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Investigation on sensitivity of photo-thermal conversion efficiency of an enclosed type evacuated U-tube solar collector using Fe_3O_4-MWCNT/water hybrid nanofluid

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ABSTRACT: The thermal performance of an enclosed type evacuated U-tube solar collector (EEUSC) was investigated experimentally using Fe_3O_4-multi-walled carbon nanotube (MWCNT)/water hybrid nanofluid with various proportions of Fe_3O_4 and MWCNT nanoparticles. The sensitivity of thermal performance and photo-thermal conversion efficiency was analyzed under different operating conditions. The maximum efficiency of the EEUSC was 80.1% when hybrid nanofluid with 80 wt% MWCNT and 20 wt% Fe_3O_4 nanoparticles (weight ratio = 8 : 2) was applied, which corresponded to 15.5% and 25.6% improvement compared to Fe_3O_4 nanofluid and water, respectively. In addition, the efficiency of EEUSC was increased by 10.1% when the flow rate of the working fluid was increased from 0.036 kg/s to 0.054 kg/s. The experimental results demonstrated that adding MWCNT nanoparticles into Fe_3O_4 nanofluid was an effective way to enhance the sensitivity of thermal performance of the EEUSC.

KEYWORDS: hybrid nanofluids, solar collector, thermal performance

INTRODUCTION

The demand for renewable energy has become more intense due to rapid economic development and continuous population growth. With a growing global focus on renewable energy, solar collectors have gained widespread attention as an effective, sustainable and eco-friendly energy conversion method. Solar collectors are the primary method of harnessing solar energy [1, 2]. In addition, the use of solar collectors can reduce dependence on non-renewable energy sources, resulting in lower energy costs and increased energy security. There are several ways to improve the efficiency of solar collectors, such as updating the structures of solar collectors, adjusting the tilt angle of solar collectors, adding reflection or light-gathering devices or using working fluid with higher thermal conductivity [3–7]. For example, a new type of flat plate solar collector (FPSC) was fabricated with an internal absorber tube receiver, which showed improvement in efficiency from 45% to 67% compared to normal working fluid. Nanofluids are an ideal alternative to conventional working fluids due to their extremely high thermal conductivity [8]. Nanofluids are specialized fluids containing certain nanoparticles. Due to the inclusion of these nanoparticles, nanofluids typically have higher thermal conductivity than conventional fluids, so they can transfer heat more efficiently than conventional fluids. As a result, their application in solar collectors can significantly enhance the heat transfer efficiency and improve the overall performance. Ram and coworkers [9] reviewed the performance of different types of solar collectors using various nanofluids as working fluid in recent two decades, and provided a comprehensive analysis of the performance of various nanofluids in solar collectors. Aissa et al [10] provided an overview of advancements in methods for increasing thermal performance of solar collectors. They also discussed the significant developments in recent years and the future prospects in the hybrid nanofluids. The efficiency of a concentrating parabolic solar collector using aluminum nanofluid was studied, which performed approximately 5% to 10% better than the traditional parabolic solar collector [11]. It was reported that the size of nanoparticles was not the critical factor for determining the optical properties of nanofluid while the volume fraction of nanoparticles was proportional to the extinction coefficient [12]. Eltaweel et al [13] studied the thermal performance of MWCNT nanofluid with different concentrations and found that energy and exergy efficiency of solar collector increased with the increase in weight concentration of nanofluid. The optimal concentration of Fe_3O_4 nanofluid was found to be 3 vol% by analyzing the efficiency of solar collectors under various operating conditions [14]. According to Cho's study [15], Fe_3O_4 nanofluid showed better optical and thermal performance than the base fluid (water). Moreover, 0.01 wt% MWCNT nanofluid showed nearly 30% improvement of thermal conductivity and almost 32.5% improvement of thermal properties compared to water [16]. Qu et al [17] discussed the preparation and photo-thermal conversion performance of stable water-based nanofluids containing MWCNT. Their results indicated that the optimal concentration of the nanofluid was 0.01 wt%, which increased the extinction coefficient and temperature of the nanofluid after optical irradiation. Experimental studies using CeO_2 nanofluid as working fluid showed that its thermal efficiency was improved dramatically compared to water [18]. Another study investigated the thermal efficiency of a solar collector with various concentrations of working fluids, and revealed that using MWCNT nanofluid led to the maximum thermal efficiency, which was nearly 29% higher than that using water [19]. It was also found that a maximum increase of 29.32% was obtained in thermal efficiency of the collector using MWCNT/water nanofluid with 0.75 vol% and a mass flow rate of 0.025 kg/s [20]. Recent progress in internal treatment and modification of carbon based materials and catalyst introduction were summarized, and some practical suggestions for further development were put forward [21].

In addition, there has been a recent increase in research on hybrid nanofluids. For example, Ahmad et al [22] analyzed the pressure drop and heat transfer performance of single and hybrid nanofluids. They demonstrated that 3 vol% Al_2O_3/CuO hybrid nanofluid showed the maximum heat transfer coefficient compared to single nanofluid. Esfe et al [23] studied the thermal conductivity of Fe_3O_4/SWCNT hybrid nanofluid and concluded that the 1 vol% hybrid nanofluid had a 40% higher price-performance than the single nanofluid. The efficiency of solar collectors using Al_2O_3, MWCNT and MWCNT/Al_2O_3 hybrid nanofluids as working fluids was investigated and it was found that the efficiency using hybrid nanofluid increased by 29% when flow rate was 2.5 l/m [24]. The thermal performance of an evacuated tube solar collector using MgO/MWCNT hybrid nanofluid with various weight ratios was studied experimentally, which revealed that the optimal weight ratio was 1:1 [25]. Moreover, it was reported that hybrid nanofluids provided an attractive way to enhance the thermal performance of solar collectors [26].

Compared to previous studies, this work initially investigated the sensitivity of photo-thermal conversion efficiency of the EEUSC using Fe_3O_4-MWCNT/water hybrid nanofluids with various weight ratios of the two nanoparticles. The hybrid nanofluid has both MHD properties and the high thermal conductivity of MWCNT. Moreover, the optimal concentration of the hybrid nanofluid cannot be consistently maintained under different operating conditions. Thus, it is necessary to accurately analyze the properties of the hybrid nanofluid under various operating conditions.

MATERIALS AND METHODS

Preparation of the hybrid nanofluid

Experiments on the sensitivity of photo-thermal conversion of the EEUSC in this study were performed using water and MWCNT-Fe_3O_4/water hybrid nanofluid as the working fluids. Fe_3O_4 nanoparticles have high potential for enhanced thermal properties under an external magnetic field. The thermally enhanced properties can be further improved by adding MWCNT nanoparticles to the Fe_3O_4 nanofluid. In addition, the MWCNT/Fe_3O_4 nanofluid has excellent dispersion stability, as the Fe_3O_4 nanoparticles stick to the MWCNT nanoparticles due to their unique cylindrical structure. The hybrid nanofluids with several weight ratios of the two nanoparticles were prepared by a two-step method. Arabic gum was used as surfactant. The two kinds of nanoparticles were first added to water, and the mixture was then stirred for three hours. After thorough mixing, the ultrasonic homogenizer was then applied to the ultrasonic dispersion to produce nanofluids. The hybrid nanofluids with various weight ratios of nanoparticles were obtained, they were kept standing for more than a month and no agglomeration was observed. It can be seen that all samples showed good dispersion stability. Furthermore, with the increase in weight fraction of Fe_3O_4 nanoparticles, the color of the hybrid nanofluids changed from yellow to black gradually.

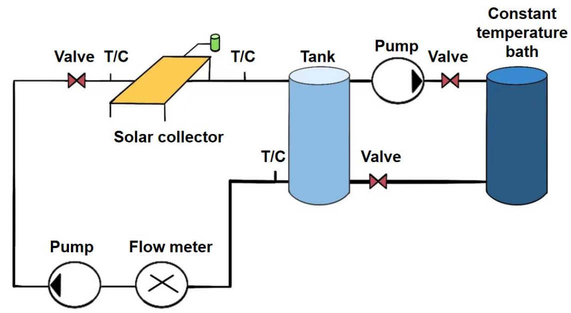

Fig. 1 Schematic and site photographs of the experimental system.

Economically, some nanoparticles remain prohibitively expensive for widespread use, while others pose challenges for mass production. Nonetheless, if nanofluid adoption becomes prevalent and extends across various industries, it can lead to economy of scale. Consequently, increased production volume has the potential to substantially lower the cost of nanofluid, enhancing its affordability and applicability in various fields.

Test facilities and methods

In this study, an enclosed type evacuated U-tube solar collector (EEUSC), which was proposed by Tong [27], was employed for experimental study using nanofluids. The whole thermal system is shown in Fig. 1. The experiment was carried out on a certain day and lasted for one week in order to fully investigate the thermal performance of the EEUSC using nanofluids under

Table 1 Specifications of equipment.

Equipment	Parameter	Specification
Solar collector	Outer tube outer diameter (mm)	47
	Outer tube thickness (mm)	2
	Transmittance	0.907
	Inner tube outer diameter (mm)	37
	Inner tube thickness (mm)	2
	Absorptivity of the absorber tube	0.93
	Solar collector length (mm)	1200
	Emissivity of absorber tube	0.06
Pyranometer	Range	0–2000 (W/m^2)
	Accuracy	2%
Thermocouple	Range	−200 to 200 (°C)
	Accuracy	0.5%
Flowmeter	Range	2–350 (LPM)
	Accuracy	5%

various operating conditions and uncontrolled factors such as solar radiation and ambient temperature. The photo-thermal conversion efficiency can be obtained by Eq. (1) [28]:

$$\eta = \frac{Q_u}{A_e G t} = \frac{m C_{\mathrm{p(nf)}} (T_{\mathrm{out}} - T_{\mathrm{in}})}{A_e G t}, \tag{1}$$

where m represents the flow rate of the nanofluid, $C_{\mathrm{p(nf)}}$ represents the specific heat capacity of the nanofluid, A_e equals to the collection area of the EEUSC, G is the intensity of the solar radiation, and t represents the exposure time. Due to the low concentration of the nanoparticles, the values of specific heat capacity of the nanofluid and water are nearly the same.

Error evaluation

Error evaluation is required to validate the test results [29]:

$$\frac{\delta\eta}{\eta} = \left[\frac{\delta m}{m} + \left(\frac{\delta(T_{\mathrm{out}} - T_{\mathrm{in}})}{T_{\mathrm{out}} - T_{\mathrm{in}}}\right)^2 + \left(\frac{\delta C_{\mathrm{p(nf)}}}{C_{\mathrm{p(nf)}}}\right)^2 + \left(\frac{\delta G}{G}\right)^2\right]^{0.8} \tag{2}$$

The errors of the specific heat can be assumed to be negligible. The accuracies of the flow meter, pyranometer and thermocouple were approximately 5%, 2% and 0.5%, respectively. Thus, the efficiency uncertainty of EEUSC can be obtained by Eq. (2), which was within 5.4%.

Experimental setup

The solar system consisted of an EEUSC, a constant-temperature bath, a water tank, two pumps, two heat exchangers and some other measurement facilities. The specifications of the solar collector are shown in Table 1. The measurement devices used included a pyranometer, a flow meter, and some thermocouples. The measured quantities were the temperatures of working fluid at the inlet and outlet of the EEUSC, the flow rate of the working fluid, the solar radiation, and the ambient temperature. The pyranometer was installed on the solar collector to measure solar radiation. The aperture of the pyranometer was kept level with that of the collector without casting a shadow on the collector. Radiation levels were continuously recorded along with other data. The ambient temperature sensor was placed behind the collector which was away from direct irradiance. T-thermocouples were used to measure the temperature, which were placed in the inlet and outlet of the solar collector. The flow rate of the working fluid was measured by the flowmeter, which was circulated by the pump. The working fluid flowed through the pump to the EEUSC, and then collected in the constant-temperature bath in order to exchange heat. After that, it flowed into the flowmeter and water heater. The mass flow rate of the working fluid was kept constant at 0.036 kg/s.

Table 2 $F_R(\tau\alpha)$ and $F_R U_L$ for the EEUSC using the hybrid nanofluid.

Fluid	$F_R(\tau\alpha)$	$F_R U_L$	R^2
Water	0.6379	17.19	0.9766
Fe_3O_4	0.7024	22.79	0.9547
Al_2O_3 [30]	0.7330	17.70	0.9380
CeO_2 [31]	0.7013	11.09	0.9886
WO_3 [32]	0.7187	7.86	0.9670
80 wt%Fe_3O_4-20 wt%MWCNT	0.7457	24.17	0.9429
60 wt%Fe_3O_4-40 wt%MWCNT	0.7695	25.49	0.9316
40 wt%Fe_3O_4-60 wt%MWCNT	0.7872	27.13	0.9518
20 wt%Fe_3O_4-80 wt%MWCNT	0.8013	28.99	0.9381

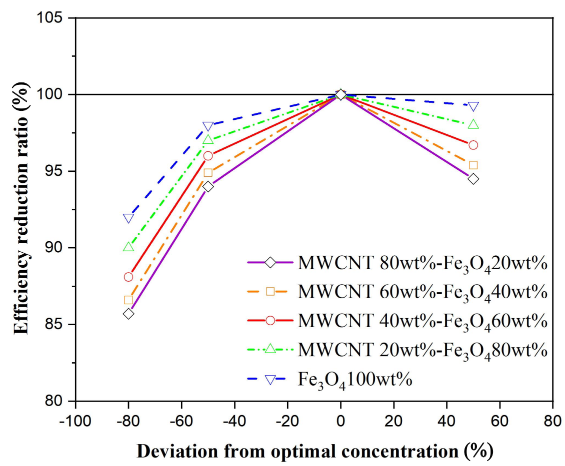

Fig. 2 Sensitivity of photo-thermal conversion efficiency to deviations from optimal concentration.

RESULTS AND DISCUSSION

The results of the heat loss and heat gain coefficients of the EEUSC with water and various proportions of Fe_3O_4-MWCNT/water hybrid nanofluid are shown in

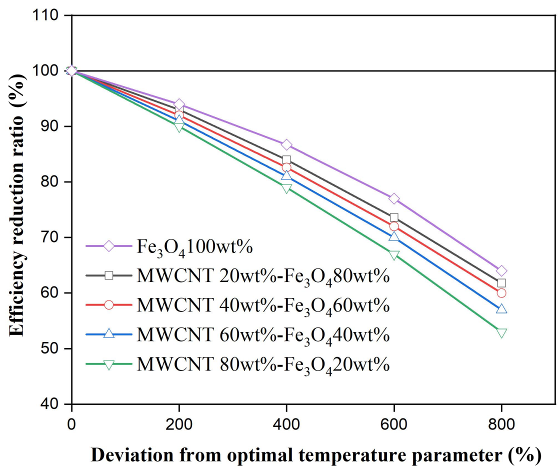

Fig. 3 Sensitivity of photo-thermal conversion efficiency to deviations from optimal temperature parameter.

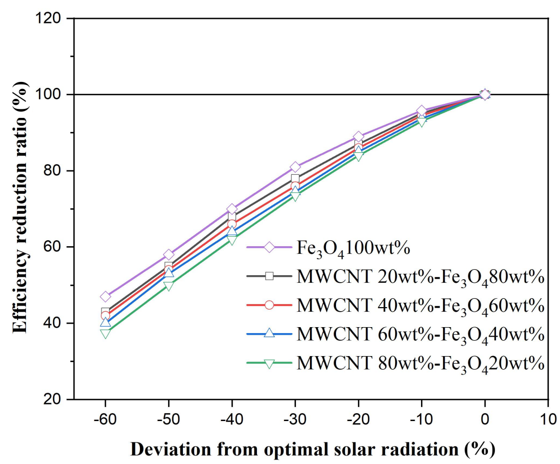

Fig. 4 Sensitivity of photo-thermal conversion efficiency to deviations from optimal solar radiation.

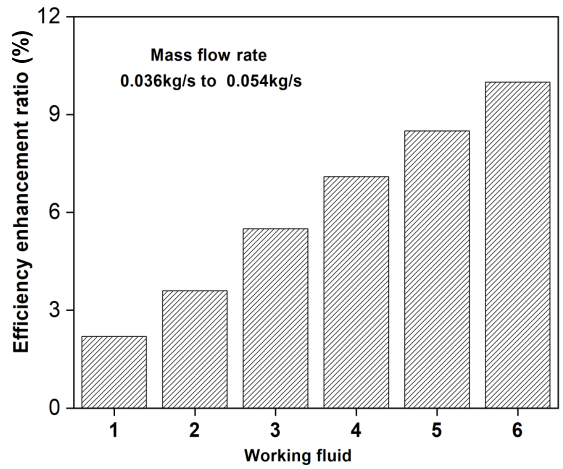

Fig. 5 Efficiency enhancement with the increase in flow rate of working fluid. 1, water; 2, 100 wt% Fe_3O_4; 3, 20 wt% MWCNT - 80 wt% Fe_3O_4; 4, 40 wt% MWCNT - 60 wt% Fe_3O_4; 5, 60 wt% MWCNT - 40 wt% Fe_3O_4; 6, 80 wt% MWCNT - 20 wt% Fe_3O_4.

Table 2. It can be seen that the hybrid nanofluid showed better thermal performance than the Fe_3O_4 nanofluid, which indicated that addition of MWCNT nanoparticles can effectively improve the ability of energy conversion efficiency. Although the heat loss coefficient was increased to a certain extent, the highest heat gain coefficient (80.1%) was achieved when Fe_3O_4-MWCNT/water hybrid nanofluid with 80 wt% MWCNT and 20 wt% Fe_3O_4 nanoparticles was applied. This corresponded to 15.5% improvement compared to Fe_3O_4 nanofluid and 25.6% compared to water. According to previous studies [30–32], Al_2O_3, CeO_2 and WO_3 nanofluids showed the same thermal performance as Fe_3O_4 nanofluid. After mixing the Fe_3O_4 nanofluid with MWCNT nanoparticles, the heat gain coefficient of the hybrid nanofluid increased remarkably with the increase in weight ratio of MWCNT nanoparticles.

Fig. 2 shows the sensitivity of photo-thermal conversion efficiency to deviations from optimal concentration of the Fe_3O_4-MWCNT/water hybrid nanofluid under the condition of $G = 800\ \mathrm{W/m^2}$ and $m = 0.036$ kg/s. It can be seen that when the optimal concentration was reduced by 50% and 80%, the Fe_3O_4 nanofluid without addition of MWCNT nanoparticles showed the lowest reduction in efficiency (2.3% and 8.1%). It showed the highest efficiency reduction (6.2% and 15.3%) when the weight ratio of MWCNTs in total nanoparticles was 80 wt%. In contrast, when the optimal concentration increased by 50%, the efficiency remained relatively unchanged due to the higher possibility of aggregation and lower dispersion stability of the nanofluid. Compared to the lower concentrations, the efficiency decreased by 1.6% and 4.4% with Fe_3O_4 nanofluid and 80 wt% MWCNT-20wt% Fe_3O_4/water hybrid nanofluid, although the conductivity of nanofluid was increased.

Fig. 3 presents the results on sensitivity of photo-thermal conversion efficiency to deviations from optimal temperature parameter using various weight ratios of the two nanoparticles in Fe_3O_4-MWCNT/water hybrid nanofluid as working fluid. The temperature parameter in this study was defined as $(T_i - T_a)/G$, and the solar radiation and flow rate were 800 $\mathrm{W/m^2}$ and 0.036 kg/s, receptively. With the increase in weight proportion of MWCNT nanoparticles, the reduction in efficiency decreased. The lowest reduction (5.6%) was obtained when Fe_3O_4 nanofluid was used as working fluid and the deviation was 200%. The highest reduction in efficiency (47%) was observed when the weight ratio of MWCNT and Fe_3O_4 nanoparticles was 4:1 and the temperature parameter deviation achieved 800%. The results revealed that the energy conversion ability of the EEUSC was reduced significantly with increase in temperature parameter. This was because when the temperature difference increased between ambient temperature and inlet of the EEUSC, the heat loss also increased gradually.

Fig. 4 shows the sensitivity of photo-thermal conversion efficiency to deviations from optimal solar radiation. In this study, the optimal solar radiation represents the value that yields the highest energy conversion efficiency of EEUSC. The results demonstrated that the thermal efficiency of EEUSC was proportional to the solar radiation when the hybrid nanofluid was applied. When solar radiation decreased by approximately 10% from optimal value, the efficiency decreased by 4.2% and 7% for Fe_3O_4 nanofluid (lowest) and 80 wt% MWCNT-20 wt% Fe_3O_4/water hybrid nanofluid (highest). Moreover, as the solar radiation decreased gradually, the maximum efficiency reduction was found (62.5%) when the weight ratio of MWCNT and Fe_3O_4 nanoparticles was 4:1 with 60% deviation from the optimal value. This result indicated that adding MWCNT nanoparticles into Fe_3O_4 nanofluid was an effective way to enhance the sensitivity of thermal performance of the EEUSC.

Fig. 5 shows the efficiency enhancement of the EEUSC with the increase in flow rate of working fluid using Fe_3O_4-MWCNT/water hybrid nanofluids with various weight ratios. It can be seen that the efficiency of the solar collector increased with the increase in flow rate of the working fluid. This is because when the flow rate of the working fluid increased, the contact time between the working fluid and the solar collector decreased, resulting in a shorter time and distance for heat conduction. The increased flow rate also reduced the dwell time of the working fluid within the solar collector, further reducing the opportunity for heat transfer to the surrounding environment.

When the flow rate was increased from 0.036 kg/s to 0.054 kg/s (Fig. 4), the efficiency increased by 2.7% when water was used, which was the lowest improvement in photo-thermal conversion efficiency. When 80 wt% MWCNT-20 wt% Fe_3O_4/water hybrid nanofluid was used, the efficiency enhancement reached the maximum value, which was approximately 10.1% improvement compared to the flow rate of 0.036 kg/s. Moreover, when Fe_3O_4 nanofluid and Fe_3O_4-MWCNT/water hybrid nanofluid with 1:4, 2:3 and 3:2 weight ratios of two nanoparticles were used, the efficiency was enhanced by 3.6%, 5.5%, 7.1% and 8.5%, respectively. Therefore, the addition of MWCNTs resulted in a higher efficiency sensitivity of the EEUSC, as the MWCNTs increased the thermal conductivity of the nanofluid.

CONCLUSION

In this study, the thermal properties and photo-thermal conversion efficiency sensitivity of an EEUSC were experimentally investigated using Fe_3O_4-MWCNT/water hybrid nanofluids with different weight ratios of two nanoparticles under different operating conditions.

The maximum photo-thermal conversion efficiency of EEUSC was achieved when hybrid nanofluid with 80 wt% MWCNT and 20 wt% Fe_3O_4 was used, showing improvements of 15.5% and 25.6% compared to Fe_3O_4 nanofluid and water, respectively. After mixing the Fe_3O_4 nanofluid with MWCNT nanoparticles, the heat gain coefficient of the hybrid nanofluid increased remarkably with the increase in weight ratio of MWCNT nanoparticles.

In addition, when the flow rate of the working fluid was increased from 0.036 to 0.054 kg/s, the efficiency of the EEUSC was increased in all cases. The maximum efficiency improvement was obtained with 80 wt% MWCNT-20 wt% Fe_3O_4/water hybrid nanofluid, while the minimum improvement was obtained with water.

Moreover, due to the high thermal conductivity of MWCNT nanoparticles, the fraction of MWCNT nanoparticles in the hybrid nanofluid was found to be proportional to the sensitivity of the photo-thermal conversion efficiency of the EEUSC under the same operating conditions. When solar radiation was decreased from the optimal value, the efficiency of the EEUSC decreased. When the optimal concentration of nanofluid was reduced, the efficiency of EEUSC decreased significantly, while it barely changed when the optimal concentration was increased. This was due to the higher possibility of aggregation and low dispersion stability of the nanofluid. The energy conversion ability of the EEUSC was also reduced significantly with increase in temperature due to the higher heat loss.

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REFERENCES

1. Liu L, Wang Z, Zhang H, Xue Y (2010) Solar energy development in China – A review. *Renew Sust Energy Rev* **14**, 301–311.
2. Badran AA, Yousef IA, Joudeh NK (2010) Portable solar cooker and water heater. *Energy Convers Manag* **51**, 1605–1609.
3. Pucar MDJ, Despic AR (2002) The enhancement of energy gain of solar collectors and photovoltaic panels by the reflection of solar beams. *Energy* **27**, 205–223.
4. Tong YJ, Kim HM, Cho HH (2016) Theoretical investigation of the thermal performance of evacuated heat pipe solar collector with optimum tilt angle under various operating conditions. *J Mech Sci Technol* **30**, 903–913.
5. Subiantoro A, Ooi KT (2013) Research on the compen-

sation of the end loss effect for parabolic trough solar collectors. *Applied Energy* **104**, 392–399.
6. Balakin BV, Struchalin PG (2023) Eco-friendly and low-cost nanofluid for direct absorption solar collectors. *Mater Lett* **330**, 133323.
7. Tong YJ, Lee H, Kang WB, Cho HH (2019) Energy and exergy comparison of a flatplate solar collector using water, Al_2O_3 nanofluid, and CuO nanofluid. *Appl Therm Eng* **159**, 113959.
8. Ahmed AM, Raed AR, Kadhim HT, Ali A, Talal K, Karim E (2022) Experimental and numerical study to develop TRANSYS model for an active flat plate solar collector with an internally serpentine tube receiver. *Int J Thermofluids* **15**, 100189.
9. Ram S, Yadav SK, Kumar A (2023) Recent advancement of nanofluids in solar concentrating collectors: A brief review. *Mater Today: Proc **72**, 2032–2038.*
10. Aissa A, Qasem NAA, Mourad A, Laidoudi H, Younis O, Guedri K, Alazzam A (2023) A review of the enhancement of solar thermal collectors using nanofluids and turbulators. *Appl Therm Eng* **220**, 119663.
11. Khullar V, Tyagi H, Phelan PE, Otanicar TP, Singh H, Taylor RA (2013) Solar energy harvesting using nanofluids-based concentrating solar collector. *J Nanotechnol Eng Med* **3**, 031003.
12. Saidur R, Meng TC, Said Z, Hasanuzzaman M, Kamyar A (2012) Evaluation of the effect of nanofluid-based absorbers on direct solar collector. *Int J Heat Mass Transf* **55**, 5899–5907.
13. Eltaweel M, Ahmed AAR, Ahmed AAA (2020) Energetic and exergetic analysis of a heat pipe evacuated tube solar collector using MWCNT/water nanofluid. *Case Stud Therm Eng* **22**, 100743.
14. Zhang XL, Zhang YL (2021) Heat transfer and flow characteristics of Fe_3O_4-water nanofluids under magnetic excitation. *Int J Therm Sci* **163**, 106826.
15. Tong YJ, Boldoo T, Ham JG, Cho HH (2020) Improvement of photo-thermal energy conversion performance of MWCNT/Fe_3O_4 hybrid nanofluid compared to Fe_3O_4 nanofluid. *Energy* **196**, 117086.
16. Liu MS, Lin MCC, Huang IT, Wang CC (2005) Enhancement of thermal conductivity with carbon nanotube for nanofluids. *Int Commun Heat Mass* **32**, 1202–1210.
17. Qu J, Tian M, Han X, Zhang R, Wang Q (2017) Photo-thermal conversion characteristics of MWCNT-H_2O nanofluids for direct solar thermal energy absorption applications. *Appl Therm Eng* **124**, 486–493.
18. Sharafeldin MA, Gróf G (2018) Experimental investigation of flat plate solar collector using CeO_2-water nanofluid. *Energy Convers Manage* **155**, 32–41.
19. Verma SK, Tiwari AK, Chauhan DS (2016) Performance augmentation in flat plate solar collector using MgO/water nanofluid. *Energy Convers Manage* **124**, 607–617.
20. Verma SK, Tiwari AK, Chauhan DS (2017) Experimental evaluation of flat plate solar collector using nanofluids. *Energy Convers Manage* **134**, 103–115.
21. He ZX, Lv YR, Zhang TA (2022) Electrode materials for vanadium redox flow batteries: Intrinsic treatment and introducing catalyst. *Chem Eng Jl* **427**, 131680.
22. Ahmad F, Mahmud S, Ehsan MM, Salehin M (2023) Thermo-hydrodynamic performance evaluation of double-dimpled corrugated tube using single and hybrid nanofluids. *Int J Thermofluids* **17**, 100283.
23. Esfe MH, Alirezaie A, Toghraie D (2021) Thermal conductivity of ethylene glycol based nanofluids containing hybrid nanoparticles of SWCNT and Fe_3O_4 and its price-performance analysis for energy management. *J Mater Res Technol* **14**, 1754–1760.
24. Engy E, Ahmed AAR, Iman EM (2022) 4E study of experimental thermal performance enhancement of flat plate solar collectors using MWCNT, Al_2O_3, and hybrid MWCNT/Al_2O_3 nanofluids. *Results Eng* **16**, 100723.
25. Shady MH, Ahmed AAR (2022) The performance response of a heat pipe evacuated tube solar collector using MgO/MWCNT hybrid nanofluid as a working fluid. *Case Stud Therm Eng* **33**, 101957.
26. Abid H, Khan MS, Ratlamwala TAH, Malik MN, Ali HM, Cheok Q (2021) Thermodynamic analysis and comparison of different absorption cycles driven by evacuated tube solar collector utilizing hybrid nanofluids. *Energy Convers Manage* **246**, 114673.
27. Tong YJ, Kim JH, Cho HH (2015) Effects of thermal performance of enclosed-type evacuated U-tube solar collector with multi-walled carbon nanotube/water nanofluid. *Renew Energy* **83**, 463–473.
28. Zeiny A, Jin H, Bai L, Lin G, Wen D (2018) A comparative study of direct absorption nanofluids for solar thermal applications. *Sol Energy* **161**, 74–82.
29. Moffat RJ (1985) Using uncertainty analysis in the planning of an experiment. *J Fluids Eng* **107**, 173.
30. Kim HM, Kim JH, Cho HH (2017) Experimental study on performance improvement of U-tube solar collector depending on nanoparticle size and concentration of Al_2O_3 nanofluid. *Energy* **118**, 1304–1312.
31. Sharafeldin MA, Gróf G (2018) Experimental investigation of flat plate solar collector using CeO_2-water nanofluid. *Energy Convers Manage* **155**, 32–41.
32. Sharafeldin MA, Gróf G, Mahian O (2017) Experimental study on the performance of a flat-plate collector using Wo_3/Water nanofluids. *Energy* **141**, 2436–2444.