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STATE-OF-THE-ART REVIEW: NANOFLUIDS FOR PHOTOVOLTAIC THERMAL SYSTEMS

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ABSTRACT. High operating temperatures significantly impede the efficiency of photovoltaic (PV) cells. This review paper comprehensively examines the potential of nanofluids as a novel approach to mitigate this challenge and boost the PV systems' performance. We elucidate the fundamental principles governing nanofluid behavior and their thermophysical properties that contribute to higher heat transfer compared to conventional coolants. Subsequently, the integration of nanofluids within photovoltaic thermal systems is explored, with a detailed analysis of their impact on both electrical power generation and thermal output. Recent advancements in nanofluid research for PV cooling are critically reviewed, highlighting the documented improvements in total energy and exergy efficiencies. Additionally, we address the inherent challenges associated with nanofluid implementation, including stability, cost-effectiveness, and potential environmental considerations. Finally, the review offers valuable insights into future research directions and explores potential breakthroughs in nanofluid technology for optimized PV cooling and a consequential increase in overall PV system efficiency.

KEYWORDS: PV cooling, Nanofluid, PVT systems, energy, exergy, electrical conversion efficiency

1. INTRODUCTION

National energy consumption serves as a well-established metric for gauging economic development. Projections anticipate a substantial increase in energy demand by 2030, with a predicted 33% rise compared to 2010 [1-4]. This escalating demand presents a significant challenge, as conventional power plants fueled by fossil sources – responsible for 67% of global electricity production – are major contributors to greenhouse gas emissions and subsequent global warming [5-8]. In response to this critical issue, renewable energy sources (RESs) are rapidly emerging as a vital solution. Beyond their environmental benefits, RESs possess the capacity to meet the anticipated surge in energy demand. Moreover, they offer a sustainable approach to providing electricity in remote areas, functioning either independently or in flexible combinations with other energy sources [9, 10]. Solar radiation, encompassing both thermal and light components, can be harnessed using dedicated technologies. Solar collectors capture this energy for thermal applications, while photovoltaic panels convert it into electricity for power generation [11, 12]. Among RESs, photovoltaic (PV) systems have garnered widespread deployment due to their operational simplicity, increasingly cost-competitive implementation, and significant strides in both manufacturing processes and control technology [13]. A report released in 2023 shows that the global market for solar PV energy has grown significantly [14]. As illustrated in Fig. 1, The amount of solar power installed worldwide has skyrocketed, jumping from around 100 billion watts in 2012 to an estimated 1,185 billion watts by 2022. This remarkable growth path demands a corresponding rise in research efforts. This is crucial to guarantee continued technological advancements and knowledge acquisition in the solar energy field. While PV technology offers numerous advantages, it faces several hurdles to achieving peak performance. These challenges encompass limitations in electrical conversion efficiency [15], the accumulation of dust on cell surfaces, which can significantly impact efficiency [16-19]. However, the most critical factor influencing PV system output is cell temperature. A well-established body of research confirms a negative correlation between cell temperature and electrical conversion efficiency [20-24]. This phenomenon can be explained by energy conservation principles. A non-negligible portion of the impinging solar radiation on PV cells fails to be harnessed and converted into electrical energy. From a thermodynamic perspective, this unconverted energy transforms into heat, leading to a rise in cell temperature. Consequently, efficiency diminishes by almost 0.5% for every degree Celsius rise in cell temperature above standard test conditions [25, 26].

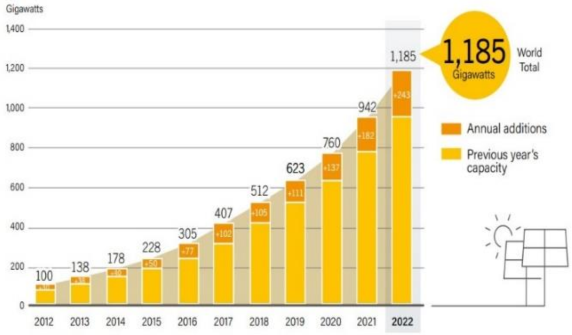

Fig. 1. Growth of global solar photovoltaic capacity through the last decade [14].

Therefore, maintaining high PV cell efficiency necessitates the implementation of appropriate cooling strategies. These strategies aim to enhance conversion efficiency by mitigating thermal rise and regulating cell temperature within optimal operating ranges. Extensive research efforts have been devoted to evaluating various passive and active cooling methods for PV systems, as documented by Nižetić et al. [27]. A particularly innovative approach lies in the utilization of hybrid PVT systems. PVT systems offer a two-fold benefit: enhanced electrical efficiency achieved through PV cell cooling, and the concurrent recovery of heat extracted as a valuable thermal energy resource applicable to diverse applications [28]. There are many cooling techniques that are used for PVT cooling such as air-cooling, water cooling, nanofluid cooling, and cooling with phase change materials (PCMs).

The paper aims to comprehensively analyze and integrate key findings from various research endeavors focused on the development of nanofluid cooling techniques and their impact on enhancing photovoltaic system performance.

The manuscript is structured into six distinct sections. After the introduction (Section 1). Section 2 delves into the fundamental operating principles of PV cells, explaining the electricity generation process and the impact of temperature on their performance. Section 3 focuses on the evaluation methods used to assess the performance of photovoltaic panels. A comprehensive overview of nano-enhanced PV cooling techniques is presented in Section 4, including detailed discussions on various system designs and their key findings. Section 5 indicates the limitations and challenges of using nanofluid in PV cooling. Finally, a conclusion and prospect recommendations are presented in Section 6.

2. UNDERSTANDING PHOTOVOLTAIC CELL OPERATION AND TEMPERATURE EFFECTS ON PERFORMANCE

2.1. ELECTRICITY GENERATION IN PV CELL

Solar radiation encompasses a vast spectrum of electromagnetic waves, ranging from short-wavelength ultraviolet waves to visible light and long-wavelength infrared waves. PV cells are constructed from semiconducting materials, such as silicon (Si), which exhibit low electrical conductivity. This limitation is overcome through a process called doping, where specific impurities are introduced into the semiconductor to enhance its ability to conduct electricity [29].

The semiconducting region of a PV cell typically comprises three layers. The top layer is formed by silicon doped with a small amount of pentavalent atom, such as phosphorus (P). These phosphorus atoms contribute five electrons, four of which form covalent bonds with neighboring silicon atoms. The remaining single, unbound electron allows for easy movement within the material, creating an N-type semiconductor. Conversely, the bottom layer consists of silicon doped with a trivalent atom, such as boron (B). Boron atoms possess only three electrons, forming bonds with three surrounding silicon atoms. This creates a vacancy, referred to as a hole, where a missing electron could reside. This deficiency allows for the movement of positive charges within the material, characterizing a P-type semiconductor.

When the N-type and P-type layers are brought into direct contact, a diffusion process occurs. free electrons from the N-type region, with a high concentration of electrons, diffuse across the junction to recombine with the holes in the P-type region, which has a high concentration of holes. This movement creates a depletion region at the junction between the two layers, where both free electrons and holes are depleted. As electrons migrate, the N-type region acquires a net positive charge at its boundary, while the P-type region develops a net negative charge. This charge separation establishes an electric field within the depletion region. When sunlight strikes the solar cell, the energy carried by photons can penetrate the layers and reach the depletion region. Inside this region, the photon's energy can boost electrons from their normal state (valence band) to a higher energy state (conduction band). This creates pairs of free-moving electrons and missing electrons (holes), which is the foundation for generating electricity in the solar cell. While electron-hole pair generation occurs within the depletion region, the pre-existing electric field in this zone exerts a directional force, separating the photogenerated carriers. This separation establishes a concentration gradient, characterized by an accumulation of holes in the P-type region and electrons in the N-type region. This non-equilibrium condition establishes a potential difference, or voltage, across the junction. When an external load is connected between these two regions, a direct current (DC) current known as photocurrent (I_PH) flows through the circuit in response to the potential difference. This photocurrent is the electrical output generated by the photovoltaic cell (I_PH) (Fig. 2), PV cell does not produce any voltage or current during darkness but generates a diode current (I_D) if it is connected to a voltage supply [29]. So, the net electrical current produced by the solar cell reflects the difference between the current generated by the absorption of light (photon current) and the inherent current flow within the diode structure (diode current), as follows:

$$I = I_{PH} - I_D = I_{PH} - I_o\left\{exp\left[\frac{e(V+IR_S)}{kTc}\right] - 1\right\} - \frac{V+IR_S}{R_{SH}} \qquad (1)$$

Where I_{PH} is the photocurrent, I_D is the diode or dark current, R_S is the series resistance, and R_{SH} is the shunt resistance.

In order to minimize the internal power dissipated in the cell, the cell shunt resistance should be much bigger compared to load resistance whereas the load resistance should be much higher than the series resistance. Therefore, if these two resistances are ignored the equation becomes:

$$I = I_{PH} - I_D = I_{PH} - I_o\left\{exp\left[\frac{eV}{kTc}\right] - 1\right\} \qquad (2)$$

Where k is Boltzmann's gas constant (J/k,) TC is the absolute temperature of the cell (K), e is the charge of electron (J/V), V is the voltage across the cell (V), and I_o is the dark saturation current which depends on temperature (A).

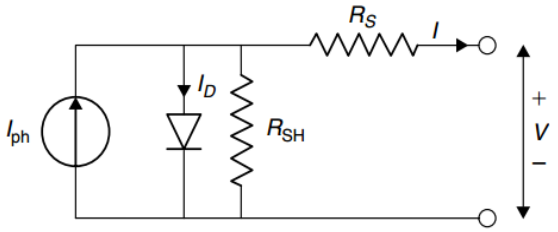

Fig. 2. A model of a single solar cell [29].

When the circuit of PV cell is an open circuit, the voltage become open circuit voltage (V_{oc}), which could be determined from:

$$V_{oc} = \frac{kT_C}{e} ln(\frac{I_{SC}}{I_O} + 1) \qquad (3)$$

Where I_{SC} is the short circuit current (A).

2.2. I-V CURVE CHARACTERISTICS

The influence of solar irradiance, the intensity of incident solar radiation, on crucial photovoltaic cell parameters such as open-circuit voltage and short-circuit current is a critical consideration. As depicted in Fig. 3, the relationship between I_{SC} and V_{oc} is demonstrably dependent on varying irradiance levels. It is evident from the figure that a direct correlation exists, with both I_{SC} and V_{oc} exhibiting an increase as solar irradiance strengthens [29].

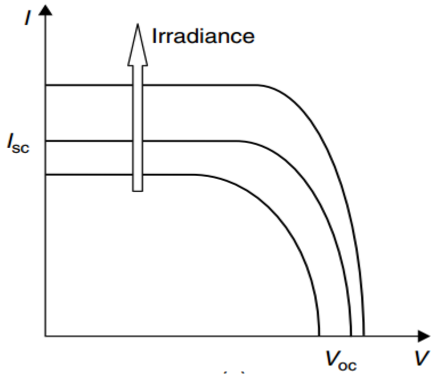

Fig. 3. The dependence of open-circuit voltage and short-circuit current on solar irradiance [29].

In order to evaluate the cell performance, it is necessary to measure cell characteristics curves. The most common curve for any PV cell is the I-V curve which represents a relation between PV cell current and the external applied voltage. It is noteworthy that a rise in PV cell surface temperature induces an increase in circuit resistance. This phenomenon impedes electron transport within the cell, directly impacting its open-circuit voltage (V_{oc}) through a reduction in available potential energy. Moreover, elevated operating temperatures can have deleterious consequences for the long-term stability and performance of the cell materials themselves. the linear decrease of V_{oc} with increasing cell temperature and the I_{SC} slightly increasing, so the PV cell efficiency drops with increasing the operating temperature of the cell as shown in Fig. 4.

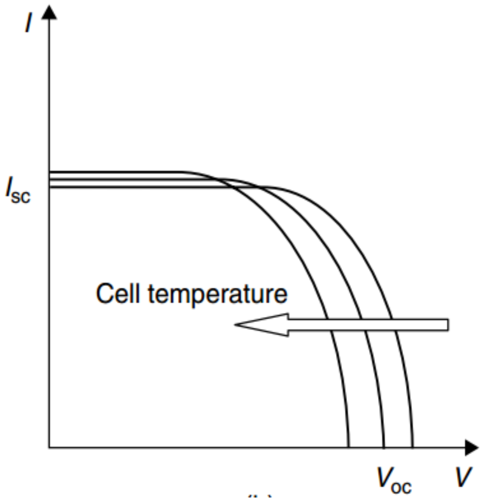

Fig. 4. Effect of cell temperature on PV characteristics [29].

The PV performance is influenced by the cell temperature, as evidenced by a decline in both electrical conversion efficiency and output voltage with rising temperatures (Fig. 5). This figure depicts a clear negative correlation between these parameters and cell surface temperature under constant solar radiation [30-32]. Consequently, cooling techniques are recognized as a critical strategy for enhancing PV cell performance.

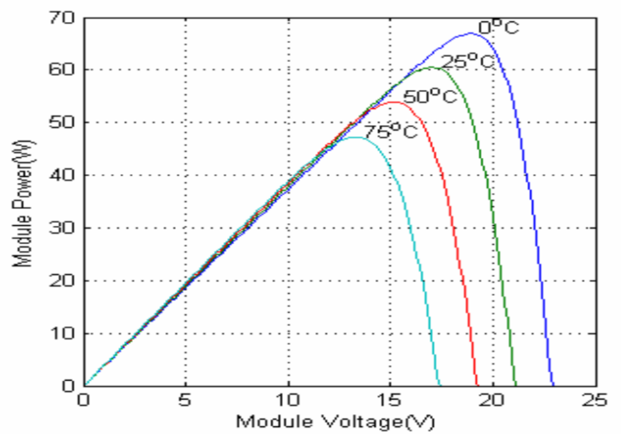

Fig. 5. PV curves with constant radiation (1 kw/ m^2) at various temperature [30].

3. PHOTOVOLTAIC PANELS PERFORMANCE EVALUATION

The core principle of photovoltaic cells lies in their ability to convert solar power into electrical power. Therefore, the input power to the panel (P_{in}), the peak output power (P_{max}), and the PV module electrical conversion efficiency (η_{elec}) is assessed from the following equations [33, 34].

$$P_{in} = I_t \times A \quad (4)$$

$$P_{max} = I_{mp} \times V_{mp} \quad (5)$$

$$\eta_{elec} = \frac{P_{max}}{P_{in}} \quad (6)$$

Where I_t is the incident solar radiation (W/m²), A is the aperture PV module area (m²), I_{mp} is the current at the maximum power (A), and V_{mp} is the voltage at the maximum power (V).

If the PV system is to be cooled using an absorber plate (thermal collector) then the system is called a photovoltaic/thermal system (PVT). then the amount of heat extracted from the PV module (Q_u) to the cooling fluid can be calculated through the next equation [35, 36].

$$Q_u = \dot{m}\, C_f\, (T_{out} - T_{in}) \quad (7)$$

Where the fluid flow rate is represented by $\dot{m}$ (kg/s), C_f indicates the specific heat of the working fluid (J/kg°C), and ($T_{out} - T_{in}$) is the temperature difference between the outlet and the inlet temperatures of the working fluid (K).

The thermal efficiency of a PVT system (η_{th}) can be determined by calculating the ratio between the PV panel recovered usable thermal energy output (Q_u) and the total incident solar power input (P_{in}). This calculation is depicted in the following equation [33, 37, 38].

$$\eta_{th} = \frac{\dot{m}\, C_{nf}\, (T_{out} - T_{in})}{I_t \times A} \quad (8)$$

Building upon the concept of thermal efficiency, the PVT system overall efficiency ($\eta_{overall}$) can be readily determined by employing the following equation. This equation calculates the overall efficiency by simply adding the electrical efficiency and thermal efficiency of the system [39, 40], as follows.

$$\eta_{overall} = \eta_{elec} + \eta_{th} \quad (9)$$

4. AN OVERVIEW OF NANOFLUID PV COOLING

4.1. THE INFLUENCE OF NANOPARTICLES ADDITION IN A FLUID

Conventional cooling liquids exhibit diminishing effectiveness in mitigating temperature rise within PV panels as operating temperatures increase. To address this challenge, research efforts have explored the utilization of additives to augment the thermal characteristics of these liquids, with a primary focus on improving heat capacity and thermal conductivity. These additives, crucial for maintaining a well-suspended mixture, require a suitably fine particle size for optimal performance within the liquid coolant [36].

Nanofluids, typically ranging from 1 to 100 nanometers in diameter, into a base fluid [41-45]. Common base fluids in these applications include water, ethylene glycol, and refrigerants [43, 44, 46]. Nanoparticles can be composed of various materials such as iron oxides, aluminum oxides, titanium oxides, zinc oxide, copper oxide, or even carbon nanotubes. The inclusion of these nanoparticles results in a substantial augmentation of the base fluid's thermal conductivity, enabling nanofluids to remove excess heat more effectively from solar energy systems [47, 48]. Consequently, nanofluid technology has emerged as a promising strategy for managing thermal loads and improving PV performance. The nanofluids efficacy is influenced by several factors, including the nanoparticles concentration within the base fluid, the nanoparticles shape and size, and the base fluid and the nanoparticles thermal conductivities.

4.2. NANO ON THE RISE: EXPLORING THE LATEST TRENDS IN NANOFLUID COOLING FOR SOLAR PANELS

Cooling PV panels with nanotechnology is a rapidly growing field of research attracting considerable interest from the scientific community. To gauge the extent of this growing trend, a bibliometric analysis was conducted utilizing VOS viewer software in conjunction with the Scopus database. Scopus was chosen due to its well-established reputation as one of the most comprehensive and longstanding citation databases in existence. The search strategy employed a combination of relevant keywords including "PV," "PV/T", "Cooling", and "nanofluid.". For pinpointing the latest breakthroughs, the search concentrated on articles published between 2020 and 2023, excluding review papers. As shown in Fig. 6, the blue cluster indicates a strong connection between the keywords nanofluid, solar power generation, energy efficiency, and phase change materials. Whereas a strong connection is made between these words (cooling, electrical efficiency, thermal efficiency, and copper oxide) in the yellow cluster. The purple cluster indicates a good connection between (photovoltaic thermals, aluminum oxide, silica, thermal efficiency, and computational fluid dynamics).

Fig. 7 visually depicts the evolution of research trends within the 2020-2023 timeframe. The yellow cluster represents publications with a focus on research conducted in 2023. The progressively lighter shades of purple (dark purple for 2020 and light blue for 2021) indicate a shift in research focus across the years. Notably, the green cluster highlights the emergence of nanofluid applications for photovoltaic panels in 2022.

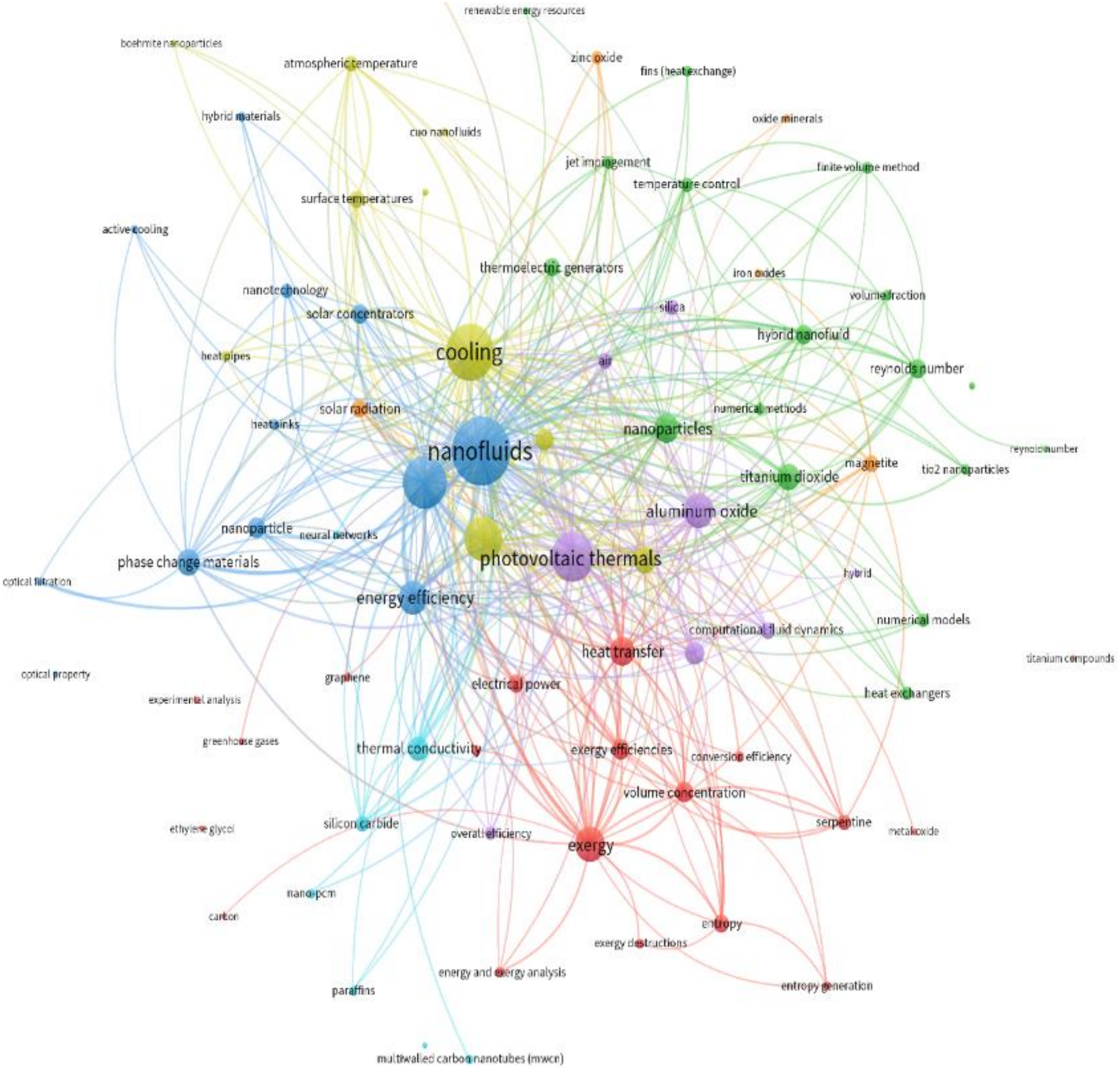

Fig. 6. Network visualization map

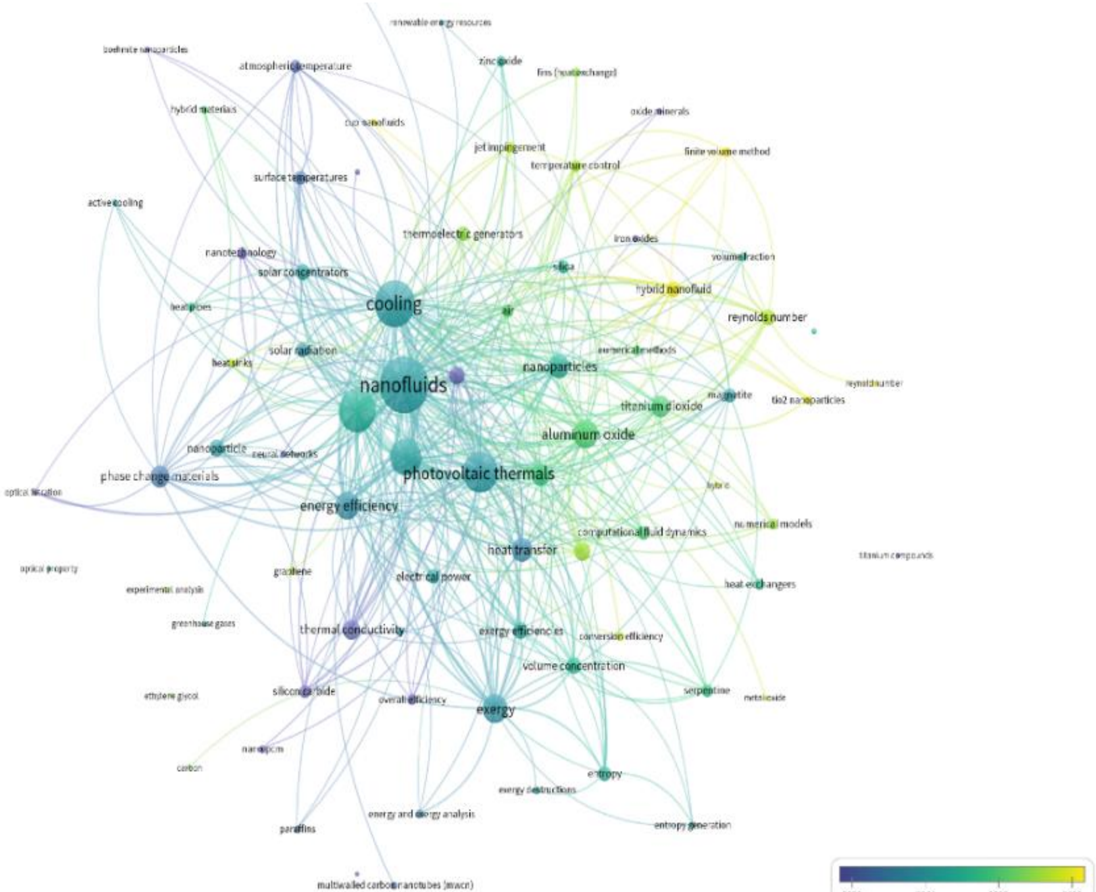

Fig. 7. Publications research focus between (2020-2023)

4.3. NANOFLUID PROPERTIES EVALUATION

The subsequent section delves into the governing equations employed to calculate the nanofluids thermophysical properties. These properties are determined according to the characteristics of both the suspended nanoparticles and the base fluid. The nanofluid-specific heat [49-53] and density [49-51] could be evaluated using following correlations.

$$C_{nf} = C_{np}(\phi) + C_{bf}\,(1 - \phi) \qquad (10)$$

$$\rho_{nf} = (\phi)\rho_{np} + (1 - \phi)\rho_{bf} \qquad (11)$$

Where ϕ as expressed by the next equation [54], indicating a particular amount of nanoparticles, measured as a volume fraction, present in the base fluid.

$$\phi = \frac{\frac{m_{np}}{\rho_{np}}}{\frac{m_{np}}{\rho_{np}}+\frac{m_{bf}}{\rho_{bf}}} \qquad (12)$$

The following equation allows us to calculate the dynamic viscosity of the nanofluid [36, 55].

$$\mu_{nanofluid} = \frac{\mu_{basefluid}}{(1-\phi)^{2.5}} \qquad (13)$$

The nanofluid thermal conductivity can be evaluated from the equation below [36].

$$k_{nanofluid} = \frac{[(k_{np}+k_{bf})+2\phi+(k_{np}-k_{bf})]}{[(k_{np}+2k_{bf})-\phi(k_{np}-k_{bf})]} \qquad (14)$$

4.4. EXPLORATION OF NANOFLUID COOLING TECHNIQUES FOR IMPROVED PHOTOVOLTAIC PERFORMANCE

Among the various cooling methods employed for PV panels, one technique utilizes a liquid coolant to absorb thermal energy from the panels. In most cases, this heat can be harnessed for other thermal applications within a PV/T system, as previously mentioned. Incorporating nanomaterials with superior thermal conductivity into coolants presents a significant advantage for keeping PV panels cooler during operation. Which in turn translates to a boost in the generated electrical power output. Conventional techniques for nanofluid-based cooling typically involve circulating the nanofluid through channels positioned beneath the PV panel. This heated nanofluid is then passed through a heat exchanger, enabling the extraction of thermal energy for other applications. Extensive research efforts have been undertaken to elucidate the key parameters influencing the efficacy of this cooling technique. These parameters include the nanofluid type, the concentration of nanoparticles within the NF, the NF flow rate, and the configuration of the cooling channels. Such investigations have been conducted using both experimental [56-58] and numerical methods [34, 59].

Sharaby et al. [60] investigated a nanofluid coolant made with MWCNT/ZnO mixed with water (see Fig. 8). Their experiment used a very low flow rate (0.0026 kg/s) and a dilute concentration (0.1 wt%). The results showed significant improvements: a 14.9 °C temperature decrease in the solar panel, a 17.2% increase in average power output compared to an uncooled panel, and thermal efficiency at peak of 51.3%. In terms of exergy efficiency, the nanofluid cooling led to a maximum overall efficiency increase of 27% compared to conventional system. The implementation of the nanofluid coolant resulted in a demonstrably reduced rate of entropy generation and exergy destruction within the system, translating to a 3.5% improvement in overall thermodynamic efficiency compared to the uncooled panel.

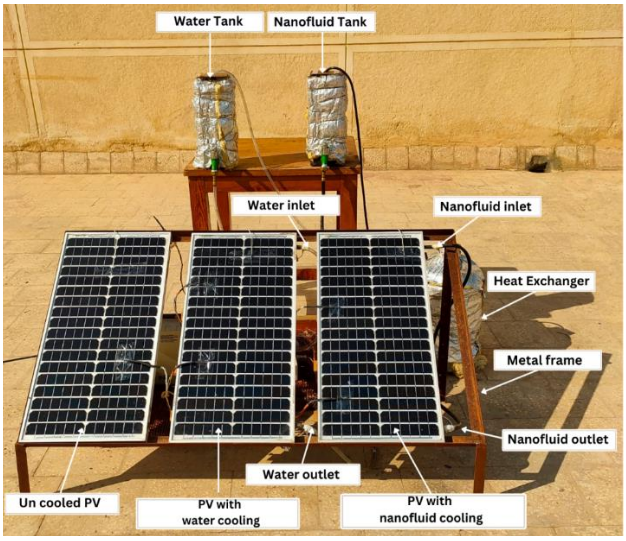

Fig. 8. Experimental setup [60]

Sathyamurthy et al. [61] explored the efficacy of NF and water for cooling PV panels, evaluating their impact on electrical efficiency compared to uncooled systems. The investigation incorporated a helical copper tube affixed to the posterior surface of the photovoltaic panel to facilitate the circulation of the cooling fluids. Tested fluids included pure water and a specific NF formulation. The findings revealed demonstrably superior cooling performance achieved by the NF compared to both water-based cooling and the absence of cooling altogether. This led to a meaningful increase in the output power.

A study is conducted by Menon et al. [62] to assess the impact of cooling of an unglazed PVT system. The experiment incorporated a water-based nanofluid containing copper oxide nanoparticles at a dilute concentration of 0.05 weight percent. The experiment yielded demonstrably superior results for the nanofluid cooling system. Employing a nanofluid coolant yielded a remarkable 35.67% enhancement in average electrical efficiency compared to the conventional water-cooling system, which exhibited a more modest increase of 12.32%. It is noteworthy that the nanofluid itself achieved an average electrical efficiency of 17.61%.

In a series of outdoor experiments, Abdallah et al. [63] evaluated the efficacy of MWCNT as a coolant for PV/T system. They meticulously controlled the MWCNT-NF flow rate at 1.2 L/min and systematically varied its concentration between 0 vol% and 0.3 vol%. An optimal concentration of 0.075 vol% was identified for maximizing system efficiency. At this concentration, the system achieved impressive peak efficiencies of 83.26% at noon and a commendable average efficiency of 61.23% throughout the day.

Employing a SWCNT nanofluid coolant at varying weight concentrations, Kazem et al. [64] assessed its efficacy in PVT system. Their investigation compared the resultant PVT system's performance to a standalone PV system. Statistical analysis revealed a significant improvement in the electrical efficiency of the PVT system, exceeding that of the standalone system by 25.2%. Furthermore, the PVT system exhibited a noteworthy 11.7% enhancement in electrical power generation. Additionally, the study demonstrated a substantial improvement in thermal management, with an average reduction in cell temperature of 18% over a 24-hour operational period.

In a comparative investigation, Alous et al. [65] assessed both the energetic and exergetic performance of PV/T collector using three coolant types: distilled water, GNP-water nanofluid (0.5 wt%), and MWCNT-water nanofluid (0.5 wt%). Their investigation identified MWCNT-water nanofluid as the most effective for overall energetic conversion, while the superior thermal energetic efficiency amongst the investigated coolants was achieved by GNP. This study highlights the potential of nanofluids to enhance the energetic PV/T performance. Furthermore, the research demonstrates a significant enhancement in total energetic effectiveness (57.2% and 63.1% for MWCNT and GNP nanofluids, respectively) when the PV module is integrated with the thermal unit. Similarly, noteworthy improvements in total exergetic efficiency (12.1% and 20.6% for the respective nanofluids) were observed.

Alktranee et al. [66] carried out a rigorous experimental investigation to assess the effectiveness of zirconium oxide (ZrO_2) nanoparticles suspended in deionized (DI) water as a coolant for PV modules. The experiment utilized ZrO_2 nanoparticles at varying volume concentrations (0.015%, 0.025%, and 0.0275%) dispersed within the DI water. The experimental setup is detailed in Fig. 9. The findings demonstrated a statistically significant reduction in PV module temperature (10.2°C) when employing a 0.0275 vol% ZrO_2 nanofluid coolant compared to the uncooled panel. Notably, DI water alone exhibited a more modest temperature decrease of 5.1°C. Moreover, the research revealed a compelling improvement in exergy efficiency (66.8% enhancement) achieved with the 0.0275 vol% ZrO_2 nanofluid. This enhancement was accompanied by a concomitant reduction in exergy losses (7%) and entropy generation (26%).

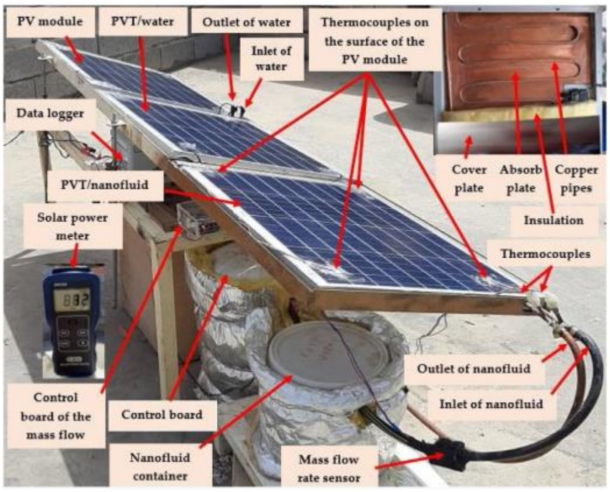

Fig. 9. Visual representation of the experimental system [66]

Employing a synergistic approach that incorporates both experimental and computational methods, Diwania et al. [67] investigated the efficacy of Cu and Al_2O_3 nanofluids as coolants in the PVT system. Their work definitively demonstrated the superior performance of Cu nanofluid relative to the Al_2O_3 counterpart. Notably, a low volume concentration of Cu nanoparticles (2%) resulted in significant enhancements. The Cu/water nanofluid exhibited a 4.98% improvement in average electrical efficiency, signifying an increase in power generation from the solar panels. Additionally, it achieved a 5.23% increase in average thermal efficiency, indicative of enhanced heat transfer within the PVT system.

Al-Waeli et al. [33] evaluated the silicon carbide (SiC) effectiveness as a coolant in PV/T systems, capitalizing on their superior thermophysical properties. Their experimental investigation employed a 3 wt% concentration of SiC nanoparticles dispersed in water as the coolant. The incorporation of these nanoparticles did introduce a modest increase in fluid viscosity (1.8%), it demonstrably enhanced thermal conductivity by 8.2% within the tested temperature range (25°C to 60°C). A visual representation of the test rig components is in Fig. 10. Notably, the electrical efficiency increased by 24.1%, while thermal efficiency exhibited a remarkable enhancement of 100.1%.

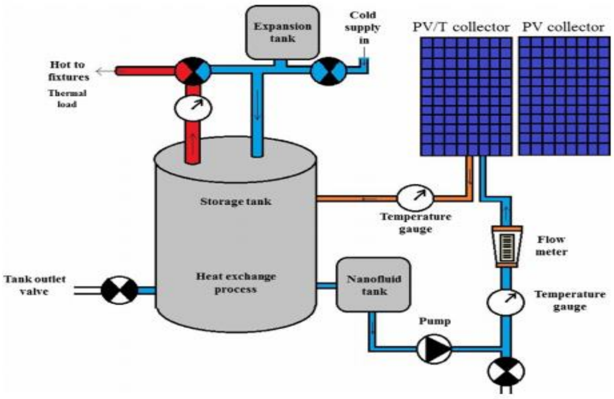

Fig. 10. The schematic diagram of the test rig [33]

Abdallah et al. [68] utilized an experimental methodology to assess the performance characteristics of a PVT system employing alumina-water nanofluid (Al_2O_3-water) as a coolant. Their investigation examined the varying impact of both flow rates and concentrations of the nanofluid. Fig. 11 shows the experimental setup. The findings revealed a significant enhancement in the PV/T system overall efficiency. Notably, a maximum increase of 56.1% was observed. Furthermore, under conditions of maximum solar radiation, the efficiency achieved a particularly impressive improvement of 74.14% when employing a 0.1% volume concentration of the nanofluid.

In an experimental study, Sangeetha et al. [69] evaluated the effects of nanofluids on the performance characteristics of a PVT system. Al_2O_3, CuO, and MWCNTs were dispersed in water at various volume fractions. The results showed a 19% reduction in cell temperature when employing MWCNTs and CuO.

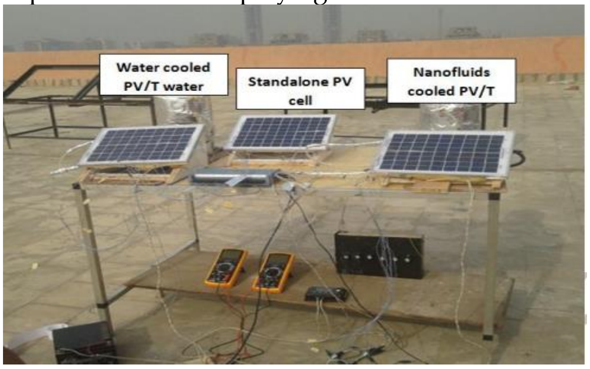

Fig. 11. Setup test rig implemented [68]

Rukman et al. [70] studied how well titanium oxide and MWCNTs suspended in water (nanofluids) cool PV/T systems. Their experiment (detailed in Fig. 12) used different concentrations of the nanofluids, various flow rates (0.012 to 0.0255 kg/s), and varying levels of solar radiation (500 to 900 W/m^2). The PV module's lowest recorded temperature was 66.9°C. This occurred when using 1.0 wt% titanium oxide nanofluid, under high solar radiation (900 W/m²) and a high flow rate (0.0255 kg/s). Interestingly, MWCNT nanofluid achieved a comparable temperature (67.8°C) under the same conditions.

Fig. 12. Setup of the experiment established [70]

In an experimental investigation, Al-Waeli et al. [71] evaluated the performance of a PVT system integrated with nano-PCM comprised of paraffin wax. Their findings revealed a significant improvement in the maximum PV efficiency. The nano-PCM PV/T system achieved a peak efficiency of 13.7%, representing a notable enhancement compared to the 7.1% efficiency observed in a conventional PV module (Fig. 13).

Finally, some nano-cooled PVT systems are summarized in Table 1.

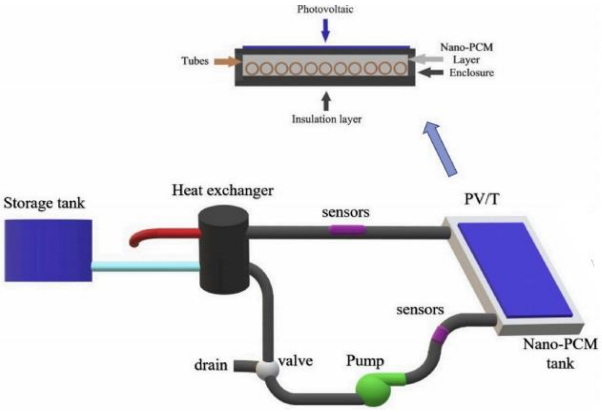

Fig. 13. 3D schematic model of the setup [71]

Table 1. A summary of nano-cooled PVT system

Author	Nanofluid Type	Key Findings
Sharaby et al. [60]	MWCNTs/ZnO	• A temperature drop of 14.9 °C of nano cooled PV module. • A significant enhancement of 17.2% in the average power output. • A meaningful increase in the maximum overall exergy of 27%. • Entropy generation and exergy destruction were demonstrably reduced by 3.5%
Sathyamurthy et al. [61]	MWCNTs/Al_2O_3	• The improvement in electrical efficiency on average was 8.2%. • The overall efficiency using nanofluids increased by 27.3%.
Menon et al. [62]	CuO	• By 23.7°C, the panel's temperature decreased. • Electrical efficiency on average increased to 17.61%. • Thermal efficiency of 71.17%.
Abdallah et al. [63]	MWCNTs	• System efficiency reached its peak at a nanofluid concentration of 0.075 vol%. • 83.26% was the overall system efficiency.
Kazem et al. [64]	SWCNT	• The PVT system achieved a 11.7% increase in electrical power generation. • A 18% reduction in the average cell temperature.
Alous et al. [65]	MWCNTs GNP	• Adding graphene flakes to the PV/T system's coolant boosted its overall and usable energy output by 63.1% and 20.6%, respectively.
Alktranee et al. [66]	ZrO_2	• Decrease in PV module temperature of 10.2°C with 0.0275 vol% concentration. • Efficiency of exergy increased by 66.8% with 0.0275 vol% concentration.

Author	Nanofluid Type	Key Findings
Diwania et al. [67]	Cu Al_2O_3	• copper concentration (2%) boosted thermal efficiency by 5.23% and electrical efficiency by 4.98%.
Al-Waeli et al. [33]	SiC	• A 24.1% gain in electrical efficiency was achieved. • The thermal efficiency demonstrated a noteworthy increase of 100.1%.
Abdallah et al. [68]	Al_2O_3	• a maximum increase of 56.1% in combined efficiency of the PV/T system.
Rukman et al. [70]	MWCNTs TiO_2	• The lowest temperature reached by the PV module was 66.9°C with titanium oxide nanofluid. • MWCNT-water nanofluid achieved a comparable temperature (67.8°C) under the same conditions.
Al-Waeli et al. [71]	Nano-PCM.	• PV's greatest efficiency was 13.7% as opposed to the 7.1% of a typical PV module.

5. THE LIMITATIONS AND CHALLENGES OF USING NANOFLUID IN PV COOLING

As discussed in the previous sections, the benefits of nanofluid implementation in PV cooling to enhance its thermoelectric performance and increase the PVT overall efficiency. Despite their complexity, nanofluids offer a significant benefit: improved heat transfer in working fluids, achieved by boosting thermal conductivity [72], increasing the density and specific heat of the fluid allowing it to transport large amounts of thermal energy [44], both electrical and thermal efficiencies are enhanced and protecting the material because of lowering the temperature of the absorber. But there are some limitations and challenges. These limitations include:

- The production and preparation of it represents a high-cost challenge.
- Stable nanofluids remain elusive for researchers to accomplish during preparation.
- The implementation of nanofluids may introduce challenges related to material compatibility. Specifically, erosion and corrosion of system components can occur [73].
- Utilizing nanofluids could result in high operational costs due to the increase in pumping work [44, 74-77].
- Numerous studies claim that nanoparticles could harm both the environment and human health [78, 79].

These challenges can be used to sum up the difficulties and potential directions for future research

6. CONCLUSIONS AND RECOMMENDATIONS

This review article comprehensively analyzes research efforts focused on enhancing PV panel performance through the application of nanotechnology-based cooling methodologies. Employing VOS viewer software, the authors conduct a bibliometric analysis to identify key research trends within the field. Additionally, the review delves into the governing equations utilized to determine material properties, both with and without the inclusion of nanoparticles, which are crucial for evaluating performance in PV and PV/T systems. Furthermore, detailed illustrations of the designed cooling systems are presented, accompanied by a concise summary of the main findings gleaned from the reviewed investigations. The key takeaways and conclusions derived from this analysis are subsequently presented:

- Nanofluids significantly reduced PV module temperature and boosted electrical & thermal efficiencies compared to water cooling or no cooling (up to 74% increase).
- The pumping power could be decreased with a lower mass flow rate with incorporating nanofluids like (MWCNTs/ZnO-water).
- Studies observed enhanced exergy efficiency (up to 66.8%).
- Nanofluid Active cooling methods are more efficient than passive cooling as the temperature reduction of PV cells in active cooling is more than passive cooling. But passive cooling is more economical because of lower operation cost.
- Adding nano particles to PCM can help to improve the phase change material thermal conductivity. So, absorbing more heat from

PV cell.

- This review underscores the significant potential of nanofluid-based cooling for PV systems. As a result, we can anticipate a surge in research efforts and advancements in this exciting field. These innovations will lead to the development of enhanced PV cooling systems using nanotechnology. This will ultimately broaden the applicability of PV panels by achieving superior conversion efficiency. To contribute to this growing field, the following research investigations are recommended:
- The investigation of the influence exerted by the integration of hybrid nanomaterials on the performance of PV or PV/T systems. This integration can occur either within PCMs or directly as nanofluid coolants.
- Computer modeling using computational fluid dynamics (CFD) can provide valuable insights into the heat transfer processes within nanofluid-based PVT systems.
- To assess the financial feasibility of nano cooled PVT systems, an economic analysis should be conducted. This analysis should prioritize calculating the payback period and considering the time value of money for various design options.

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