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A Novel Integrated Photovoltaic System with a Three-Dimensional Pulsating Heat Pipe

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ABSTRACT

Solar energy is a valuable renewable energy source, and photovoltaic (PV) systems are a practical approach to harnessing this energy. Nevertheless, low energy efficiency is considered a major setback of the system. Moreover, high cell temperature and reflection of solar irradiance from the panel are considered chief culprits in this regard. Employing pulsating heat pipes (PHPs) is an innovative and useful approach to improving solar panel performance. This study presents the results of the power performance of a PV panel attached to a newly designed spiral pulsating heat pipe, while graphene oxide nanofluid with three different concentrations was used as a working fluid to maximize the efficacy of the solar panel. The study proved that the cooling method delivered high efficiency by reducing the temperature, especially in the middle of the day. Using nanofluid graphene oxide at concentrations of 0.2, 0.4, and 0.8 gr/lit as the working fluid can reduce the thermal resistance of PHPs by over 30%, 24%, and 15%, respectively. This, in turn, enhances the system's electrical power output by approximately 9%, 7%, and 6%, respectively.

KEYWORDS

Solar panel; nanofluid; pulsating heat pipe; heat transfer; electrical efficiency

Nomenclature

A	Panel aperture area (m²)
C_p	Heat capacity of flowing medium (J/kg.k)
G	Incident solar radiation (W/m²)
I	Electric current (A)
$\dot{m}$	Mass flow rate (kg/s)
Q	Heating power (W)
P	Power (W)
T	Temperature (°C)
R	Thermal resistance (°C W⁻¹)
V	Voltage (V)
η	Efficiency (%)

Acronyms

OHP	Oscillating heat pipe
PHP	Pulsating heat pipe
PV	Photovoltaic
S	Speed

Subscripts

a	Ambient
b	Improvement
c	Condenser
el	Electrical
e	Evaporator
in	Input
mp	Maximum power point
oc	Open-circuit
out	Output
s	Solar panel
sc	Short-circuit
w	Wind

1 Introduction

The depletion of fossil resources has become a highly controversial issue. Conventional energy resources such as oil and natural gas will be drained in less than 70 years [1]. Developing reliable and sustainable sources is identified as one of the most pragmatic approaches to resolving this issue. Renewable energy technology has been considered a viable and attractive option to tackle the energy crisis [2]. However, the application of this technology faces two grave problems, namely low efficiency and manufacturing cost [3]. Photovoltaic (PV) technology has caught considerable attention due to its cost-effectiveness, durability, and simple structure [4,5]. Generally, the efficiency of PV panels varies from 10% to 23% [6]. On the other hand, increasing cell temperature produces an adverse effect on PV efficiency [7]. Solar radiation intensity and ambient temperature are considered two decisive factors that dramatically affect photovoltaic efficiency [8]. PV cell efficiency is lowest at the highest solar intensity and lowest wind speed, leading to cell overheating [9]. Therefore, to enhance PV efficiency, the generated heat should be dissipated. A large number of methods have been implemented to cool PV cell temperature, and the major ones are the active methods (air cooling [10] and water cooling [11,12]) and passive methods (heat pipe [13], PCM [14], and nanofluid [15]) listed in Fig. 1.

On the other hand, there are major disadvantages related to air cooling and water cooling, such as low efficiency and freezing problems [16]. Heat pipes are considered a viable solution to address these problems, making a significant contribution to improving photovoltaic efficiency [17]. Heat pipes are divided into five types (cylindrical heat pipe, loop heat pipe, rotating heat pipe, variable conductance heat pipe, and pulsating heat pipe (PHP) [18]), which offer high performance in terms of heat transfer [19]. Heat pipes are highly advantageous due to their low weight, cost-efficiency, reliability, and easy-to-manufacture structure [20]. Heat pipe performance is vulnerable to some factors, such as the heat input [21], filling ratio [22], tube diameter [23], inclination angle [24,25], and the length of tubes [26]. Xu et al. [27] designed a new type of PV connected with an oscillating (pulsating) heat pipe. It was observed that the thermal resistance of the PHP absorber diminishes with increasing evaporation

temperature, and they also showed that the system can offer promising efficiency. Ersoz [28] applied acetone, hexane, ethanol, petroleum ether, methanol, and chloroform as coolants and investigated their impact on the thermal behavior of a heat pipe solar collector in Turkey. When the air velocity was between 2–4 m/s, acetone and chloroform offered the most optimal performance.
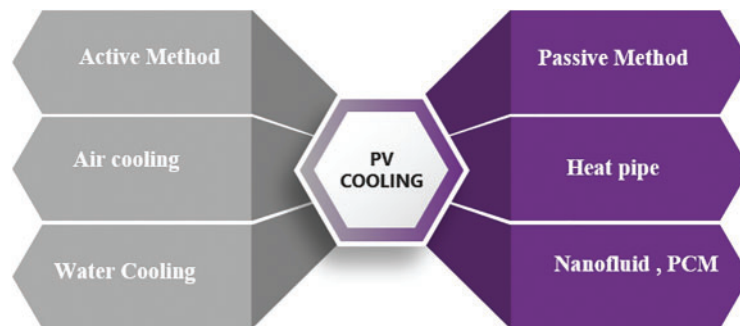

Figure 1: Cooling approaches of solar panels

The emergence of pulsating heat pipes (PHPs) in the early 1990s [29] as one of the most efficient, innovative pieces of equipment has drawn a lot of attention, thanks to their impressive performance in terms of heat transfer and unique design [30]. Patel et al. [31] investigated the effect of eleven coolants on a pulsating heat pipe solar water heater. Pure fluids (DI water, acetone, methanol, and ethanol) and binary fluids (a mixture of water with the mentioned coolants) were used. It was observed that acetone was the best pure working fluid, and concerning binary fluids, water-acetone provided greater performance.

Nanofluid, which comprises a base fluid and solid nanometer particles, has broadened perspectives to promote the performance of thermal control devices [32]. It has proven that adding nanoparticles significantly contributes to improving the thermal performance of the coolant [33]. Pulsating heat pipes achieve remarkable performance when nanofluids are utilized as the coolant [34]. Dehaj et al. [35] studied the efficiency of a heat pipe solar panel using Al_2O_3, and CuO nanofluids. Their findings showed that the nanofluids enhanced the panel's efficiency by over 9%.

The research conducted by Alizadeh et al. [36] highlights the effectiveness of single-turn pulsating heat pipes in improving the thermal management of photovoltaic (PV) panels. Their numerical simulations offer valuable insights into optimizing PHP designs to maximize cooling efficiency, resulting in an 18% enhancement in the overall performance of PV systems.

Graphene oxide (GO) nanofluids have the potential to significantly enhance the performance of heat pipes through improved thermal conductivity and heat transfer efficiency [37,38]. GO nanofluids typically demonstrate good stability and dispersion in the base fluid, which is crucial for maintaining consistent thermal performance [39].

Both 2D and 3D pulsating heat pipes (PHPs) are effective for thermal management, but 3D PHPs, with their superior thermal performance and intricate fluid dynamics, are better suited for high-power, multi-dimensional applications requiring excellent heat dissipation and operational stability [40]. Thompson et al. [41] investigated three-dimensional flat-plate oscillating heat pipes (3D FP-OHPs) filled with water or acetone, noting that the lowest thermal resistance achieved was 0.08°C/W with water. Additionally, Ling et al. [42] demonstrated that a PCM/3D-PHP cooling system for electronic devices could reduce thermal resistance by up to 36.3% by efficiently transferring heat to the environment.

Jung et al. [43] compared a 3D pulsating heat pipe (PHP) with a conventional PHP, finding that the 3D-PHP had enhanced heat transfer due to additional flow, leading to reductions of up to 14.7% in thermal resistance and 6.7°C in evaporator temperature under uniform heating conditions. Dia et al. [44] designed a new 3D-PHP and studied the effects of geometric parameters and operating conditions on its performance, noting that a uniform distribution of vapor-liquid plugs significantly improved the PHP's performance.

The review reveals a noticeable gap in experimental research aimed at optimizing PV panel efficiency using 3D-PHPs, with most studies focusing solely on 2D-PHP designs. In response, this study involves modeling PV panels equipped with innovative 3D-PHPs using various working fluids to determine the optimal configuration for maximizing electrical efficiency. The goal of this research is to introduce a new 3D-PHP design that is both practical for real-world applications and capable of handling higher heat flux compared to previous designs. This research is exceptional and presents significant findings by introducing a practical and innovative cooling method for lowering solar panel temperatures. Additionally, the proposed system demonstrated high efficiency, as it could dissipate heat from the solar panels without relying on an external power, thereby enhancing its cost-effectiveness.

2 Experimental Procedure

This section provides an in-depth explanation of the experimental setup and the formulas used for calculating the results.

2.1 System Setup

An experimental setup was tested in Iran (Mashhad). It should be mentioned that in this study, two monocrystalline solar panels were used. One of them was considered the cooled panel equipped with a spiral 3D-PHP, and the other served as the reference panel. Fig. 2 displays the electrical features of the solar panel.
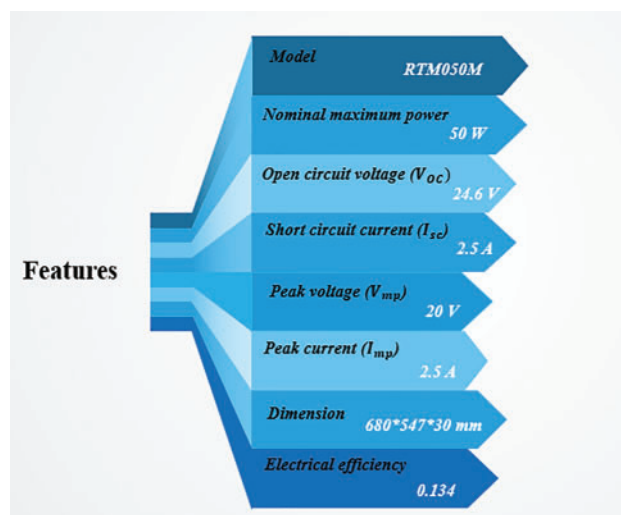

Figure 2: Electrical features of the solar panel

Fig. 3 depicts the new three-dimensional PHP fabricated with the copper. While in Table 1, detailed design of 3D-PHP is demonstrated.
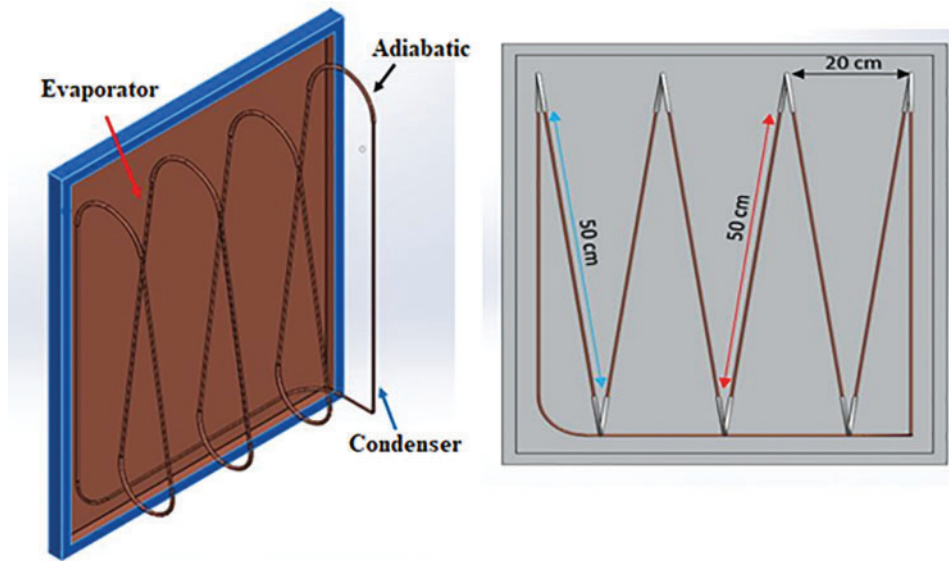
Figure 3: Configuration of PHP from different views

Table 1: Specifications of PHP

Specification	
Number of turns	4
Evaporator	200 cm
Condenser	200 cm
Adiabatic	109.5 cm
Inner diameter	3
Outer diameter	4

Research has demonstrated that a 50% filling ratio yields the best performance for PHPs [45,46]. Consequently, all tests were conducted using this ratio. A vacuum was provided by a vacuum pump before the PHP was loaded with coolant. The experimental setup is shown in Fig. 4, while a schematic of the experiment is depicted in Fig. 5.

Despite many studies that have used the lamination technique to attach the evaporator to solar panels [47], in this study, a copper sheet was attached to the solar panel with thermal paste, which contributed to lowering the operation costs and simplifying the system. Graphene oxide nanofluid with three different concentrations (0.2, 0.4, 0.8 gr/lit) was prepared, with distilled water as the base fluid, to be used as a coolant. The graphene oxide used in this study was sourced from US Research Nanomaterials, Inc. As mentioned earlier, nanofluids improve the base fluid's overall thermal conductivity, but they also need to be stable and durable [48]. Thus, the surfactant sodium dodecyl sulfate was added. The scanning electron microscopy image of GO is shown in Fig. 6.
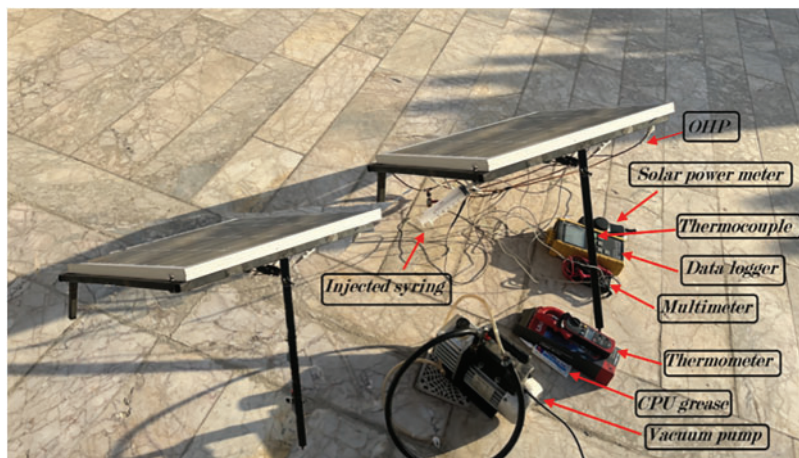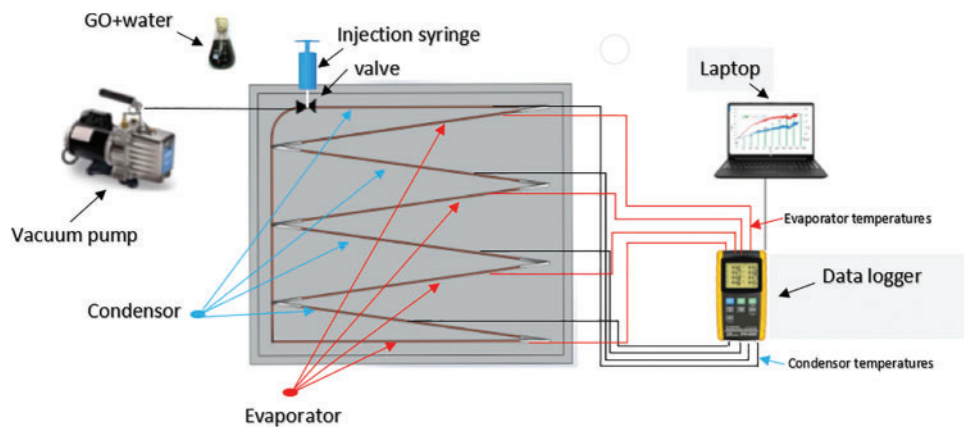
Figure 4: Picture of experiment setup

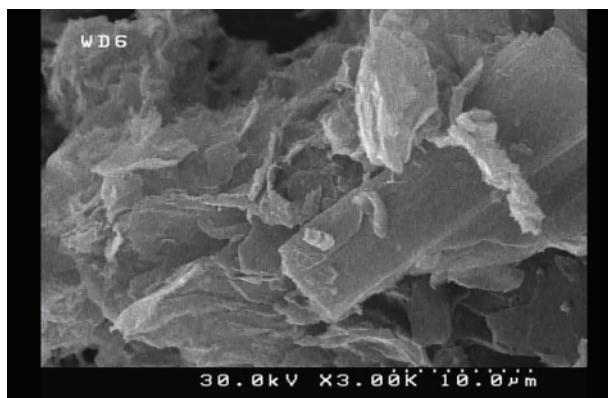**Figure 5:** Schematic diagram of experiment

Figure 6: Scanning electron microscopy image of GO

Raman spectroscopy analysis of GO is illustrated in Fig. 7. Characteristic peaks are demonstrated, specifically at around 1400 cm^{-1} for the D band and 1600 cm^{-1} for the G band of graphene oxide.
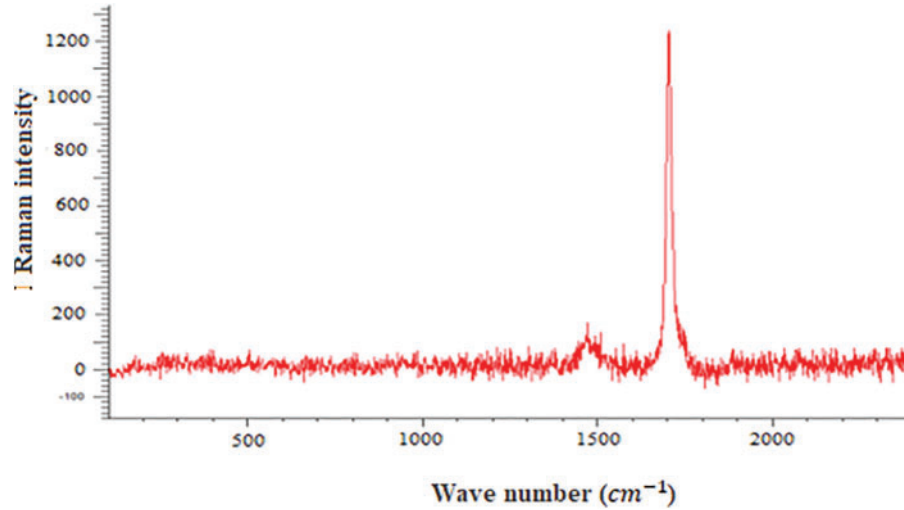

Figure 7: Raman spectroscopy analysis of GO

Table 2 illustrates thermal conductivity of and GO with three different concentrations used in this investigation.

Table 2: Thermal conductivity of coolants

Coolant	Thermal conductivity (W/K.m)
0.2 gr/lit	0.626
0.4 gr/lit	0.642
0.8 gr/lit	0.656

2.2 Data Processing

In this study, to measure temperature, four K-type thermocouples were installed in the condenser section, and four were placed in the evaporator section. Their values were calculated as follows:

$$T_c = \frac{T_{c1} + T_{c2} + T_{c3} + T_{c4}}{4} \tag{1}$$

$$T_e = \frac{T_{e1} + T_{e2} + T_{e3} + T_{e4}}{4} \tag{2}$$

The thermal resistance is defined as:

$$R = \frac{\Delta T}{Q} \tag{3}$$

And Q is defined as heat which PHP receives [49], while ΔT is calculated as:

$$\Delta T = T_e - T_c \tag{4}$$

Thermal efficiency of a solar panel is demonstrated as [50]:

$$\eta_x = \frac{\dot{m}C_p \int_{t_1}^{t_2} (T_o - T_x)dt}{A \int_{t_1}^{t_2} Gdt} \tag{5}$$

Hence, the electrical efficiency of solar panel is defined as the percentage of sunlight that a solar cell converts into usable electricity, calculated by Eq. (6) [51].

$$\eta_{el} = \frac{P_{out}}{P_{in}} = \frac{V_{mp}I_{mp}}{AG} \tag{6}$$

The amount of improvement of proposed system in terms of efficiency is defined as [52]:

$$\eta_b = \frac{\eta_{PHP-PV}}{\eta_{PV}} - 1 \tag{7}$$

2.3 Uncertainties

In experimental investigations, the accuracy of the gathered data is essential. Therefore, to evaluate this accuracy, an uncertainty analysis must be conducted. The uncertainty in the calculation of values is measured based on both direct and indirect data [53]. Measurement errors of the instruments and data acquisition errors are calculated and listed in Table 3.

Table 3: Uncertainty of parameters

Parameter	Uncertainty
T_a (°C)	±0.1
T_c (°C)	±0.1
T_e (°C)	±0.1
T_s (°C)	±0.1
G(W/m²)	±1
S_w (m/s)	±0.1
V_{OC} (V)	±0.05
I_{sc} (A)	±00.015

3 Results and Discussion

The temperature, power output, and efficiency of the solar panels were assessed. Tests were conducted on clear days, reflecting the climate of Mashhad, Iran. Additionally, two panels were used in the study: one was equipped with a 3D-PHP, while the other served as a reference panel.

3.1 Initial Conditions

Fig. 8 illustrates that both the ambient temperature and the solar panel temperature rise steadily until reaching their highest point at midday. After this peak, both temperatures begin to decline. Similarly, solar intensity follows a comparable trend, peaking at over 1120 W/m² around 11:30 local time, and dropping to a minimum of 750 W/m² (as shown in Fig. 9).
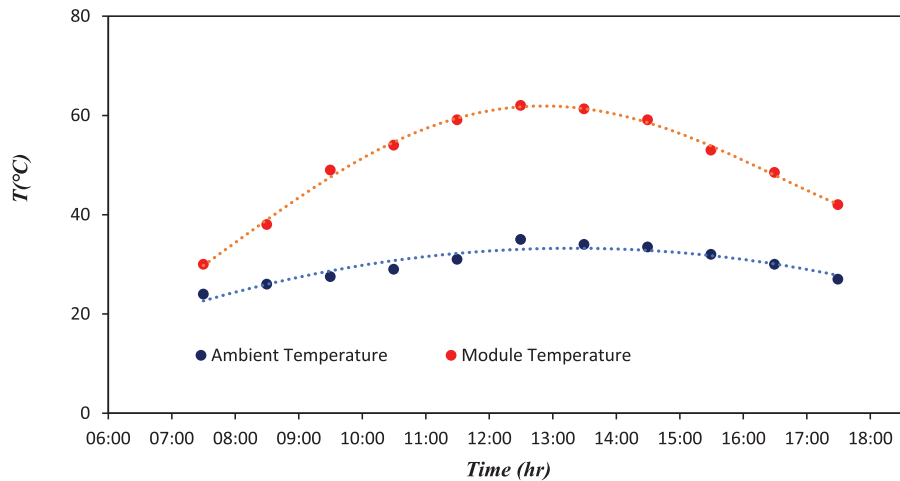
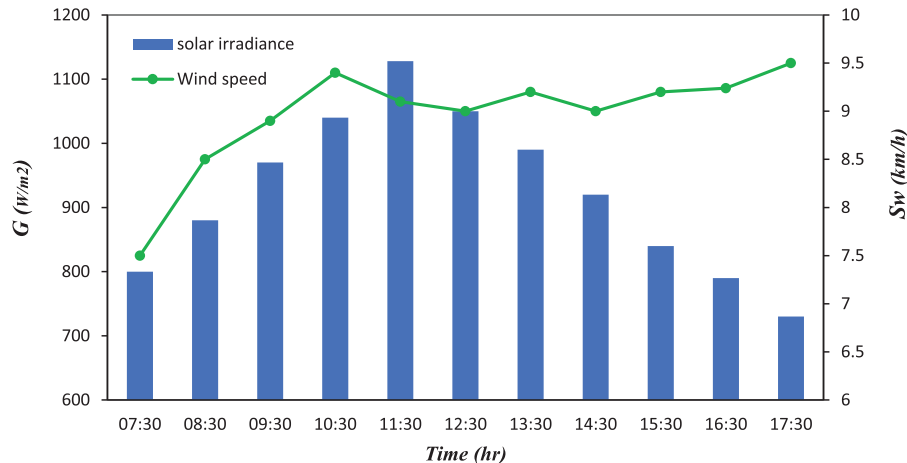**Figure 8:** Ambient temperature and solar panel temperature

Figure 9: Solar intensity and wind speed

Wind speed is a parameter that affects solar panel efficiency and PHP performance. Over time, the average value (as shown in Fig. 9) increases, reaching over 9 km/h by the end of the test.

Electrical efficiency is influenced by solar irradiance and panel temperature [54]. The more irradiance the panel receives, the higher its efficiency. Nonetheless, I_{sc} and V_{OC} exhibit quite the opposite behavior as the panel temperature changes (Fig. 10).

3.2 System Performance

Solar panels are responsible for capturing sunlight and converting it into electricity. The larger the area covered by solar panels, the better the chance of capturing the sun's energy. One of the parameters that strongly influences the efficiency of a solar panel is its angle of tilt with the horizon, which consequently affects the amount of solar radiation received; therefore, they need to be tilted at the optimal angle to achieve maximum efficiency [55]. The system was tested at a 30° tilt angle, which is the best angle for solar panels in Mashhad [56].
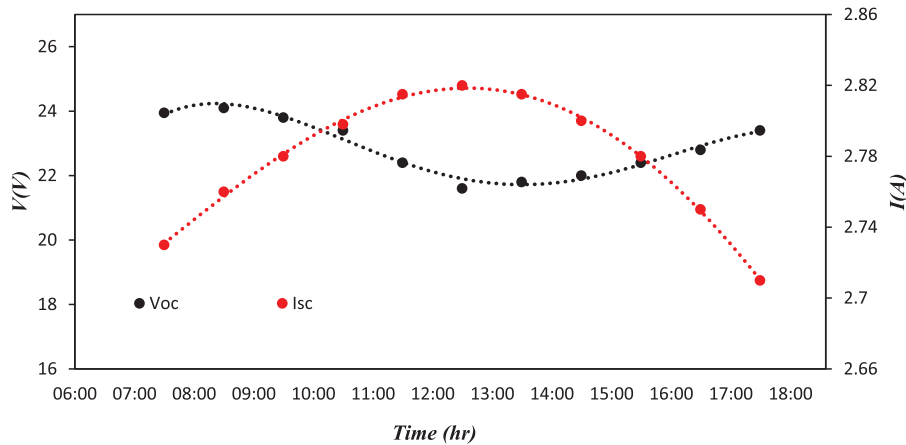
Figure 10: I_{sc} and V_{OC} behavior during the test

The amount of thermal resistance of the 3D-PHP for different coolants has been calculated. At lower heat transfer rates, conduction is the primary mode of heat transfer. However, at higher temperatures, the presence of nanoparticles increases the number of active nucleation sites in the evaporator, facilitating the boiling process in the PHP, which leads to better PHP performance. Using graphene oxide helps reduce the thermal resistance of the PHP; however, as the concentration increases, dynamic viscosity also increases, which impedes fluid movement in the tube and, as a result, deteriorates thermal performance. On the other hand, at higher temperatures, the working fluid moves more easily, which mitigates the impact of high dynamic viscosity. As demonstrated in Fig. 11, graphene oxide with a concentration of 0.2 gr/lit produces the best performance.
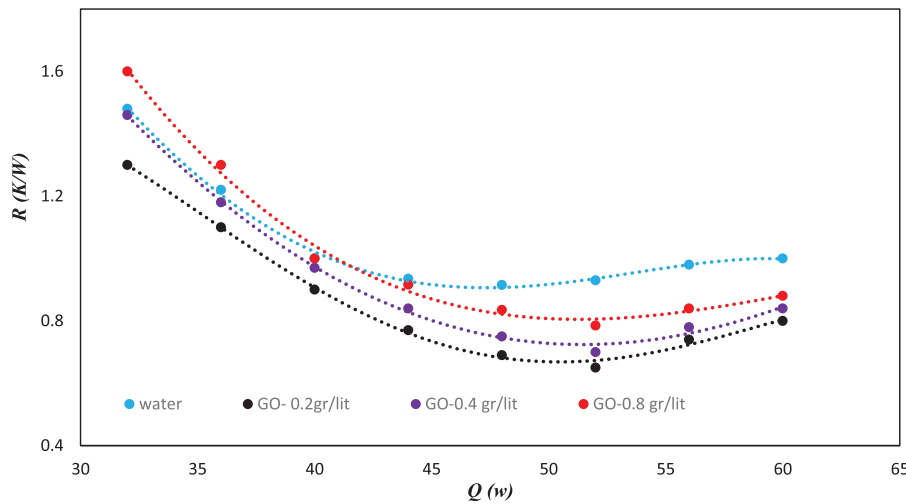
Figure 11: Thermal resistance *vs*. received heat

The maximum solar panel performance occurs at 25°C and above that it suffers loss due to high temperature which strongly affects it. As mentioned earlier, by increasing temperature (more than 25°C), PV power output decreases. The higher the PV cell temperature gets, the more it suffers in terms of performance. On the other hand, the difference in solar irradiance (SI) is not significant

enough to compensate for the negative effect of rising temperature. In other words, the negative impact of temperature rise outweighs the benefit of increased solar irradiance received by the cells. In this experiment maximum P_{out} is over 46 W, which is quite noticeable, when graphene oxide with the concentration of 0.2 gr/lit was employed as a coolant (Fig. 12).
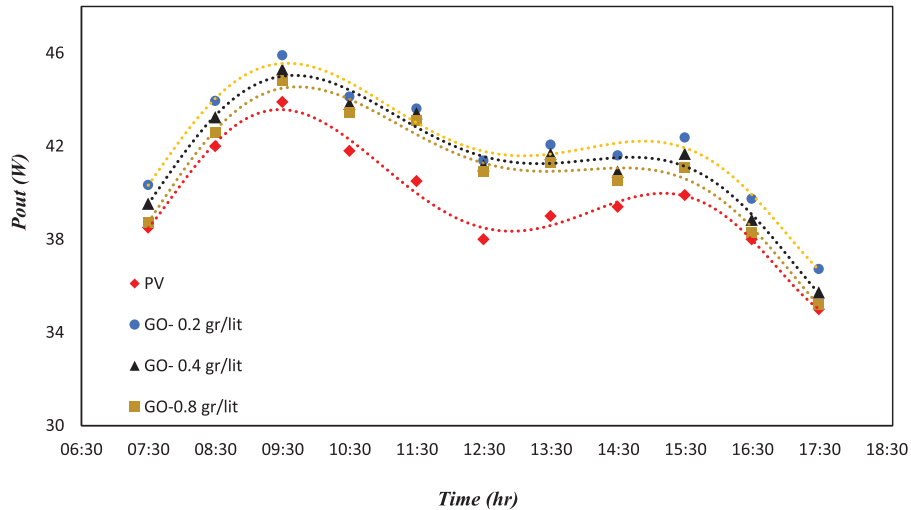

Figure 12: Effect of coolants on P_{out}

Since PV efficiency is highly sensitive to cell's temperature, in other words, negative impact of temperature rise outweighs solar irradiance the cells receive. On the other hand, using a PHP can significantly contribute to minimizing the loss, especially at higher temperatures. Furthermore, at the hottest time of the test, PHPs with different graphene oxide concentrations showed similar performance (Fig. 13).
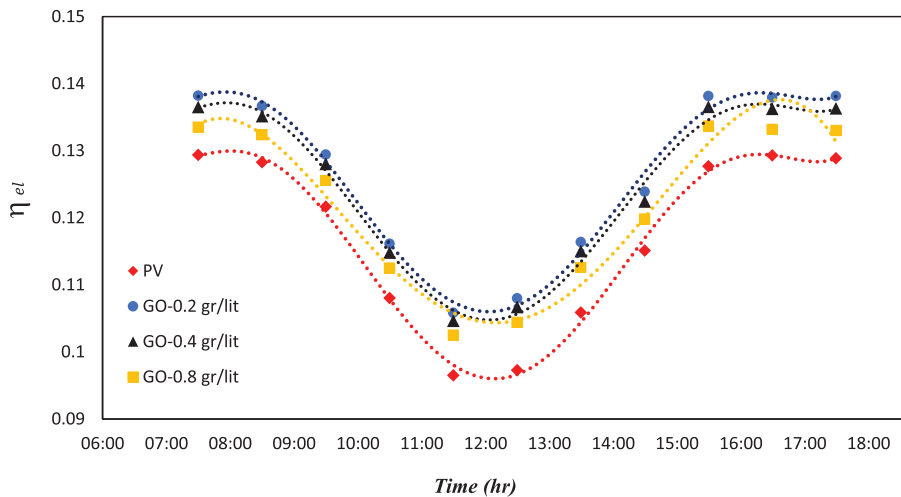

Figure 13: Effect of coolants on electrical efficiency

Fig. 14 demonstrates how varying concentrations of graphene oxide influence the enhancement of a solar panel's electrical efficiency. The data clearly show that the system reached peak performance with a coolant concentration of 0.2 gr/lit, particularly during the hottest part of the day.
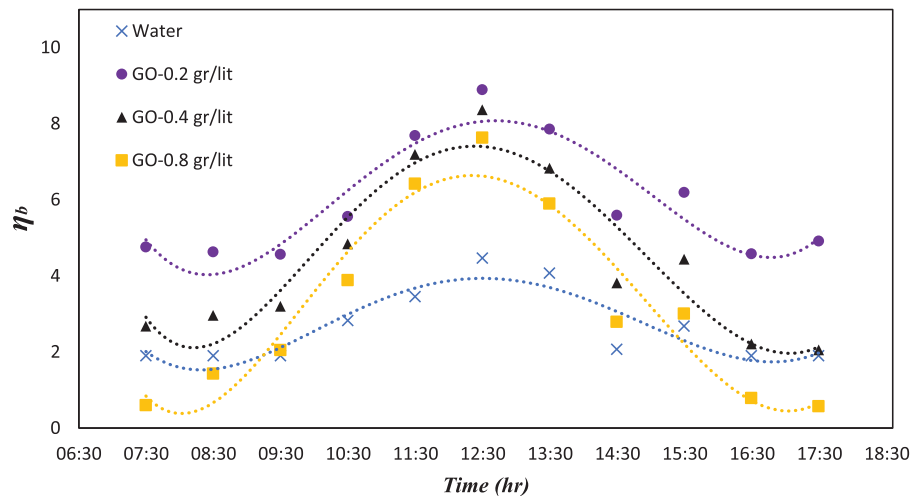
Figure 14: Electrical efficiency improvement with different coolants

4 Conclusions

The power output of solar panels is significantly influenced by the temperature of the cells, which decreases as the temperature increases. In this study, a new cooling method was implemented to improve the electrical efficiency of the solar panel. It was observed that at higher temperatures, nanoparticles increase the number of active nucleation sites in the evaporator, enhancing the boiling process and improving PHP performance. The experimental results reveal that using graphene oxide nanofluids at various concentrations effectively reduces thermal resistance, with the most notable reduction observed at a concentration of 0.2 gr/lit. This reduction in thermal resistance directly translates into increased electrical power output, thereby validating the efficacy of this cooling method. Furthermore, using a 3D pulsating heat pipe with nanofluid effectively lowered the temperature, leading to improvements in maximum power output of over 9%, 7%, and 6% for graphene oxide concentrations of 0.2, 0.4, and 0.8 gr/lit, respectively. The proposed cooling system is simple and cost-effective, requiring no external power sources like pumps, making it promising for industrial and residential rooftop applications. However, despite numerous studies, PV systems integrated with heat pipes, especially PHPs, have not yet been commercialized. Further investigation is needed to ensure the long-term reliability and performance of these systems in real-world conditions.

Author Contributions: The authors confirm contribution to the paper as follows: study conception and design: Mahyar Kargaran; data collection: Mahyar Kargaran, Hamid Reza Goshayeshi; analysis and interpretation of results: Mahyar Kargaran, Hamid Reza Goshayeshi, Ali Reza Alizadeh Jajarm; draft manuscript preparation: Mahyar Kargaran. All authors reviewed the results and approved the final version of the manuscript.

Availability of Data and Materials: The data are available from the corresponding author upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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