

ENHANCEMENT OF EFFICACY AND HEAT TRANSFER CHARACTERISTICS OF TiO₂ NANO FLUIDS UNDER TURBULENT FLOW CONDITIONS IN PARABOLIC TROUGH SOLAR COLLECTOR

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ABSTRACT

The efficacy of a parabolic trough solar collector (PTSC) was improved by using TiO₂/DI-H₂O (De-Ionized water) nanofluid. Working samples consisting of nanofluids with concentrations of 0.05%, 0.1%, 0.2%, 0.3% and 0.5% were compared with deionized water (the base fluid) at different flow rates under turbulent flow regimes ($2850 < Re < 7440$). The experiments were designed as per ASHRAE 93 (2010) standards. Heat transfer and the flow characteristics of nanofluids through the collector were studied, and empirical correlations were developed in terms of the Nusselt number, friction factor, and performance index. The convective heat transfer coefficient was improved up to 23.84% by using TiO₂ nanofluids instead of the base fluid. It was found that TiO₂ nanofluid with a volume fraction of 0.3% (at a mass flow rate of 0.0689 kg/s) will provide the maximum efficiency enhancement in the PTSC (9.66% higher than the water-based collector). Consequently, the absorbed energy parameter was found to be 10.3% greater than that of the base fluid.

Keywords: parabolic trough solar collector (PTSC) ,TiO₂ nanofluid, Nusselt number, convective heat transfer coefficient.

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1. INTRODUCTION

Nowadays, researchers are seeking clean energy sources as alternatives to fossil fuels. One of these sources is solar energy. Solar energy is abundant and could be used as a potential resource to meet global energy demands. According to the International Energy Agency (IEA), the demand for concentrated solar energy will be about 1000 GW by the end of 2050 [1]. Using solar trough collectors are one of the methods to produce power from solar energy. Many studies have been done on the performance of solar trough collectors. For example, Bakos and Tsehelidou [2] have conducted an analysis of solar trough collectors using TRNSYS simulation software. They calculated plant efficiency, variations in power production, fuel usage, and emissions. Karathanassis et al. [3] experimentally evaluated the performance of a concentrating parabolic thermal/ photovoltaic (CPVT) system equipped with heat sinks to enhance cooling of the PV panels. The extent of improvement in electrical efficiency and thermal efficiency were 6% and 44%, respectively. To optimize the collector performance, studies were conducted on the design aspects of parabolic trough solar collectors (PTSCs) and their geometrical parameters, such as the aperture area, rim angle, focal length, absorber diameter, concentration ratio, and other important optical parameters (such as reflectivity, receiver tube intercept factor, and incident angle) [4-7]. Realizing the importance of these variables, improvement in heat transfer capacity of working fluid was primarily developed by Xuan and Li [8], by implementing nanoparticles in the working fluid for effective convective heat transfer. Subsequently, many investigators have used metal oxide-based nanoparticles (TiO₂, Al₂O₃, CuO) blended with water for various heat transfer enhancement applications using the constant heat flux method.

Nanofluid applications have been explored in various types of solar collectors. For instance, Tyagi et al. [9] observed that the addition of Al₂O₃ nanoparticles enhances the solar absorption rate by nine times that of pure water. This result suggests that the use of Al₂O₃ nanofluid enhances the efficiency of the system by 10%. Saidur et al. [10] experimentally investigated the thermal performance of Al₂O₃/H₂O as the working fluid on a direct solar absorption system. The result showed that the increase in volume fraction of Al₂O₃ up to 1% enhanced the collector performance and absorption rate. Otanicer et al. [11] investigated the effect of various nanofluids (graphite, CNT, silver nanoparticles) on the performance of the direct absorption solar collector (DASC). The results indicated that the use of nanofluids improved the efficiency of the (DASC) by 5%. He et al. [12] examined the light-to-heat swap performance of CNT/water and TiO₂/water in a vacuum tube solar collector and observed a higher efficiency for CNT/H₂O as compared to TiO₂ nanofluids. Yousefi et al. [13] studied the effect of Al₂O₃/H₂O nanofluids on the performance of a flat plate solar collector. The result revealed that nanofluids with 0.2% volume concentration increased the collector efficiency by 28%. Mahian et al. [14] studied the effects of Nusselt number and the thermal effects of four different nanofluids (CuO/H₂O, Al₂O₃/H₂O, TiO₂/H₂O, and SiO₂/H₂O) on the mini-channel based solar collector.

Abdolbaqi et al. [15] studied the effects of heat transfer characteristics using bio glycol/water-based TiO₂ nanofluids in a 2% volume concentration in flat-tube flow geometry.

The thermal conductivity, viscosity, Nusselt number, and friction factor were enhanced by 12.6%, 20.5%, 28.2%, and 14.3%, respectively.

Uddin and Harmand [16] studied the transient operating condition of various nanofluids and concluded that $\text{TiO}_2/\text{H}_2\text{O}$ provides a better natural convective heat transfer than CuO and Al_2O_3 nanofluids. Considering the characteristics of TiO_2 nanofluid, there is need for a study on the performance and heat transfer effects of PTSC using transient heat flux method.

The study of Arani et al. [17] revealed that $\text{TiO}_2/\text{H}_2\text{O}$ nanofluid with a 20-nm particle size diameter yielding optimal results with particle size varied from 10 to 50 nm range. The present work focuses on the PTSC thermal performance and heat transfer characteristics with a transient heat flux method using TiO_2 nanofluids. Another key goal of this investigation is to determine the maximum possible amount of heat energy from a stationary concentrating collector using low-volume concentration of TiO_2 nanofluid, as well as to estimate the efficiency and heat transfer characteristics of the PTSC. Based on the experimental outcomes, empirical correlations for the Nusselt number, friction factor, and performance index are developed using multiple linear regression models.

2. EXPERIMENTAL METHODS AND INSTRUMENTATION

The construction parameters for a solar PTC are the aperture, rim angle, acceptance angle, focus, depth, arc length, and receiver tube diameter, which were determined using the equations proposed by Kalogirou [18]. The solar PTC design was mathematically verified by Duffie [19]. The experimental setup was located in Vijayawada, India (16.5088 Latitude and 80.6154 Longitude). The collector was made of an anodized aluminium reflector sheet with a mean measured reflectance value of 0.94. The receiver tube was a 2 m copper tube with inner/outer diameters of 13 and 16 mm, respectively. The arrangement was sealed by a high temperature resistant cork for maintaining a partial vacuum for reducing convective heat losses and harnessing the incident solar energy by the greenhouse effect. The outer surface temperature was measured with WIKA TC50, and the thermo couples were placed at lengths of 20, 50, 90, 120, and 160 cm apart. The gradient pressure across the test rig was measured using an M5100 piezoelectric pressure transducer with an accuracy of $\pm 1\%$ and a range of 0-3.5 bar. The TiO_2 nanofluid was stored in a reservoir and circulated to the entrance of the absorber tube by a centrifugal pump, which was operated by a rotameter with a range of 0-10 lpm and accuracy of $\pm 1\%$. The absorber tube outlet was connected to a heat exchanger for diminishing the temperature of the nanofluids. While the heat exchanger reduced the temperature by up to 3°C , a constant temperature bath was employed to balance the nanofluid temperature in accordance with the specifications of the ASHRAE 93 (2010) [20] standards. The trough collector was always situated perpendicular to the solar noon, and the thermal performance of the non-tracking method (stationary) was studied according to the ASHRAE standards. The test parameters were also recorded based on these standards, including the ambient temperature, flow rate, wind velocity, solar radiation, temperatures at the entry and outlet of the test section, and gradient pressure. A pyranometer was used for the determination of direct solar radiation, while the wind velocity and ambient temperatures were measured using a vane-type anemometer with a range of 0-25 m/s and accuracy of $\pm 3\%$. The solar collector test facility was designed and mounted for the outside ambient conditions with a mean wind speed of 5 m/s with an operating humidity range of 60-80%. Detailed specifications of the PTSC are shown in Table 1.

**Figure: 1** Parabolic trough solar collector**Table-1** Specifications of the parabolic trough solar collector

S.no	Specifications	Dimensions
1	Parabolic trough collector length (L)	2.0 m
2	Parabola aperture length (W)	0.80 m
3	Focal distance(f)	0.24 m
4	Aperture Area (A_a)	1.6 m ²
5	Rim angle (θ_r)	80°
6	Acceptance angle (θ)	0 A°
7	Reflector thickness	3mm
8	Concentration ratio	15.6
9	Receiver tube inner diameter (d_i)	0.013 m
10	Receiver tube outer diameter (d_o)	0.016m

Table-2 Stability of TiO₂ nanoparticles in water

S.No	Nanopowder	Particle concentration C (%)	Zeta potential	Stability activities	Stability time (days)
1	TiO ₂	0.05	-23	Moderate	15
2	TiO ₂	0.1	-28	Good stability	20
3	TiO ₂	0.2	-45	Good stability	20
4	TiO ₂	0.3	-52	Good stability	20
5	TiO ₂	0.5	-62	Good stability	20

3. NANOFLUID PREPARATION AND CHARACTERIZATION

The nanofluid was prepared from TiO₂ powder with 99.7% purity, an average size of 20 nm, a pH of 7, and a density of 4170 kg/m³. The TiO₂ nanoparticles were obtained from Nano Wings pvt Ltd, India. The nanofluids were prepared with nanoparticle volume percentages of 0.05%, 0.1%, 0.2%, 0.3% and 0.5%. The nanoparticles were dispersed in DI water by ultrasonication to prevent agglomeration and ensure a pH value of 7. The zeta potential stability test was carried out for each concentration as shown in Table 2. The TiO₂ nanoparticles were filtered using a mesh size of 0.5 mm and then dried in ambient air. The nanoparticles were characterized by SEM and EDAX as shown in Fig. 3 and 4. The SEM analysis was carried out on a CARL ZEISS SUPRA 55 scanning electron microscope. The theoretical and experimental thermo-physical properties of the nanofluids are compared in Table 3. The peaks for Ti and O for the EDAX results confirmed that the particles were TiO₂. The theoretical thermo-physical properties of the TiO₂ nanofluids are shown in Table 3.



Figure: 2 Preparation of TiO₂ Nano fluid

Table-3 Thermal conductivity and viscosity measurements

S.No	Nanopowder	Particle concentration C(%)	Thermal conductivity(W/mK)	% Enhancement in thermal conductivity	Dynamic viscosity
1	TiO ₂	0.05	0.62	1.67	0.92
2	TiO ₂	0.1	0.68	9.35	1.03
3	TiO ₂	0.2	0.69	13.56	1.28
4	TiO ₂	0.3	0.70	13.42	1.33
5	TiO ₂	0.5	0.72	13.34	1.35
6	Base fluid	-	0.6	-	-

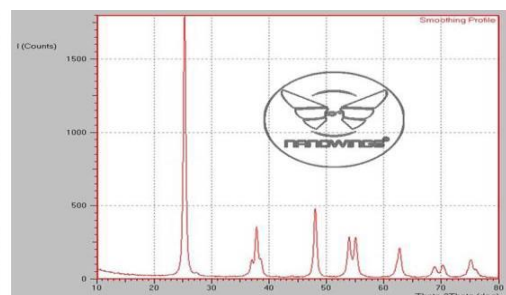


Figure 3 & 4 SEM & EDX images of TiO₂ Nanoparticles

4. ASHRAE STANDARDS, TESTING METHODS, AND DATA COLLECTION

In order to avoid the influence of weather ambiguity, ASHRAE [20] has established specific test methods for outdoor conditions using a stationary concentrating collector model. The investigations were carried out based on the ASHRAE test procedure. The irradiance of the direct beam should have been greater than 800 W/m^2 , and the maximum radiation with a clear sky should have been 32 W/m^2 at a time interval of 10 min each. The wind velocity should have been between 2 and 4 m/s with a natural wind flow, and the heat transfer fluid flow rate should have been 0.02 kg/sm^2 . The performance analysis was conducted using two different methods, and the readings considered for the calculation were based on the time period around solar noon (9:00AM to 16:00PM). Testing was done with different fluid concentrations and flow rates in the receiver tube. The experiments were conducted by dividing the test cycles into six parts consisting of 60 min each. Every 60- min cycle was further divided into 15 min sub-cycles to achieve steady-state conditions and to obtain a collector time constant of 63.2% to conform to the ASHRAE [20] standards. To implement the steady-state model, a minimum of 16 data points were obtained at various inlet fluid temperatures, and were used to identify the collector efficiency of the PTSC by linear regression. Data were collected daily for three months.



Figure 5: Ultrasonic vibrator



Figure 6: Pyranometer

Table:4: Equations for calculating Properties of nanofluids

S.No	Model name	Equations for models	Purpose
1	Wasp model	$K_{nf} - K_f \frac{k_p + 2kf - 2\alpha(kf - kp)}{k_p + 2kf + \alpha(kf - kp)}$	Thermal conductivity K_{nf}
2	Brink man	$\frac{\mu_{nf}}{\mu_f} = \frac{1}{(1 - \phi)^{2.5}} = \frac{1}{(1 - \phi)^{2.5}}$	Viscosity (μ_{nf})
3	Pak & Xuan	$\rho_{nf} = (1 - \phi)\rho_b + \phi\rho_p$	Density (ρ_{nf})
4	Pak & Cho	$C_{p,nf} = \frac{(1 - \phi)\rho_b C_{p,b} + \phi\rho_p C_{p,p}}{\rho_{nf}}$	Specific heat ($C_{p,nf}$)

4.2. Evaluation of collector efficiency

The collector efficiency depicts the useful heat gain in relation to the whole incident radiation received by the collector aperture area, which is given by Eqs. (1)-(3). The useful heat gain of a TiO_2 nanofluid was calculated by Ref. [9]:

$$Q_g = mC_{p,nf}(T^o - T^i) \quad (1)$$

The collector efficiency of the solar PTC can be obtained by equations [9] [11]:

$$\eta_c = Q_g / A_a I = mC_{pnf} (T^o - T^i) / A_a I \quad (2)$$

The resultant curve of the collector efficiency was a series of 16 data points. The slope and intercept were found using a linear regression fit method. The efficiency of the collector was determined by equations [13]:

$$\eta_c = F_R (\tau\alpha) - F_R U_L / C ((T^o - T^a) / I) \quad (3)$$

4.3. Data reduction

The Reynolds number, Nusselt number, friction factor, convective heat transfer coefficient, and solar collector efficiency were the five effective factors on the solar PTC performance that could be calculated using the test results. The required equations to evaluate the PTC efficiency are shown in Table 5.

Table 5: Equations to Evaluate the Efficiency of Parabolic solar concentrator training kit

Specification	General Equation
Reynolds Number	$Re = \left(\frac{\rho_{nf} u d_i}{\mu_{nf}} \right)$
Convective Heat transfer	$h_{nf} = \left(\frac{Q_g}{A_i (T^w - T^b)} \right)$
Nusselt Number	$Nu = \left(\frac{h_{nf} d_i}{K_{nf}} \right)$
Friction factor	$f = \left(\frac{2 \Delta p}{\rho_{nf} u^2} \right)$
Performance index	$P_{index} = \left(\frac{h_{nf}}{h_{bf}} \right)$

Table 6: Parameters of the present study

S.No	Study cases	Direct normal irradiance (W/m ²)	Wind velocity (m/s)	Mass flow rate (kg/s)	T ⁱ °K	T ^o °K	Q _g (W)	h(W/m ² K)	Collector efficiency (η _c)
1	DI-Water	872	2.31	0.017	304.64	315.76	707.22	616.12	50.65
2	DI-Water	865	2.53	0.067	305.62	309.21	718.06	620.65	51.95
3	TiO ₂	876	2.42	0.033	304.45	310.46	752.37	1310.75	53.68
4	TiO ₂	855	2.14	0.050	305.12	309.24	759.52	1928.16	55.49
5	TiO ₂	875	2.54	0.061	304.53	308.42	814.27	2701.41	56.86
6	TiO ₂	896	2.89	0.067	306.25	309.56	815.36	2702.69	56.95

5. RESULTS AND DISCUSSION

A peak value of 0.5761 was obtained, which was 10.3 % greater than that of the base fluid. The enhancement in the absorbed energy factor was achieved by an addition of nanoparticles, because it is a function of the nanofluids velocity, thermal conductivity, and specific heat capacity of the working fluid. Although the nanoparticles caused an increase in the heat absorption rate, this yielded only an optimal result at a 0.3% volume concentration because of the fact that “as the viscosity increased, the flow rate decreased.” This, in turn, reduced the Reynolds number. As a result, the heat transfer coefficient declined and subsequently lowered the Nusselt number. Thus, a lower concentration was used for avoiding a reduction in the

absorbed energy factor. The overall collector heat loss coefficient (UL) was 8.845 - 9.042 $\text{W/m}^2\text{K}$, and the average removal energy factor of the collector FR (UL) was 7.48. Hence, the flow rate changed the internal heat transfer coefficient, but the (UL) was almost constant around 8.86 $\text{W/m}^2\text{K}$. Therefore, the overall collector heat loss coefficient (UL) was roughly constant upon variations in the flow rates regardless of the nanoparticle concentration. The removal energy factor, FR (UL), deviated moderately as a result of the pH value of nanofluids [22]. Fig. 7(a-b) shows the characteristic curves of the PTSC for three different flow rates: 0.0086, 0.0356, and 0.0667 kg/s. The efficiency is plotted against the heat loss parameter, $(T_i - T_a)/I$, for each mass flow rate. Among the various flow rates and concentrations, a maximum collector efficiency of 57.06% was obtained at 0.0667 kg/s at a 0.3% volume concentration as shown in Fig. 7b. This result shows that there was 9.66% increase in collector efficiency and 22.76% rise in convective heat transfer compared to that of water. Such an increase in collector efficiency and convective heat transfer was due to an increase in the absorptivity and absorption coefficient of the nanoparticles.

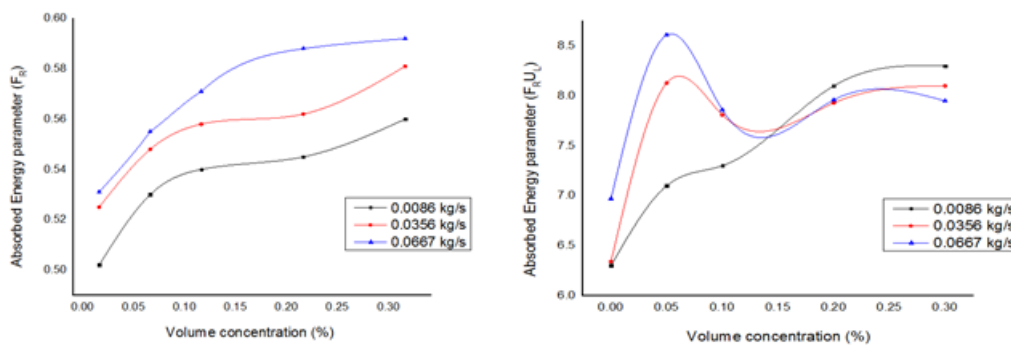


Figure.7: Variation in the absorbed energy parameter (a) and removal energy parameter (b) with variations in volume concentrations at different flow rates.

Enhancement of Efficacy and Heat Transfer Characteristics of Tio2 Nano Fluids under Turbulent Flow Conditions in Parabolic Trough Solar Collector

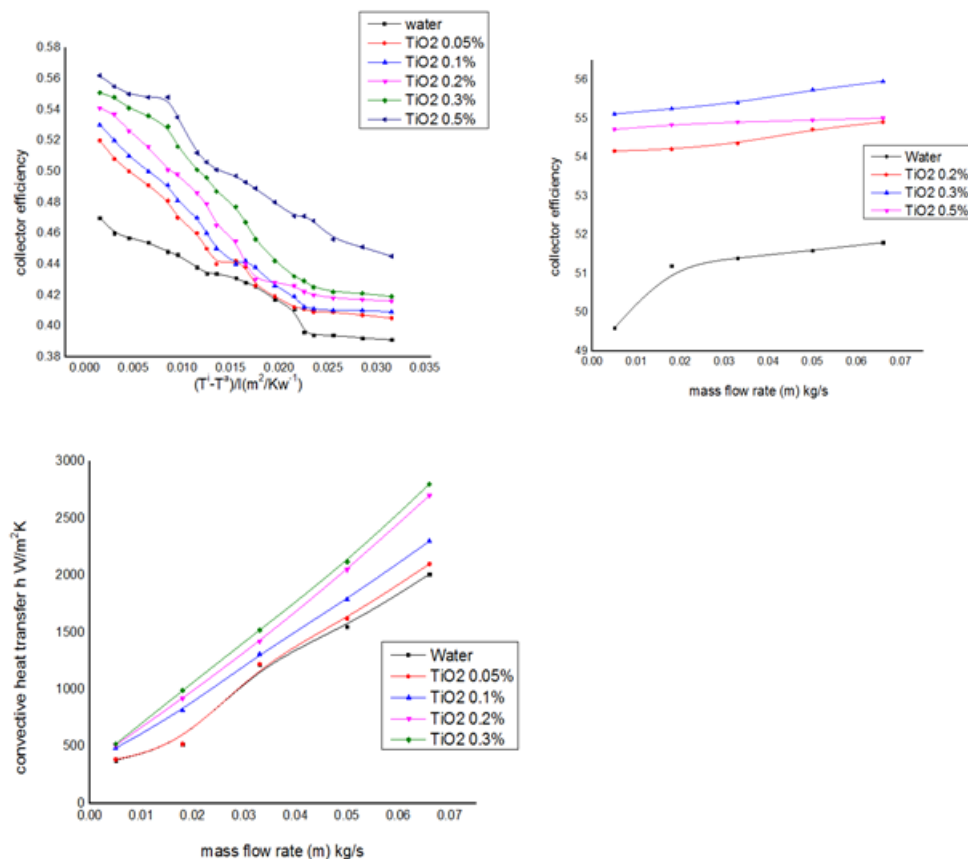


Figure. 8. (a) Effect of the heat loss parameter on collector efficiency (b) Variation of collector efficiency for different flow rates with variations in the volume concentrations (c) convective heat transfer coefficient comparison with various mass flow rates.

Consequently, this increased the convective heat transfer coefficient of the nanofluid as a result of the reduction in the gradient temperature, $DT^{1/4}(T_w - T_b)$. It was also observed that an average overall collector heat loss coefficient (U_L) of $8.86 \text{ W/m}^2\text{K}$ was achieved for each of the varying flow rates and concentrations. Further increases in the volume concentration from 0.2% to 0.5% resulted in an enhancement in solar PTC efficiency of only 10.3% compared to that of water. This result clearly showed an incremental addition in the collector efficiency as only 0.6% for the increased volume concentration of 0.5 % for the varying flow rates as shown in Fig. 8a. As a result, a rise in flow rate caused improvement in heat transfer coefficient and a decrease in the gradient temperature (DT), leading to increased collector efficiency. Fig. 8 (a-c) shows the temperature gradient for different flow rates and nanoparticle concentrations, as well as the convective heat transfer coefficients for different mass flow rates. From these two graphs, the flow rate, temperature gradient, and convective heat transfer coefficient can be correlated. For higher flow rates, the temperature gradient was low and the heat transfer coefficient was higher. At lower flow rates, the temperature gradient was higher while the heat transfer coefficient was lower because the surface contact time (flow through time) was more in comparison to the higher flow rates. When using nanofluids, it was possible to achieve a temperature gradient of 16.24°C at lower mass flow rates and 3.877°C at higher mass flow rates, which resulted in a reduction of 35.88% when compared to water. The present model was developed for the Reynolds number range of $(2950 < Re < 8142)$ and the Prandtl number range of $(5.78-4.65)$ with a collector efficiency of around 57%. The friction factor was estimated as a function of the pressure drop and roughness fraction of

the absorber tube, which was negligible. Consequently, the average pressure drop in the solar PTC system was measured as 1.46 kPa. The performance index of the TiO₂ nanofluid was greater than 1, implying that it would enhance the heat transfer in a solar PTC application. Variations in the performance index are based on variations in the pH and thermo-physical properties of the nanofluids. The particle size also influences the performance of the solar PTC. Nanoparticles with larger sizes that tend to scatter radiation rather than absorb it. Hence, it is recommended that the dimension of the nanoparticles be < 50 nm to have an effective heat transfer. In the present study, the TiO₂ nanoparticles had an average size of 20 nm. Hence, the heat transfer was enhanced and the nanoparticles were found suitable for solar PTC applications.

5. CONCLUSIONS

The present study investigated the performance of TiO₂/water nanofluids in a solar PTC under turbulent regime. Tests were conducted using different nanoparticle concentrations and mass flow rates, and the following outcomes were obtained:

1. Nanofluids have a 9.5% higher absorbed energy factor compared to water.
2. At $\phi = 0.3\%$ and a mass flow rate of 0.0667 kg/s, the absorbed energy factor reaches the maximum value, while the removal energy factor FR (UL) value fluctuates marginally.
3. A higher convective heat transfer coefficient is achieved at a maximum flow rate of 0.0667 kg/s because of the lower temperature gradient ($\Delta T = 3.89\text{ }^{\circ}\text{C}$). The overall collector heat loss

Coefficient (UL) does not deviate significantly from 9.86 W/m²K despite variations in flow rates and concentrations.

4. The performance index has a peak value of 1.39 for the nanofluid with a volume concentration of 0.3% and a mass flow rate of 0.0667 kg/s.

5. The maximum overall efficiency of the PTSC using TiO₂ nanofluid is 57%, which is 10.3% greater than that of the base fluid.

6. The empirical correlations for the heat transfer characteristics in the collector are as follows:

$$Nu_c = 0.02169 Re^{0.836} Pr^{0.071} (1+\phi)^{0.30}$$

$$f_c = 0.46673 Re^{-0.349} Pr^{0.246} (1+\phi)^{0.204}$$

$$P_{indexc} = 0.69628 Re^{0.0399} (1+\phi)^{1.387}$$

The above correlations are valid for volume concentrations up to 0.3% and Reynolds numbers between 2850 and 7862 in which the working fluid is TiO₂/water nanofluid.

REFERENCES

- [1] C.S. Power, Technology roadmap concentrating solar power, Current 5 (2010) 1e52, <https://doi.org/10.1787/9789264088139-en>.
- [2] G.C. Bakos, C. Tsechelidou, Solar aided power generation of a 300 MW lignite fired power plant combined with line-focus parabolic trough collectors field, Renew. Energy 60 (2013) 1e8, <https://doi.org/10.1016/j.renene.2013.05.024>.
- [3] I.K. Karathanassis, E. Papanicolaou, V. Belessiotis, G.C. Bergeles, Design and experimental evaluation of a parabolic-trough concentrating photovoltaic/ thermal (CPVT) system with high-efficiency cooling, Renew. Energy 101 (2017) 467e483, <https://doi.org/10.1016/j.renene.2016.09.013>.

- [4] J.A. Clark, An analysis of the technical and economic performance of a parabolic trough concentrator for solar industrial process heat application, *Int. J. Heat Mass Transf* 25 (1982) 1427e1438, [https://doi.org/10.1016/0017-9310\(82\)90136-3](https://doi.org/10.1016/0017-9310(82)90136-3).
- [5] A. Thomas, H.M. Guven, Parabolic trough concentrators-design, construction and evaluation, *Energy Convers. Manag* 34 (1993) 401e416, [https://doi.org/10.1016/0196-8904\(93\)90090-W](https://doi.org/10.1016/0196-8904(93)90090-W).
- [6] S. Kalogirou, parabolic trough collector system for low temperature steam generation: design and performance characteristics, *Appl. Energy* 55 (1996) 1e19, [https://doi.org/10.1016/S0306-2619\(96\)00008-6](https://doi.org/10.1016/S0306-2619(96)00008-6).
- [7] H. Price, E. Lüpfer, D. Kearney, E. Zarza, G. Cohen, R. Gee, R. Mahoney, Advances in parabolic trough solar power technology, *J. Sol. Energy Eng* 124 (2002) 109, <https://doi.org/10.1115/1.1467922>.
- [8] J.A. Clark, An analysis of the technical and economic performance of a parabolic Trough concentrator for solar industrial process heat application, *Int. J. Heat Mass Transf* 25 (1982) 1427e1438, [https://doi.org/10.1016/0017-9310\(82\)90136-3](https://doi.org/10.1016/0017-9310(82)90136-3).
- [9] A. Thomas, H.M. Guven, Parabolic trough concentrators-design, construction and evaluation, *Energy Convers. Manag* 34 (1993) 401e416, [https://doi.org/10.1016/0196-8904\(93\)90090-W](https://doi.org/10.1016/0196-8904(93)90090-W).
- [10] S. Kalogirou, parabolic trough collector system for low temperature steam generation: design and performance characteristics, *Appl. Energy* 55 (1996) 1e19, [https://doi.org/10.1016/S0306-2619\(96\)00008-6](https://doi.org/10.1016/S0306-2619(96)00008-6).
- [11] H. Price, E. Lüpfer, D. Kearney, E. Zarza, G. Cohen, R. Gee, R. Mahoney, Advances in parabolic trough solar power technology, *J. Sol. Energy Eng* 124 (2002) 109, <https://doi.org/10.1115/1.1467922>.
- [12] H. Tyagi, P. Phelan, R. Prasher, Predicted efficiency of a low-temperature nanofluid-based direct absorption solar collector, *J. Sol. Energy Eng* 131 (2009) 41004, <https://doi.org/10.1115/1.3197562>.
- [13] R. Saidur, T.C. Meng, Z. Said, M. Hasanuzzaman, A. Kamyar, Evaluation of the effect of nanofluid-based absorbers on direct solar collector, *Int. J. Heat Mass Transf* 55 (2012) 5899e5907, <https://doi.org/10.1016/j.ijheatmasstransfer.2012.05.087>.
- [14] T.P. Otanicar, P.E. Phelan, R.S. Prasher, G. Rosengarten, R.A. Taylor, Nanofluidbased direct absorption solar collector, *J. Renew. Sustain. Energy* 2 (2010) 1e13, <https://doi.org/10.1063/1.3429737>.
- [15] Y. He, Shufu Wang, J. Ma, F. Tian, Y. Ren, Experimental study on the light-heat conversion characteristics of nanofluids, *Nanosci. Nanotech. Lett.* 3 (4) (2011) 494e496, <https://doi.org/10.1166/nnl.2011.1194>.
- [16] T. Yousefi, F. Veysi, E. Shojaeizadeh, S. Zinadini, An experimental investigation on the effect of Al₂O₃-H₂O nanofluid on the efficiency of flat-plate solar collectors, *Renew. Energy* 39 (2012) 293e298, <https://doi.org/10.1016/j.renene.2011.08.056>.
- [17] O. Mahian, A. Kianifar, A.Z. Sahin, S. Wongwises, Performance analysis of a minichannel-based solar collector using different nanofluids, *Energy Convers. Manag* 88 (2014) 129e138, <https://doi.org/10.1016/j.enconman.2014.08.021>.
- [18] M.K. Abdolbaqi, R. Mamat, N.A.C. Sidik, W.H. Azmi, P. Selvakumar, Experimental investigation and development of new correlations for heat transfer enhancement and friction factor of BioGlycol/water based TiO₂ nanofluids in flat tubes, *Int. J. Heat Mass Transf* 108 (2017) 1026e1035, <https://doi.org/10.1016/j.ijheatmasstransfer.2016.12.024>.
- [19] Z. Uddin, S. Harmand, Natural convection heat transfer of nanofluids along a vertical plate embedded in porous medium, *Nanoscale Res. Lett.* 8 (2013) 64, <https://doi.org/10.1186/1556-276X-8-64>.

- [20] A.A. Abbasian Arani, J. Amani, Experimental investigation of diameter effect on heat transfer performance and pressure drop of TiO₂-water nanofluid, *Exp. Therm. Fluid Sci.* 44 (2013) 520e533, <https://doi.org/10.1016/j.expthermflusci.2012.08.014>.
- [21] S. Kalogirou, *Solar Energy Engineering: Process and Systems*, 2009, <https://doi.org/10.1016/B978-0-12-374501-9.00014-5>. Copyright.
- [22] John A. Duffie, William A. Beckman, *Solar Engineering of Thermal Processes*, John Wiley & Sons, 1980, p. 367. Copy right.
- [23] ASHRAE, *Methods of Testing to Determine the Thermal Performance of Solar Collectors*, ANSI/ASHRAE Stand. 93e2010, Am. Soc. Heating, Refrig. Air- Conditioning Eng. Inc, RA, 2010, 2014, www.ashrae.org.
- [24] O.A. Jaramillo, M. Borunda, K.M. Velazquez-Lucho, M. Robles, Parabolic trough solar collector for low enthalpy processes: an analysis of the efficiency enhancement by using twisted tape inserts, *Renew. Energy* 93 (2016) 125e141, <https://doi.org/10.1016/j.renene.2016.02.046>.
- [25] T. Yousefi, E. Shojaeizadeh, F. Veysi, S. Zinadini, An experimental investigation on the effect of pH variation of MWCNTeH₂O nanofluid on the efficiency of a flat-plate solar collector, *Sol. Energy* 86 (2012) 771e779, <https://doi.org/10.1016/j.solener.2011.12.003>.