JJMIE

Volume 8 Number 1, February. 2014
ISSN 1995-6665
Pages 1- 5

Jordan Journal of Mechanical and Industrial Engineering

Design and Performance Assessment of a Parabolic Trough Collector

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Abstract

Parabolic trough collectors (PTCs) represent a proven source of thermal energy for industrial process heat and power generation; unfortunately it is still not highly implemented due to technical and economical barriers.

In recent years, environmental issues have focused attention on green energy resources, improving the chance for PTCs to be commercially competitive in the market. The Middle East region is considered an interesting area for implementing solar energy projects since the sun is shining most of the year with high direct irradiance values.

In this study, a six meter long parabolic trough collector was designed, constructed and tested to assess its performance. The result of this work proves the efficiency and potential of such green energy sources for both local society and decision-makers. The mechanical analysis of the structure of the trough was simulated both manually and using the finite element software ABAQUS. The experimental test focused on direct steam generation, temperature variation with mass flow rate and thermal efficiency. The maximum steam temperature measured was 123˚C at a pressure of 2 bars, and the maximum efficiency obtained was 22.4%.

Keywords: *Solar Energy; Concentrated Solar Power; Parabolic Trough Collector; Direct Steam Generation.*

1. Introduction

A legend has it that Archimedes used a "burning glass" to concentrate sunlight on the invading Roman fleet and repel it from Syracuse (Sicily). In 1880 John Ericsson constructed the first known parabolic trough collector. He used it to power a hot air engine. In 1907, the Germans Wilhelm Meier and Adolf Remshardt obtained the first patent of parabolic trough technology. The purpose was the generation of steam [1, 2].

In 1913, the English F. Shuman and the American C.V. Boys constructed a 45 kW pumping plant for irrigation in Maadi, Egypt, which used the energy supplied by trough collectors. The pumps were driven by steam motors, which received the steam from the parabolic troughs. The system was able to pump 27,000 liters of water per minute. Despite the success of the plant, it was shut down in 1915 due to the onset of World War I and also due to lower fuel prices, which made more rentable the application of combustion technologies [3].

In this study, a six-meter long parabolic trough collector was designed, constructed with the least possible cost, and tested to assess its performance. Thermal, optical and mechanical analyses of the parabolic trough were done.

Simple available materials in the Jordanian market were used due to a limited budget. The work was completed through several stages; the first stage was to deal with the theory and mathematical equations for the design of a parabolic trough collector, while the second stage was to manufacture the components and parts needed. The third and fourth stages were designing and building the PTC according to design criteria. The last stage was testing and measuring the temperature and pressure of the obtained steam at several running tests to calculate the efficiency of the manufactured six meter long PTC.

2. CSP Projects in Jordan

There are still no serious CSP projects in Jordan, but there are some experimental small-scale projects in operation:

2.1. Dead Sea Spa Hotel

Parabolic troughs are used to generate hot water to drive a two-stage ammonia absorption chiller in summer and to pre-heat domestic hot water in winter. The system consists of three rows of parabolic solar collectors connected in series with a total number of fourteen collectors.

The reflectors are made of 0.8mm Aluminum sheets covered with Aluminum coating, the HTF is distributed among the collectors through 38mm steel pipe which is insulated with 80mm Rockwool. The absorber tube is connected to the distribution pipe via stainless steel flexible connectors [4].

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2.2. Mutah University Tri-Generation CSP Project

The project is located at the Roof top of the engineering department of Mutah University. It utilizes CSP technology for a Tri-Generation of electricity, Water Distillation, and Cooling/Heating.

The project comprises 40 CSP parabolic trough reflector panels that cover 240 m^2 of solar matrix area to generate 120 kW thermal power (kW_{th}) peaks with 15 kW electrical (kW_e), 100 kW_{th} heating and 20 kW_{th} cooling; it also can produce 150 L/Hr of distilled water [5].

3. Theoretical Background

3.1. Thermal Analysis of PTC

A parabolic trough solar collector takes the radiant energy from the sun and converts it to useful thermal energy in the heat transfer fluid (HTF) that circulates through the solar field. Once the geometry and thermal properties are defined, the thermal performance and energy gained by the HTF can be calculated under different configurations and meteorological conditions.

In measuring the thermal efficiency, we apply different flow rates at noontime and record the temperature difference. The input energy is the beam irradiance incident on the aperture multiplied by the projected reflector area. The irradiance can be measured using a pyranometer. The thermal efficiency is given by [1, 2]

$$\eta_{th} = \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = \frac{\dot{m}\ C_p\ \Delta T}{G_b A} \tag{1}$$

where:

$\dot{m}$ is the mass flow rate in the pipe and can be measured by recording the time for filling a specific mass,

ΔT is the difference between the outlet and inlet temperatures measured by thermocouples (K).

C_p is the specific heat of water = 4.2 kJ/kg.K.

G_b is the beam irradiance at the time of test (kW/m^2).

A is the projected reflector area (m^2).

3.2. Stress Analysis:

A mechanical analysis of the trough was done, this was important to predict if mechanical failure may occur in any of the components.

As mentioned, the effect of wind on the trough is an important factor that has to be analyzed. The force produced by wind on the trough can be calculated by the generic formula for actual wind speed:

$$F = APC_d \tag{2}$$

where:

P is the wind dynamic pressure,

A is the projected area

C_d is the drag coefficient

$$F_{wind} = (0.5 \times 1.19 \times 7^2)(1.6 \times 6)(1.6) = 450N$$

And per unit length

$$F_{wind} = 450/6 = 75N/m$$

The weight of the trough will also have a distributed load effect (270 N/m) on the trough as shown in figures 1 and 2, those two figures show the action and reaction forces acting on the trough, in addition to shear force and bending moment diagram.

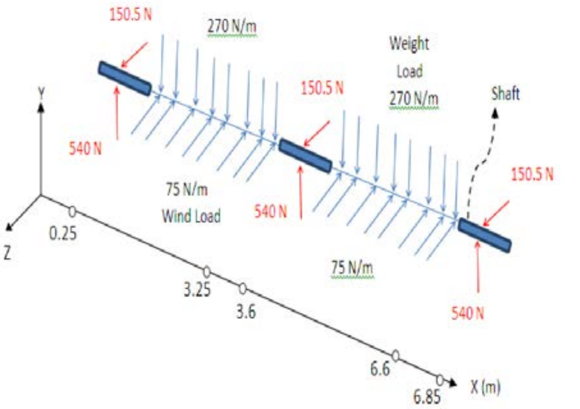

Figure 1.The action and reaction forces acting on the trough.

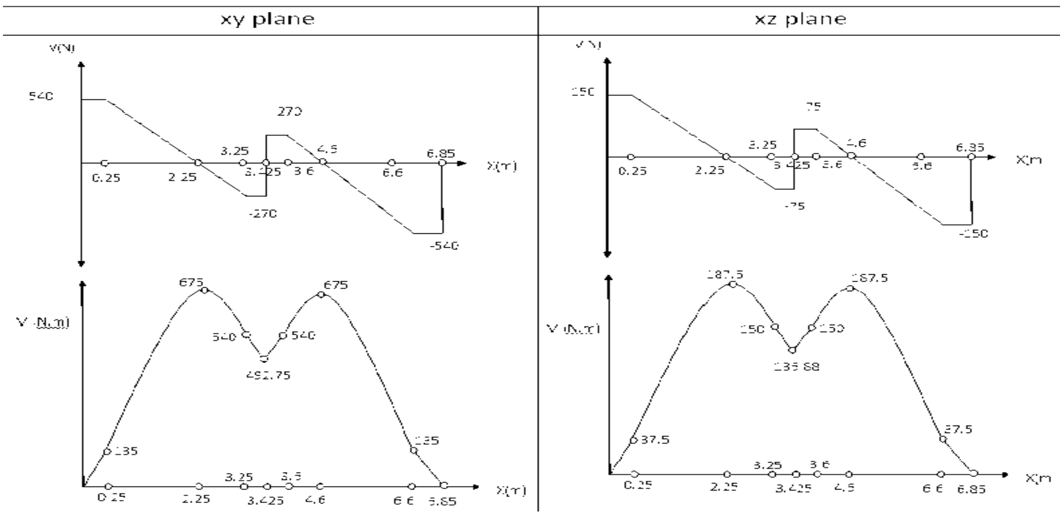

Figure 2. Shear force and bending moment diagrams.

Using an appropriate software, the above boundary and loading conditions were introduced to obtain the deformation and maximum allowable stress as shown in Figures 3-5. The obtained results showed that the loading conditions are within the elastic limits of the complete structure.

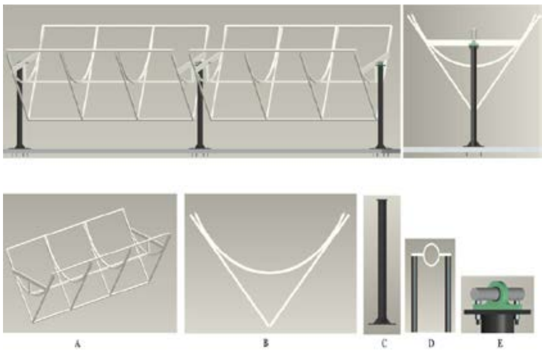

Figure 3. Modelling of the PTC collector.

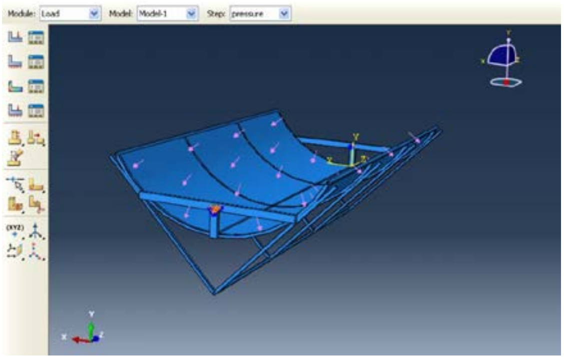

Figure 4. Loading conditions of the PTC.

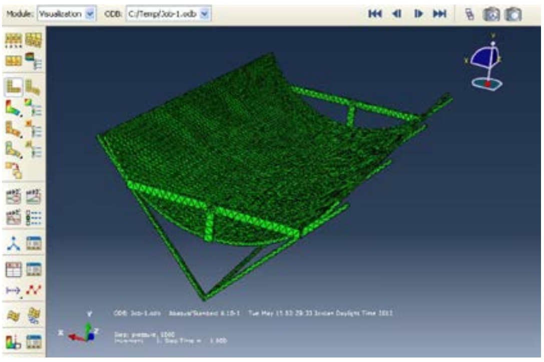

Figure 5. The equivalent Von-Mises stresses.

4. Manufacturing and Testing

The manufacturing process of the locally manufactured CSP is illustrated in the following set of figures:

Figure 6. Tube rolling and welded frame.

Figure 7. Stainless steel mirror used in the project.

Figure 8. Receiver tube and glass tube.

4.1. Experimental Setup

The PTC will be tested in an open circuit flow. The inlet valve is connected to a water supply line and the inlet temperature of the flow is close to ambient temperature. Before the outlet, a pressure gauge which can read up to 14 bar is connected, next to it is a K-type thermocouple connected using a T-connection and a pierced plug. The thermocouple wire is inserted in the plug's small hole and held in it using epoxy droplet glue to avoid water leakage especially at high pressure. After the end valve a one meter length of PEX pipe is connected to send the steam to the air in a safe way. Sun tracking is done manually and is held in position using a rope connected between the PTC frame and ground. The bearing structure is installed on wheels to adjust the solar south and test the system at different positions.

The components of the final product including the measuring and flow control devices used are illustrated in Figure 9 and table 1, while the manufactured system characteristics and the cost of the system components from local market are presented in tables 2 and 3.

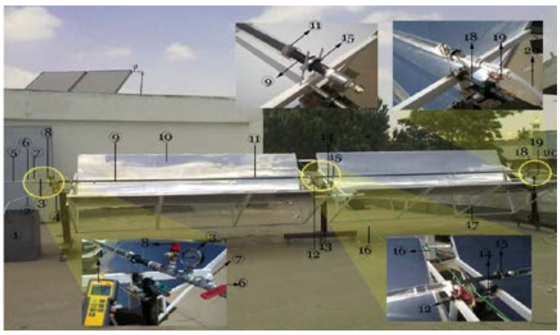

Figure 9. PTC components and test rig description (see table 1 for items 1-21).

Table 1. PTC components (see Fig. 9).

1	Outlet water tank	12	Pulley
2	Four bar pressure pipe	13	Stand
3	Pressure gauge	14	Connection shaft
4	Thermocouple	15	Receiver holders
5	Outlet pipe	16	Rope
6	Outlet valve	17	Space frame structure
7	Thermocouple wire inlet to pipe	18	End shaft
8	Pressure relief valve	19	Inlet valve
9	Absorber pipe	20	Inlet pipe
10	Reflecting material	21	Pillow block bearing
11	Glass tube		

Table 2. System characteristics.

No. of PTC modules	2
Concentration Ratio	21
Rim angle	100º
Focal length	0.35 m
Aperture width	1.67 m
Length (per module)	3 m
Total row length	6 m
Total surface area of reflecting mirrors	12 m^2
Total aperture area	10.02 m^2
Tracking axis orientation	North–south
Absorber pipe inner/outer diameter	25/32 mm
Receiver Absorptivity	85%
Mirror Material (Reflectivity)	Stainless steel 68%
Frame material	iron
HTF	Direct steam generation (open feed)

Table 3. Cost analysis of system components.

	Part Name	No. Of Parts Used	Material	Cost (JD Per Part)	Total Cost JD
1	Frame	2	Cast Iron	50	100
2	Mirror Sheet	6	Stainless Steel	30	180
3	Bearing	3	Cast Iron, steel	4	12
4	Pylons Holders	3	Cast Iron	10	30
5	Short Shafts	2	Steel, 1005-1009, Cd	2	4
6	Long Shafts	1	Steel, 1005-1009, Cd	1	1
7	Long bolts	12	Cast Iron	0.02	0.24
8	Short Bolts	6	Cast Iron	0.02	0.12
9	Nuts	6	Cast Iron	0.01	0.06
			Total cost		**327.42**

4.2. Time Constant Testing

An aspect of collector testing is the determination of the heat capacity of a collector in terms of a time constant. It is also necessary to determine the time response of the solar collector in order to be able to evaluate the transient behaviour of the collector and select the correct time intervals for the quasi-steady-state or steady-state efficiency tests. The time constant of a collector is the time required for the fluid leaving the collector to reach 63.2% of its ultimate steady value after a step change in incident radiation. The procedure for performing this test is as follows. The heat transfer fluid is passed through the collector at the same flow rate. The aperture of the collector is shielded from the solar radiation by defocusing the collector and the temperature of the heat transfer fluid at the collector inlet is set approximately equal to the ambient air temperature. When a steady state has been reached the collector is focused again and measurements continue until steady-state conditions are achieved again. For the purpose of this test, a steady-state condition is assumed to exist when the outlet temperature of the fluid varies by less than 0.05°C per minute. The temperature at 63.2% steady state is given as follows:

$$T_{t=r} = 0.632\left(T_{o,steady\ state} - T_i\right) + T_i \qquad (3)$$

where T_i is the inlet temperature

T_o is the outlet temperature, and τ is the time constant.

5. Results

5.1. Time Constant

Figure 10 shows the temperature response of the collector with three different values of mass flow rates. The average value of the time constant is τ = 4.25 min.

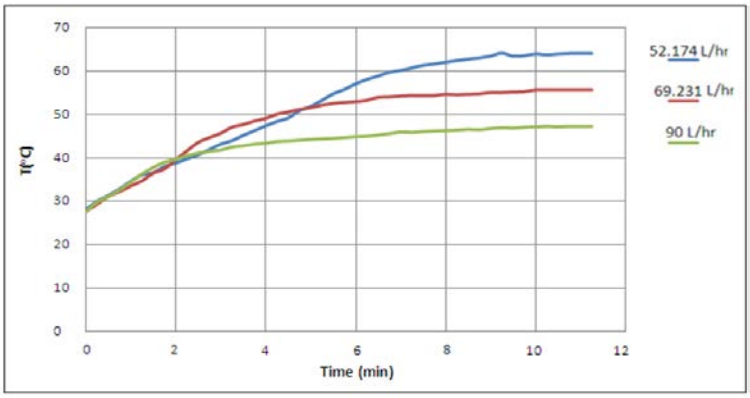

Figure 10. Temperature response of the collector with three different values of mass flow rate.

5.2. Thermal Efficiency

The normal irradiance on the collector surface was measured to be G_n= 1032 W/m^2, so the thermal efficiency was calculated using equation 1 as:

$$\dot{m} = \frac{69.231L}{hr}, P = 1bar$$

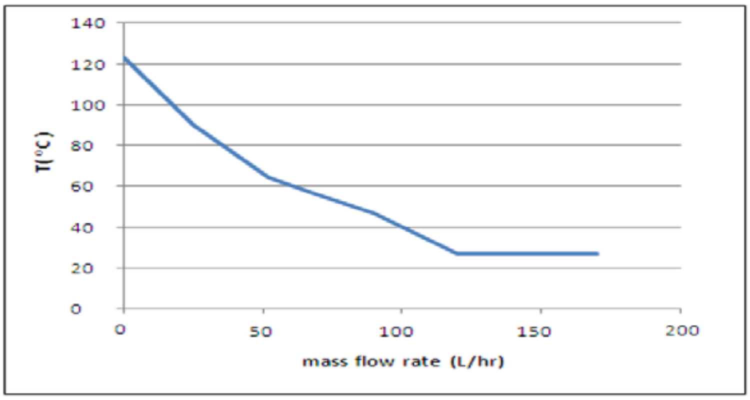

Figure 11. The relation between exit temperature and mass flow rate.

$$\eta_{th} = \frac{(69.231/3600)\text{kg/s}(4.186)\text{kJ/kg.K}(55.7-27)}{\frac{(1.032)kW}{m^2(1.67\times 6)m^2}} \times 100\%$$

$$= 22.4\%$$

For a fixed inlet temperature of 27 ˚C, the maximum outlet temperature in the test reached 123 ˚C at low flow rate, as shown in Figure 11.

5.3. Steam generation process

The required flow rate to generate steam was 2.642 L/hr, it gave superheated steam at 123˚C and 2 bars. The enthalpies at the inlet and outlet are 113.23 and 2731.15 kJ/kg, respectively. The thermal efficiency for the steam generation can be calculated as the following:

$$\eta_{th} = \frac{\dot{m}\Delta h}{G_b A} = \frac{(2.642/3600)\text{kg/s}(2731.15\text{-}113.23)\text{kJ/kg}}{(0.87)kW/m^2(1.66\times 6)m^2} \times 100\% = 18.6\%$$

The peak thermal efficiency obtained during the test was 22.4%. Steam was generated with temperatures up to 123°C and a pressure of 2 bars at low flow rate of 2.64 L/hr.

6. Conclusion

A parabolic trough solar collector was designed, constructed and tested with acceptable performance and results. The length of the PTC was 6m with an aperture width of 1.67m, a rim angle of 100º and concentration ratio of 21. The surface consisted of 304 AB stainless steel sheets (2×1× 0.00045 m3) and the frame was made of iron tubes. The collector's sun tracking was adjusted manually

while ABAQUS software was used for the mechanical design of the bearing structure. The peak thermal efficiency obtained during the tests was 22.4%. Steam was generated with temperatures up to 123˚C and a pressure of 2 bar at low flow rate of 2.64 L/hr.

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