Performance Evaluation of Dual-axis Tracking System of Parabolic Trough Solar Collector

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Abstract. A parabolic trough solar collector with the concentration ratio of 24 was developed in the College of Engineering; Nanjing Agricultural University, China with the using of the TracePro software an optical model built. Effects of single-axis and dual-axis tracking modes, azimuth and elevating angle tracking errors on the optical performance were investigated and the thermal performance of the solar collector was experimentally measured. The results showed that the optical efficiency of the dual-axis tracking was 0.813% and its year average value was 14.3% and 40.9% higher than that of the eat-west tracking mode and north-south tracking mode respectively. Further, form the results of the experiment, it was concluded that the optical efficiency was affected significantly by the elevation angle tracking errors which should be kept below 0.6o. High optical efficiency could be attained by using dual-tracking mode even though the tracking precision of one axis was degraded. The real- time instantaneous thermal efficiency of the collector reached to 0.775%. In addition, the linearity of the normalized efficiency was favorable. The curve of the calculated thermal efficiency agreed well with the normalized instantaneous efficiency curve derived from the experimental data and the maximum difference between them was 10.3%. This type of solar collector should be applied in middle-scale thermal collection systems.

Keywords: Parabolic Trough Solar Collector, Dual-axis Tracking, Heat Collector, Azimuth-elevation Angle, Tracking Error, Optical and Thermal Efficiency.

1. Introduction

Energy is basic need for agriculture and other industries. Different resources, like wood, coal, fossil fuels and nuclear chemicals were used as sources for energy, but all these sources are getting scarce (Naidoo and Van Niekerk, 2011). The solar collector had been widely used to reduce the fossil energy consumptions for different purposes *i.e.* water heating, distillation, drying and ventilation etc. and had been widely used in China for water heating and drying purposes (Argeseanu *et al.*, 2009). Parabolic trough solar collector system was a mature concentrating solar thermal technology, its working temperature was in the range of 100~450 ℃ and were widely used in power generation, industrial heating, cooling, desalination of sea water and many other fields (Chen and Jinhong, 2003). Concentrated and tracking system was a key technology of the parabolic trough solar collector. Traditional, one-dimensional single-axis tracking, using horizontal North-South axis, East-West tracking axis horizontal, North-South track, condenser efficiency (Chong and Wong, 2009). Dual-axis tracking system can track the changes in solar altitude and azimuth, the Sun's angle of incidence was 0, effectively improving the collectors of solar radiation received (Fenrandez-Garcia *et al.*, 2010).

(Feuermann *et al.*, 2002) studied the simulation and experimental analysis of the parabolic trough solar collector under the dual-axis tracking collectors. Pisticci used in the dual-axis tracking parabolic trough solar collector for the saturated steam production at 280 ℃ in a chemical plant (Gang *et al.*, 2010). Spain PSA built 0.5 MWe DCS test station Germany M.A.N produced in trough Helioman 3/32 dual-axis parabolic tracking solar collectors. However, the collector connection pipeline between long, large heat loss, mechanical complexity, the high cost of maintenance, its price lower than that of the single-axis tracking system (Hang *et al.*, 2008). Therefore, large-scale trough power generation using single-axis tracking system, for heating and cooling as the main objective of the small and medium heat collection system *i.e.* distributed or regional energy supply, dual-axis tracking parabolic trough collector had some space because of its high efficiency.

(Helwa *et al.*, 2000) they implemented two-axis sun tracking system for the purposes of tracking on the current, power and voltage with the different loads. They indicated that 43.87% increased with the using of two-axis sun tracking system. Tracking was required only due to the change in inclination of the earth and efficiency was found to increase by providing the dual-axis tracking and the maximum efficiency attained was 72% (Kalogirou, 2009). For dual-axis tracking system to track the sun radiation intensity in one point, collector types of solar collector were classified *i.e.* PTSC (parabolic trough solar collector), CPC (compound parabolic collector) and PDC (parabolic dish collector), while among them parabolic trough solar collector had been known the high temperature solar thermal application system with the high collection of energy source easily and increased the optical efficiency of the collector (Kalogirou, 2012). The most efficient and popular tracking device was the polar-axis and azimuth/elevation type of tracker of sun radiation with the highest efficiency of the collector (Kumaresan *et al.*, 2012). Different researchers (Lei *et al.*, 2011) studied the use of sun tracker with the $\pm 0.05°$ average accuracy in solar fiber-optic mini-dish collector with a diameter of 200mm. Therefore, the accuracy of the azimuth-elevation tracking system in the collector highly relies on that how well the azimuth axis was aligned to be parallel with the zenith axis of the collector reported by (Liu and Changsheng, 2011).

In this regard, based on the low temperature in the solar collector system, the study was proposed to the using of dual-axis tracking technology and a homemade tube, dual-axis tracking parabolic trough collector system was established in the college of Engineering, Nanjing Agriculture University, China. Based on the Monte Carlo Light Tracing (MCRT), TracePro software used for the optical simulation and optical efficiency of the collector, the model established for the simulation of tracing and tracking error effects on optical efficiency and its thermal performance of parabolic trough solar collector. Further, studied the steady-state collector characteristics and analyzed the efficiency of dual-axis tracking parabolic trough solar collector in the warm areas of research and application.

2. Methods and Material

2.1. Description of Experimental Site Location
The performance of dual-axis tracking parabolic trough solar collector was developed in the College of Engineering, Nanjing Agriculture University, China for the purposes of the tracking system. The experimental setup was installed at the latitude of $32.06°$ and $118.77°$ longitude of the area as showed in the figure 1, while the experimental setup of the performance of dual-axis tracking parabolic trough solar collector as showed in the figure 2. Thermal Performance of parabolic trough solar collector testing location for the Jiangsu campus of Nanjing Agriculture University, College of Engineering with the 10:00-15:00 test time for the 11th, 13th and 15th April 2016 during a mostly sunny with the outdoor temperature is 24~38 ℃ and solar radiation intensity of 900~1100W/m^2, while during the 3 days of heat-conducting parabolic trough solar collector the oil flow was 0.8, 0.6, 0.8m^3/h. Similarly, the parameters and instruments used in the experiments are given in table 1.
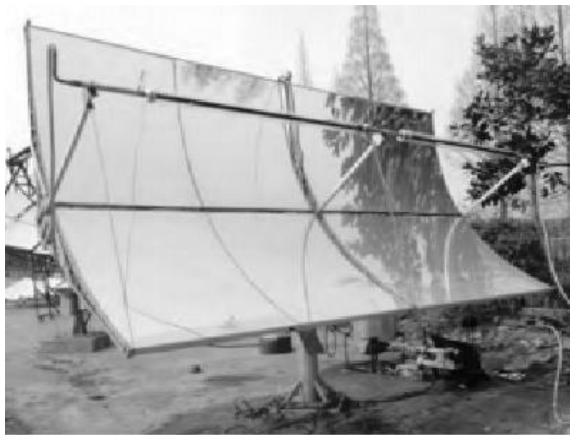
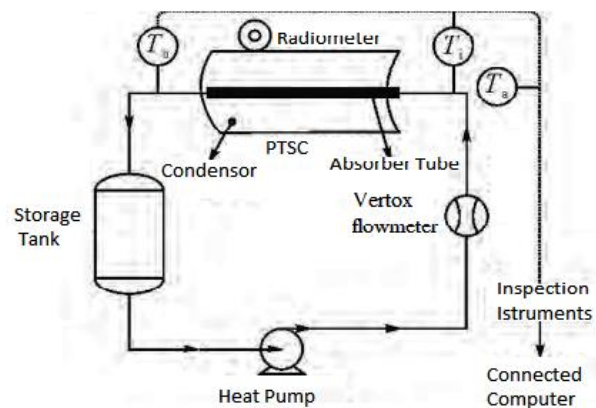Figure 1. Experimental setup of Parabolic Trough Solar Collector

Figure 2. Schematic diagram of dual-axis tracking Parabolic Trough Solar Collector

2.2. Description of Experiment and Calculation Methods for Test Device

The figure 2, shows the schematic diagram of the dual-axis tracking of parabolic solar collector flow and test apparatus. The device mainly by the parabolic trough solar collector, heat-conducting oil storage tanks, heat conduction oil pumps, Vortex flow meter measurement recording instruments and parameters. Condenser lens material for ultra-low iron floats glass using domestic straight-vacuum collector parameters and major apparatus are shown in table 1.

Table 1. Parameters and instruments used in parabolic trough solar collector

S. No	Materials	Unit	Dimension
1	Concentrated	-	24
2	Collector open area	m^2	12
3	Mirror reflectivity	-	0.93
4	Tube length	m	2.00
5	Metal pipe outside diameter	m	0.040
6	Metal pipe inside diameter	m	0.036
7	Glass transmittance	-	0.90
8	Coating absorption rate	-	0.96
	Instrument	**Model**	**Unit**
1	Radiation detector	TBQ-2	±2%
2	Testing the Sun recorder	PC-2	1 W/m^2
3	Heat conduction oil pump	WRY26-20-100	-
4	Vortex flow meter	LUGB-21/1	±1%
5	Data logging devices	WP-816	0.5%
6	Platinum resistance	Pt100/Φ3mm	±0.1 K

2.3. Efficiency Calculation

Instantaneous efficiency (η_i) of the dual-axis tracking parabolic trough solar collector determined with the measuring of the tube inlet, outlet collector temperature and thermal oil flow calculation of following equation 1. Where, in the equation (ρ) for the oil density in kg/m^3, (v) volume flow rate in m^3/h, (C_p) for the specific heat capacity at constant pressure of oil in j/(kg. ^{o}C), A_a for the collector opening area in m^2, T_o for set heat temperature in ^{o}C, T_i for collector tube inlet temperature in ^{o}C, G_b for sun radiation intensity in W/m^2, Generally G_b for G range from 0.55~0.70 (Liu, 2012), we get G_b=0.625G, G for total solar radiation intensity in W/m^2. In the present study of efficiency, the determination was carried out with the same methodology adopted by (Liu, 2010).

$$\eta_i = \frac{\rho V_{C_P}(T_{0\_}T_i)}{A_a G_b} \times \frac{1}{3600} \qquad (1)$$

2.4. Description of Models for Collector Efficiency

2.4.1 Optical Efficiency. The rate of short wavelength (optical) energy reaching to the absorber of the collector, divided by the energy coming from the solar resource was called optical efficiency. Collector center was the origin of open surfaces with the positive x-axis and y-axis for the North and east respectively Cartesian coordinate system was established. Sun angle of the incident light unit vector was normal with the opening angle of the collector surface. Equation 2, was used for the calculation of the optical efficiency of single-axis tracking with the angle of sun day time location of the center of the sun. In equation a_s as the sun elevation angle, γ_s as the azimuth angle, for dual-axis tracking solar incidence angle was 0, optical efficiency η_{op} remains constant throughout the day. η_{op} was the absorption of radiation for the receiver power/collector receives direct sunlight radiated power ratio. Ignore concentrating lens surface processing error, the collector installation error and tracking error. Using three-dimensional modeling software TracePro for the collector solid-works, (*s*) for mirror track angle, set the collector opening of incident light 1000 to simulate at different times the optical efficiency of the collector as showed in table 1.

$$S = (\cos a_s \cos \gamma_s , \cos a_s \sin \gamma_s , \sin \alpha_s) \tag{2}$$

2.4.2. Thermal Efficiency. In-line-tube one-dimension heat transfer model calculations heat transfer oil outlet temperature and efficiency can be determined with the using of equation 3 (Meng *et al.*, 2013). In addition, the evaluation of a dual-axis tracking trough solar collectors in different solar radiation, thermal performance under ambient temperature and the inlet temperature, its normalization processing efficiency obtained efficiency over time (Morin *et al.*, 2012); (Parikh, 2016). Where in the equation F_R represent the heat transfer (W), U_L the total heat loss coefficient (W.m^{-2}.K), T_a denotes temperature ^{o}C and C the concentration ratio.

$$\eta = F_R \eta_{op} - \frac{F_R U_L}{C}\left(\frac{T_i - T_a}{G_b}\right) \tag{3}$$

3   Results Discussion

3.1. Tracking Mode of Optical Efficiency Analysis
The accuracy of tracking was very important in parabolic trough solar collector, higher the accurate tracking of the sun, higher the temperature of the collector and thus can increase the efficiency. To increase the sun tracking in the collector, reduce the area of the focal point of the reflector used in the collector so that the radiation intensity of solar energy increased at the receiver point of the collector. A different tracking method has been studied in parabolic trough solar collector reported in the literature (Mousazadeh *et al.*, 2009); (Naidoo and Van Niekerk, 2011). To simulate the optical efficiency of the collector with the 4 solar terms the day of the sun location in the whole year *i.e.* 4 seasons was analyzed as showed in figure 3 with the 3 different tracking mode *i.e.* single-axis, dual-axis and North-South axis tracking. The figures results show the simulation, without comparative analysis of the optical efficiency of the heat exchanger, view tracking for an ideal state without deviation.
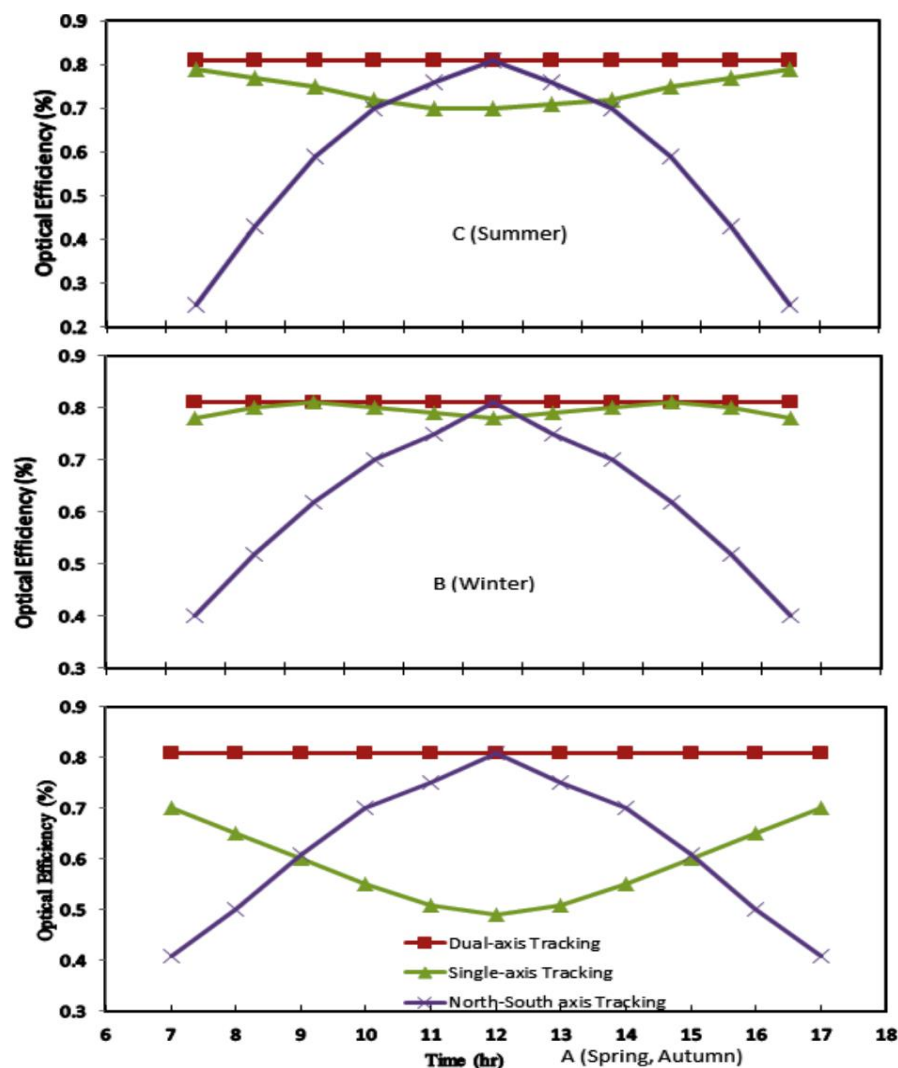
Figure 3. Optical efficiencies of the solar collector of three tracking modes

From the figure 3 (A, B and C), it was clearly shown that under the dual-axis tracking, the sun angle was 0 and the daily average optical efficiency remained at 0.813% which was higher than single-axis tracking efficiency 2.5-36.4% and higher than North-South axis tracking the efficiency of the collector was in the range of 30.8-52.3%. The 4 average daily efficiency was the average annual efficiency of the solar day (simplified estimates the average annual efficiency) single-axis and North-South axis tracking system with 14.3 % and 40.9% respectively (Odeh *et al.*, 2003). Therefore, thermal dual-axis tracking allows maximizing the solar radiation, high optical efficiency and stable, designed for stable heating all year round. All the experimental results of the present study have provided a clear agreement with the previous study (Oner *et al.*, 2009); (Parikh, 2016). Dual-axis tracking system increased the optical efficiency of the parabolic trough solar collector reported by (Park and Kang, 2001), which was nearly in agreement with our results.

3.2. Tracking Error
Under the dual-axis tracking, when the Sun's rays not perpendicular to the collector openings surface than high angle tracking error ε_e and azimuth tracking error ε_a was generated as shown in figure 4 with the result of the optical simulation, ε_e for 0~1.4 °, step 0.1 °, ε_a for 0~14, step 1 ° respectively. In one of the previous study (Saad and Hosni, 2013) evaluate the accuracy of the sun tracking system for 7 hours (from 09:00AM to 04:00PM) with the system position in azimuth and elevation angle of the area,

and they computed the 0.4345 maximum error in azimuth tracking and 0.2008 minimum error was found to be elevation tracking.
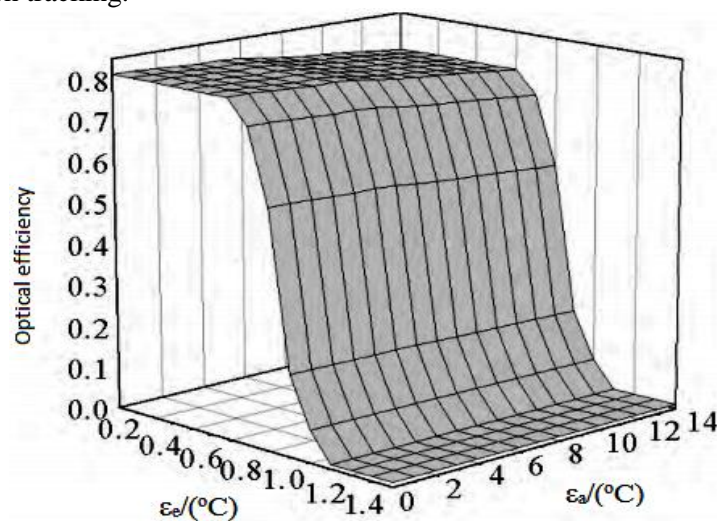

Figure 4. Influence of tracking error in optical efficiency

Therefore, when the ε_e<0.6 ° then the optical efficiency remained at about 0.810 and when ε_a>0.6 °, the optical efficiency drops rapidly, while when ε_e>1.1 °, it only receive the sunlight on the upper surface of the tube and the bottom surface was no longer under the spotlight, the concentrated efficiency was close to 0, optical efficiency increased with the decrease of ε_a, but decrease marginally, ε_a from 0° to increase 14°, optical efficiency by 0.813 to 0.758, this was because that ε_a sunlight vertical incident angle was not 0. (Saban *et al.*, 2015) they studied the efficiency of end-loss formula in combination with the model and they calculated that ε_a was 14° and optical efficiency of 0.752, which was similar to our results. So, when ε_e<14 °, the end-loss has little effect on the optical efficiency.

Tracking collectors to the solar altitude elevation angle tracking accuracy of high LS-1-LS-3 the tracking precision of the trough solar collector have reached 0.1 °, but with the increase of the accuracy of tracking system costs will be considerably increased (Schweiger *et al.*, 2000). When ε_e was less than 0.6 °, the collectors maintain high optical efficiency, which can effectively reduce system costs. The comparison between single-axis and dual-axis tracking can be reduced to a single track and precision of the shaft for high optical efficiency. For example the collector uses tracking error-free run in the winter and at noon the optical efficiency of 0.500 (Figure 3 (c)); if they were in dual-axis tracking, ε_e was 0.6 °, ε_a was 14 °, then the optical efficiency up to 0.757 (Figure 4), more efficient than single-axis tracking was increased by 0.257. Different study had been reported the elevation angle tracking error of parabolic trough solar collector to make sure the proper dual-axis tracking system with the tracking error of 0.1^o-0.3^o (Stafford *et al.*, 2009), 0.4^o (Wang *et al.*, 2007), 0.6^o -0.7^o (Xiong *et al.*, 2012) and ±1-2° reported by (Xu *et al.*, 2013) also found that error in tracking system due to wind loading was also a measurable quantity. All the experimental results of the previous study had been provided clean and clear agreement with the present research study.

3.3. Thermal Characteristics
Experimentally measurement of heat-conducting oil outlet temperature, ambient temperature, and solar radiation intensity trend was shown in figure 5, 6. It can be seen in figure 5, 6, the thermal oil change outlet temperature with time basic linear upward trend, which 11th April 2016 in running the original due to low solar radiation, smaller temperature rise, starting from 50^oC and heat conduction oil outlet temperature finally reached to 170^oC.
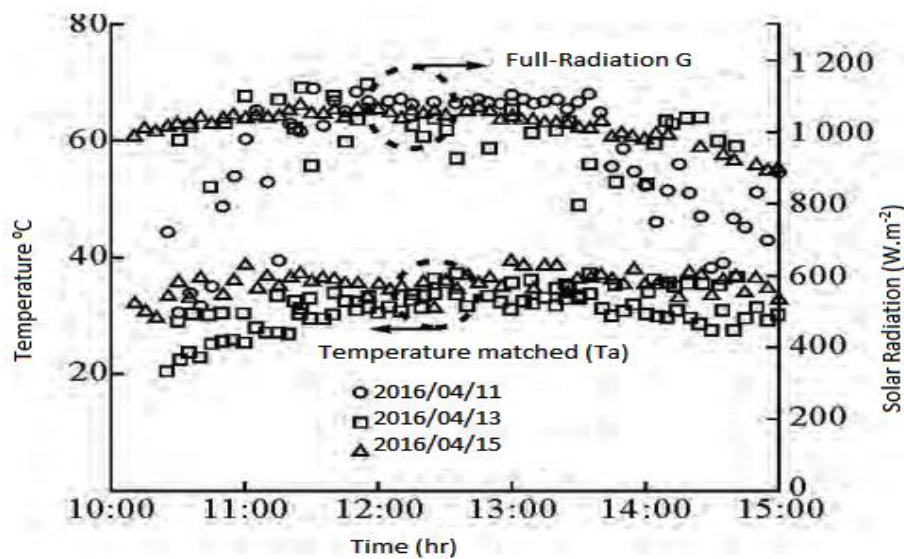
Figure 5. Ambient temperature and solar irradiation

Similarly, on 13th April 2016 and 15th April 2016 the initial temperature 123°C and 71°C respectively and the thermal conductivity oil outlet temperature should ultimately reach up to 200^{0}C. (Yuezhao and Jiang, 2007) observed that increasing of solar radiation intensity increased the temperature of the collector, which increased the instantaneous efficiency of the parabolic trough solar collector. The increasing of inlet temperature was a direct relationship with the increasing of efficiency of the parabolic trough solar collector, with the increasing of solar radiation and heat transfer oil in the collector reported by (Liu and Changsheng, 2011).
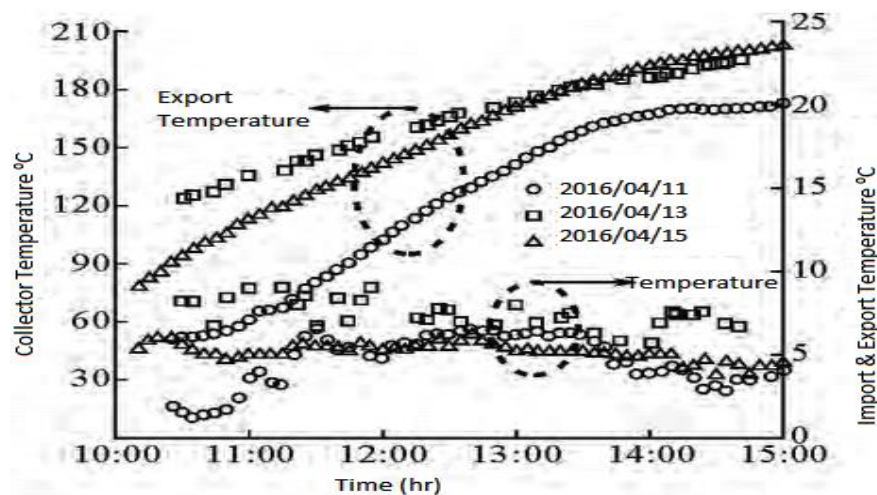
**Figure 6.** Outlet temperature and temperature of heat transfer oil

The figure 7, showed the calculated model of heat-conducting oil outlet temperature. Maximum error calculated values and experimental values were less than 2%, and verify the validity of the model. According to the findings of (Meng *et al.*, 2013), they studied the heat-conducting inlet and outlet temperature of the collector, which was similar to our results.
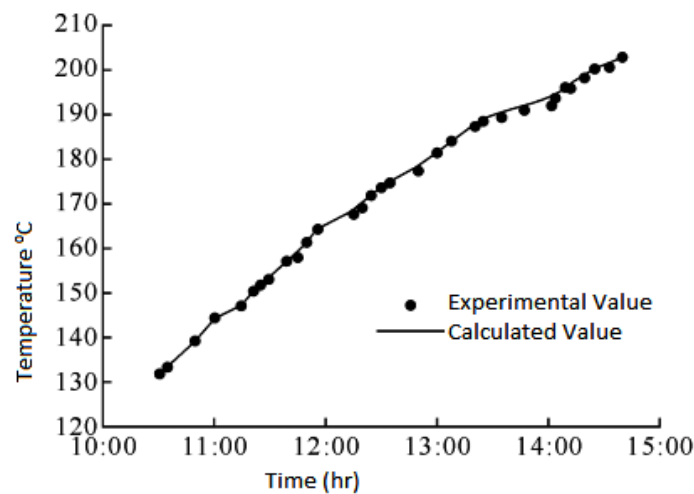
Figure 7. Comparison of calculated and experimental values of heat transfer oil temperature

3.4. Thermal Efficiency

Dual-axis tracking system based on the measured data of 3 days instantaneous efficiency was shown in Figure 8, within the range of 0.600-0.775. Partial radiation intensity fluctuation in efficiency caused by shock large and radiation stability and efficiency as the oil temperature rises gradually on 13th April 2016 on time of 10:35. Thermal efficiency was noted 0.739 on the time of 13:00 with the temperature 150°C, efficiency drops significantly after 14:40 at the temperature of 202°C and the efficiency was reduced to 0.637. Causes of efficiency decrease as follows *i.e.* 1) oil temperature, the temperature difference between oil and environment temperature increase collector tube heat loss was longer than efficiency decreased; 2) the homemade tube under high temperature, coating color changes with the resulting in thermal performance degradation. The results were in contradictory with the findings of (Parikh, 2016). Our results were in agreement with the findings of (Fenrandez-Garcia *et al.*, 2010), they reported that instantaneous efficiency of the collector increased with the increasing solar radiation intensity. (Kalogirou, 2012) they reported that efficiency of the collector increased with the using of dual-axis tracking system in the collector, which was found to be similar to our results.
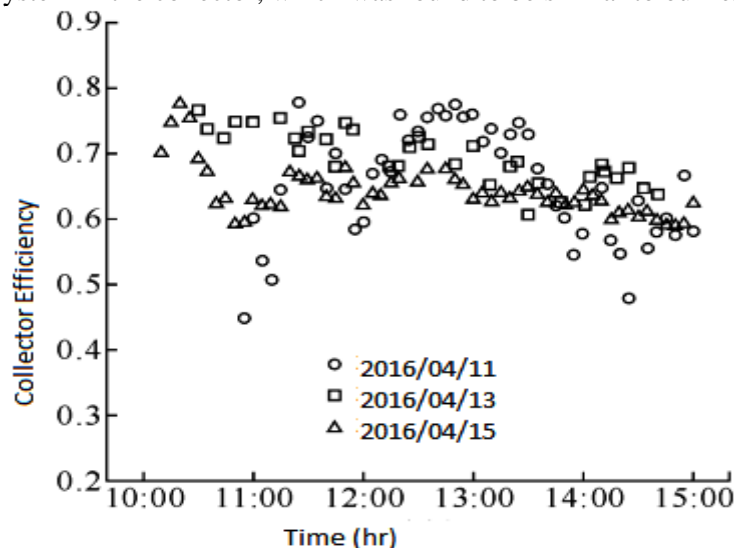

Figure 8. The instantaneous thermal efficiencies

Select 11th April, 2016 heat-conducting oil inlet temperature was 130~200 ℃ test stability and radiation intensity fluctuation of velocity data, the instantaneous efficiency were normalized, tube inlet temperature T_i obtained the normalized on the basis of the instantaneous efficiency, while straight-tube,

one-dimensional steady-state efficiency curve of the model system, results were showed in figure 9. (Liu and Changsheng, 2011) Studied the optical performance analysis for parabolic trough focusing collector with several tracking modes which results were in agreement with our results. The previous results were matched with the present results with the findings of (Hang *et al.*, 2008). The results were matched with the findings of (Naidoo and Van Niekerk, 2011); (Kumaresan *et al.*, 2012), they studied that heat conducting inlet temperature increased the instantaneous efficiency of the collector and also they tested the model for the steady-state condition of the collector with one-dimensional efficiency curve.
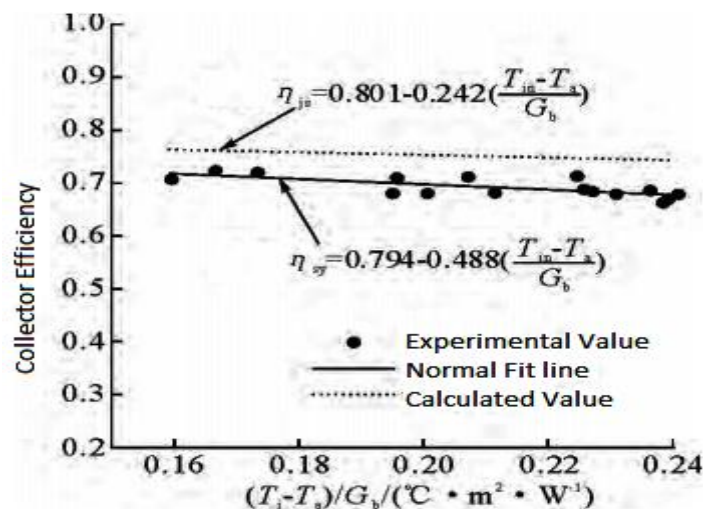
Figure 9. The normalized instantaneous efficiencies with Ti basis

Figure 9, show the test intercept efficiency value of fitting curve was 0.794, slightly smaller than the calculated value; normalized linear calculated and experimental values of the normalized trend, error 10.3%, this because the system was ignored in the calculation model of the system components and heat conduction properties of heat loss. Results showed that the model was correct with the high efficiency of the dual-axis tracking system, for the dual-axis parabolic trough solar collector design and performance optimization of the collector. (Odeh *et al.*, 2003); (Xu *et al.*, 2013) studied the thermal performance of a parabolic trough collector and reported that with the using of dual-axis tracking system in a parabolic trough collector gets the highest efficiency, which was similar to our results. The results were in agreement with the finding of (Morin *et al.*, 2012); (Odeh *et al.*, 2003), they studied the comparison of linear Fresnel and parabolic trough collector power plants and concluded that a parabolic trough collector was better for the heating purposes.

4. Conclusion
Simulation and the model experiment dual-axis tracking parabolic trough solar collector with the better optical performance of collector tube temperature of 200 ^{o}C can be used to obtain a higher set of thermal efficiency and the temperature of the collector which was to be used for small and medium heating system. In order to achieve the efficient use of energy, support steam generator, the temperature of the steam can be used to heat and efficient refrigeration.

5. Acknowledgment
   Conflicts of Interest: Declare conflicts of interest or state "The authors declare no conflict of interest.

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