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Study on the performance of solar cells cooled with heatsink and nanofluid added with aluminum nanoparticle

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ABSTRACT

The cooling of photovoltaic (PV) panels based on nanofluids is one of the emerging cooling methods to improve the efficiency of PV panels. In this study, the effects of aluminum nanoparticles on the cooling performance and conversion efficiency of PV panels were investigated experimentally. The surface temperature, output power, and efficiency of the PV panels were assessed in Mashhad, Iran on a sunny winter day in November 2020 under ambient temperatures between 10 and 17 °C. Experimental results indicated that the nanofluid with aluminum nanoparticle improved the solar panel efficiency and solar PV panel's output power by an average of 13.5 and 13.7%, respectively compared to that of water cooling without aluminum nanoparticles. A temperature reduction between 13.08 and 16.34 °C on the solar PV panels surface was observed for heatsink cooling with nanofluid containing aluminum nanoparticles. Overall, the results suggest that nanofluid added with aluminum nanoparticles is effective in improving the conversion efficiency of PV panels.

1. Introduction

Solar energy is considered an important renewable energy source with continuous availability and minimal waste products [1,2]. Demand for clean and renewable energy has resulted in the increase of electricity generation methods employing solar irradiance. However, conventional solar panel technologies face challenges such as low energy conversion efficiency and thermal management issues. The efficiency and durability of solar panels are directly influenced by climate conditions and operating temperatures [3–5]. Solar irradiance emitted by the sun, ambient temperature, and surface temperature of solar panels have a significant effect on the solar cell's conversion efficiency. At 25 °C ambient temperatures, about 80 % of the absorbed sunlight in solar panels is in the form of heat, while only 20 % is converted into electricity, whereas an increase in solar cell temperature of 1 °C would reduce the efficiency of solar panels by 0.5 % [6]. In extreme cases, ambient temperatures can exceed 60 °C and reduce the solar energy conversion efficiency that result in low electricity generation [7]. Therefore, an effective cooling system for solar panels is crucial to ensure they operate in optimal conditions.

Recently, various novel active and passive solutions have been explored by researchers for improving the cooling performance on solar panels [8,9]. Active methods such as water spray and hybrid collision jets relying on an external actuating force to establish flow of the fluid are some of the typical cooling systems used for photovoltaic (PV) panel [10–12]. For instance, Gilmore et al. [13] studied solar panel cooling using micro-channels embedded on the back side of the panels and evaluated heat depletion processes and solar panel efficiency gains. The operational temperature of solar panels was reported by Siecker et al. [14] as an important factor in achieving high-cooling performance for solar-photovoltaic systems . Furthermore, they observed that adequate cooling can improve electrical efficiency and slow down cell deterioration, thereby achieving maximum solar panel longevity in transparent solar panels operated with air cooling. In another study performed by Zubeer and Ali [15] reported that active cooling system and reflectors can improve the electrical performance of the PV module. Furthermore, Zhang et al. [16] investigated a hybrid PV/T collector/evaporator integrated with the evaporation section of the heat pipe and the

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refrigerant pipe of the heat pump.

Despite the above-mentioned cooling solutions for PV panels, the potential of utilizing nanofluids as cooling medium in solar panels has recently been found to be very effective owing to their enhanced heat transfer properties [17–19]. Nanofluids are colloidal suspensions of nanoparticles at low concentration with diameters less than 100 nm in a base fluid that has enhanced thermo-physical and optical properties [20]. By introducing nanoparticles into the fluid, properties such as thermal conductivity, specific heat capacity, and optical properties can be significantly altered. The nanoparticles are capable of transferring heat more quickly when it is suspended in the base fluid due to their exceptionally low specific heat capacity. Furthermore, heat can be transported and distributed more efficiently between the nanoparticles and the base fluid owing to their large surface area to volume (specific surface area) and high thermal conductivity. Consequently, the temperature of solar panel can be decreased for the same mass flow rate thereby improving the thermal efficiency of the grid [21].

Recently, there have been significant research efforts done in exploring the viability of various metal nanoparticles for solar panel applications including metallic, metal oxides, and novel metal composites [22,23]. Murtadha and Hussein [24] investigated the effects of water and aluminum oxide nanofluid at concentrations of 1, 2, and 3 wt %, respectively on the cooling performance of monocrystalline solar panels. They found that the most significant decrease in photovoltaic surface temperature and greatest output power were achieved using a nanofluid at a concentration of 3 wt%. A similar study on nanofluids containing alumina nanoparticles in water (base fluid) at 1, 2, 3, and 4 % concentrations of by volume, respectively was also performed by Manirathnam et al. [25]. Their results show the enhancement of heat transfer rate from 1.77 to 37.35 % due to the nanoparticles presence in the cold fluid. In another study, Mashaei and Shahryari [26] reported that nanofluids in thermal tubes with dual evaporators is a viable alternative for cooling of satellite equipment. In the experimental evaluation on the cooling performance of alumina/water nanofluid flow in a heated copper tube performed by Ho et al. [27], they reported improvement in heat transfer effectiveness ratio with higher concentration of alumina nanoparticle in nanofluid. In another study by Gupta et al. [28], they investigated the performance of a flat solar panel collector using aluminum nanoparticles with 2 % concentration at different flow velocities. An improvement in the thermal efficiency of collector between 9 and 40 % compared to that of the non-nanoparticle fluid was reported in their study.

Despite promising outcomes from the studies on various metal nanoparticles for effective cooling of PV panels, the potential of aluminum nanoparticles utilization for cooling PV panels has not been explored to date. Aluminum nanoparticles could be a more practical solution for cooling large-scale PV panels compared to other metal nanoparticles due to their excellent heat transfer properties and their wide availability in the market. The high thermal conductivity of aluminum nanoparticles enables them to transfer heat rapidly and facilitates efficient transfer of heat away from heat sources. Besides, the presence of aluminum nanoparticles can enhance convective heat transfer and increases the overall heat transfer coefficient of nanofluid. Therefore, the present study aims to explore the potential of utilizing aluminum nanoparticles in nanofluid on a solar panel equipped with a heatsink. The solar panel efficiency, power output, and surface temperature of a solar panel cooled using nanofluid with and without aluminum nanoparticle are the focus of our study. The outcome of this study will provide insights into the performance of solar panels cooled by heatsink and nanofluid containing aluminum nanoparticles.

2. Methodology

The flow chart depicted in Fig. 1 represents the sequential steps of research activities involved to evaluate the solar panel performance cooled with nanofluid containing aluminum nanoparticles. The details of each step are explained in the following sub-sections.

2.1. Nanofluid preparation

Aluminum nanoparticles of an average of 30 nm in diameter were acquired from FINEPOL. The properties of aluminum nanoparticles used in the experiment are summarized in Table 1. The method adopted for preparing nanofluid containing aluminum nanoparticles was sourced from the work of Salehi et al. [29]. The nanofluid was prepared by mixing water with aluminum nanoparticle at a volumetric concentration

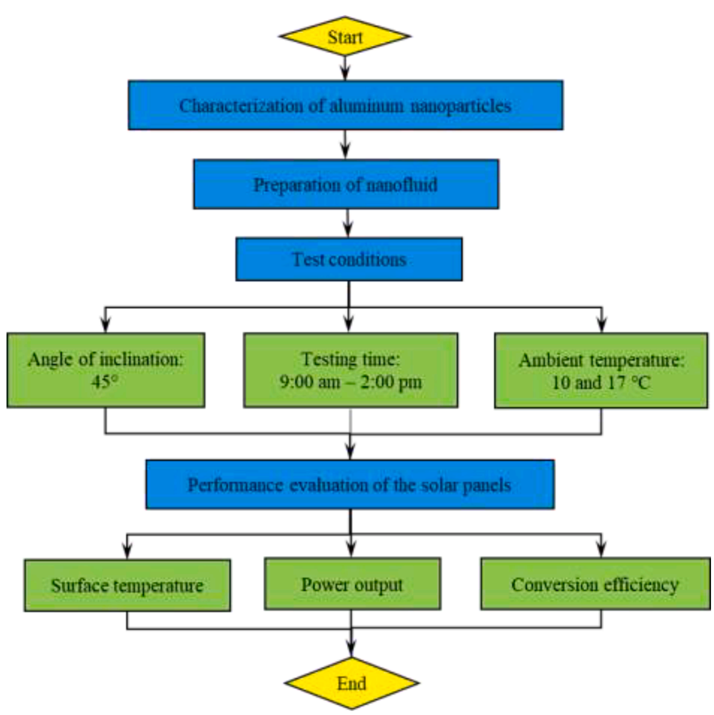

Fig. 1. Flow chart of research activities of this study.

Table 1
Pertinent properties of aluminum nanoparticles.

Property	Magnitude	Unit/Symbol
Purity	99.9	%
Molecular weight	26.98	g/mol
Physical form	Powder	-
Color	Grey	-
Average particle size	30	Nm
Density	2.70	g/cm^3
Melting point	660	°C
Thermal conductivity	88 - 251	kW/m·K

of 2 %. Water was used as the base fluid because of its high specific heat, in which it could absorb and transfer high amounts of heat. On the other hand, aluminum nanoparticles were added in water to enhance the heat transfer properties of water due to its high thermal conductivity (i.e., 88 to 251 kW/m·K) and large surface area to volume. Consequently, the nanofluid were homogenized using a Q500 Sonicator ultrasonic homogenizer at a frequency of 20 kHz and 500 W of power at temperature between 292 K and 296 K for one hour to ensure the that the nanofluid mixture is stabilized and homogenized, as shown in Fig. 2.

2.2. Experimental setup and measurements

The solar cell experiment mainly consists of the solar panel, heatsinks with multiple cooling fins, and reservoir circulating nanofluid that transfers the heat from the hot solar panel to the heat sinks, as shown in Fig. 3. A Yingli 10-watt solar panel with dimensions of 280 mm by length, 358 mm by width, and 18 mm by depth was used in the experiment. The electrical characteristics of the PV module at Standard Test Conditions (STC) is shown in Table 2, whereas the equipment and apparatus that were used to evaluate the performance of solar cell together with their range of measurement, accuracy, and uncertainty are summarized in Table 3. An intensimeter was used to measure the solar irradiance power generated from the solar panel. On the other hand, a multimeter was used for measurement of the current and voltage produced by the solar cell. A laser thermometer was employed to measure ambient temperature and solar panel surface temperature a laser thermometer has been employed. The set up and measurements performed in this solar cell experiment are comparable to other recent works investigating solar cells equipped with monolithic heatsinks under STC [30–32]. The innovation of this experimental setup is the application of aluminum nanofluid as the enhanced heat transfer medium to improve the cooling performance of heatsinks integrated to the solar panel, which can result in better solar cell conversion efficiency.

Fig. 2. The Q500 Sonicator ultrasonic homogenizer for preparing nanofluid.

2.3. Test conditions

Experiments were performed on a sunny winter day in November 2020 simultaneously under controlled temperatures and 45° angle of inclination on a standard 10 W solar panel. The annual average of total monthly solar radiation in Mashhad (Razavi Khorasan Province), Iran was estimated around 433 W/m^2. The experiments were performed from 9:00 am morning to 2:00 pm afternoon under ambient temperatures between 10 and 17 °C. The variations in ambient temperature can influence the solar panel surface temperature distribution, power output, and conversion efficiency. For instance, greater ambient temperature would reduce the solar energy conversion efficiency and result in low power output. Experimental measurements taken for 5 hours duration in a day were decided based on other similar studies on solar panel equipped with heat sink [29,33]. The maximum temperature and power generated from solar panel were evaluated under two different cooling fluids: pure water (without aluminum nanoparticle) and nanofluid containing aluminum nanoparticle. Prior to conducting the experiments, the heatsinks and cooling fluid source were visually inspected for any leakages. During the inspection, any visible signs of leakage like observing drips, puddles, stains, discoloration, or any other indications of fluid or gas escaping from the system were carefully checked. Temperature readings were taken at ten different test points of the solar panel surface using instantaneous thermometers and the maximum values were recorded simultaneously. The performance variables of P_{max} (maximum power output), V_{max} (maximum voltage output) and I_{max} (maximum current output) generated by the solar panel were also recorded. The maximum temperature and performance variables were recorded at 15 mins intervals and repeated three times to assess the statistical validity of the results.

2.4. Performance evaluation

The maximum electrical power output, P_{max} generated from the solar panel was obtained by V_{max} and I_{max}, as shown in Eq. (1) [34]. On the other hand, the solar cell efficiency is defined as shown in Eq. (2) [35].

$$P_{max} = I_{max} \times V_{max} \tag{1}$$

$$\eta = \frac{P}{I_r A} \tag{2}$$

where, I_r denotes the solar irradiance (W/m^2), and P is the panel power output (W), and A denotes the area of the solar panel (m^2). Statistical analysis of the results was performed to determine the mean values and standard deviation. Consequently, t-tests were performed at a significance level of 1 % using Eq. (3) to compare between the solar panel cooled with pure water and solar panel cooled using nanofluid containing aluminum nanoparticle.

$$t = \frac{\bar{x} + \mu}{\sigma^2 / \sqrt{n}} \tag{3}$$

where, $\bar{x}$ is the mean of the sample, μ is the assumed mean, σ is the standard deviation, and n is the number of observations.

3. Results and discussion

Results of the present study were separately reported as follows, including solar panel surface temperature variations, solar panel electrical power output, and solar panel efficiency under regular operating conditions and compared with those of operation using solar panel cooling mechanisms comprised of heatsinks with aluminum nanoparticle source.

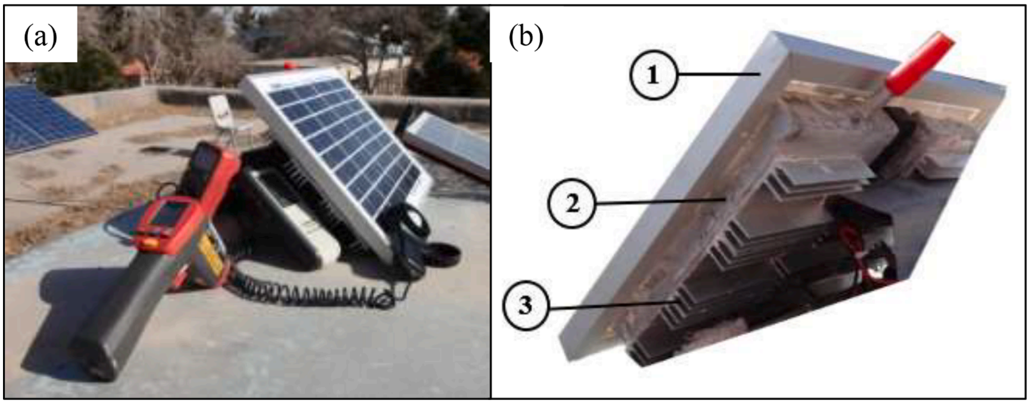

Fig. 3. (a) Actual view of the solar cell experiment and the back view depicting the main components: (1) solar panel, (2) reservoir containing nanofluid, and (3) heat sink made of cooling fins.

Table 2
Characteristics of the YL10C-18b PV module at Standard Test Conditions (STC).

Model	Magnitude	Unit/Symbol
Power tolerance	±3	%
Maximum power	10	W
Cells efficiency	17.4	%
Optimum operating voltage	17.96	V
Optimum operating current	3.40	A
Open-circuit voltage	22.5	V
Short-circuit current	0.61	A

The measurements were made at STC: 1000 W/m^2 irradiance, 25 °C cell temperature, AM = 1.5

Table 3
Uncertainties of the solar panel measuring devices.

Equipment	Model	Accuracy	Resolution	Range
Multimeter	UT-136C	± (1+0.8 %)	0.1 V	0 – 500 V at 10 A
Intensimeter	ST-1307	±10 W/m^2	1 W/m^2	0 - 1999 W/m^2
Laser Thermometer	UT-301A	±1.8 °C	0.1 °C	-18 to 350 °C

3.1. Solar panel surface temperature distribution

The temperature variations of the solar panel surface over the test period for water cooling and nanofluid containing aluminum nanoparticles are depicted in Fig. 4. The solar panel surface temperature with nanofluid cooling gradually increases from 9:00 to 11:00 and then stabilizes from 11:00 to 14:00. A similar temperature variation trend is also observed for solar panels with water cooling. The initial temperature rise followed by stabilization in a fluid exposed to solar radiation is attributed to the dynamics of heat transfer and the thermal properties of the fluid. During the initial hours, the fluid absorbs heat at a higher rate than it loses heat to the surrounding environment due to the significant temperature difference between the fluid and its surroundings. As the fluid's temperature rises, the temperature difference between the fluid and its surroundings starts to decrease. Consequently, a thermal equilibrium is established, where the rate of heat absorption equals the rate of heat dissipation. At this point, the temperature stabilizes because there is no net gain or loss of heat. Additionally, it is deduced that the enhanced thermal conductivity of cooling fluid with aluminum nanoparticles provides more efficient heat transfer to its surroundings thereby influencing the stabilization process. Both trends indicate that the solar panel temperature remains the highest and the heat generated from sunlight is optimum between 11:00 and 14:00 due to no interference from clouds. The solar panels temperature varied between 13.1 to 16.3 °C over the duration of the experiment for both cooling fluids: water and nanofluid. However, an average temperature reduction by 13 °C is achieved for nanofluid cooling compared to that of water cooling. Significant temperature reduction between 10 °C and 15 °C was also reported by other recent studies on the use of different nanofluid to cool a PV solar cell equipped with a heatsink [36,37]. This improvement can be attributed to the high thermal conductivity of aluminum nanoparticle and the enhanced heat distribution within the fluid due to the presence

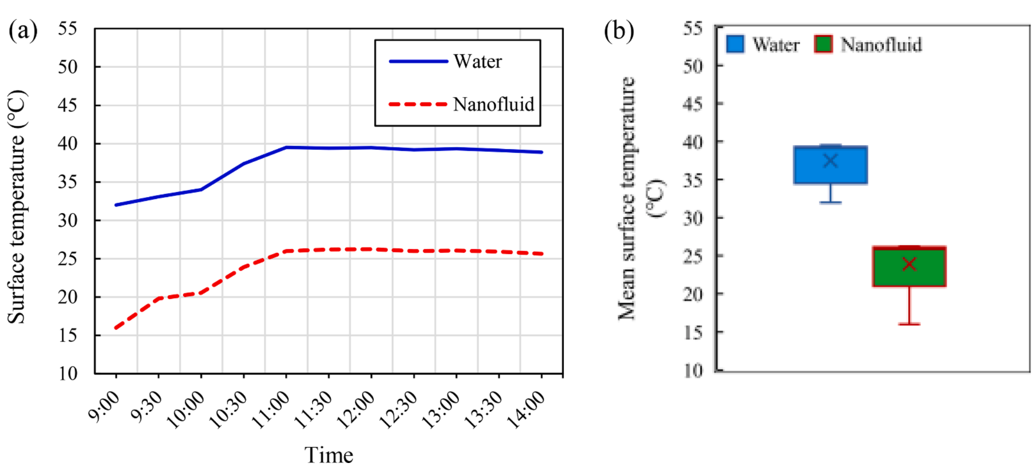

Fig. 4. Comparison of (a) the solar panel surface temperature variations with time and (b) the mean surface temperature between water cooling and nanofluid cooling at 1 % significance levels.

of nano-sized aluminum nanoparticle. This allows more heat to be absorbed from the solar panel to the nanofluid and dissipated to the surrounding through the heatsink by natural convection the temperature. Consequently, the surface temperature of solar panel is reduced significantly. Therefore, it is expected that the application of nanofluid cooling in heatsink can prolong the lifespan of the solar panels.

3.2. Solar panel power output

The solar panel power output variations over the period with water cooling and nanofluid cooling are demonstrated in Fig. 5. Both nanofluid and water showed similar output power distribution over the test period, as depicted in Fig. 5(a). However, the solar output power for nanofluid cooling is observed to be greater than that of water cooling in a range between 9.2 % and 20.8 % over the test period. An average power output of 13.7 % is achieved for solar panels with nanofluid cooling compared to that of solar panel cooled by water. This improvement can be associated to the enhanced convective heat transfer coefficient between the solar panel surface and nanofluid as well as the enhanced heat transfer between the nanofluid and the heatsink. The presence of aluminum nanoparticle of dimension between 20 nm and 30 nm act as an optimum heat carrier within the fluid thereby allowing more heat to be dissipated from one point to another [38]. Therefore, it is inferred that the nanofluid cooling containing aluminum nanoparticle for solar panel is suitable for maintaining optimum output power. However, it is observed that the output power is optimum at 9:00 and 11:30, respectively for nanofluid cooling, whereas lower output power is seen from 9:30 to 10:30. The output power inconsistency may be caused by the non-uniformity of solar irradiance on the solar surface panel over the test period [39].

3.3. Solar panel efficiency

Fig. 6 presents the solar panel efficiency distribution against time for nanofluid cooling and water cooling, respectively. In comparison to the solar efficiency over the period, as depicted in Fig. 6(a), the efficiency is the greatest at 9:00 for both nanofluid and water but decreased significantly at 10:15. The significant reduction in solar panel efficiency observed from 9:00 to 10:15 is mainly due to the gradual increase in temperature, as evident in Fig. 4. The rapid accumulation of heat within the solar panels contributed to gradual increase in the surface temperature thereby resulting in reduced overall efficiency. However, the efficiency for both nanofluid and water cooling are observed to be quasi-steady from 10:30 to 14:00 due to the steady surface temperature trend occurring at 11:00 onwards as depicted in Fig. 4. The efficiency variations over a duration of 5 hours for both water cooling and nanofluid are found to be similar to other studies reporting the cooling performance of PV solar cells equipped with a heatsink under normal operating conditions [29,33]. The solar efficiency of nanofluid cooling is found to be higher than that of water cooling in the range between 9.2 and 19.4 % over the test period. Furthermore, the nanofluids cooling contributed to an average of 13.5 % in solar efficiency, whereas water cooling achieved an average of 11.8 % in solar efficiency as observed in Fig. 6(b). Overall, the abovementioned trends clearly depict that nanofluid containing aluminum nanoparticles is more effective in improving solar efficiency compared to that of water. This can be attributed to the high thermal conductivity of nano-sized aluminum particle that enhances the heat transfer process within the fluid thereby allowing more heat to be dissipated from the solar panel to the heat sink. Consequently, resulting in greater temperature reduction as evident in Fig. 4 and higher solar efficiency.

4. Conclusion

The effects of aluminum nanoparticles on the surface temperature, output power, and efficiency of solar panel equipped with heatsink was investigated experimentally. From the results, greater reduction in the surface temperature by an average of 13 °C was achieved for solar panels cooled with nanofluid containing aluminum nanoparticles as compared to water cooling. Compared to water cooling, the efficiency and power output improved by an average of 13.5 and 13.7 %, respectively for solar panels cooled with aluminum nanoparticles. The improvements are mainly attributed to the high thermal conductivity and large surface area-to-volume ratio of aluminum nanoparticles. Since only two types of cooling fluids were investigated, a conclusive remark on the effectiveness of aluminum nanoparticles for cooling PV panels can hardly be drawn out. Nevertheless, the positive outcome from this study provides insights into the use of nanofluid containing aluminum nanoparticle in solar panels equipped with heatsink. Moreover, it is evident from the present study that aluminum nanoparticles can effectively reduce the temperature of solar panels and may hold the future key to enhance the conversion efficiency of solar panels. Therefore, extensive research on the effectiveness of aluminum nanoparticles in different types of cooling fluids, concentrations, and solar panels is needed to verify their potential. Moreover, the stability of aluminum nanoparticles (e.g., life span, size distribution, etc.) in cooling fluids and variations in ambient temperature are also critical to understand the underlying reason behind their capability in enhancing conversion efficiency in solar panels.

CRediT authorship contribution statement

Rouhollah Salehi: Project administration, Supervision, Data

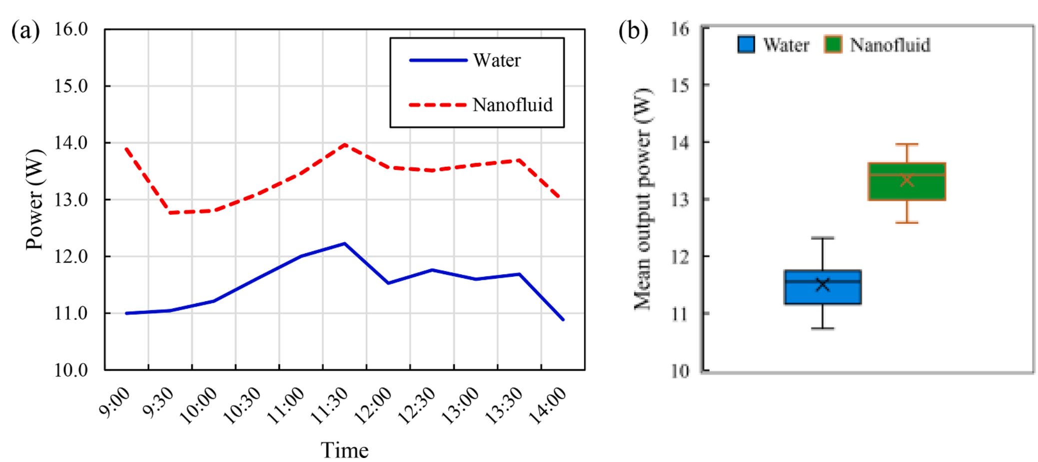

Fig. 5. Comparison of (a) the solar panel power output variations with time and (b) the mean power output between water cooling and nanofluid cooling at 1 % significance levels.

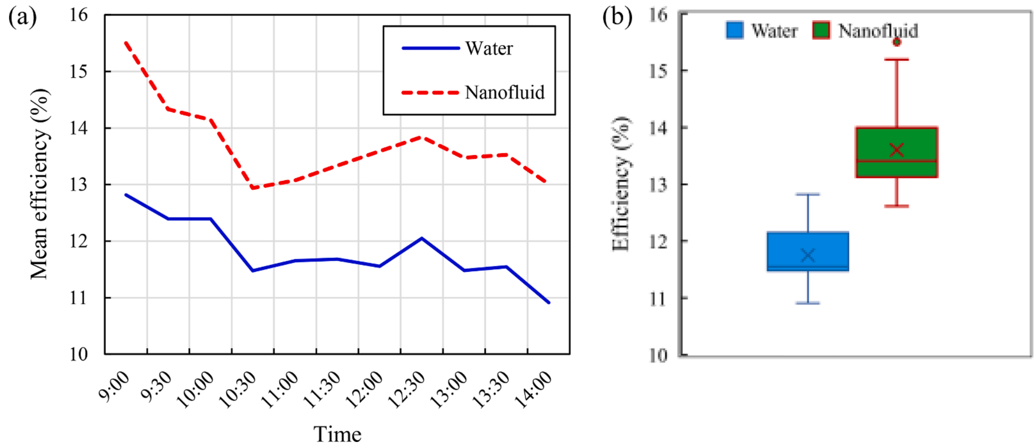

Fig. 6. Comparison of (a) the solar panel efficiency variations with time and (b) the mean efficiency of solar panel between water cooling and nanofluid cooling at 1 % significance levels.

curation, Investigation, Software, Formal analysis, Methodology, Validation, Writing – original draft. **Ahmad Jahanbakhshi:** Conceptualization, Methodology, Investigation, Validation, Writing – original draft, Writing – review & editing. **Jong Boon Ooi:** Conceptualization, Methodology, Investigation, Validation, Writing – review & editing. **Abbas Rohani:** Software, Formal analysis, Validation, Writing – review & editing. **Mahmood Reza Golzarian:** Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflicts of interest.

Data availability

The data that support the findings of this study are available from the corresponding authors, upon reasonable request.

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