9] GB/T 17049 (2005) Chinese Standard for Technical Specifications, Testing Methods and Testing Rules, for All-Glass

Evacuated Solar Collector Tubes.

[10] EN12975-1 (2001) Thermal Solar Systems and Components, Solar Collector Part 1: General Requirements.

[11] Jouhari, M.S., *et al.* (2014) Thermal Performance Evaluation of (Compound) Solar Collector for Solar Water Heating under Climate Condition of Damascus. Damascus University, *Journal for Engineering Science*. Paper approved for publishing (1632), 21-9-2014.

Symbols and Units

a_1	Heat loss coefficient at $(T_m - T_a = 0)$	[W/m^2·k]
a_2	Temperature dependence of the heat loos coefficient	[W/m^2·k]
A_A	Absorber area of collector	[m^2]
A_a	Aperture area of collector	[m^2]
A_G	Gross area of collector	[m^2]
G	Global solar irradiance	[W/m^2]
$m^{\cdot}$	Mass flow rate of heat transfer fluid	[kg/sec]
Q_u	Useful power gain from collector	[W]
T_a	Ambient air temperature	[˚C]
T_e	Collector outlet temperature	[˚C]
T_i	Collector inlet temperature	[˚C]
T_m	Mean temperature of heat transfer fluid	[˚C]
T_m^*	Reduced temperature difference $(T_m - T_a / G)$	[m^2·K/W]
ΔT	Temperature difference between fluid outlet and inlet	[K]
α	Absorptance	
ε	Emittance	
ρ	Reflectivity	
η	Collector efficiency	
η_0	Zero-loss (optical) collector efficiency (η at $T^* = 0$)	
τ	Transmittance	
C_p	Specific heat capacity of heat transfer fluid	[J/kg·K]