Experimental Evaluation of a Solar Parabolic Trough Collector under Libyan climate

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Abstract: *— Solar energy is the oldest form of renewables utilized by human, and it is the future energy source. It can meet the increasing energy demand without raising the environmental concerns. In this paper, the performance of parabolic trough solar collectors fabricated from the locally available materials has been experimentally investigated under Libyan climate. It was outdoor tested at the roof of Environmental Department, Sabratha University which located at latitude 32.8°N, longitude 12.5°E, and 10 m elevation. It was East-West oriented with a manual tracking mechanism. The heat transfer fluid (water) flows naturally from a supply tank. The experimental results showed that the maximum instantaneous thermal efficiency reached 43.9% for a direct solar radiation of 474 W/m2at a flow rate of 0.24 L/min at 11:00 AM on 27th of January 2016.Moreover, a maximum outlet temperature of 79.5 °C for a direct solar radiation of 650W/m2at a flow rate of 0.24 L/min at 12:45 PM on the same day. These results proved that Cities of Libyan coast holds a real potential for such energy generation technology and highly encourage the commercial companies to invest in the Parabolic Trough Concentrator technology in Libya to meet the increasing demand for water heating systems.*

Keywords *— Parabolic Trough Collector, useful heat gained, collector thermal Efficiency, Industrial process heat.*

I. INTRODUCTION

The sun radiates annually an energy equals 10,000 times the energy consumed by the world population during the same period. Because the radiation is not uniformly distributed over the planet surface, the solar energy that arrives the earth is still little used[1]. In fact, sun energy distribution depends on the latitude, the season and the atmospheric conditions. In recent years, the risk of global warming associated with the emission of greenhouse gases during the combustion of fossil fuels is driving research in the efficient use of energy and renewable energies[2].

The use of the southern Mediterranean countries areas for solar energy harvesting would be far sufficient to supply the energy needs of those countries and all the northern European industrialized countries[3]. In a study carried by Greenpeace[4], it has been found that the use of concentrating solar power can prevent the emission of 148 million tons of carbon dioxide annually by 2020, rising to 2.1 billion tons by 2050.They also found that one 50 MW parabolic trough power plant can cut the annual heavy oil consumption by 30 million liters and thus eliminate 90000 tons of carbon dioxide emissions.

Libya is one of the largest countries in Africa with an area of 1,759,540 km^2, lies between latitudes 19° and 34°N, and longitudes 9° and 26°E. The annual daily average of global solar irradiance ranges between 5 and 7 kWh/m2.day on horizontal surfaces, and this corresponds to a total annual value of 1600 - 2300 kWh/m^2.day [5], [6]. Thus, it owns a high potential of solar energy. Recent studies have shown that the significance of renewable energy resources represents the best alternative to traditional fossil fuel in Libya [7]. One of the main renewable energy issues is the degree of matching between load patterns and renewable energy production. However, the demand of energy for water heating and air-conditioning is one of the key areas for energy consumption which is proportional to the availability of solar radiation during the day. Introducing renewable energies on the housing and industrial sectors should lead to energy savings. Therefore, solar thermal systems became one of the most attractive solutions for these problems.

Parabolic trough collectors (PTC) are devices use metal sheet mirrors or aluminum foil sheets in the shape of parabolic cylinders to reflect and concentrate sun radiations towards a receiver tube located at the focus line of the parabolic cylinder. The receiver absorbs the incoming radiation and transforms it into thermal energy which was absorbed and transported by a fluid medium circulating within the receiver tube. This method of concentrated solar collection has the advantage of high efficiency and low cost. Therefore, PTC is an important technology for large scale exploitation of solar energy, and currently became the most proven solar thermal technology for a solar steam generation. The applications of PTCs are divided into two main groups. The first one is the parabolic trough power generation that requires temperatures ranging from 300 °C to 400 °C and the second group is the industrial process heat applications which require temperatures ranging from 100 °C to 250°C.

The systematic study of PTC design began several decades ago by many authors. An excellent application of the PTC was reported by P. Bendt et al. for line-focus solar concentrators in a Solar Energy Research Institute (SERI)[8]. In his paper, Treadwell considered how optical and thermal effects influence the efficiency of a PTC[9]. He found that rim angles of 90 minimized the maximum distance between the parabolic reflector and the focus. Since the receiver diameter is proportional to this distance, thermal losses, which are proportional to the diameter itself, are reduced.

The PTC has been studied analytically and experimentally by many investigators [10]–[13].Thomas developed a sample structure of PTC to study its deflection and optical characteristics under various load conditions [14]. The author proved that in absence wind tunnel facilities, the test gives sufficient information about the effect of wind load on the optical performance of a PTC. The Euro Trough project [15]proposed a torque box design with lower weight and less collector deformation than other designs. This technology presents different advantages: the first one is the possibility of connecting more collector elements on one drive, so that their number, in addition to costs and thermal losses, is reduced; the second advantage is reducing the torsion and bending increases the optical performance and wind resistance. Nitesh Rane et al.[16] developed an active type solar trekking system for a novel modular sized parabolic trough. They found that the maintenance cost is reduced and hence proving it useful for the application in small-scale industries as the temperature of 150 C is achieved with no difficulty..

A torque box structure was also used by Brooks et al. with a mix of advanced and less sophisticated technologies to manufacture a reflector made of stainless steel sheets covered with an aluminium film[17]. This solution grants accessibility, accuracy, ease of fabrication, and cost reduction. The authors also reported that the instantaneous thermal efficiency for a low-temperature PTC that uses a glass cover does not translate into a significant increase in the efficiency of temperatures near 100 ^{o}C. Rosado Hau and Escalante Soberanis illustrated the production of a water-heating system based on PTC technology limited to a maximum temperature of 55^{o}C[18]. The collector presented uses a sheet of polished stainless steel. The receiver is a copper tube coated with a thin black paint and shielded by a polycarbonate-evacuated glass.

Venegas-Reyes et al. described a light but robust structure of aluminum made only using hand tools designed for low-enthalpy steam generation and hot water[19]. This PTC has a rim angle of 45o and the receiver without a glass cover to reduce costs. In another work published in 2013 [20], the authors presented five PTCs for the same purpose; three of them have a rim angle of 90^{0} and the other two have a rim angle of 45^{0}. In the construction and assembly of both collectors, only hand tools are required. The design of both collectors consider unshielded receivers and without glass cover to reduce manufacturing and transportation costs. They carried out thermal and optical analyzes for each collector, and the results showed apeak efficiency of 35% and 67% for the PTC with a rim angle of 45oand 90o respectively.

Using the solar energy for different industrial heat processes in Libya has been carried out by many researchers; however, to the best of authors' knowledge, they did not study the utilization of the PTC for any solar application.

The objectives of this paper are to test and evaluate the performance a PTC to produce a medium water temperature from the sun's energy for industrial process applications. The prototype is to be designed and tested from local materials to obtain higher thermal performance.

II. THE COLLECTOR DESIGN

A. PTC design

A prototype PTC is made from available local materials. The collector is designed with simple parabolic equations. A cross-section of the parabolic trough collector is shown in Figure1, where various important parts are named. The radiation incident on the reflector at the rim of the collector makes the rim angle, φ_r with the center line of the collector. .From geometrical relations of the parabolic section, the equation of the parabola in terms of the coordinate system is given as:

$$x^2 = 4fy \qquad (1)$$

From equation (1) the parabola height $y = h$ regarding the focal length and aperture diameter is $x = a/2$:

$$h = \frac{a^2}{16f} \qquad (2)$$

For a parabolic reflector, the radius, r, shown in Figure1 is given by:

$$r = \frac{2f}{1+\cos(\varphi)} \qquad (3)$$

Where φ is the angle between the collector axis and the reflected beam at the focus. As φ varies from 0 to φ_r, r increases from f to r_r, therefore, equation (3) become

$$r_r = \frac{2f}{1+\cos(\varphi_r)} \qquad (4)$$

Another parameter related to the rim angle is the aperture of the parabola, (a). From Figure1 and simple trigonometry, it can be found that:

$$a = 2\, r_r\, Sin(\varphi_r) \quad (5)$$

Substituting equation (4) into equation (5) gives

$$a = \frac{4\, f \sin(\varphi_r)}{1+\cos(\varphi_r)} \quad (6)$$

$$\tan\left(\frac{\varphi_r}{2}\right) = \frac{a}{4f} \quad (7)$$

The Geometrical concentration ratio C is defined as the area of the aperture A_a, to the receiver surface area A_{rec}

$$C = \frac{A_a}{A_{rec}} = \frac{a}{\pi\, D_o} \quad (8)$$

The reflective surface curve length of is given by: [22]

$$S = \frac{H}{2}\left[\sec\left(\frac{\varphi_r}{2}\right)\tan\left(\frac{\varphi_r}{2}\right) + In\left(\sec\left(\frac{\varphi_r}{2}\right)+\tan\left(\frac{\varphi_r}{2}\right)\right)\right] (9)$$

Where H is the lactus rectum of the parabola calculated by:

$$H_P = 4\, f \tan\left(\frac{\varphi_r}{2}\right) \quad (10)$$

For the same aperture length, various rim angles are possible as shown in Figure2. It is also seen that, for different rim angles, the focus to aperture ratio, the curvature of the parabola, changes. It can be proven that, with a 90° rim angle, the mean focus-to-reflector distance and hence the reflected beam spread is minimized. The collector surface area, decreases as the rim angle is decreased. Thus, there is a temptation to use smaller rim angles because the sacrifice in optical efficiency is small, but the saving in reflective material cost is great[21].

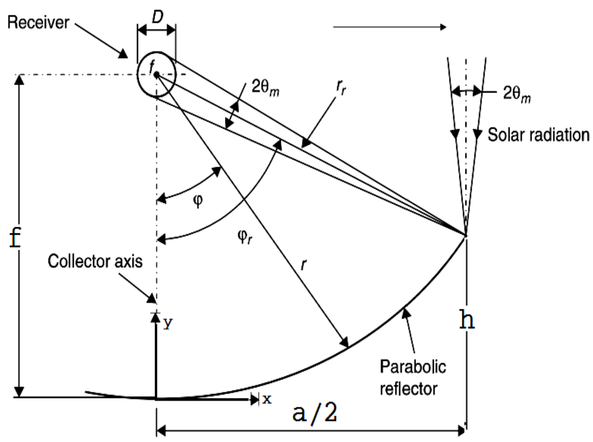

Figure 1: Cross-section of the PTC with circular Receiver

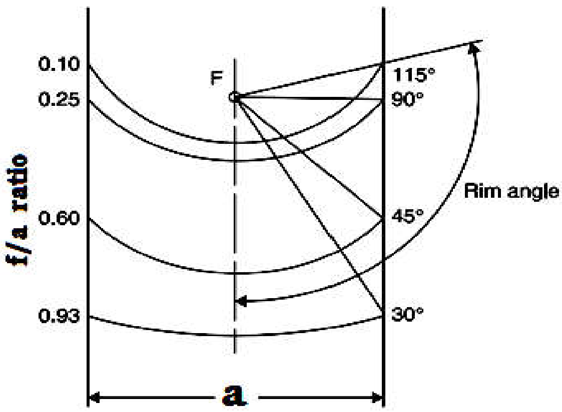

Figure 2 : parabola focal length and curvature

B. PTC construction

Design, construction, and assembly of the PTC are done at the workshop of the mechanical engineering department at the faculty of engineering of Zawia University. A galvanized steel tube was selected from the available local tubes to serve as a receiver. The geometrical specifications of the PTC are given in table1.

TABLE1: GEOMETRICAL DATA OF THE PTC MODEL

Characteristic	Symbol	Value
Aperture width (m)	a	1.0
Aperture area (m^2)	A_a	4.992
Collector height(m)	h	0.125
Collector Length(m)	L	4.8
Focal length(m)	f	0.5
Geometrical concentration ratio	C	15.76
Parabola curve length(m)	S	1.04
Receiver area (m^2)	A_{rec}	0.3167
Receiver inner diameter(m)	D_i	0.017
Receiver outer diameter(m)	D_o	0.021
Rim angle(^{0})	φ_r	53.13
Rim radius(m)	r_r	0.625

III. EXPERIMENTAL SETUP AND PROCEDURE

A schematic diagram of the PTC used in the experimental investigation shown in Figure3. The experimental work was done in an open flow on 27th of January 2016. The test rig was outdoor, and the readings were taken from 10:00 AM to 4:00 PM. The system consists of the constructed collector, 1m3 storage tank and measuring instruments. The storage tank used for storing the cold water, was made of iron sheet and fixed at 3m above the collector level so that the water flow due to the gravity. A flexible pipe made of plastic used for carrying the cold water from the storage tank to the receiver. A control valve connected to the storage tank and the flowmeter was used for controlling the mass flow rate. The flowmeter was connected to the inlet of the receiver tube to measure the water flow rate. During the experiment, many measurements were taken at a time interval of 15 minutes. The temperature of water inlet, outlet, ambient, and tube surface were measured using digital thermometers, air velocity was measured using a digital anemometer, water flow rate was measured using flowmeter, and the solar radiation intensity was measured using digital CMP 6 pyranometer.

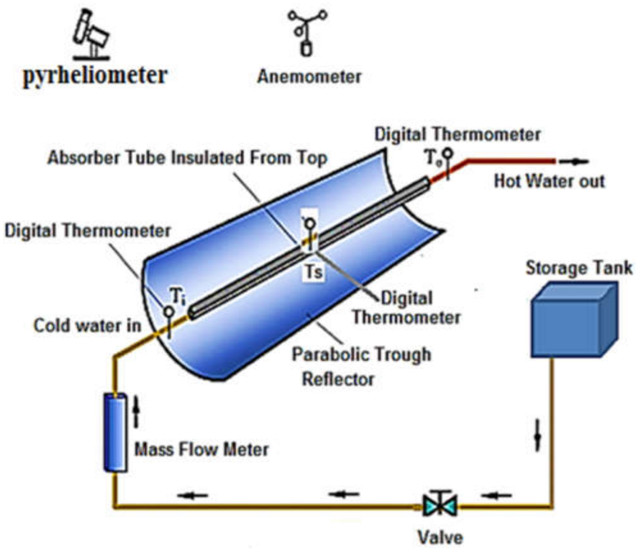

Figure 3: Schematic diagram of the experimental work

IV. SYSTEM PERFORMANCE CALCULATIONS

Thermal performance of PTC was evaluatedin terms of the thermal efficiency and the useful heat gained using the measured temperatures of heat transfer fluid (HTF) for inlet and outlet, mass flow rate, ambient temperature, wind speed, and solar radiation intensity.

A. *Useful heat gain (Q_u)*

The useful heat gain is the instantaneous heat energy gained by the HTF during its flow between the inlet and outlet of the receiver. It was calculated from the flowing equation:

$$Q_u = m^{\cdot} C_p (T_{ou} - T_{in}) \tag{11}$$

Where T_{ou} and T_{in} denote the temperature of the HTF at the outlet and inlet of the receiver measured at the same time in ^oC, $(C_p)$is specific heat of the water in$(J/(kg.K))$, and $(m^{\cdot})$ is the mass flow rate of the HTF measured in(g/s)

B. *Thermal Efficiency:*

The efficiency of the PTCis defined as the ratio of the instantaneous useful heat gained by the HTF, and the instantaneous solar beam radiation incident (I) on the given aperture area (A_a) of the collector. The instantaneous thermal efficiency $(\eta_{th})$was calculated as follows:

$$\eta_{th} = \frac{m^{\cdot} C_p (T_{ou} - T_{in})}{I.A_a} = \frac{Q_u}{I.A_a} \tag{12}$$

Where $(I)$is the instantaneous solar beam radiation $(w/m^2)$and (A_a)a is collector aperture area(m^2)

V. RESULTS AND DISCUSSION

Figure4 shows variations of the solar radiation and the useful heat gained measured during the test period on 27th of January 2016. At 10:00 AM, the solar intensity is 310 W/m^2. As the time passes, the intensity starts to rise until reaching the peak value of 659 W/m^2 at 1:30 and 1:45 P.M. After that time, the intensity decreases to of 451 W/m^2 at the end of the experiment. At 10:00 AM, the gained heat is 134 W/m^2 due to the low rate of solar radiation, then as time passes, it starts to increase until reaching the peak value of 224.6 W/m^2 at 12:45 PM. These results indicate that the useful energy gained influenced by the solar radiation rate and the temperature difference between the inlet and the outlet of the receiver. Then, the useful heat gain decreases until the end of the experiment as a result of the decreased solar intensity.

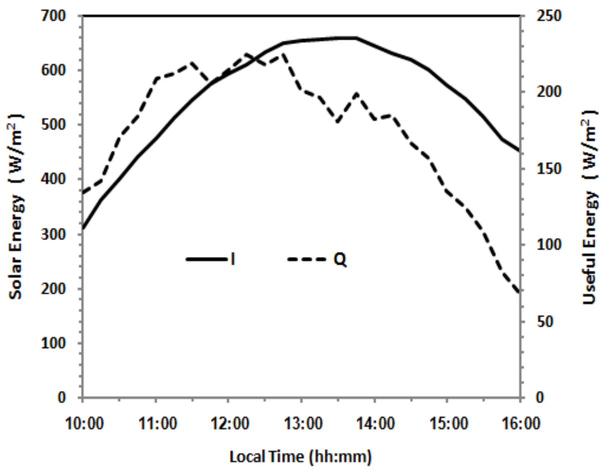

Figure 4: Variation of the Solar Radiation(I) and the useful heat gained (Q_u) with time

Figure5 shows the instantaneous thermal efficiency during the experiment period. It is noticed that the efficiency is high at the beginning of the experiment because the solar radiation is lower and the difference between the inlet and outlet of HTF is high (equation (2).Maximum values of the efficiency are 43.9% at 11:00 A.M. As time passes; the efficiency starts to decrease until it reaches its minimum values at the end of the experiment. From equation (1) because mass flow rate $(m^{\cdot})$, the specific heat of the HTF (C_p), and the aperture area (A_a) are constants, it is expected that the thermal efficiency from figure5 has the same behavior as the ratio of $(T_{ou} - T_{in})/I$ as shown in Figure5.

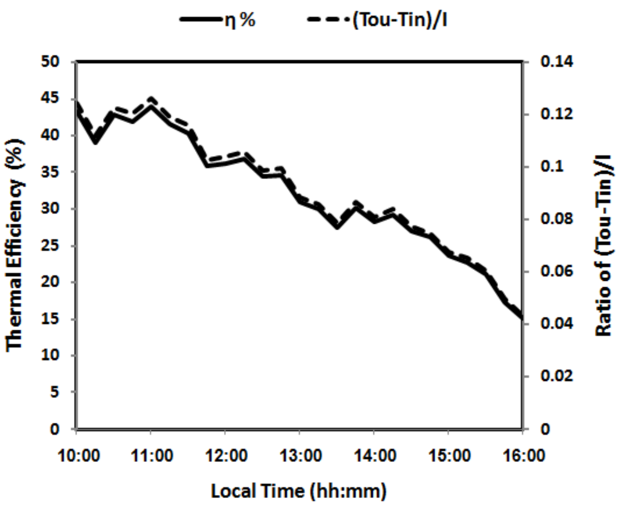

Figure 5: Variation of the Thermal efficiency (η) and the ratio of (Tou-Tin)/I with time

Figure6 shows the variation of wind speed, ambient temperature, inlet temperature, outlet temperature and the difference between inlet and outlet temperature with time. At the beginning of the test, the ambient temperature is low with values around 11°C to 14°C, and it starts to increase as the radiation intensity increases until it reaches a maximum value of 17.2°C at 2:15 PM. Then, it decreases slightly until the end of the test. The minimum and the maximum wind speed are 0.1 m/s and 1.1 m/s, and between these values it is fluctuating up and down until the end of the test according to the local weather condition. It can be noticed that at the beginning of the experiment the outlet temperature starts to rise at a faster rate than the inlet until it reached its maximum value of 79.5 °C at 12:45 PM. Then, it begins to decrease until the end of the experiment with an outlet temperature around 37.2°C. Because the HTF during the experiment has an open flow, the inlet temperature behavior is the same as the ambient temperature. The minimum and maximum temperature values are found to be 12.7°C and 18 °C respectively. It can also be noticed that the inlet and outlet temperature difference has the same behavior of the outlet temperature because the outlet temperature changes influenced by the inlet temperature changes.

VI. CONCLUSIONS

An experimental study was conducted to evaluate the performance of a PTC under Libyan. The experiments are done at winter season on 27th of January 2016. The collector thermal efficiency and useful heat gained obtained from this study showed good agreement with data published by other researchers in other regions. The results showed that the maximum and average thermal efficiencies were 43.9 % and 32%, respectively. Maximum and average useful heat gain were found to be 225 W/m^2 and 174 W/m^2 respectively. The maximum outlet temperature of the HTF was found to be79.5°C.

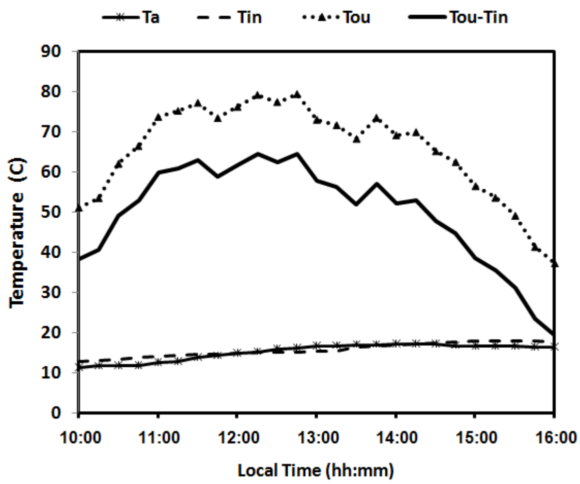

Figure 6: Variation of ambient, inlet, outlet temperatures and wind speed with time

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