Analysis, fabrication, and optimization of solar thermal parabolic trough

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Abstract

This paper presents an analysis, fabrication and optimization of solar thermal parabolic trough. The solar parabolic trough is shaped as a parabola and has a reflective surface on it. The focal line is varied depending on the trough parameters. The parabolic trough size determines the upper limit reached by the absorber tube and it could reach high as $400°C - 600°C$. This heat is utilized to heat fluids and is connected to thermals systems to generate electricity. This work intends to analyze the performance of a parabolic trough type solar collector through direct experimentation as well as using simulation methods. It analyzes the effect of the focal length of the parabolic trough and the different absorber tube material, on the thermal performance of the system. The result of the research shows that the thermal losses are more prevalent using the stainless-steel absorber tube and the overall performance is better with a larger parabolic trough.

Keywords: *Parabola; Electricity; Pipe water; Simulation*

1.0 INTRODUCTION

Solar power is a source energy which an inexhaustible energy source with photonic energy from the sun. It is reliable and readily available for free, whilst essentially not emitting any greenhouse emissions.

Solar water heating systems using s reproducible parabolic trough solar water heater is an appropriate renewable technology, which negates heating costs whilst harnessing the thermal energy of the sun. The equipment is made up of the reflector surface which is curved mirror, a reflector support, an absorber pipe and a stand. The receiver assembly consists of a circular absorber tube with a thermally viable coating, and it is enclosed in a sealed glass envelope is placed along the reflector focal line. The working fluid circulates through the absorber tube and absorbs the incident energy from the tube. The reflector is a linear-focus solar collector which reflects direct solar radiation placed on the receiver or absorber tube in the centre of the parabolic platter. The collector's larger aperture area concentrates direct solar radiation reflected on the receiver tube's smaller outer surface, heating the fluid that circulates through it or discharging through it. This thermal energy can then be used to fuel heat demanding industrial processes of any kind.

For pipe heating, the solar radiation incident falling onto the collector is used. The thermal fluid flows inside the vessel, and through the incoming radiation, its temperature increases. We can then measure the outlet fluid temperature and determine the efficacy of the proposed parabolic trough collector as a function of the pipe diameter, outlet temperature, incoming solar radiation intensity and active diameter of the parabolic collector (Bruce et al,2010). The parabolic trough shape is perfect for the reflector to absorb the sunlight more efficiently and maximize heat energy capture. A parabolic central tower is where a centralized concentrated solar power systems which consists of many reflectors focusing on a central tower. All the energy is sent to a central main point receiver where is processed and converted into electrical energy.

Parabolic trough collector is the most proven technology for indirect steam generation in solar thermal power plants. Malaysia is a prime location to harness this source as we have solar radiation ranging from 4.21 kWh/m^2 to 5.56 kWh/m^2 and solar hours duration of more than 2200 hours per year (Tijani & Roslan, 2021). The purpose of the research is to analyze and determine the heat losses (radiation and convection) associated with heat collection element (HCE) of Solar Parabolic Trough Collector (PTC). The convection and radiation heat loss to the surrounding was calculated by the resulting temperature of the system envelope from the simulation model.

2.0 METHODOLOGY/PROCEDURE

2.1 Test setup

Parabolic trough system consists of the reflector and receiver sections. For the reflector, a parabolic barrel or curve is fabricated and assembled by welding its joints without any gaps. The material should be durable and tough. The surface of the parabolic should be clean and smooth without any dents and scratches (Alberti et al., 2012). The glass mirror on the surface can be replaced with a glazing or reflective material such a reflective sticker, aluminium sheet, glass mirror and any other highly reflective surface. In this experiment an aluminium sheet is used as the reflective surface. It will be bent according to the specification of the curve focal point and angle at different points. To further enhance the reflectivity a sticker of the reflective material is placed on it, carefully stuck on the surface without any dents or surface perturbations, to ensure that the material is able the reflect the sun ray without any issues.

The receiver of the parabolic trough collector (PTC) is to harness solar radiation and to transfer heat towards heating the water. For our experiment the materials used for the receiver absorber tubes is copper and stainless steel. There two types of absorber tubes, the evacuated and non-evacuated tube. The tubes are a long-shaped hollow cylindrical tube, consisting of two concentric tubes. Most of the outer layer receiver tubes are made from borosilicon glass tube with the inner tube made from a metal tube. This is the non-evacuated receiver tube configuration as we utilized in our experiment, whereby the inner tube was a copper and stainless-steel tube respectively. In evacuated receiver tubes to minimize heat loss, there is a vacuum between the inner and outer tubes, which is typically used in systems where the system harnesses temperature above 300 Celsius

Two variations of parabolic trough collector parameters were designed for this research. Both receiver plates are aluminium and polished daily during the testing time. Table 1 show the parameter of both parabolic trough collectors. The two parabolic trough collectors ‘A’ and ‘B’ illustrated in Fig. 1 and Fig. 2 are fabricated according to the defined angle at each defined point as tabulated in Table 2 and Table 3. These points are calculated based on the focal length of the two troughs to ensure that the correct curvature is obtained for both focal lengths. A parabola always has a focal point where all angles will be situated at one point. The deflection of the rim angle towards the ground affects the distance of the focal point and the size of the plane where the focal point is located. The bigger the plane size the shorter the focal point distance. The diameter of the plane is measured and divided with the diameter by two to obtain its x-axis radius. The value of the parabola's bending height towards the ground determines the y-axis.(Carrizosa et al., 2015)

Table 1: Dimension Parabolic trough

Parameters	Parabolic trough "A"	Parabolic trough "B"
Length	1 Meter	1.5 Meter
Width	1 Meter	1.5 Meter
Thickness	2 mm	2 mm
Focal Point	208 cm	100 cm

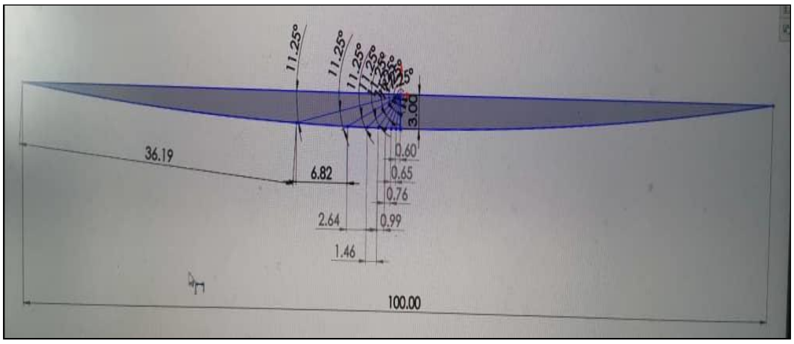

Fig. 1. Parabolic trough "A" 1M x 1M Aluminium Sheet

Table 2: Segment of each length and angle of parabolic trough plane for Parabolic trough "A"

Part	Length (cm)	Angle
A	36.19	11.25
B	6.82	11.25
C	2.64	11.25
D	1.46	11.25
E	0.99	11.25
F	0.76	11.25
G	0.65	11.25
H	0.60	11.25

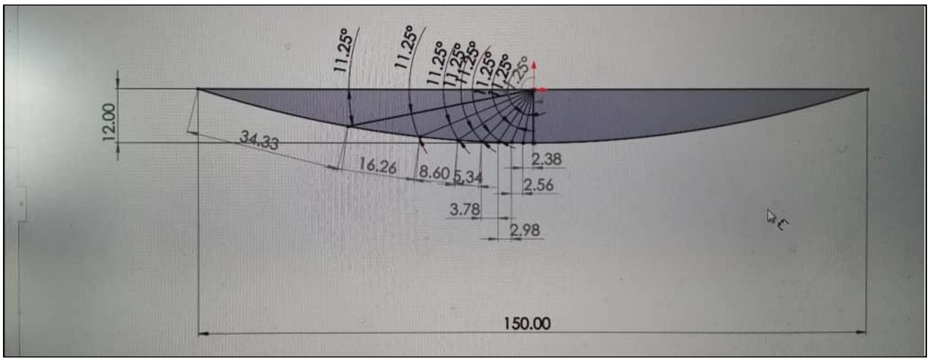

Fig. 2. Parabolic trough "B" 1.5M x 1.5M Aluminium Sheet

Table 3: Segment of each length and angle of parabolic trough trough "**B**"

PART	Length	Angle (°)
A	34.33	11.25
B	16.26	11.25
C	8.60	11.25
D	5.34	11.25
E	3.78	11.25
F	2.98	11.25
G	2.56	11.25
H	2.38	11.25

The two absorber tube materials for testing the prototypes are copper tube and stainless steel. which have the different dimensional parameters. The absorber tube is placed on the focal length which depends on the trough selected. Both absorber tubes are tested with two different parameters of troughs, Parabolic trough "A" and "B", as defined in the table below.

Table 4: Dimension of Absorber Tube

Dimension	Copper	Stainless steel
Diameter of pipe inner	1.8 cm	2.3 cm
Diameter of pipe outer	2.0 cm	2.5 cm
Length of pipe	1.52m	1.52m
Specific heat	378.8 J(kg.K)	502.4J (kg.K)

2.1.1 Parabolic Trough Stand

The stand is made of mild steel with a length 1.21m and a width of 0.61m. Below table given the specification of the stand.

Table 5: Dimension Parabolic trough stand

Dimension	Value (m)
Length of frame	1.220
Width of frame	0.600
Thickness of frame	0.015

2.3 Data Collection and Analysis

The parabolic troughs were field tested for 1 week from 15th November to 22nd November 2020, on an open rooftop with no obstructions to prevent shading on the parabolic surfaces. Parabolic trough A and B were tested concurrently from 9:00 am till 17:00pm. The absorber tube was changed for both configuration after week 1 with the copper pipe absorber which was preceded by the stainless-steel absorber. From the data collected we can determine the absorber's heat transfer and thermal efficiency performance and evaluate the best absorber tube material for the parabolic trough collector. The data was taken in hourly intervals. The temperature measurement is taken through a fixed thermocouple and a non-contact industrial thermometer. A thermocouple is the sensor utilized to detect the temperature of the water as it enters and exits the absorber tube. The experiment setup is shown in the Fig. 3 below.

Fig. 3. The solar parabolic trough test setup stand

3.0 RESULTS AND DISCUSSION

3.1 Theoretical Calculation

A cross-section of a schematic drawing of a parabolic trough collector (PTC) is shown in Fig. 4 below.

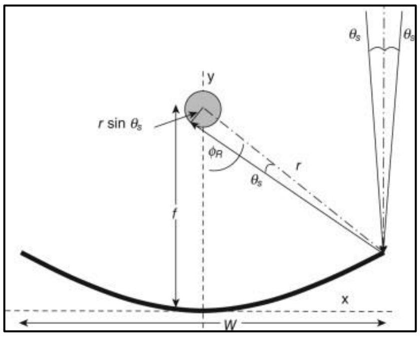

Fig. 4. A schematic drawing of a parabolic trough collector (PTC) Source*: (Lovegrove & Stein, 2012)*

First, the focal points of the parabola are calculated by

$$f = \frac{d^2}{4(\frac{W}{2})} \qquad \ldots (1)$$

where d is the depth of the parabola. And w is the width.

Then by trigonometry, the rim angle, ϕ_R is calculated by

$$\tan\phi_R = \frac{W/2}{f-d} \qquad \ldots (2)$$

As ϕ varies from 0 to ϕ_R, the radius from the center of the receiver to the collector varies as well, and the radius, r is governed by the following relation

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

At the maximum radius away from the receiver, i.e., at the rim, the angle becomes ϕ_R, and Eq. (3) can then be written as

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

Next, we compute the acceptance angle, θ which is dependent on the diameter of the receiver and the distance between the receiver and collector, r. At the rim, the acceptance angle,

$$\theta_s = \sin^{-1}(\frac{d_o}{2r_R}) \qquad \ldots (5)$$

where d_o is the outer diameter of the receiver.

As the light energy is concentrated from a larger area (collector) to a smaller area (receiver), the energy flux on the receiver is increased by a factor known as the concentration ratio (Duffie & Beckman, 2013a). By ignoring micro-surface defects and assuming that the concentration factor is only a function of the geometric properties, we can compute the geometric concentration factor, which depends on the area of both the collector and receiver.(Gerhard et al,2014) Therefore, we can compute the maximum geometric concentration factor, C_{max} which is at the rim,

$$C_{max} = \frac{\sin\phi_R}{\pi\sin\theta_s} \qquad \ldots (6)$$

The calculations are tabulated to identify the thermal loss from the receiver tube to the surroundings.

Table 6: Parameters for Parabolic trough (PTC) "A" and "B"

Parameters	PTC A (1.0 m × 1.0 m)	PTC B (1.5 m × 1.5 m)
Length, L (m)	1.0	1.5
Aperture, W_a (m)	1.0	1.5
Depth, d (m)	0.03	0.12
Focal length, f (m)	2.08	1.17
Aperture area, A_a (m^2)	1.00	2.25
Rim angle, ϕ_R	13.71°	35.54°
Rim radius, r_R (m)	2.11	1.29
Acceptance angle, θ_s	0.27°	0.44°

Maximum concentration ratio, C_{max}	**7.96**	**11.94**
The inner diameter of the receiver, d_i (m)	0.018	
The outer diameter of the receiver, d_o (m)	0.020	

We begin by calculating the thermal loss from the absorber tube to the surroundings. Typically, the heat loss would include convection to the surrounding air, radiation from the surface, and conduction through the support structure. To simplify our calculations, the following assumptions are taken:

i. The conductive heat loss from the receiver to the support structure is negligible, as the contact surface is minimal compared to the whole area of the receiver.
ii. There are no temperature gradients around the receiver in the radial direction and along the length.
iii. The water outlet temperature, T_{out} will be taken as the fluid temperature along with the receiver.
iv. The ambient temperature, T_a is taken at 30°C throughout the sampling period (Mohammad, Al-Kayiem, Aurybi, & Khlief, 2020).
v. The sky temperature, T_{sky} is estimated at 20°C throughout the sampling period (Tian & Zhao, 2013)
vi. The wind speed, v is estimated at 1.8 m/s throughout the sampling period (Tian & Zhao, 2013)
vii. Firstly, to estimate the wind heat transfer coefficient, we find the Reynolds number for an air temperature that is the average of the pipe surface and the ambient temperature. Air properties are taken from a common reference (Cengel, 2003) at $T_{est} = 312.9\text{K} \approx 40°\text{C}$, and are summarized in Table 8 below:

Table 8: Air properties are taken from a common reference

Temperature, T	Density, ρ	Specific heat, c_p	Thermal conductivity, k	Thermal diffusivity, α	Dynamic viscosity, μ	Prandtl number, Pr
40°C	1.127 kg/m^3	1007 J/kg·K	0.02662 W/m·K	2.346×10^{-5} m^2/s^2	1.918×10^{-5} kg/m·s	0.7255

The Reynolds number of the wind around the receiver tube is then given by

$$Re = \frac{\rho v d_o}{\mu} \qquad \ldots(7)$$

Using the equation for the flow of air across a single tube in an outdoor environment, the following equation is used (Duffie & Beckman, 2013b)

$$Nu = \begin{cases} 0.40 + 0.54\, Re^{0.52} & \text{for } 0.1 < Re < 1000 \\ 0.30\, Re^{0.6} & \text{for } 1000 < Re < 50{,}000 \end{cases}$$

(8) The heat transfer coefficient for wind convection (heat loss to the wind) is then written as:

$$h_w = \frac{Nu \cdot k}{d_o} \qquad \ldots(9)$$

The total heat lost by the pipe surface to the surroundings by wind convection and heat radiation is then:

$$Q_{loss} = Q_{conv} + Q_{rad} = A \cdot h_w\left(T_{pipe} - T_a\right) + A \cdot \varepsilon\sigma\left(T_{pipe}^4 - T_{sky}^4\right) \qquad \ldots(10.1)$$

$$Q_{loss} = \pi d_o L h_w\left(T_{pipe} - T_a\right) + \pi d_o L \varepsilon\sigma\left(T_{pipe}^4 - T_{sky}^4\right) \qquad \ldots(10.2)$$

The emissivity $\varepsilon\sigma$ is given at 0.06 (Kim, Conway, Ostroumov, & Shepard, 2013). The loss coefficient, U_L is then found by rearranging the heat loss equation in Eq. 10.1,

$$\frac{Q_{loss}}{A} = (h_w + h_r)\left(T_{pipe} - T_a\right) = U_L\left(T_{pipe} - T_a\right), \qquad \ldots(11)$$

where $h_r = \frac{\varepsilon\sigma\left(T_{pipe}^4 - T_a^4\right)}{T_{pipe} - T_a}$, and the heat loss coefficient,

$$U_L = \frac{Q_{loss}}{A \cdot (T_{pipe} - T_a)} \qquad \ldots(12)$$

By assuming the solar energy received by the collector is reflected the receiver at some factor, the useful energy gain by the fluid is then given by

$$Q_u = Q_s - Q_{loss} = R(\tau\alpha)A_a G_b - Q_{loss} \qquad \ldots(13)$$

where R is the reflectivity of the collector, $\tau\alpha$ is the transmittance-absorptance product, G_b is the solar irradiance in W/m^2, and A_a is the aperture area of the collector. Here, an educated assumption is made regarding the coefficient, $R(\tau\alpha)$ = 0.8015 (Tzivanidis, Bellos, Korres, Antonopoulos, & Mitsopoulos, 2015). The global solar radiation, G_b is taken as an average from 9 am to 5 pm (the sampling period), extracted from Malaysia's Weather Data.

The temperature rise in the fluid can then be calculated as,

$$\Delta T = \frac{Q_u}{\dot{m}c_p} \Rightarrow T_{out} = T_{in} + \frac{Q_u}{\dot{m}c_p} \qquad \ldots(14)$$

However, the experimental value of the water outlet temperature is only 51.4°C, therefore we surmise that our loss coefficient is underestimating the actual heat lost, there are several factors here that could contribute to this discrepancy, including some cloudy times where the pipe cools down significantly faster, the heat dissipated by the collector itself, and uneven heating of the pipe and the fluid. Hence, by a posteriori, we can calculate the actual heat loss coefficient,

$$U'_{loss} = \frac{Q_s - Q_u}{A(T_{pipe} - T_a)} \qquad \ldots(15)$$

Finally, we calculate the theoretical thermal efficiency of the solar collector,

$$\eta_{th,theoretical} = \frac{Q_u}{Q_s} \qquad \ldots(16)$$

and the actual thermal efficiency based on the experimental temperature,

$$\eta_{th,experimental} = \frac{Q_u}{Q_s} = \frac{\dot{m}c_p\Delta T}{392.5} = 0.44. \qquad \ldots(17)$$

Table 9: The summary of the calculation results

Equation	Variable	Results
7	Re	2115
8	Nu	30
9	h_w	$39.93\ W/m^2K$
10.2	Q_{loss}	63.1 W
12	U_L	$40.5\ W/m^2K$
13	Q_u	329 W
14	T_{out}	66.3°C
15	U'_{loss}	$141.2\ W/m^2K$
16	$\eta_{th,theoretical}$	0.84
17	$\eta_{th,experimental}$	0.44

The calculations are for every hour based on the data gathered from the field test from November 15 to November 22, for both parabolic troughs, PTC A and PTC B using copper pipe, and their experimental efficiencies. The hourly efficiency is calculated as per equations above, Eq 7 to Eq 17 and the results are summarized in Table 9 above. .

4.0 RESULTS AND DISCUSSION

Fig. 5 and Fig. 6 below presents the water outlet temperature, from the theoretical calculations and the experimental measurements, and the absolute percent difference. The horizontal axis presents the time series in hourly data, where measurements are taken for 8 consecutive days, modelled by the 64 hour cycle time-dependent hourly data, whereby hour 1 to 8 represent the first day, 9-16 the second day, and so forth. The hour 56 to 64 represent the 8th day results as seen in Fig. 7 and Fig. 8 below.

From Fig. 5 and Fig.7 below we can see that the theoretical calculations consistently present greater values than the experimental values, except for two data points. The trend here is that the percent difference dips every day at midday, while peaks at the start and end of the day. This is anticipated as in our theoretical calculations, the heat absorbed by the receiver tubes is assumed to be constant throughout the day, whereas in reality, the solar radiation is non-uniform throughout the day. Moreover, the theoretical model doesn't account for the heat loss which occurs during the field test.

However, for Fig. 6 and Fig. 8 below, the discrepancies of parabolic trough "B" are significantly larger than that in parabolic trough "A". Furthermore, we observe that the theoretical calculations yielded water temperature outlet that is above boiling point (>100°C), however, in the experimental measurement, the maximum achieved is 71.4°C.

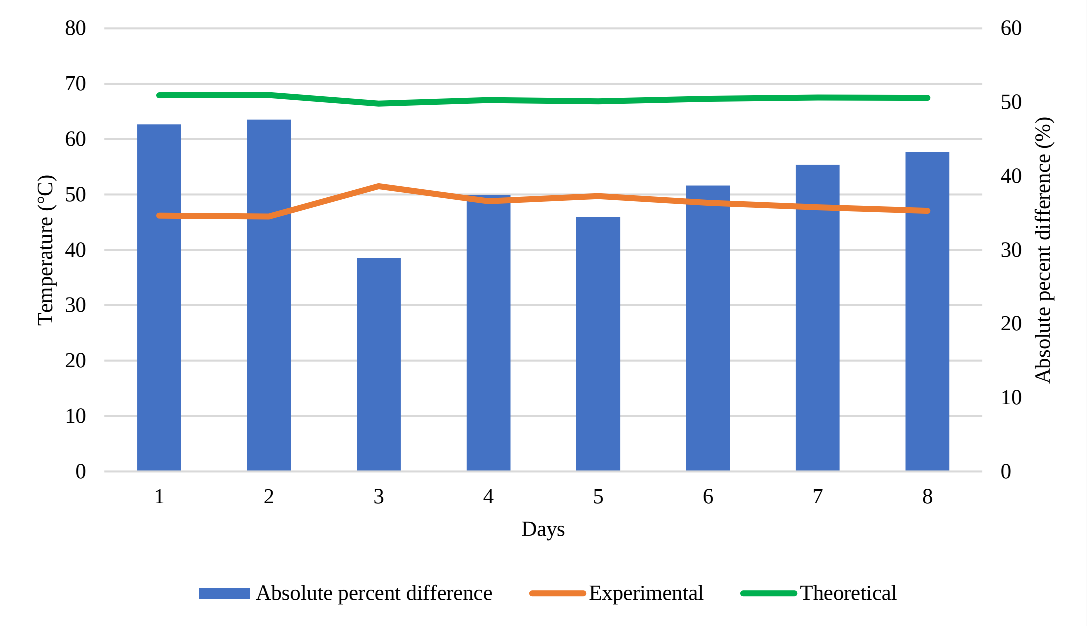

Fig. 5. The temperature of the water outlet for PTC A (1m x 1m)

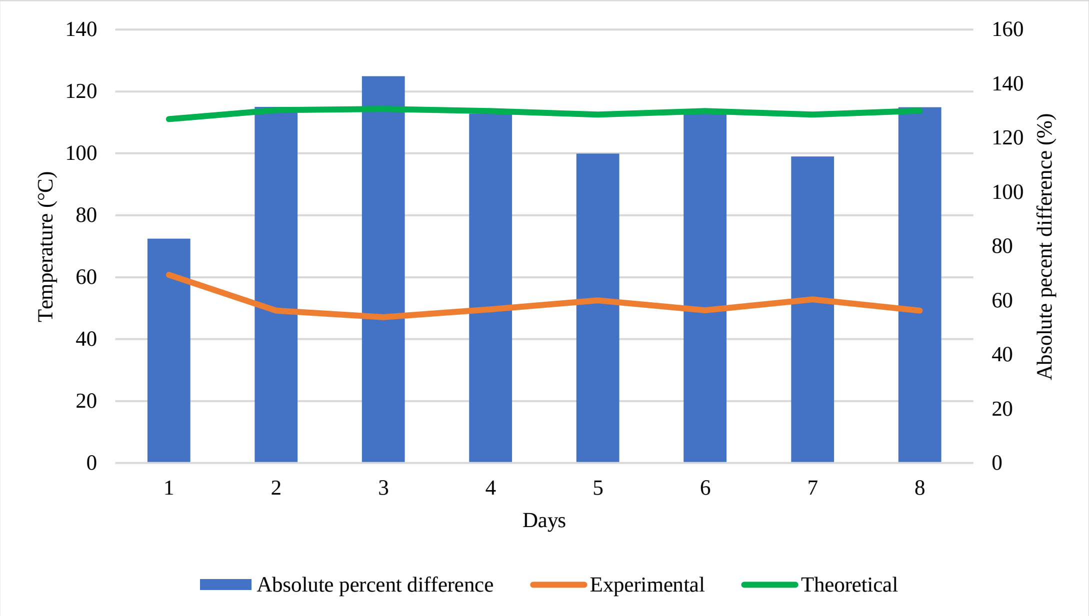

Fig. 6. The temperature of the water outlet for PTC B (1.5m x 1.5m)

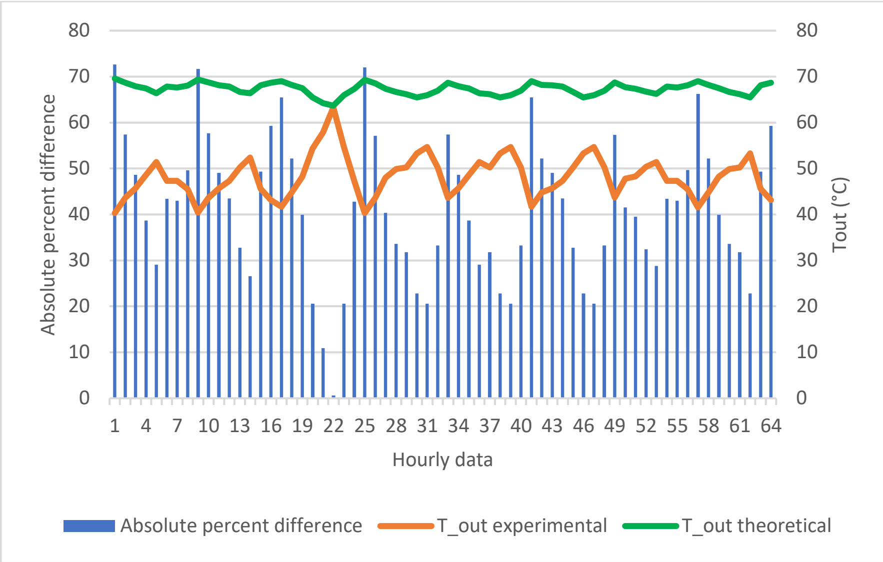

Fig. 7. The theoretical and experimental data variation for the PTC A water outlet (1m x 1m)

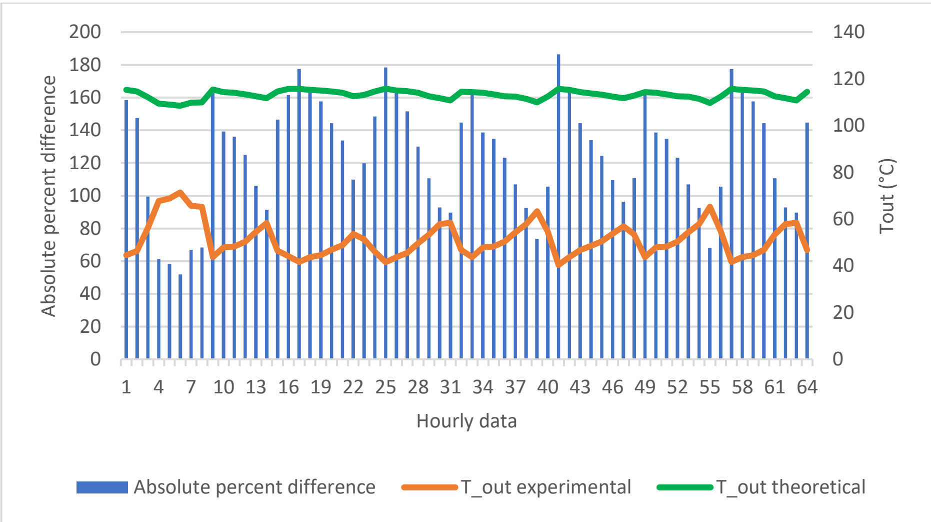

Fig. 8. The theoretical and experimental data variation for the PTC B water outlet (1.5m x 1.5m)

Based on Fig. 7 and Fig. 8 above, the discrepancy between theoretical and experimental efficiency in PTC B is significantly larger than that in PTC A. This is due to the assumption that the full area of the parabolic is utilized and it reflects the solar radiation onto the absorber tube, which based on our results, is inaccurate.Losses in the form of environmental dissipation through radiative losses occurs on the parabolic surface.

Table 10: Solar thermal parabolic trough temperature profile for both copper and stainless-steel absorber tubes

Plane Parameter	Pipe Material	Temperature Profile Max	Temperature Profile Min
1M X 1M	Copper Pipe	4.379e+02	3.936e+02
1M X 1M	Stainless Steel Pipe	3.721e+02	3.426e+02
1.5M X 1.5M	Copper Pipe	4.797e+02	4.273e+02
1.5M X 1.5M	Stainless Steel Pipe	4.129e+02	3.524e+02

The table above shows the average temperature profile with two different absorber materials with two different parabolic troughs. From the comparisons above we can indicate that copper pipe with 1.5M X 1.5M has the highest reading for temperature profile on the performance of absorber tube. The temperature profile indicates that both parabolic trough performed better with the copper absorber tube. In conclusion and based on the experiment, the copper pipe with 1.5 M X 1.5 M shows the best thermal performance.

5.0 CONCLUSION

Two difference sized parabolic trough collectors “A” and “B” were designed, assemble and tested for eight days with two different absorber tube materials. The results showed that the copper pipe achieved the best thermal efficiency with a temperature output of 71.3℃. The final findings were that the solar parabolic trough performs better with copper tube 1.5 M X 1.5M. Theoretical calculation had been analysed and calculated to test on the thermal build up in the absorber tube. As compared to the experimental result, there were heat losses across the pipe. The experiment was conducted, calculated and compared with the theoretical calculation. It illustrated the difference in the outlet temperature values and surface area temperature values between the experiment and theoretical model. The inconsistency of the results was due to external factors such as solar radiation which is non-uniform and inconsistent due to shading and cloud cover, causing net heat loss from the absorber tubes to vary depending on the time of day. This was not considered in the theoretical model, where it assumes constant solar irradiation. Since the collector does not receive a uniform and consistent solar radiation, the solar capture capability of the 1.5m parabolic trough collector is much larger than 1m parabolic trough collector. Moreover, the position of the sun was not considered, despite the fact that the solar radiation received by the collector and reflected to its focal point. The focal point is also dependent on the position of the sun, which varies throughout the day. Consequently, this was not included in the calculations. Another factor contributing to the inconsistency, is. the wind cooling effect and environmental heat loss which is significant. Overall, all we can conclude that copper has the highest rate of absorption compared to the other material used. Hence parabolic trough collector is a better substitute for solar collector energy system to generate heat as it doesn't need any external power to produce heat.

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