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A multi-method approach to investigating porous media cooling for enhanced thermal performance of photovoltaic panels: Exploring the effects of porosity, flow rates, channel design, and coolant types

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ABSTRACT

Elevated temperatures in photovoltaic (PV) panels adversely affect their efficiency and lifespan, necessitating effective cooling strategies. This study introduces a novel approach by integrating porous media within cooling channels to improve thermal management and energy output. While several cooling techniques have been explored, the integration of porous media with various coolants and their combined effects on cooling channel design, porosity size, flow rates, and porous media type have not been thoroughly investigated. This study fills this gap by conducting both experimental and numerical investigations to analyze key parameters, including porosity size (0.35–0.5), flow rates (1–4 L/min), cooling channel design, and coolant types (water, chemical alcohol, engine oil). Experimental tests were performed on 30-watt polycrystalline PV cells under real-world conditions, employing porous media such as gravel, marble, flint, and sandstone. The study was structured into three phases: (1) a comparative analysis of cooling performance with and without porous media, (2) optimization of porosity size for enhanced cooling, and (3) identification of optimal flow rates for system efficiency. The study identified optimal configurations, achieving up to 35.7 % temperature reduction and a 9.4 % power output increase with a porosity size of 0.35 and a flow rate of 2 L/min. ANSYS simulations validated experimental findings, with deviations in PV surface temperature below 3 %. Simulations further revealed that a tapered cooling channel design (5 mm inlet to 3 mm outlet), combined with water as the coolant and sandstone as the porous medium, reduced PV temperatures to 36.6 °C. This comprehensive analysis highlights the potential of porous media-integrated cooling systems to enhance PV panel performance and longevity.

1. Introduction

The impact of temperature on the performance of photovoltaic (PV) panels is a critical consideration in the field of solar energy. As the temperature rises, the efficiency and lifespan of PV panels are significantly affected. This is primarily due to the sensitivity of the materials used in PV cells to temperature changes [1]. When the temperature increases, the efficiency of PV panels generally decreases. Specifically, an increase in temperature results in a reduction of open-circuit voltage and an increase in short-circuit current—both of which are highly sensitive to temperature variations. For example, a study by Kassar et al. [2] found that the efficiency of a solar cell decreased from 21.3 % at 25 °C to 17.41 % at 70 °C. Similarly, Al-Ghezi et al. [3] reported an approximate efficiency drop of 0.586 % for every 1 °C increase in temperature.

The temperature-dependent behavior of PV cells can be attributed to the narrowing of the forbidden energy gap and the shifting of the Fermi energy level within the PV cell materials, as reported by Libra and Poulek [4]. The open-circuit voltage tends to decrease in a nearly linear pattern over a wide range of temperatures, while the short-circuit current increases, further contributing to the reduction in overall efficiency [5]. This temperature-induced decrease in voltage and increase in current results in lower power output, making temperature a crucial factor to consider in the design and operation of PV systems [6].

Moreover, higher temperatures accelerate the degradation of materials in PV cells, which leads to a decrease in their lifespan [7,8]. This accelerated degradation can result from both the physical breakdown of cell materials and potential damage to the protective encapsulation of the cells [9]. Over time, the accumulation of such thermal stress weakens the structural integrity of the PV panels, making them more

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Nomenclature, symbols, and abbreviations

AM	Air mass
CFD	Computational fluid dynamics
CPV	Concentrated PV
EVA	Ethyl vinyl acetate
HAWSC	Hybrid air-water solar collectors
LCOE	Levelized cost of energy
LCPV	Low concentrator PV
NFs	Nanofluids
NP	Nanoparticle
NP-PCMs	Nano-enhanced phase change materials
Nu	Nusselt number,
PCMs	Phase change materials
Pr	Prandtl number
PV	Photovoltaic
PVT	Photovoltaic thermal
Re	Reynolds number
ROI	Return on investment
STC	Standard test condition
A	Cross-sectional area of the channel (m^2)
Cp	Specific heat capacity (J/kg. °C)
$h_{c,f}$	convective heat transfer coefficient for water flowing through a channel filled with a porous medium (W/m²·K)
h_c	convective heat transfer coefficient (W/m²·K)
$h_{r,pm}$	radiation heat transfer coefficient from Tedlar to the porous medium (W/m²·K)
h_r	radiant heat transfer coefficient (W/m²·K)
k_g	thermal conductivity of the glass (W/m²·K)
$R_{c,r}$	combined thermal resistances for convection and radiation (°C/W)
R_{cond}	thermal resistance for conduction (°C/W)
R_{conv}	resistance for convection (°C/W)
R_{rad}	thermal resistances for radiation (°C/W)
T_a	temperature of the surrounding air (K)
T_f	temperature of the fluid (K)
T_g	temperature of the front surface of the solar panel (K)
k_g	thermal conductivity of glass (W/m². K)
ρ_f	fluid density (kg/m³)
C_P	Specific heat capacity (J/kg.K)
d_m	Diameter of the particle in (mm)
E	electrical power output from the solar panel (W)
G	Solar intensity (W/m²)
I	Current (A)
I_{sc}	Short-circuit current (A)
k	Thermal conductivity (W/m². K)
k	Thermal conductivity (W/m². K)
k_{EVA}	thermal conductivity of the EVA layer (W/m²·K)
k_T	thermal conductivity of the Tedlar (W/m²·K)
L	length of the cooling channel (m)
L_{EVA}	Thickness of the EVA layer (mm)
L_g	Thickness of the glass (mm)
L_T	Thickness of the Tedlar (mm)
P	Power (W)
P_{max}	Maximum power (W)
pm	Porous material
Q	Volume flow rate (L or m³) or heat transfer (W)
T	Temperature in °C, or K
T_f	temperature of the water
U	Uncertainty
U_1	overall heat transfer coefficient from the glass to the water (W/m²·K)
U_2	overall heat transfer coefficient from the glass to the bottom Tedlar (W/m²·K)
$U_{c,r}$	coefficient of heat transfer between the PV cell and the surrounding environment (W/m²·K)
V	Voltage (volt)
V	velocity of the surrounding air around the PV cells (m/s)
V_{oc}	Open-circuit voltage (volt)
w	Width of the cooling channel (m)
α	absorbance
ε	emissivity
ρ	Density in kg/m³
σ	Stefan-Boltzmann constant
Φ	Porosity of the material
$\forall_f$	Volume of the fluid (or water) that interacts with the material, in liters (L)
$\forall_t$	Total volume of the material, in liters (L)
$\frac{\partial p}{\partial x}$	pressure gradient in the x direction
$\frac{\partial u}{\partial x}, \frac{\partial v}{\partial y}, \frac{\partial w}{\partial z}$	rate of change of velocity in the x, y, and z directions

susceptible to failure. The degradation of performance and the reduction in lifespan due to elevated temperatures are of particular concern in regions with high ambient temperatures, where PV panels may frequently operate outside of their optimal temperature range [10,11]. In such environments, PV systems may experience a significant loss in efficiency, which can directly impact on the expected energy output and, in turn, the financial viability of solar energy projects [12]. This inefficiency poses a financial risk, as the return on investment (ROI) for solar projects may fall meet of expectations [13].

Addressing the challenges posed by high temperatures requires innovative approaches in PV system design. To mitigate the adverse effects of elevated temperatures, careful selection of materials and the incorporation of effective cooling mechanisms are essential. Researchers emphasize the need for designs that can withstand higher temperatures without significant loss of efficiency. These solutions may include advanced materials with better thermal stability or the integration of active or passive cooling systems to maintain optimal operating conditions.

Several technologies have been developed to address these challenges, including phase change materials (PCMs), heat sinks, water- and air-based cooling systems, thermoelectric cooling, and passive cooling techniques [14–16]. PCMs, for instance, help stabilize the temperature of PV panels by absorbing excess heat during peak sunlight hours and releasing it when temperatures drop [17]. This method has been shown to reduce panel temperatures by up to 18 °C, resulting in a 10.89 % increase in electricity generation [18]. The incorporation of nano-enhanced PCMs (NP-PCMs), which include materials such as silver, copper, zinc ..etc., further improves thermal conductivity and efficiency [19]. NP-PCMs have demonstrated a temperature reduction of 10.04 °C and an efficiency improvement of 12.15 % [20]. Integrating heat sinks with PCMs can further enhance the cooling effect. For example, a system using a latent heat storage unit with fins reduced temperature by 17.93 % and increased output power by 13.93 % [21].

Another strategy, Water- and air-based cooling systems involve circulating water or air over the PV panels to dissipate heat. These methods are effective but may require additional infrastructure and maintenance [22]. Thermoelectric cooling, which uses thermoelectric modules to transfer heat away from the panels, offers a promising solution with significant improvements in energy efficiency and a positive environmental impact [23–25]. Passive cooling methods such as radiative cooling, evaporative cooling, and material coating reduce temperatures without the need for external energy sources. These techniques are cost-effective and environmentally friendly [26].

Numerous studies have explored various cooling strategies. Table 1. provides a detailed and holistic comparison of PV cooling strategies [27–31]. Idoko et al. [32] investigated several cooling methods, including conductive, air-passive, and water-passive techniques, to improve the performance and efficiency of PV systems. Their study showed a significant improvement, with a 3 % increase in efficiency and a 20.96 W increase in power output. In a study by Yogesh et al. [33], the power output of PV panels utilizing semi-transparent PV cells with a solar chimney was analyzed. The study found that system efficiency was influenced by radiation intensity and structural variables, with each intensity level exhibiting an optimal packing factor that enhanced power output. Alizadeh et al. [34] used numerical methods to assess PV cooling through one-turn pulsating heat pipes, observing an 18 % increase in power output compared to non-cooled conditions. Jakhar et al. [35] used an earth-water heat exchanger in PV cooling models, finding higher outlet temperatures with increased flow rates.

The use of nanofluids (NFs) for cooling PV systems has shown promise, as demonstrated in studies by Mahdi et al. [36] developed a low-complexity cooling system to improve the performance of Photovoltaic Thermal (PVT) systems integrated with hybrid air-water solar collectors (HAWSC). The modified system, incorporating PCM, porous media, and MWCNT-water NF, reduced the PV panel surface temperature by 28 °C (compared to 22 °C without NF). It achieved improvements in overall efficiency (16.49 % vs. 12.80 %), total thermal efficiency (56.25 % vs. 43.16 %), and electrical efficiency (93.64 % vs. 79.90 %) compared to the traditional system. Additionally, the modified system showed a total thermal energy gain of 302.72 W, exergy efficiency of 14.32 %, a levelized cost of energy (LCOE) of 0.043 $/kWh, a payback period of 4.36 years, and a CO_2 mitigation of 36.55 tons. Al-Waeli et al. reported significant efficiency improvements in PV thermal systems by incorporating SiC NF. Similarly, Castanheira et al. [37] simulated a cooling system for PV plants in Portugal, noting a 12 % increase in energy production with the implementation of cooling systems. Ebaid et al. [38] investigated the cooling of PV systems using TiO_2 and Al_2O_3-based NF mixtures, observing enhanced power output and efficiency. Yazdanifard and Ameri [39] reviewed various strategies for improving the energetics of PV thermal systems, highlighting the use of NFs and optical filters as particularly effective in enhancing the energy efficiency of PV systems. Furthermore, Said et al. [40] investigated the effects of NFs on cooling methods for PV panels and emphasized the significant impact of high surface temperatures on PV efficiency. Khanafer and Vafai [41] reviewed NFs in PV cooling systems, noting efficiency improvements with different nanofluid applications. Bijjargi et al. [33] found active cooling reduced back surface temperatures, enhancing system efficiency. Nižetić et al. [42] reviewed active cooling techniques for PV panels, focusing on air, water, and NFs as coolants. Water-based cooling showed the highest performance boost, improving PV efficiency by 10–20 %, but economic viability remains limited, with the LCOE for a 30 kW PV system ranging from 0.096 €/kWh to 0.159 €/kWh. Environmental analysis found air-based cooling most harmful, with greater global warming and acidification impacts. Alami [43] studied a passive cooling technique using a synthetic clay layer with evaporative water film to reduce PV module temperatures. This approach proved technically feasible, achieving up to 19.4 % higher output voltage and 19.1 % increased power. Al-Waeli et al. [44]

Table 1
Comprehensive comparison of current PV cooling strategies.

Cooling Strategy	Advantages	Drawbacks	Typical Applications	Efficiency Improvement	Environmental Impact
Air-based Cooling	Simple, cost-effective, easy to implement, and can use natural or forced convection.	Limited cooling capacity, highly dependent on ambient temperature, and may require additional components like cooling fins for better efficiency.	Small-scale residential PV systems, low-heat environments.	5–10 %	Low environmental impact; uses ambient air, no consumables required.
Phase Change Material (PCM) Cooling	High thermal storage capacity, stable performance over time, help regulate PV cell temperatures.	Limited to specific temperature ranges, expensive materials, and less effective in high-temperature environments.	Medium-scale PV systems, regions with moderate temperature fluctuations.	10–15 %	Moderate impact; depends on PCM material (some may not be biodegradable or recyclable).
Heat Pipe Cooling	High efficiency, no moving parts, self-contained system, durable, reduces heat effectively.	High initial cost, complex design, space requirements for installation.	Industrial PV systems, high-heat environments.	15–20 %	Low to moderate impact; durable and long-lasting but requires manufacturing resources.
Micro-channel Cooling	High heat transfer rates, compact design, efficient heat removal, suitable for high heat flux conditions.	Complexity in design, expensive manufacturing, risk of clogging, limited scalability.	High-performance PV systems, concentrated solar power (CSP) applications.	20–25 %	Moderate impact; efficient but requires precise manufacturing and maintenance.
Nanofluids-based Cooling	Improved thermal conductivity, more efficient heat transfer than water alone, can be used in various cooling methods (e.g., air or water cooling).	Higher cost, complexity in preparation and maintenance, possible sedimentation of nanoparticles.	Advanced PV systems, research applications, high-efficiency solar farms.	25–30 %	Moderate to high impact; nanoparticles may pose environmental risks if not managed properly.
Immersion Cooling	Highly effective in reducing temperature (over 20 °C reduction), can handle high heat loads, directly cools PV cells.	Issues with radiation refraction, challenges with reaching solar cells, significant water evaporation.	Large-scale solar farms, high-heat environments, experimental PV systems.	30–35 %	High impact; significant water usage and evaporation, potential environmental concerns.
Spray Cooling	Quick cooling, efficient for short bursts of high heat.	Requires large water volumes, significant evaporation loss, might be impractical for continuous use.	Temporary or intermittent cooling, small-scale PV systems in hot climates.	10–15 %	High impact; high water consumption and evaporation, not sustainable in arid regions.
Gaseous Cooling	Suitable for high-temperature and high-pressure environments, works in harsh conditions.	Low heat capacity, requires substantial energy to circulate, not suitable for lower temperature conditions.	Industrial applications, high-temperature PV systems, specialized environments.	5–10 %	Moderate impact; energy-intensive and may involve greenhouse gas emissions.
Oil-based Cooling	Can operate over a wide temperature range, cost-effective in certain conditions.	Flammability risk, more difficult to manage than water-based systems, issues with handling and disposal.	Industrial PV systems, high-temperature environments, specialized applications.	10–15 %	High impact; potential for oil spills and environmental contamination.

evaluated a water-SiC NF (3 wt%) as a coolant for PVT systems. This NF improved electrical efficiency by 24.1 % and thermal efficiency by 100.19 % over water alone, resulting in an overall system efficiency of 88.9 %. Masalha et al. [31] investigated a NF cooling system for PV panels, utilizing a back-surface cooling channel with Al_2O_3 NF at concentrations of 0.05 wt.% and 0.1 wt.% and flow rates between 1 and 2 L/min. The study found that the optimal setup—0.1 wt.% Al_2O_3 at 2 L/min—lowered PV module temperatures by 38 % and increased power output by around 9.6 %. Abdallah et al. [45] studied a PV/T system using Al_2O_3 nanofluid, finding that a 0.1 % concentration improved thermal and electrical performance by 74 % and 56 %, respectively. The optimal flow rate for maximum efficiency was 1.2 L/min. Golzari et al. [46] found that applying a corona wind with high voltage in a PVT system boosts heat transfer by creating additional airflow patterns, improving thermal efficiency by up to 28.9 %. At 11 kV, the heat transfer coefficient increased by 65 %. Gilmore et al. [47] investigated the use of microchannels for cooling concentrated PV cells, demonstrating significant enhancements in cooling efficiency. Nadda et al. [48] reviewed the use of jet impingement to enhance heat transfer in solar PV and air collectors. They discussed experimental, CFD, and modeling techniques, highlighting the impact of geometric parameters on heat transfer efficiency.

Similarly, Bahaidarah et al. [49] explored jet impingement cooling for PV systems in the hot climate of Dhahran, Middle East. Experimental and numerical evaluations were conducted on both uncooled and jet-cooled PV systems. Results showed that jet cooling significantly reduced cell temperatures, enhancing power output by up to 51.6 % in June and 49.6 % in December, with efficiency improvements of up to 82.6 %. Peng et al. [50] investigated the impact of surface temperature on solar PV efficiency and found that cooling systems can improve efficiency by up to 47 %. Their study proposed a cooling setup for residential solar PV, demonstrating a 35 % increase in PV output efficiency and a 107 % rise in total system energy efficiency. The cooling system also reduced the payback time from 15 years to 12.1 years. Sathe et al. [51] assessed a range of PV thermal systems, highlighting significant advancements in PV cooling technologies over the past decade that have substantially enhanced system efficiency. Shukla et al. [52] reviewed various cooling techniques for solar PV cells, which absorb significant solar radiation but often suffer from temperature increases that reduce efficiency and lifespan. They discussed methods such as natural and forced air cooling, hydraulic cooling, heat pipe cooling, PCMs, and thermoelectric cooling. The review emphasizes the importance of cost-effective cooling solutions, particularly for large-scale PV installations, and stresses the need for temperature control to improve heat conversion processes. Similarly, Siecker et al. [53] examined cooling methods for PV panels, including hybrid PVT systems, thermoelectric cooling, PCMs, and water immersion. They concluded that effective cooling should maintain stable surface temperatures, be reliable, and ideally utilize extracted heat to improve system efficiency. Syafiqah et al. [54] explored the use of air- and water-cooling systems for PV panels, as the efficiency of PV cells decreases with rising temperatures. They found that without a cooling system, the PV panel reached a temperature of 66.3 °C. Using air- and water-cooling systems reduced the temperature by 19.2 % and 53.2 %, respectively. Al-Masalha et al. [55] examined hybrid cooling systems that integrate water sprinklers and air fans, demonstrating their effectiveness in lowering PV module surface temperatures and enhancing overall performance. Rostami et al. [56] investigated the use of high-frequency ultrasound to enhance the cooling performance of PV modules, using atomized CuO NF and pure water as coolants. The study found that atomized NF significantly outperformed pure water in cooling efficiency and power generation. Increasing the NF concentration further improved cooling and power output. Atomizing 0.8 (w/v) NF reduced the module's average surface temperature by 57.25 % and boosted the maximum power by 51.1 % compared to a system without cooling. Wu et al. [57] analyzed a water-cooled PVT system using a 3D numerical model, focusing on factors like mass flow rate and cooling channel height. They found better heat transfer on the bottom surface of the cooling channel and identified optimal system performance at a mass flow rate of 0.003 kg/s and a cooling channel height of 5 mm. Zilli et al. [58] evaluated the impact of a water-cooling sprinkler system on PV modules, monitoring voltage, current, power, and efficiency. The study compared three cooling conditions: intermittent, none, and continuous cooling during peak hours. Results showed that cooling increased power and efficiency by 12.26 % and 12.17 % under high irradiation, and 8.48 % and 9.09 % under low irradiation. Schiro et al. [59] investigated the addition of a water-based cooling system to PV units without altering their structure. Both steady-state and dynamic models were developed to assess the thermal behavior and optimize cooling performance. The results showed that the cooling system improves energy balance, with efficiency dependent on factors like pump head and weather conditions. Hasanuzzaman et al. [60] stated that passive cooling systems reduce PV module temperature by 6–20 °C, enhancing efficiency by up to 15.5 %, while active systems achieve a 30 °C reduction and up to 22 % efficiency improvement. Jakhar et al. [61] reviewed various cooling technologies for concentrated PV (CPV) systems, including heat pipes, liquid immersion, microchannels, and hybrid CPV/T systems. The study emphasized that cooling systems should be efficient, reliable, and cost-effective, with the choice depending on location and application. The study concluded that while several cooling methods show potential, experimental work is needed to identify the most suitable technology for specific uses. Masalha et al. [62] investigated cooling processes for PV panels using porous media (gravel) with varying porosities to reduce back surface temperature and improve performance. The study tested different porosities and flow rates, finding that a porosity of 0.35 and a flow rate of 3 L/min reduced surface temperature by 35.7 % and increased power output by 9.4 %. The study identified key factors such as Nusselt number, Reynolds number, and porosity affecting heat transfer and pressure drop. Al-Oqool et al. [63] investigated the application of porous marble as a novel cooling medium for PV modules, revealing a notable enhancement in energy conversion efficiency due to improved heat dissipation from the module surface. Mojumder et al. [64] proposed an air-type single-pass PVT system with rectangular fins for enhanced heat dissipation. The study analyzed the performance under varying conditions, including fin numbers, mass flow rates, and solar radiation. Maximum thermal and PV efficiencies of 56.19 % and 13.75 %, respectively, were achieved with four fins, a mass flow rate of 0.14 kg/s, and 700 W/m² of solar radiation. Elminshawy et al. [65] examined a low concentrator PV (LCPV) with nanofluid-based cooling channels, using water and Al_2O_3/water NFs at varying concentrations. The 3 %-Al_2O_3 nanofluid reduced the LCPV temperature by 16.47 °C, keeping it below 45 °C, and improved electrical output by 24.02 % compared to an uncooled module. The results showed that increasing the nanoparticle concentration enhanced both electrical and thermal efficiencies, with the highest performance achieved using the 3 %-Al_2O_3 NF. Sheikh et al. [66] investigated a novel approach to improving PV efficiency by using multi-layered PCMs for cooling. The integration of organic PCMs and metallic PCMs reduced PV cell temperatures by 59.6 °C, enhancing performance by 35.8 %. The study found that a 15:85 thickness ratio between metallic PCM and organic PCM significantly improved PV efficiency under high solar radiation and ambient temperatures. Saeed et al. [67] compared two passive heat transfer methods, PCM and rectangular fins, to improve the efficiency of PV panels. The results showed that PCM reduced the panel's surface temperature by 11–15 %, enhancing efficiency by 2.1 %, while fins reduced the temperature by 7–13 %, improving efficiency by 1.7 %. The output power increased by 16 W with PCM and 10 W with fins. Attia et al. [68] investigated the effectiveness of active cooling systems for PV stations in Algeria. The study analyzed regions with different climates: Algiers, Djelfa, and Ghardaïa. The results showed that incorporating active cooling systems improved electrical power generation by 15.1 %, 17.8 %, and 19.7 %, respectively, with optimal strategies boosting net output by 7.65 %, 7.13 %, and 4.91 %. Elavarasan et al. [69] proposed a novel passive cooling system combining PCM, fins, and still water to enhance the efficiency of PV panels. The system utilizes the latent heat of fusion and evaporation to lower panel temperatures, resulting in an 8.57 % average efficiency improvement. The cooled panel's temperature stayed below 50 °C, compared to 73 °C for the uncooled panel. This approach offers significant energy savings, with an estimated 367 MWh annually and reduced CO_2 emissions.

Despite extensive research on cooling techniques for PV panels, significant gaps remain in understanding the combined effects of integrating porous media with various coolants and cooling channel designs. Previous studies have primarily focused on standalone cooling methods, such as air or water cooling, without thoroughly exploring the synergistic potential of porous media in enhancing thermal management. Specifically, the influence of key parameters—such as porosity size, flow rate, coolant type, and porous media material—on PV performance has not been systematically investigated. Additionally, there is a lack of comprehensive studies that combine experimental and numerical approaches to optimize these parameters under real-world conditions. This study addresses these gaps by providing a detailed analysis of porous media-integrated cooling systems, offering insights into optimal configurations for improving PV efficiency and longevity. Accordingly, the main objectives of this study are as follows:

- To investigate the impact of porous media cooling techniques on reducing PV panel temperatures and enhancing power output under real-world operating conditions.
- To examine the influence of key parameters, including porosity size (0.35–0.5), flow rates (1–4 L/min), and coolant types (water, chemical alcohol, engine oil), on the thermal and electrical performance of PV panels.
- To identify optimal cooling strategies through a combination of experimental tests and numerical simulations (using ANSYS software), ensuring significant improvements in PV panel efficiency and durability.
- To evaluate the effectiveness of different porous media materials (gravel, marble, flint, sandstone) and cooling channel designs in achieving maximum temperature reduction and power output enhancement.

This study introduces a novel, multi-faceted approach by combining both experimental and numerical investigations to explore the integration of porous media within cooling systems for PV panels. The novelty of this work stands on its comprehensive investigation of multiple variables such as porosity size, flow rates, coolant types, cooling channel design, and porous material types (gravel, marble, flint, and sandstone). Additionally, the study uses both real-world experimental testing and advanced ANSYS simulations to provide a robust and validated understanding of the cooling strategies. Finally, the research presents optimal cooling conditions, achieving a substantial reduction in PV surface temperature with a minimal error margin of 5 % between experimental and numerical results.

2. Research methodology

This study focuses on investigating the cooling dynamics of PV panels to enhance their efficiency and sustainability. The study employs both experimental and numerical approaches to explore the impact of various cooling techniques on PV panel performance. The experimental work involves detailed testing of cooling systems using porous media and water circulation, with outdoor tests conducted under real-world conditions to simulate environmental influences. Key parameters such as solar radiation, air velocity, and temperature are carefully controlled and measured. This methodology aims to identify optimal cooling strategies that can reduce solar panel temperatures and improve energy output, contributing to the development of more efficient and sustainable solar power systems.

2.1. Experimental setup and measurement system

A comprehensive experimental study was conducted to explore the cooling dynamics of PV cells, focusing on how different cooling mechanisms affect the temperature and performance of the panels. The experiments were carried out at the Faculty of Engineering Technology at Al-Balqa Applied University (BAU) in Amman. The primary objective of the study was to assess the effectiveness of various cooling strategies, particularly focusing on the use of porous media in cooling channels beneath the PV panels. The experiments included both controlled laboratory conditions and outdoor testing to reflect natural environmental factors. During the outdoor phase, the PV cells were exposed to natural sunlight, allowing the cooling systems to interact with the full spectrum of environmental variables such as ambient temperature, wind speed, and solar radiation.

In the experimental setup, 30-watt polycrystalline PV cells were employed for testing. The technical specifications of the PV panel, outlined in Table 2 [62,70,71]. These cells were integrated into a specially designed cooling system featuring a 5 cm high cooling channel beneath each panel. The channel was meticulously insulated to reduce the effects of external temperature variations. Various porous media with different porosities were placed within the channel to assess their influence on the cooling process. Gravel was selected for its availability and thermal conductivity, as outlined in Table 3 [72].

The PV system shown in Fig. 1 was used to reduce the temperature of the PV panel by circulating water through the cooling channel. Two water tanks, each with a capacity of one cubic meter, were employed: the first tank supplied cold water to the cooling channel, while the second tank collected the water discharged from the channel, preventing the mixing of cold and hot water. Fig. 2 illustrates the cooling channel installed beneath the PV panel for cooling purposes. The channel's dimensions (54 × 34 cm) were designed to match those of the panel, and precautions were taken to prevent water leakage. K-type thermocouples were strategically placed on the photocell to measure the temperature of the water entering and exiting the cooling channel, as well as the ambient temperature. Various measuring devices, including those for solar radiation intensity, voltage, current, flow rate, and pressure, were used. The solar intensity meter measures the intensity of solar radiation reaching the photovoltaic panels, providing insights into how solar radiation impacts system performance and cooling efficiency. The voltmeter and ammeter are used to monitor the electrical output of the system. The voltmeter measures the voltage across the photovoltaic panels, while the ammeter measures the current generated, both of which are essential for assessing the electrical efficiency of the system. The water flow meter gauges the flow rate of water circulating through the cooling channel, ensuring proper circulation from the cold water tank to the cooling channel and then to the hot water tank, which is crucial for evaluating cooling performance. The temperature data acquisition system, consisting of K-type thermocouples, measures temperatures at various points, including the water temperature entering and exiting the cooling channel, as well as the ambient temperature. Finally, the water pump circulates the water through the system,

Table 2
Technical specifications of the PV panel [62,70,71].

Solar PV module parameter	Value at AM 1.5 spectra STC
Maximum power, P_{max}	30 W
Open-circuit voltage, V_{oc}	22 V
Short-circuit current, I_{sc}	1.84 A
Voltage at P_{max}	18 V
Current at P_{max}	1.67 A
Operating temperature	−40 °C to+85 °C
Solar intensity, G	1000 W/m^2

AM: air mass; STC: standard test condition

Table 3
Thermal properties of porous media used in cooling channel: gravel properties [72].

d_m (mm)	Φ	$\forall_t$(Liter)	$\forall_f$(Liter)	ρ (kg/m^3)	k (W/m^2. K)	C_P (J/kg. K)
2	0.35	9.18	5.96	2630	1.19	900
5	0.4	9.18	5.5	2630	1.19	900
10	0.48	9.81	4.77	2630	1.19	900
11	0.5	9.18	4.59	2630	1.19	900

d_m: Diameter of the particle in (mm); Φ: Porosity of the material, a measure of the void spaces in a material, typically dimensionless; $\forall_t$: Total volume of the material, in liters (L); $\forall_f$: Volume of the fluid (or water) that interacts with the material, in liters (L); ρ: Density in kg/m^3; k: Thermal conductivity (W/m^2. K); and C_P: Specific heat capacity (J/kg.K).

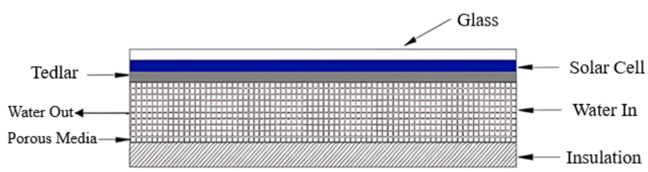


Fig. 1. Schematic of the PV system with cooling channel.

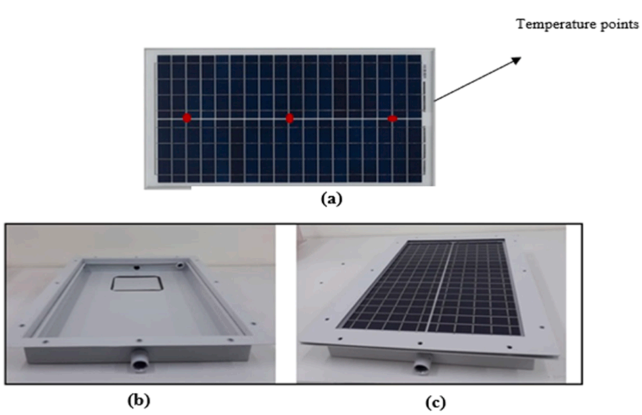


Fig. 2. Cooling channel installed beneath the PV Panel, (a) PV panel, (b) cooling channel, and (c) PV panel installed on the cooling channel.

ensuring continuous flow, which is vital for cooling the photovoltaic panels and optimizing the system's overall performance.

The temperature reduction and increase in electrical output power achieved by cooling solar panels using porous media can be quantified using two fundamental equations, as defined by Masalha et al. [73]. These equations help evaluate the benefits of cooling in terms of temperature reduction and power output enhancement:

Percentage temperature decrease:

$$\%T_{max,decrease} = \frac{T_{withoutcooling} - T_{cooling}}{T_{withoutcooling}} \times 100\% \tag{1}$$

Percentage power increase:

$$\%P_{max,increase} = \frac{P_{cooling} - P_{withoutcooling}}{P_{withoutcooling}} \times 100\% \tag{2}$$

Table 4 provides a detailed summary of the porous media used in this study, along with their key characteristics. Porous media are materials that contain voids or pores, allowing the passage of fluids or gases. These materials are critical in various applications, including heat transfer, fluid dynamics, and filtration [74,75].

The choice of porous media is crucial in experiments and simulations related to fluid flow and heat transfer. Different porous materials vary in permeability, porosity size, and thermal conductivity, all of which affect the flow dynamics and heat transfer rates within the medium. In this study, a range of porous media was carefully selected to examine their behavior under specific conditions. Their properties were thoroughly analyzed to understand their influence on fluid flow patterns, heat transfer efficiency, and other related phenomena.

Table 4
Properties of porous media used in the investigation.

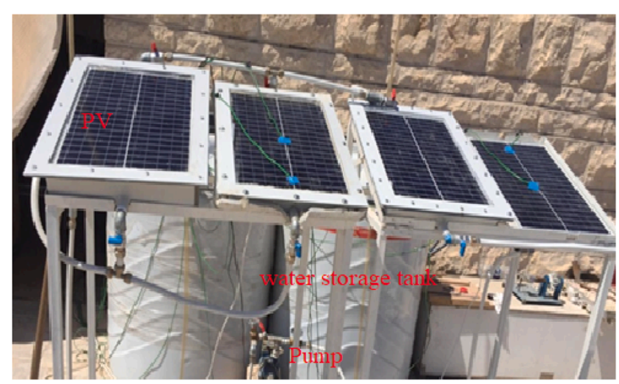
Porous material	ρ (kg/m^3)	k (W/m^2. K)	C_P (J/kg.K)
Gravel [72]	2630	1.19	900
Flint [76]	2600	3.5	740
Marble [77]	2700	3	800
Sandston [76]	2800	5	1000

2.1.1. Outdoor testing and experimental configurations

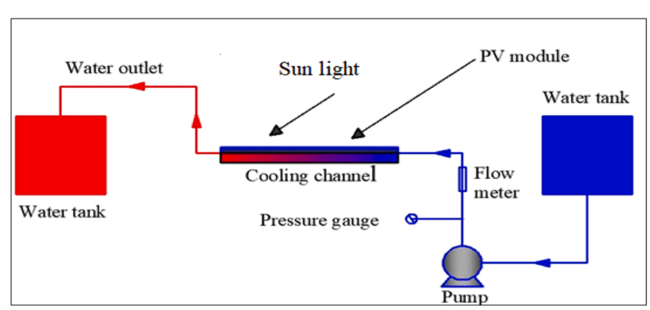
This study utilized four identical PV panels, each with dimensions of 54 × 34 cm, to conduct the experimental investigation. Fig. 3 illustrates the experimental setup, highlighting the cooling device used for the PV panels. Uniform environmental conditions were maintained throughout all experimental trials. Key parameters, including solar radiation, air velocity, and ambient temperature, were closely monitored to ensure a consistent framework for comparative analysis. This approach created a controlled environment, allowing for systematic exploration of the optimal cooling conditions for the PV panels.

The study was structured into three distinct phases to investigate different aspects of cooling efficiency:

1. Phase 1: A comparative analysis was conducted to evaluate cooling performance with porous media, comparing it to scenarios with no porous media, water cooling alone, and no cooling at all.
2. Phase 2: This phase focused on examining the impact of different porosity volumes on cooling efficiency.



(a) Experimental setup



(b) Schematic diagram

Fig. 3. (a) Experimental setup and (b) schematic diagram for cooling PV panels during outdoor testing.

3. Phase 3: The final phase investigated the influence of volumetric flow rates on the cooling performance of the PV panels.

Case. I: Comparison of cooling with and without porous media

The primary objective of this investigation was to compare the efficiency of cooling systems using porous media against water-only systems. This comparison aimed to clarify the effectiveness of porous media-based cooling in contrast to traditional water cooling.

Three identical PV panels were utilized to test different cooling methods. The first panel operated without any cooling, while the second was cooled using only water circulation. The third panel combined water circulation with porous materials featuring a pore size of 0.35. Additionally, the impact of varying water flow rates at 1 L/min, 1.5 L/min, and 2 L/min was analyzed to assess the cooling effects. The study spanned three consecutive days, with an additional six-day replication period to reinforce the reliability and robustness of the findings. This nine-day continuous testing ensured a comprehensive understanding of the cooling behavior under different conditions.

Case 2. Optimal porosity size for enhanced cooling

This phase focused on determining the ideal porosity size for effective cooling. Three PV panels were tested, each with cooling channels containing different porous media with porosity sizes of 0.35, 0.40, and 0.48. Water flow rates ranged from 1 L/min to 2 L/min. Experiments were conducted over three days and replicated for six additional days to ensure consistent results. The findings emphasized relation between porous media porosity, cooling efficiency, and PV panel performance, guiding the development of optimal cooling strategies.

Case 3. Optimal volume flow rate for enhanced cooling

In this case, four PV panels were studied under varying flow conditions to identify the best volume flow rate for effective cooling. One panel was left uncooled in ambient conditions, while another used a cooling channel with porous media of 0.35 porosity. Flow rates were adjusted to 1 L/min, 2 L/min, and 3 L/min to assess the optimal volume flow rate for the given porosity. Each trial lasted one day and was replicated over two additional days to confirm the results. The goal was to identify the flow rate that best balanced water dynamics with porous media to maximize cooling efficiency.

2.1.2. Uncertainty analysis

The instrumentation setup incorporated thermocouple sensors strategically placed across the PV panel to monitor temperature variations. These sensors captured thermal behaviour across the panel's surface and recorded the temperatures of the water entering and exiting the cooling channel, providing valuable data on cooling performance. Ambient temperature was also measured as a reference point. A voltmeter and ammeter were used to assess the PV panel's electrical output. Each instrument was calibrated to ensure accuracy, with specifications detailed in Table 5. Uncertainty quantification was carried out using Eqs. (3), 4, and 5, enabling a precise and systematic analysis [78]. This approach, combining precise instrumentation, mathematical accuracy, and observational detail, follows the methodology of Elminshawy et al. [65].

Table 5
Instrument accuracy and uncertainty values.

Instrument	Measured parameters	Accuracy	Range	Uncertainty
Solar power meter	intensity of solar radiation	±1 W/m^2	0–2000 W/m^2	0.57 W/m^2
Ammeter	Current	±1 m A	0–10 A	0.5×10^{-3} A
Voltmeter	Voltage	±1 mV	0–200 V	0.5×10^{-3} V
Thermocouple	Temperature	±0.1 °C	−210 to 200 °C	0.57×10^{-3} °C

$$\frac{UP}{P} = \sqrt{\left(\frac{UI}{I}\right)^2 + \left(\frac{UV}{V}\right)^2} \tag{3}$$

Where, I represents the current, V denotes the voltage. Based on Eq. (4), the area uncertainty was calculated to be 0.17 %.

$$\frac{UA}{A} = \sqrt{\left(\frac{UW}{W}\right)^2 + \left(\frac{UL}{L}\right)^2} \tag{4}$$

Where, w and L represent the width and length of the cooling channel, respectively. According to Eq. (5), the uncertainty in electrical efficiency was calculated to be 0.2 %.

$$\frac{U\eta}{\eta} = \sqrt{\left(\frac{UP}{P}\right)^2 + \left(\frac{UA}{A}\right)^2 + \left(\frac{UG}{Grad}\right)^2} \tag{5}$$

Where, P represents the output power with an associated uncertainty UP; A denotes the PV panel area with an uncertainty UA; Grad is the solar radiation intensity with an uncertainty UG. The uncertainties for temperature, current, and voltage were obtained directly from the measuring instruments, while the uncertainties for power and efficiency were derived using Eqs. (3), (4), and (5).

2.2. Numerical modeling and simulation

A numerical investigation was conducted to analyze the cooling of the PV panel, as well as to determine its temperature and output power. In contrast to experimental studies, numerical simulations offer a cost-effective and time-efficient approach, allowing for numerous iterations by varying parameters such as solar radiation, airspeed, ambient temperature, water flow rates, and porosity sizes. The results from these simulations were validated against experimental data to identify any discrepancies and to select the most suitable numerical model for future simulations.

2.2.1. Modeling of thermal systems

A mathematical model was developed to determine the temperature of the solar panel, as illustrated in Fig. 4. The following assumptions

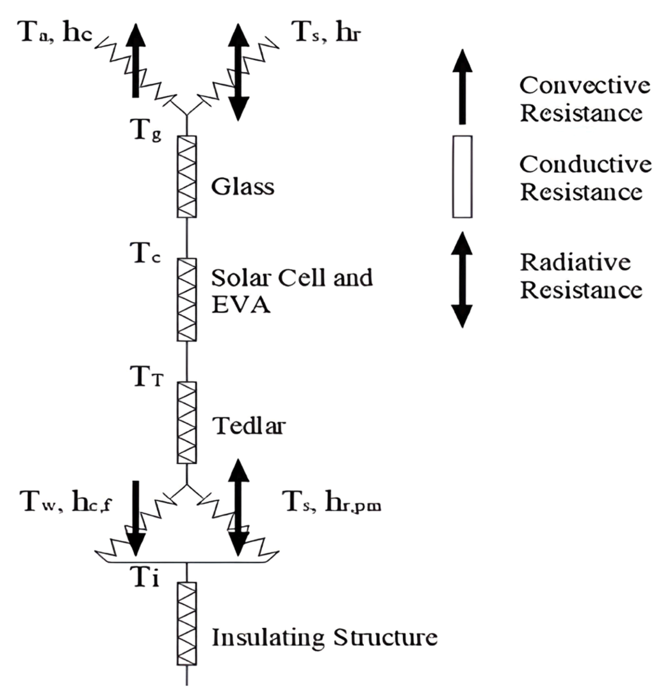


Fig. 4. Thermal resistance model for solar panel cooling.

were considered in the model:

- The cooling channel was fully insulated in all directions, except for the upper side where it was attached to the solar panel.
- No water leakage occurred, except at the inlet and outlet of the cooling channel.
- The system operated with a constant water flow rate throughout the experimental period.
- The temperature difference across the solar panel was assumed to be uniform along its surface.

PV panels absorb solar radiation, but not all of this energy is converted into electrical power. A portion of the radiation is transformed into heat, causing the temperature of the solar panel to rise. The Eq. (6) describes the total heat flux [79]:

$$q_t'' = q_{cond}'' + q_{conv}'' + q_{Rad}'' = \frac{T_g - T_f}{R_1} + \frac{(T_g - T_\infty)}{R_{conv}} + \frac{(T_g - T_{sur})}{R_{rad}} \quad (6)$$

The thermal resistances can be calculated using Eqs. (7) to 9 [79]:

$$R_1 = \frac{L_g}{k_g} + \frac{L_{EVA}}{k_{EVA}} + \frac{L_c}{k_c} + \frac{L_{EVA}}{k_{EVA}} + \frac{L_T}{k_T} + \frac{1}{h_{r,pm} + h_{c,f}} \quad (7)$$

$$R_{conv} = \frac{1}{h_c} \quad (8)$$

$$R_{rad} = \frac{1}{h_r} \quad (9)$$

Where R_{cond} represents the thermal resistance for conduction, R_{conv} is the thermal resistance for convection, R_{rad} is the thermal resistances for radiation, k_g denotes the thermal conductivity of glass, h_c is the convective heat transfer coefficient, and h_r is the radiant heat transfer coefficient. The combined thermal resistance of $R_{conv}$and R_{rad} is expressed as:

$$\sum R_{c,r} = \frac{R_{conv}\ R_{rad}}{R_{conv} + R_{rad}}, U_{c,r} = \left[\sum R_{c,r}\right]^{-1} \quad (10)$$

$$U_1 = \left[\sum R_1\right]^{-1} \quad (11)$$

Where, $R_{c,r}$ is the combined thermal resistances for convection and radiation, and $U_{c,r}$ is the coefficient of heat transfer between the PV cell and the surrounding environment. The temperature of the solar panel can be calculated as follows [80]:

$$G.\alpha_c = E + U_{c,r}(T_g - T_a) + U_1 (T_g - T_f) \quad (12)$$

Where T_f represents the temperature of the fluid, T_g denotes the temperature of the front surface of the solar panel, and T_a is the temperature of the surrounding air. G refers to the solar radiation, while E indicates the electrical power output from the solar panel. Additionally, α represents the absorbance, and U_1 is the overall heat transfer coefficient from the glass to the water. After rearranging Eq. (12), the temperature of the PV cell can be determined using Eq. (13), as below [70]:

$$T_g = \frac{G.\alpha_c - E + U_{c,r}T_a + U_1\ T_f}{U_{c,r} + U_1} \quad (13)$$

The value of $U_{c,r}$ can be determined using the following equation:

$$U_{c,r} = \left[\frac{1}{h_c + h_r}\right]^{-1} \quad (14)$$

The values h_c and h_r are determined using Eqs. (15) and (16), respectively [81]:

$$h_c = 5.7 + 3.8V \quad (15)$$

$$h_r = \varepsilon\,\sigma\left(T_g{}^2 + T_a{}^2\right)\left(T_g + T_a\right) \quad (16)$$

Where V represents the velocity of the surrounding air around the PV cells, ε denotes the emissivity, and σ is the Stefan-Boltzmann constant. By taking the inverse of Eq. (6):

$$U_1 = \left[\frac{L_g}{k_g} + \frac{L_{EVA}}{k_{EVA}} + \frac{L_c}{k_c} + \frac{L_{EVA}}{k_{EVA}} + \frac{L_T}{k_T} + \frac{1}{h_{r,pm} + h_{c,f}}\right]^{-1} \quad (17)$$

Where, L_g and k_g represent the thickness and thermal conductivity of the glass, respectively, while L_{EVA} and k_{EVA} correspond to the thickness and thermal conductivity of the EVA layer. Similarly, L_T and k_T denote the thickness and thermal conductivity of the Tedlar [82]

$$G.\alpha_c = U_{front2}(T_T - T_a) + h_{c,f}(T_T - T_f) + h_{r,pm}(T_T - T_{pm}) \quad (18)$$

Using Eq. (19), the temperature at the back of the solar panel can be determined as [62,83]:

$$T_T = \frac{U_2 T_g + h_{c,f} T_f + h_{r,pm} T_{pm}}{h_{c,f} + h_{r,pm} + U_2} \quad (19)$$

$$U_2 = \left[\frac{L_g}{k_g} + \frac{L_{EVA}}{k_{EVA}} + \frac{L_c}{k_c} + \frac{L_{EVA}}{k_{EVA}} + \frac{L_T}{k_T}\right]^{-1} \quad (20)$$

where U_2 represents the overall heat transfer coefficient from the glass to the bottom Tedlar. The convective heat transfer coefficient for water flowing through a channel filled with a porous medium $h_{c,f}$, can be determined using Eqs. (21-23) [82].

$$h_{c,f} = \left[\frac{D_{hd}}{Nu_{pm-f}.k_e}\right]^{-1} \quad (21)$$

$$k_e = \phi k_{s+}\ (1-\phi)k_f \quad (22)$$

Where ϕ represents the porosity size.

$$Nu_{pm-f} = \left(\frac{0.255}{\phi}\right) Re_{pm}^{\frac{2}{3}}.Pr_f^{1/3} \quad (23)$$

Nu_{pm-f} represents the Nusselt number, which quantifies the efficiency of heat transfer through convection in a fluid, Pr_f is the Prandtl number, which characterizes the relative importance of momentum diffusivity (viscosity) to thermal diffusivity in a fluid, Re_{pm} is the Reynolds number, which predicts the flow regime of the fluid, indicating whether the flow is laminar, turbulent, or transitional based on its value [82]:

$$Re_{pm} = \frac{\rho_f V\ d_{pm}}{\mu(1-\phi)} \quad (24)$$

where ρ_f is the fluid density, V is the inlet fluid velocity, and $h_{r,pm}$ is the radiation heat transfer coefficient from Tedlar to the porous medium. This coefficient can be calculated using Eq. (25) [79]:

$$h_{r,pm} = \mathcal{E}\sigma(T_T + T_{pm})\left(T_T{}^2 + T_{pm}{}^2\right) \quad (25)$$

2.2.2. ANSYS simulation

The ANSYS computational fluid dynamics (CFD) software was used to analyze the temperature distribution of the PV panel and study the effects of water flow and porosity size on the cooling process. The analysis procedure is illustrated in Fig. 5. The design of the PV panel components was created using AutoCAD software. ANSYS proved to be an effective tool for numerically simulating heat transfer behavior, particularly in understanding the cooling effects on the PV panel surface. Key parameters, including solar radiation intensity, ambient temperature, volume flow rates, air velocity, and porosity size, were systematically investigated. The simulation was based on several assumptions:

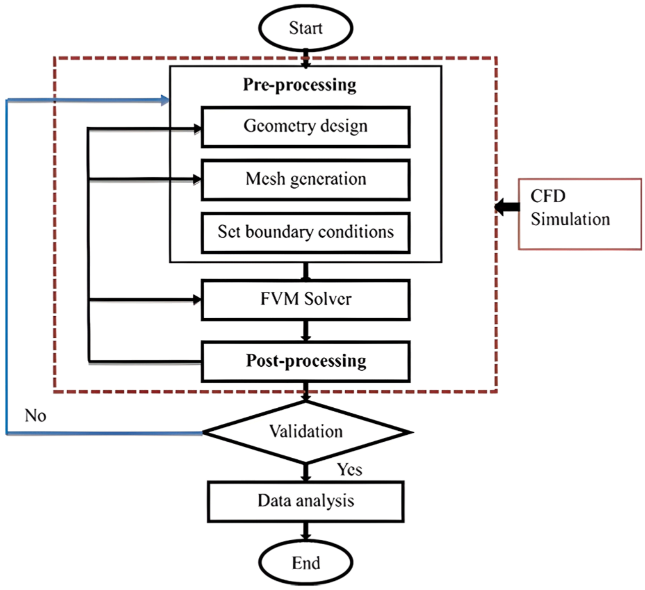


Fig. 5. Flowchart of CFD analysis for PV panel cooling.

- Uniform and incompressible flow through the cooling channel.
- The effects of dust and moisture on the surface of the PV panel were neglected in the simulations.
- The thermophysical properties of the cooling duct and PV panel, such as thermal conductivity, were considered constant across different temperature variations.
- Ethyl Vinyl Acetate (EVA), which is used as a layer in the PV panel, was considered transparent with high transmissivity for heat transfer calculations.
- The walls of the cooling channel were assumed to be adiabatic.

A multi-layered heat transfer model was developed to comprehensively analyze PV cell cooling, incorporating components such as glass, EVA, solar cells, additional EVA, Tedlar, and cooling water. ANSYS Fluent software was used for the analysis, employing a transient state condition with energy analysis enabled. The k-epsilon RNG model was applied for accurate turbulence and swirling flow simulations. Gravity effects were included to replicate real-world conditions, and appropriate material choices were made for metals and cooling liquids. The porous zone feature was activated to simulate fluid flow through the metal-layer porous media, accounting for parameters such as metal porosity size.

Boundary conditions were carefully set to ensure simulation accuracy. The velocity boundary condition was based on the inlet liquid velocity, while the pressure outlet condition was set to zero, closely resembling real-world scenarios. The walls of the cooling channel were assumed to be adiabatic to accurately represent heat transfer processes. The k-epsilon RNG model was applied for precise turbulence simulations, essential for modeling the swirling flow and heat transfer behavior in the cooling channel. The semi-implicit method for pressure-linked equations (SIMPLE) was selected for solving the system, combined with a second-order upwind scheme to enhance stability and accuracy.

To ensure reliable results, a fine mesh with a size smaller than 10^{-4} was applied around the PV panel, capturing detailed variations in temperature and flow characteristics. This high-resolution meshing ensured that the solution remained accurate, and the flow field was well-resolved. Residual convergence criteria were strictly monitored and achieved within the range of 10^{-12} to 10^{-14}, indicating a well-converged numerical solution with minimal error. These measures collectively ensured that the simulations were precise, capturing the key thermal and fluid flow phenomena in the PV cooling system with high accuracy.

ANSYS was used throughout the study to investigate key parameters, including porosity size, volume flow rates, cooling channel height and shape, cooling fluid types, and porous media types, aiming to identify the optimal configurations and conditions for efficient PV cell cooling.

2.2.3. *Governing equations*

The continuity equation can be expressed as follows [79]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{26}$$

Where $\frac{\partial u}{\partial x}$, $\frac{\partial v}{\partial y}$, $\frac{\partial w}{\partial z}$ represent the rate of change of velocity in the x, y, and z directions, respectively.

The Momentum Equations in the x, y, and z directions, as shown in Eqs. (27), 28, and 29, respectively, are based on Newton's second law and describe how forces influence fluid motion. These equations are essential for understanding fluid dynamics in PV cooling research. Integrating porosity volume into this equation is essential for modeling fluid flow through porous media in PV simulations. This adjustment helps clarify the influence of the porous structure on flow dynamics, resistance, and transport processes [84].

$$\frac{\rho_f}{\phi}\left(u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu_{eff}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-\left(\frac{\mu_f}{k}+\frac{F\phi}{\sqrt{K}}u\right)u \tag{27}$$

$$\frac{\rho_f}{\phi}\left(u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu_{eff}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\left(\frac{\mu_f}{k}+\frac{F\phi}{\sqrt{K}}v\right)v \tag{28}$$

$$\frac{\rho_f}{\phi}\left(u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu_{eff}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-\left(\frac{\mu_f}{k}+\frac{F\phi}{\sqrt{K}}w\right)w \tag{29}$$

Where, $\frac{\partial p}{\partial x}$ represents the pressure gradient in the x direction, μ_f is the viscosity of water.

The energy equation, presented in Eq. (30), governs the flow of energy within fluid systems, guiding the thermal behavior in PV cooling applications. In simulations, it models energy transfer, while experimental observations demonstrate its influence through changes in temperature and fluid movement [79]:

$$\rho_f\left(u\frac{\partial T_f}{\partial x}+v\frac{\partial T_f}{\partial y}+w\frac{\partial T_f}{\partial z}\right)=k_f\left(\frac{\partial^2 T_f}{\partial x^2}+\frac{\partial^2 T_f}{\partial y^2}+\frac{\partial^2 T_f}{\partial z^2}\right) \tag{30}$$

Where T_f represents the temperature of the water.

3. Results and discussion

This section presents a comprehensive analysis of the experimental and numerical findings. The first part, 3.1 Experimental Work: Outdoor Test, details the outdoor experimental setup and the corresponding observations obtained from real-world testing. The second part, 3.2 Numerical and Simulation Results, explores the results derived from computational models and simulations, comparing them with the experimental data to assess the accuracy and effectiveness of the proposed cooling strategies for PV panels.

3.1. *Experimental result*

This study focused on two main objectives. The first was to assess the effect of three different porosity sizes (0.35, 0.4, and 0.48) on the cooling process. The second objective was to evaluate the performance of five distinct water flow rates (1, 1.5, 2, 3, and 4 L/min) to determine the optimal flow rate for each porosity size.

To comprehensively address the factors influencing the cooling process, the study was organized into three distinct scenarios. Each scenario analyzed key results to address the critical questions surrounding cooling efficiency. By examining these factors under various conditions, the goal was to optimize the cooling process and identify the best combination of porosity size and flow rate for the system.

3.1.1. *Case I: cooling performance with and without porous media*

In this study, three PV cells were tested: one uncooled, one cooled with water, and one cooled with porous media of 0.35 porosity. The experiments, conducted over seven hours, examined flow rates of 1, 1.5, and 2 L/min, with steady cooling and solar radiation conditions. Uncooled PV panels often experience elevated surface temperatures as a result of solar radiation, with temperatures reaching as high as 50 °C. This increase in temperature can lead to a reduction in both electrical efficiency and power output.

Fig. 6 illustrates the effect of volume flow rates on the surface temperature of PV panels. While all panels experienced temperature increases due to solar exposure, the cooled panels maintained significantly lower temperatures compared to the uncooled panel, highlighting the effectiveness of the cooling methods. It is clearly observed that the higher the volume flow rate, the higher the surface temperature of the PV panel achieved. At a volume flow rate of 2 L/min, the uncooled panel peaked at 49.1 °C at noon, while the water-cooled panel reached a lower temperature of 41.5 °C. The panel cooled with porous media achieved a temperature of 39.4 °C, with the greatest reduction (19 %) occurring at a 2 L/min flow rate. Whiles, the average temperature reduction for water cooling (without porous material) and with porous material at a 1 L/min flow rate were 9.11 % and 12.14 %, respectively, compared to the uncooled panel.

Figs. 7 and 8 provide detailed insights into the influence of volume flow rates on PV output power and efficiency, respectively. The results clearly demonstrate that higher flow rates contribute significantly to improving the performance of PV panels, with the most notable enhancements observed at a flow rate of 2 L/min for the panel equipped with porous media. At this optimal flow rate, the water-cooled panel without porous media exhibited an average power increase of 14.6 % compared to the uncooled panel. Similarly, the panel utilizing porous media achieved an average power increase of 11.7 %. These findings highlight the substantial impact of cooling strategies on the energy output of PV systems, highlighting the role of both water cooling and porous media in enhancing power generation. In terms of efficiency, the improvements were equally remarkable. The water-cooled panel (without porous media) demonstrated an efficiency increase of 13.3 %, while the panel with porous media achieved a 10.2 % efficiency improvement. This indicates that the cooling methods not only lower the PV surface temperature but also directly contribute to enhanced energy conversion efficiency. These observations highlight the importance of selecting the appropriate cooling techniques and flow rates to optimize the performance of PV systems. By effectively managing heat dissipation, these methods ensure better energy output and operational

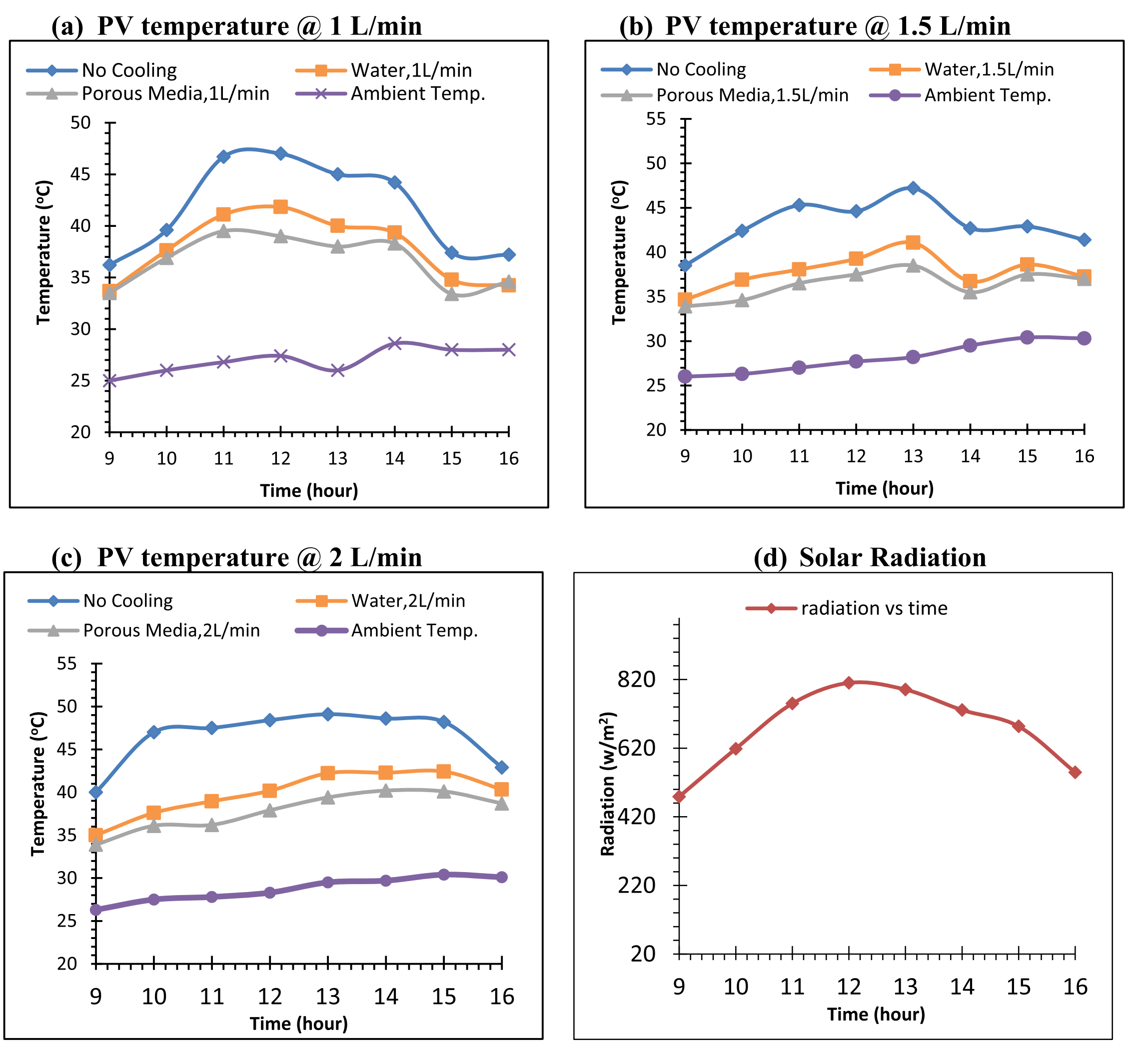


Fig. 6. Impact of volume flow rates on PV surface temperature: (a) 1 L/min, (b) 1.5 L/min, (c) 2 L/min, and (d) solar radiation for uncooled, water-cooled, and porous media-cooled PV panels.

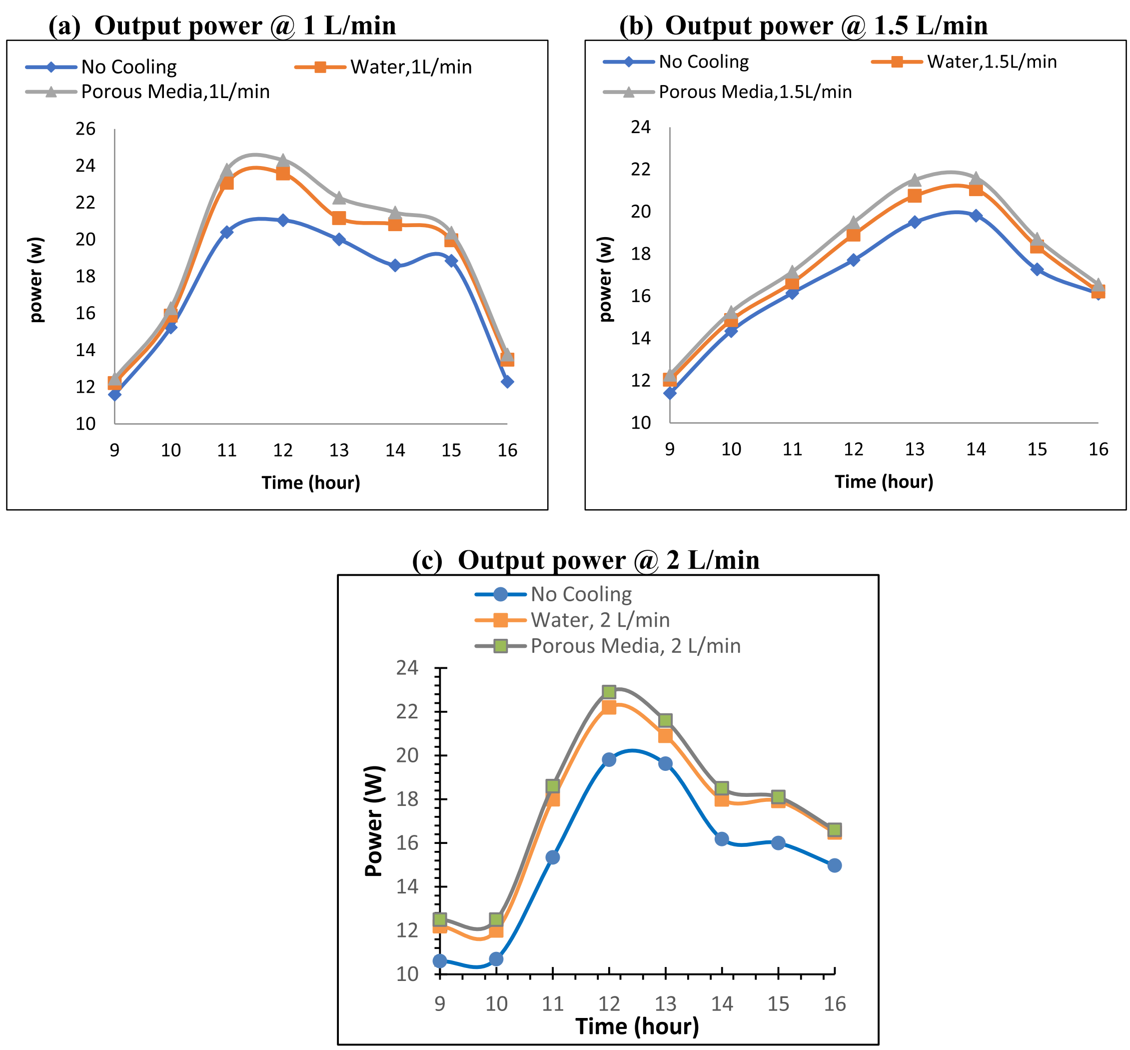


Fig. 7. Impact of volume flow rates on PV output power: (a) 1 L/min, (b) 1.5 L/min, and (c) 2 L/min, for uncooled, water-cooled, and porous media-cooled PV panels.

stability, making them vital for the design and implementation of high-performance solar energy systems. The use of porous media, in particular, proves to be a promising innovation, offering a balance between enhanced cooling and improved efficiency at higher flow rates.

3.1.2. Case II: effect porosity size for the best cooling

In this study, four PV panels underwent testing, with three utilizing channels filled with porous material (gravel) and one serving as a reference model without cooling. The objective was to determine the optimal cooling conditions for PV cells, focusing on comparing different porosity sizes to enhance the cooling process. The channels were filled as follows: the first with a porosity size of 0.35, the second 0.45, the third 0.48, and the fourth PV panel without cooling. All panels were subjected to identical ambient conditions, including solar radiation, air velocity, temperature, and humidity. Three volume flow rates (1 L/min, 1.5 L/min, and 2 L/min) were tested in the experiment. Figs. 9, 10, and 11 show the variation in PV surface temperature, out power, and efficiency across different porosity sizes at volume flow rates, respectively. Analysis these figures revealed the significant role of porosity size in PV cooling. It was observed that smaller porosity sizes in porous media yielded better cooling results. For instance, at a flow rate of 1 L/min, temperature reductions of 18.9 %, 18.06 %, and 17.24 % were achieved for porosity sizes of 0.35, 0.45, and 0.48, respectively, accompanied by increases in output power of 7.3 %, 5.7 %, and 4.1 %. Similarly, at a flow rate of 1.5 L/min, temperature reductions of 24.44 %, 22.5 %, and 20.6 % were observed, with corresponding increases in electric power of 7.9 %, 6.3 %, and 4.7 %. Finally, at a flow rate of 2 L/min, temperature reductions of 35.7 %, 34.8 %, and 34 %, and increases in power of 9.4 %, 7.8 %, and 6.2 % were recorded. These results highlight the effectiveness of a porosity size of 0.35 in enhancing heat transfer absorptivity in cooling water, facilitated by the homogeneous distribution of convective heat within the PV panel due to the smaller porosity size.

3.1.3. Case III: identifying the optimal volume flow rate for maximum cooling

In this study, four PV panels were tested to evaluate the effectiveness of cooling channels filled with porous media in regulating panel temperatures. Three of the panels incorporated cooling channels containing porous media with a uniform porosity of 0.35, while the fourth panel functioned as an uncooled reference model. The primary objective was to examine the impact of varying volume flow rates on cooling performance while maintaining a consistent porosity level. To ensure accurate and reliable comparisons, all experiments were conducted simultaneously under identical ambient conditions, minimizing external influences on the results.

Three volume flow rates (1 L/min, 2 L/min, and 3 L/min) were analyzed to assess their influence on PV panel surface temperatures and identify the most effective cooling strategy. Fig. 12 illustrates the variation in PV surface temperatures across the tested flow rates. The results showed notable temperature reductions of approximately 18 %, 20.6 %,

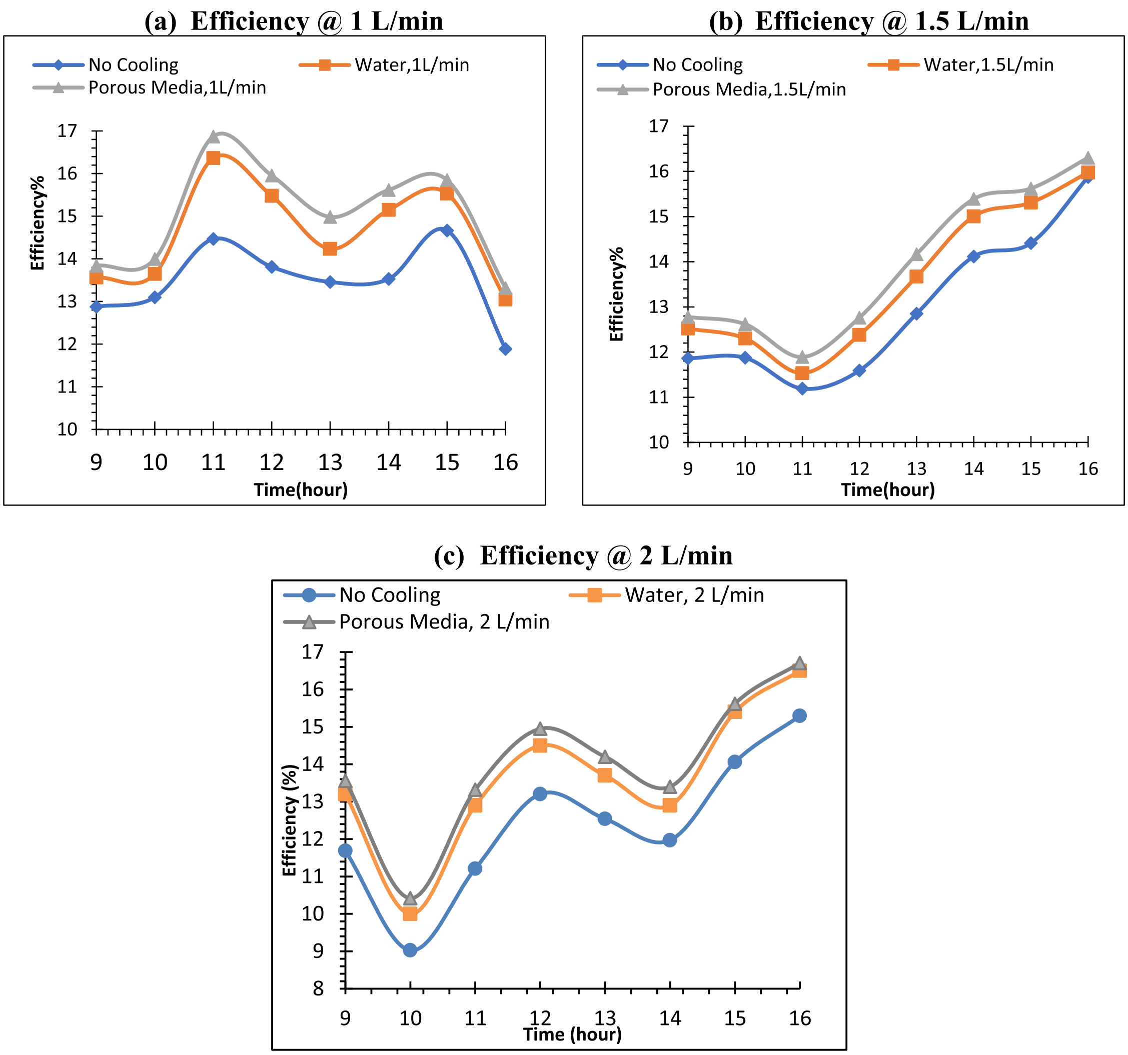


Fig. 8. Impact of volume flow rates on PV efficiency: (a) 1 L/min, (b) 1.5 L/min, and (c) 2 L/min, for uncooled, water-cooled, and porous media-cooled PV panels.

and 20.3 % for flow rates of 1 L/min, 2 L/min, and 3 L/min, respectively. These results highlight that higher flow rates improve cooling efficiency, resulting in significant temperature decreases.

This trend indicates that increasing the flow rate enhances cooling efficiency by facilitating greater heat dissipation. However, the slight reduction in efficiency gain at the highest flow rate indicates a possible diminishing return, which may be attributed to thermal equilibrium constraints or increased fluid resistance within the cooling channels, limiting further heat transfer improvements. Additionally, adjusting the flow rate directly influences heat transfer dynamics. As shown in Eq. (24), higher flow rates lead to increased fluid velocity, resulting in higher Reynolds numbers and, consequently, enhanced convective heat transfer coefficients. This mechanism strengthens heat dissipation between the fluid and porous media, further improving the cooling performance of PV panels.

These findings highlight the critical role of volume flow rates in enhancing the cooling process and maintaining optimal PV panel temperatures. A higher flow rate enhances heat transfer by increasing the convective cooling effect within the porous medium, thereby reducing the surface temperature of the PV panels. This temperature reduction is crucial in preventing thermal degradation, which can negatively impact the efficiency and lifespan of PV systems. Furthermore, optimizing the cooling process can improve overall system performance by maintaining PV panels within their optimal operating temperature range, thereby maximizing energy output.

Based on rigorous experimental research conducted under controlled real-world outdoor conditions, this study identifies a porosity size of 0.35 as the optimal choice for maximizing the performance of PV panels. This specific porosity significantly enhances the efficiency and reliability of energy output across various operating conditions. Additionally, among the flow rates tested, 2 L/min emerges as the most effective for addressing temperature-related challenges in PV panels. This flow rate strikes a balance between efficient cooling and cost-effectiveness, offering an optimal solution for temperature regulation.

The combination of a porosity size of 0.35 and a flow rate of 2 L/min represents a significant advancement in PV technology, providing both practical and economical cooling strategies. Understanding the impact of porosity size on heat transfer is key to improving performance. The equation $q''_{conv} = h\Delta T = h(T_s - T_\infty)$ highlights the direct relationship between the convective heat transfer coefficient and the heat transfer rate, emphasizing the need to control this coefficient for efficient heat dissipation. In addition, the relationship between the convective heat transfer coefficient and the Nusselt number is outlined in Eq. (21), underscoring its importance in the heat transfer process. Eq. (23) further demonstrates an inverse correlation between porosity size and the Nusselt number, revealing that smaller porosities result in a higher convective heat transfer coefficient, thus improving overall heat transfer efficiency.

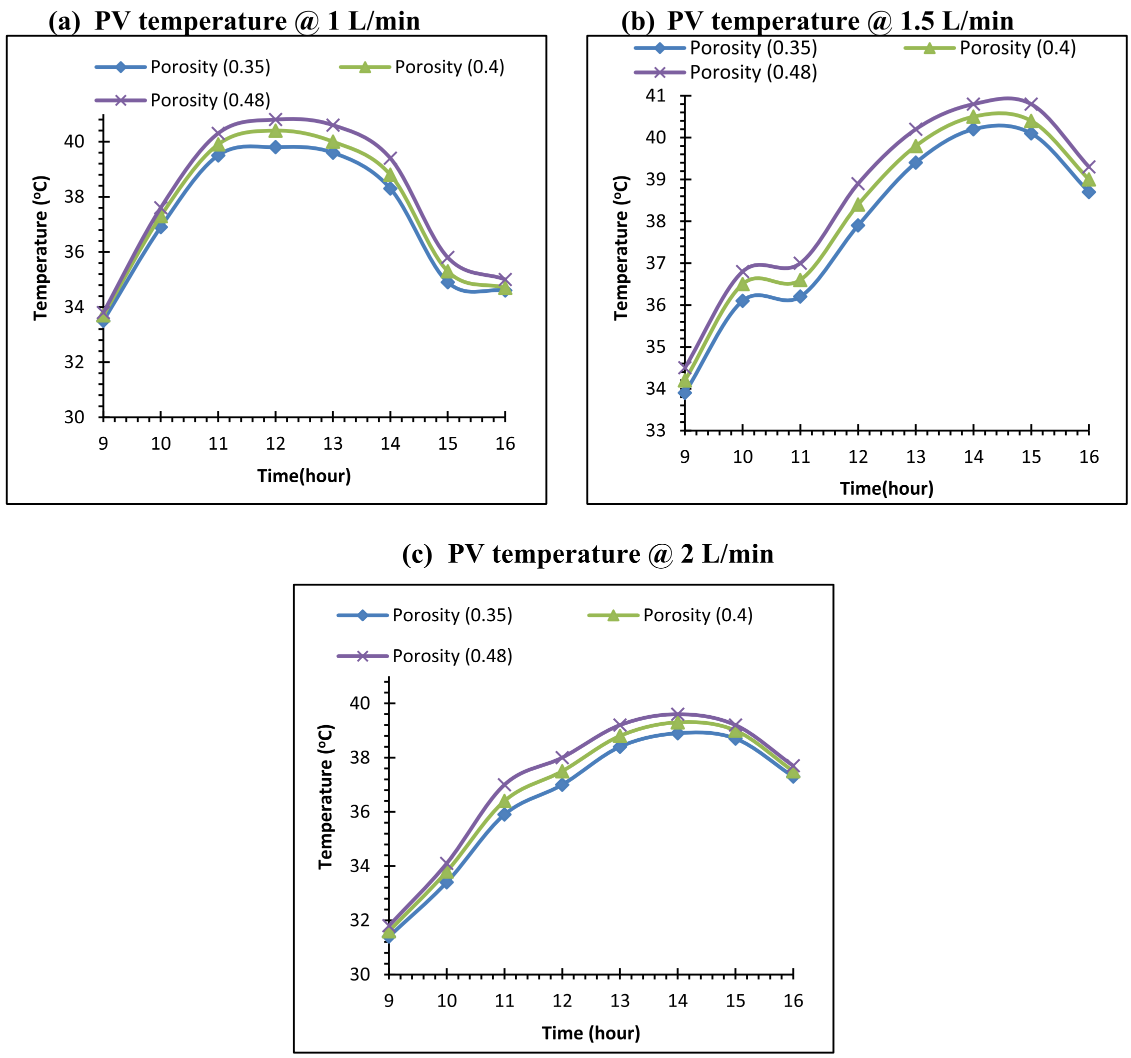


Fig. 9. Experimental results for the variation in PV surface temperature across different porosity sizes at volume flow rates of (a) 1 L/min, (b) 1.5 L/min, and (c) 2 L/min.

3.2. Numerical and simulation results

Numerical analysis is an efficient and cost-effective approach to understanding the heat transfer behavior of PV panels during cooling. By utilizing advanced tools like ANSYS software, researchers can simulate complex thermal interactions with high accuracy, reducing the reliance on time-intensive and costly experimental procedures [85]. ANSYS provides a versatile platform with advanced features for defining precise boundary conditions, material properties, and environmental factors, enabling the creation of reliable and detailed models for various cooling techniques [86]. The integration of computational fluid dynamics (CFD) and thermal analysis modules allows for the effective evaluation of cooling strategies, enhancement of design precision, and accurate prediction of system performance. This approach not only provides detailed insights into temperature distribution, flow patterns, and heat transfer mechanisms but also significantly reduces both time and cost compared to traditional experimental methods. However, while numerical simulations are invaluable for exploring a wide range of parameters and configurations, they are most effective when complemented by experimental validation to ensure real-world applicability and accuracy. Together, these approaches create a comprehensive framework for optimizing PV cooling systems.

3.2.1. Simulation validation

Prior to initiating the ANSYS simulations, preliminary experimental data were required to validate the model. An initial test was performed to examine the effect of mesh size on the simulation results, which was essential for ensuring convergence and establishing an appropriate simulation time frame.

The simulations were conducted under defined boundary conditions: a volume flow rate of 2 L/min, solar radiation intensity of 814 W/m^2, and an inlet water temperature of 24 °C. The influence of the number of nodes on the temperature outcomes is illustrated in Fig. 13. The analysis showed that increasing the mesh size beyond 85,420 nodes had negligible impact on the results, confirming this as the optimal mesh size for all subsequent simulations.

A rectangular grid mesh configuration, as shown in Fig. 14, was applied to achieve a uniform distribution around the PV cell model. The numerical results were compared with experimental data, as illustrated in Figs. 15. The comparison revealed deviations of 3 %, 2.3 %, and 1.8 % in PV surface temperature for flow rates of 1 L/min (Fig. 15a), 1.5 L/min (Fig. 15b), and 2 L/min (Fig. 15c), respectively, while maintaining a fixed porosity of 0.35. This close agreement validated the accuracy of the numerical model.

3.2.2. Parameters studies on PV cooling

The study aimed to investigate the impact of several parameters on

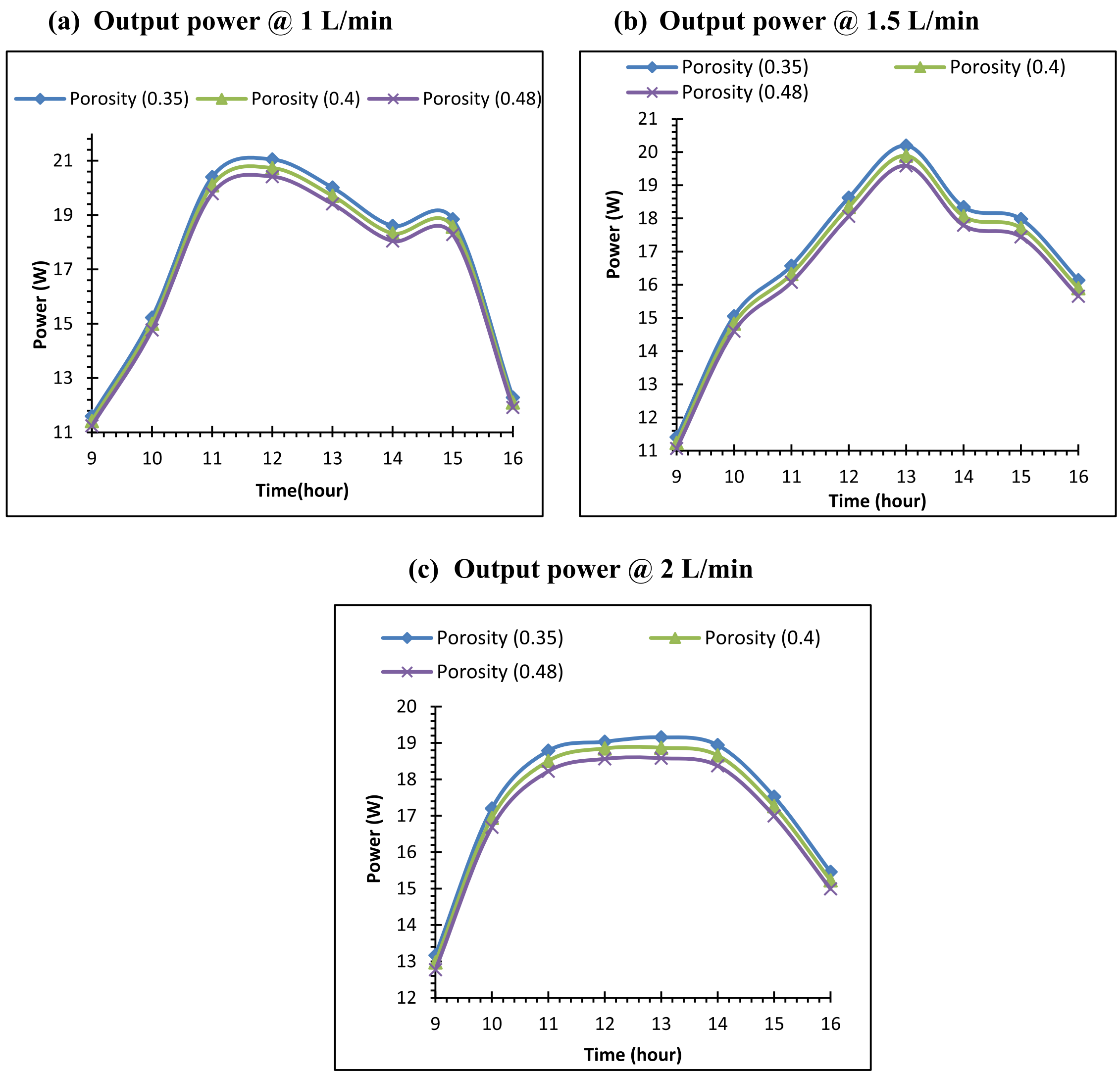


Fig. 10. Experimental results for the variation in PV power output across different porosity sizes at volume flow rates of (a) 1 L/min, (b) 1.5 L/min, and (c) 2 L/min.

PV cooling using porous media. These parameters included the height and shape of the cooling channel, the type of coolant used, and the selection of different porous media materials.

- Case I: Effect of Cooling Channel Height

Fig. 16 presents the analysis of temperature variations in PV panels with different cooling channel heights: 50 mm, 30 mm, 10 mm, and 5 mm. The study was conducted under optimal conditions derived from experimental work, including the use of porous media with a porosity of 0.35, a constant volume flow rate of 2 L/min, and solar radiation levels ranging from 350 to 1000 W/m^2 for all cooling channels. The results demonstrated a consistent increase in panel temperature with higher solar radiation levels. As shown in Figs. 16a to 16 d, at a solar radiation level of 1000 W/m^2, the maximum panel temperatures were recorded as 42 °C, 41.7 °C, 39.3 °C, and 37.3 °C for cooling channel heights of 50 mm, 30 mm, 10 mm, and 5 mm, respectively, when porous media was employed.

This analysis highlights the significant impact of cooling channel height on panel temperature. As the channel height decreases, the cross-sectional area of the channel reduces, leading to an increase in liquid velocity within the channel. This phenomenon is governed by the fundamental fluid mechanics relationship $V = Q / A$, where V is the fluid velocity, Q is the volume flow rate, and A is the cross-sectional area of the channel. With a constant flow rate, the reduction in channel height (and thus cross-sectional area) results in higher fluid velocity, which enhances the convective heat transfer coefficient. This improved heat transfer mechanism facilitates more efficient dissipation of thermal energy from the PV panel, leading to lower panel temperatures. Fig. 17 further illustrates PV temperature variations with changes in solar radiation levels across all cooling channels, demonstrating the consistent trend of improved cooling efficiency with reduced channel height.

In summary, the reduction in cooling channel height not only increases fluid velocity but also enhances the overall heat transfer efficiency, leading to a notable decrease in PV panel temperatures. This optimization is critical for improving the thermal performance and energy efficiency of PV systems, particularly under high solar radiation conditions. The findings highlight the importance of channel geometry in designing effective cooling systems for PV applications.

- Case II: Effect of Cooling Channel Shape

The performance and longevity of solar panels can be significantly impacted by temperature variations across the panel's surface. These fluctuations in temperature affect the efficiency of individual solar cells, potentially leading to reduced overall panel performance. To address this issue, a novel cooling approach was explored using cooling channels with varying heights to improve heat dissipation.

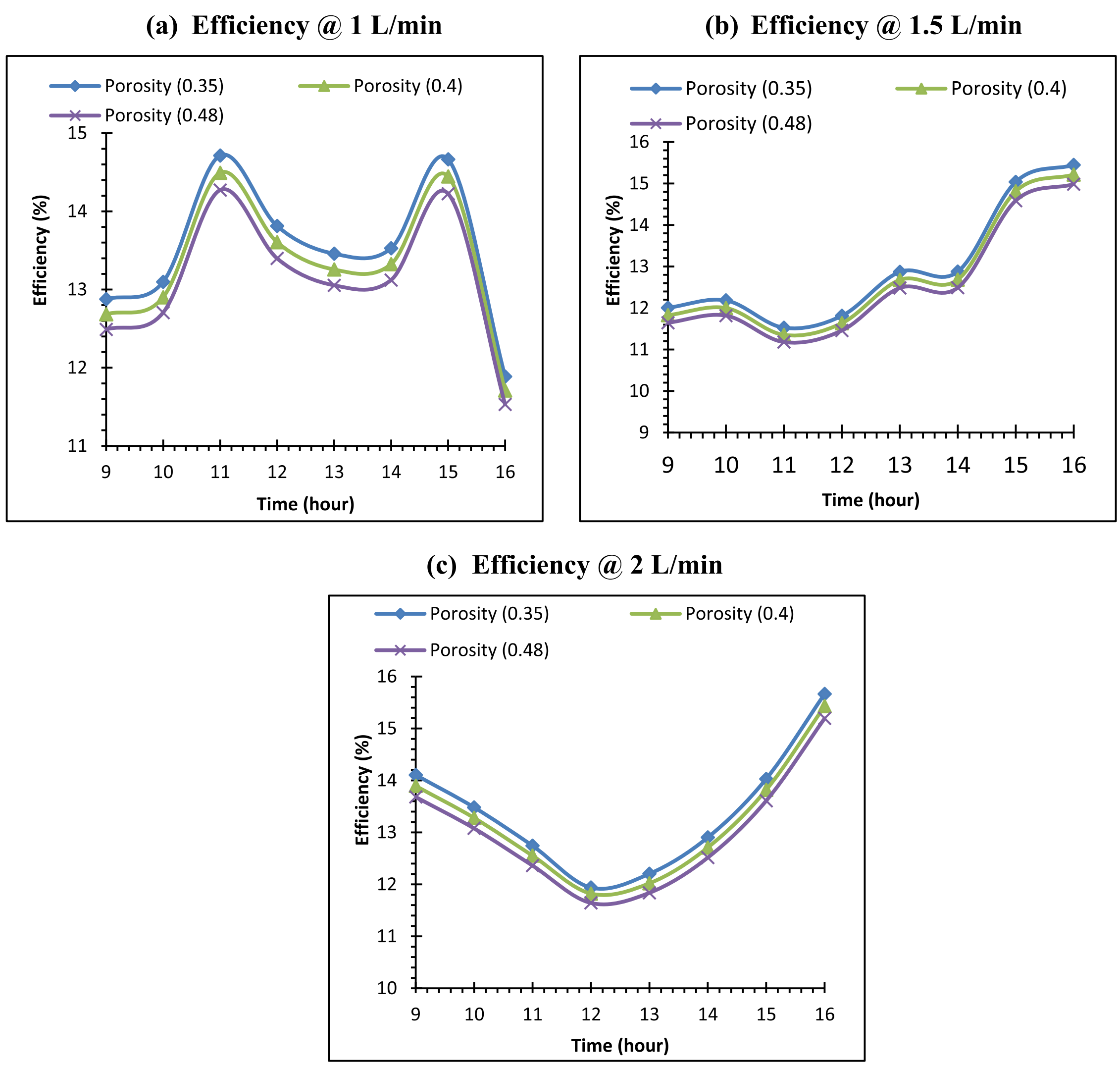


Fig. 11. Experimental results for the variation in PV efficiency across different porosity sizes at volume flow rates of (a) 1 L/min, (b) 1.5 L/min, and (c) 2 L/min.

Fig. 18 shows the temperature variations across solar cells within a panel, revealing the disparities caused by uneven heat distribution. This issue is exacerbated by higher liquid temperatures in the cooling channels, which reduce the temperature differential between the coolant and the PV panel, particularly towards the end of the channel. To counteract this, the cooling channel design was modified to feature an inlet height greater than the outlet height. This design aims to increase fluid velocity and improve heat transfer efficiency. By reducing the cooling channel height at the outlet, the fluid velocity increases, enhancing heat absorption from the cells and resulting in more uniform panel temperatures. This optimization of thermal conditions ultimately boosts energy output and extends panel longevity.

Fig. 19 provides a comparative analysis of cooling channel configurations: (A) 5 mm inlet - 5 mm outlet, (B) 5 mm inlet - 4 mm outlet, (C) 5 mm inlet - 3 mm outlet, and (D) 5 mm inlet - 2 mm outlet. The figure also illustrates PV temperature variations with changes in solar radiation levels across all cooling channels. Fig. 20 further shows the difference in PV temperature with varying solar radiation for a fixed inlet height at different outlet heights. The analysis demonstrates that reducing the outlet height correlates with lower panel temperatures. However, excessively low outlet heights can undermine temperature uniformity, highlighting the need for a balance between cooling efficiency and temperature consistency. Among the tested configurations, a 3 mm outlet height was found to be optimal, ensuring effective heat dissipation while maintaining consistent panel temperatures.

These results highlight the critical role that cooling channel shape plays in managing panel temperatures. By adopting the most effective channel configuration, panel efficiency can be maximized, contributing to the advancement of sustainable energy technologies. For example, the configuration of cooling channels also plays a critical role in determining the performance of PV cooling systems. For instance, tapered duct configurations have been found to be more effective in reducing average temperatures compared to other geometries [77]. Additionally, Fig. 21 illustrates how varying the outlet height influences fluid velocity and flow dynamics within the cooling channel.

In conventional cooling channel designs, the coolant undergoes a temperature increase towards the end due to prolonged exposure to heat from the PV cells along its path. As a result, the temperature differential between the PV panel and the coolant diminishes, causing the panel to exhibit higher temperatures at its end compared to its beginning.

To address this issue, a heterogeneous cooling channel design with a varying height profile was introduced. This design features a higher initial height that gradually transitions to lower heights towards the channel's end. This transition accelerates fluid velocity, improving heat transfer efficiency and reducing the panel's temperature at its end. The principle behind this "liquid acceleration" phenomenon can be explained by Bernoulli's law, which states that as a fluid moves through a narrower section of the channel, its velocity increases. The continuity equation further supports this by expressing the conservation of fluid flow: $A_{in}.V_{in}=A_{out}.V_{out}$; where A represents the cross-sectional area, and V

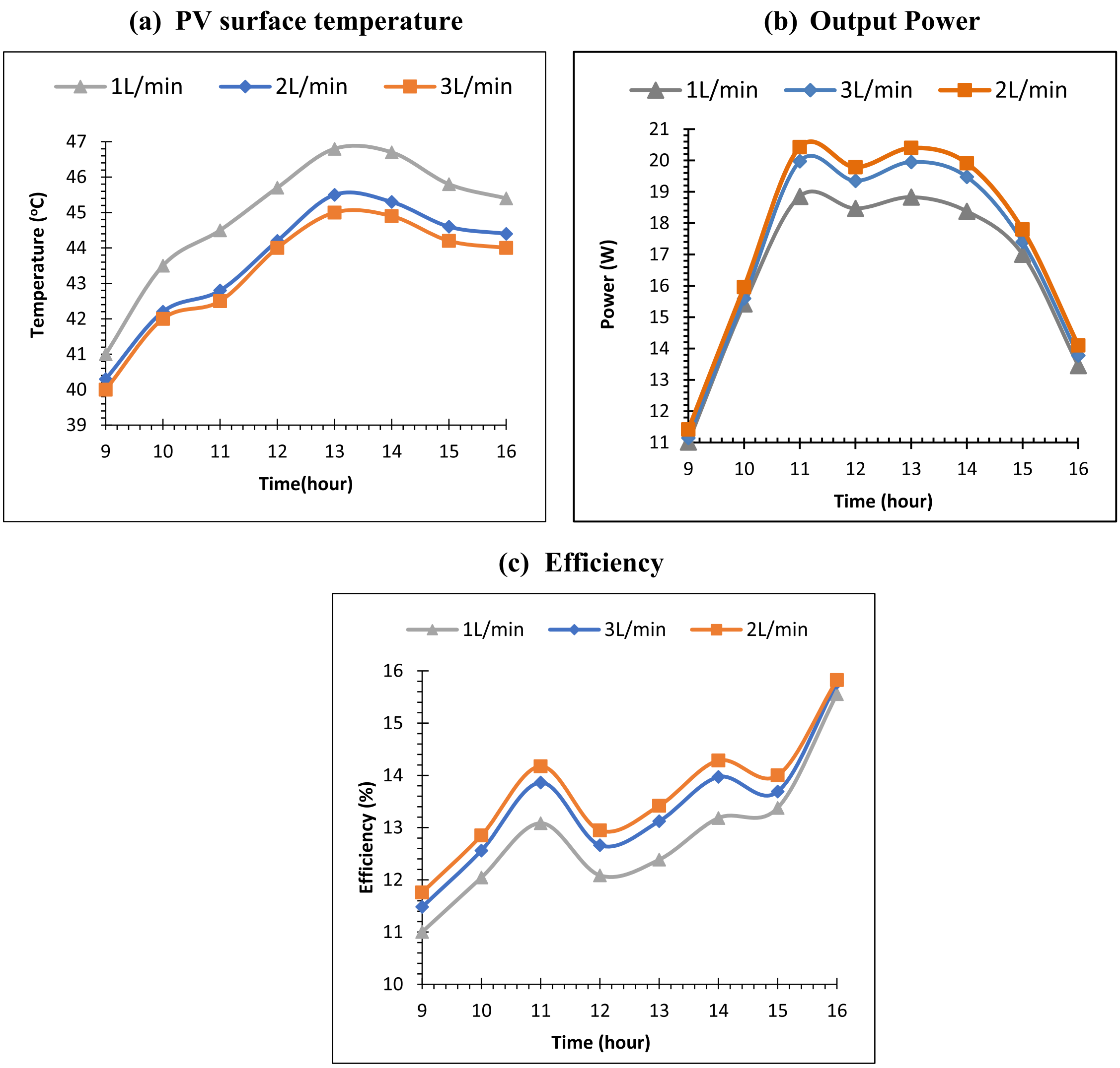


Fig. 12. Experimental results for (a) PV surface temperature, (b) power output, and (c) efficiency at different volume flow rates with a porosity size of 0.35.

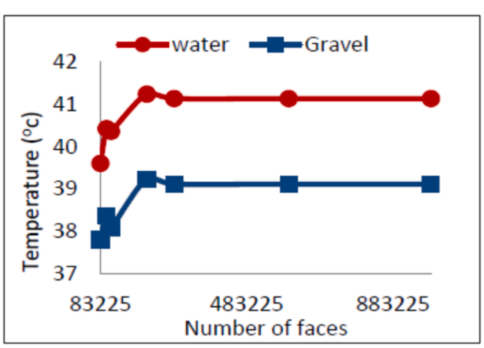


Fig. 13. Effect of mesh node number on temperature outcomes.

represents the fluid velocity. As the height differential between the inlet and outlet sections changes, the fluid velocity increases at the outlet, enhancing the heat transfer from the PV cells to the coolant. This results in a significant reduction in the panel's temperature, particularly at the end of the cooling channel.

Overall, this innovative heterogeneous cooling channel design holds great potential for improving heat transfer dynamics, cooling efficiency, and PV panel performance. By increasing fluid velocity through height adjustments along the cooling channel, the system facilitates enhanced heat dissipation, reducing PV panel temperatures and ultimately improving energy output.

- Case III: The Effect of Coolant Types

In Figs. 22 and 23, a detailed experimental analysis was conducted to assess the temperature variation within a PV panel using three distinct coolants: water, chemical alcohol, and engine oil. The experiments were carried out under controlled conditions, including a porosity size of 0.35, a volume flow rate of 2 L/min, and solar radiation levels ranging from 350 to 1000 W/m^2, uniformly applied across all coolant types. As expected, the temperature of the PV panel increased progressively with higher solar radiation levels. This trend was consistent across all coolant types, as shown in Fig. 22. However, the rate of temperature increases varied depending on the coolant's thermal properties. At the maximum solar radiation level of 1000 W/m^2, water achieved the lowest maximum temperature of 36.6 °C, followed by chemical alcohol at 37.8 °C, and engine oil at 39 °C. This demonstrates that the choice of coolant significantly impacts the PV panel's thermal performance, particularly under high solar radiation conditions.

The effectiveness of a coolant in dissipating heat is largely determined by its thermal conductivity and heat capacity. Water, with its high thermal conductivity and specific heat capacity, proved to be the most effective coolant, maintaining the lowest PV panel temperature.

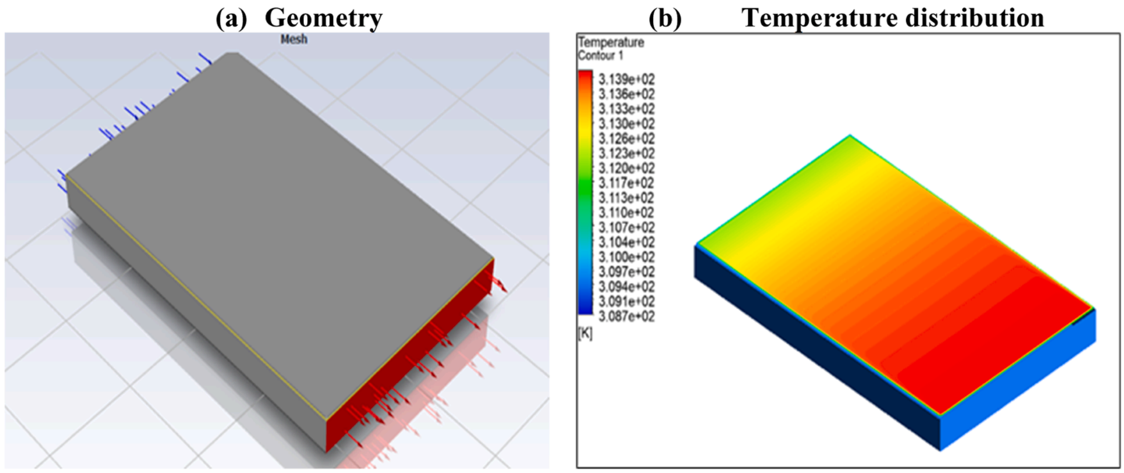


Fig. 14. Inlet and outlet boundary conditions and temperature distribution of the PV panel: (a) rectangular geometry, (b) temperature distribution.

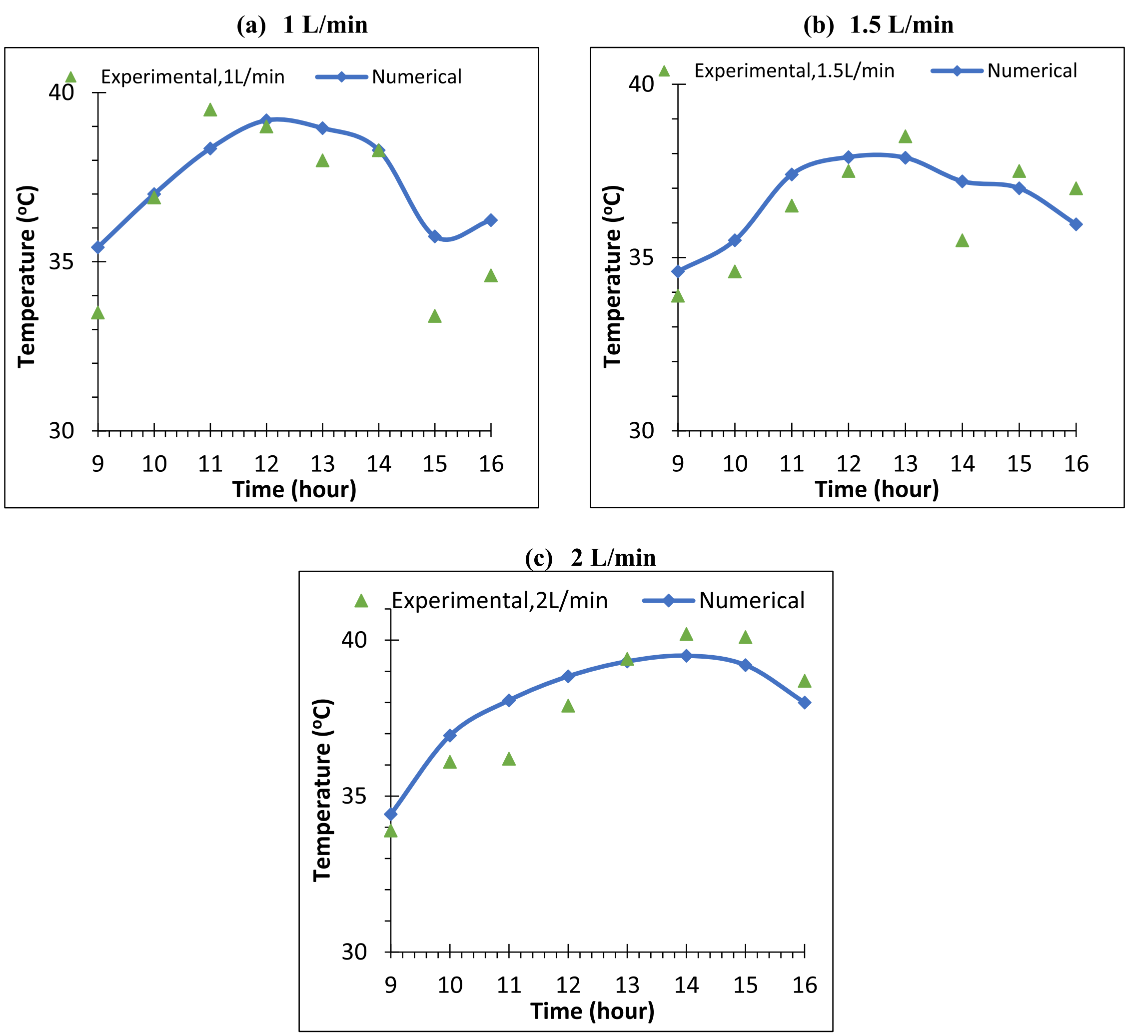


Fig. 15. Validation of numerical results through comparison with experimental data at different volume flow rates: (a) 1 L/min, (b) 1.5 L/min, (c) 2 L/min.

Chemical alcohol, while also effective, exhibited slightly lower thermal performance due to its lower thermal conductivity and heat capacity compared to water. Engine oil, with the lowest thermal conductivity and heat capacity among the tested coolants, resulted in the highest PV panel temperature. This highlights the importance of selecting coolants with favorable thermal properties for efficient heat dissipation.

The convective heat transfer coefficient (h) plays a pivotal role in determining the efficiency of heat dissipation. As highlighted by the equation $q''_{conv} = h\Delta T = h(T_s - T_\infty)$, the rate of heat transfer is directly proportional to the convective heat transfer coefficient and the temperature difference between the surface and the fluid. Higher thermal conductivity in the coolant leads to an increased convective heat

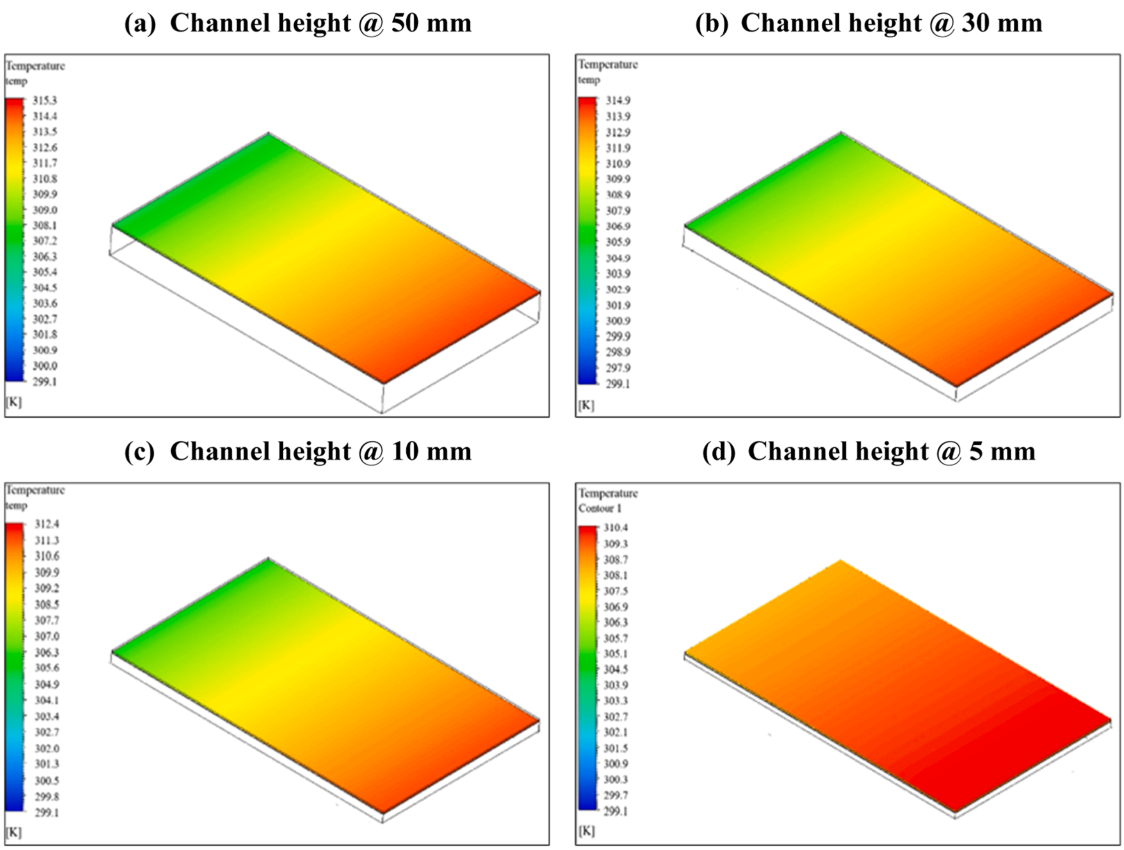


Fig. 16. Temperature variation in PV panels at different cooling channel heights: (a) 50 mm, (b) 30 mm, (c) 10 mm, and (d) 5 mm.

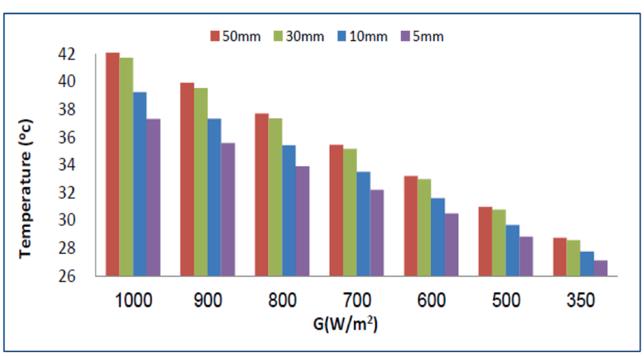


Fig. 17. PV temperature with different solar radiation at different cooling channel heights.

transfer coefficient, as demonstrated by Eq. (21). This facilitates more efficient heat transfer from the PV panel to the coolant. Additionally, the Reynolds number, which is influenced by the fluid's density and viscosity, affects the flow behavior and heat transfer characteristics of the coolant. Eq. (24) illustrates the direct correlation between fluid density and the Reynolds number, emphasizing the need to consider fluid dynamics in the design of cooling systems. Coolants with optimal density and viscosity can enhance fluid flow and improve heat transfer efficiency.

The specific heat capacity (*Cp*) of a coolant is a critical factor in temperature regulation. As shown by the equation $Q = \text{m.Cp.}\Delta\text{T}$, the amount of heat absorbed by a coolant is directly proportional to its specific heat capacity. Coolants with higher heat capacities can absorb more heat per unit mass, leading to better temperature control and more stable thermal conditions for the PV panel. Water's high specific heat capacity makes it an ideal coolant for maintaining lower temperatures, while engine oil's lower heat capacity limits its effectiveness in heat absorption.

The thermal management of PV panels is crucial for maintaining optimal energy conversion efficiency. Excessive temperatures can lead to a reduction in the electrical output of PV panels, as higher temperatures increase the semiconductor's intrinsic carrier concentration, leading to higher recombination rates and lower open-circuit voltage. By selecting coolants with high thermal conductivity and heat capacity, such as water, the PV panel's operating temperature can be effectively regulated, thereby enhancing its overall efficiency and longevity.

When selecting a coolant for PV panel cooling systems, it is essential to consider the following properties: (i) Thermal conductivity: Higher thermal conductivity facilitates efficient heat transfer from the PV panel to the coolant; (ii) Specific heat capacity: Coolants with higher heat capacities can absorb more heat, leading to better temperature regulation; (iii) Density and Viscosity: Optimal fluid density and viscosity enhance fluid flow and heat transfer efficiency; and (iv) Chemical Stability: The coolant should be chemically stable under operating conditions to prevent degradation and ensure long-term performance.

Future research could explore the potential of hybrid cooling systems that combine different coolants or incorporate PCMs to further enhance thermal management. For example, a hybrid system using water as the primary coolant and a PCM for latent heat storage could provide more stable temperature control under varying solar radiation conditions.

While water is an effective coolant, its availability and environmental impact must be considered, especially in arid regions. Alternative coolants, such as nanofluids or biodegradable oils, could be investigated for their thermal performance and environmental sustainability. Additionally, the economic feasibility of different coolants should be evaluated to ensure cost-effective solutions for large-scale PV installations.

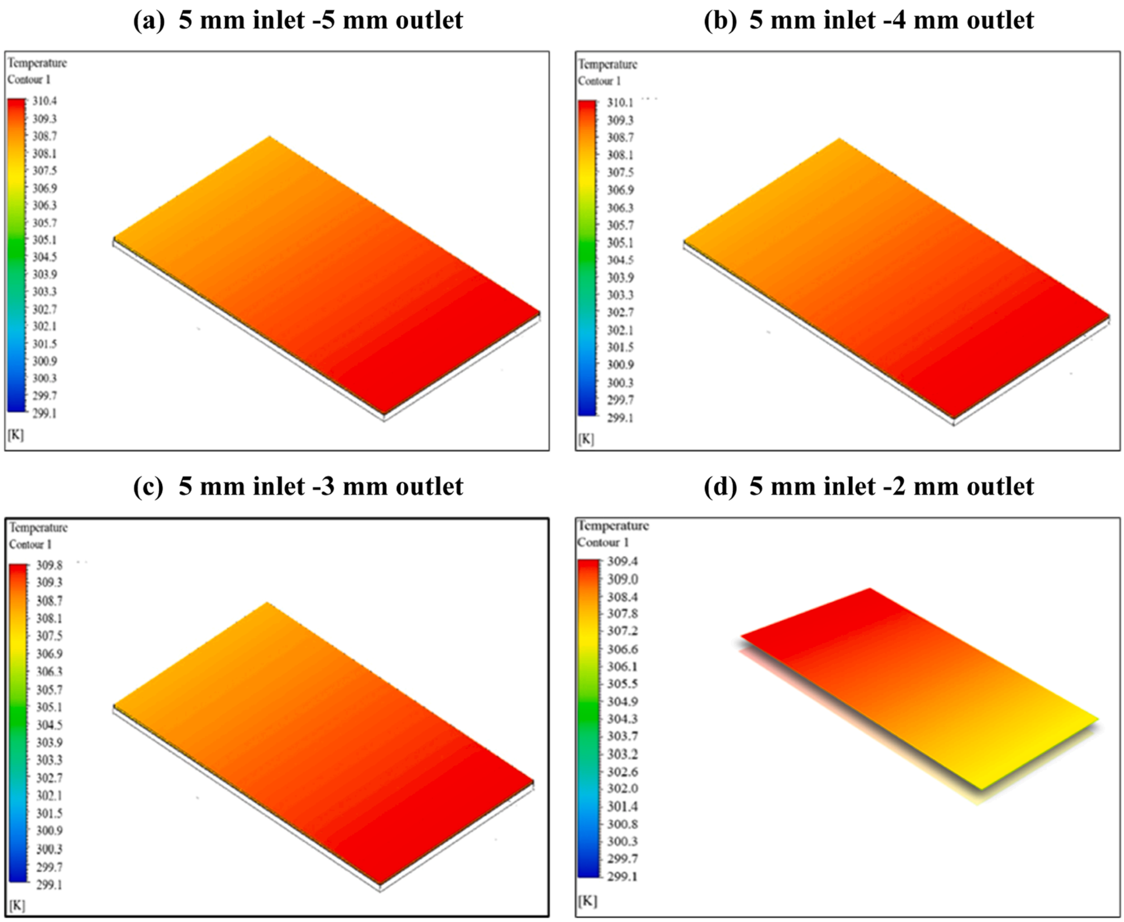


Fig. 18. PV Temperature Distribution for Different Cooling Channel Shapes and Configurations.

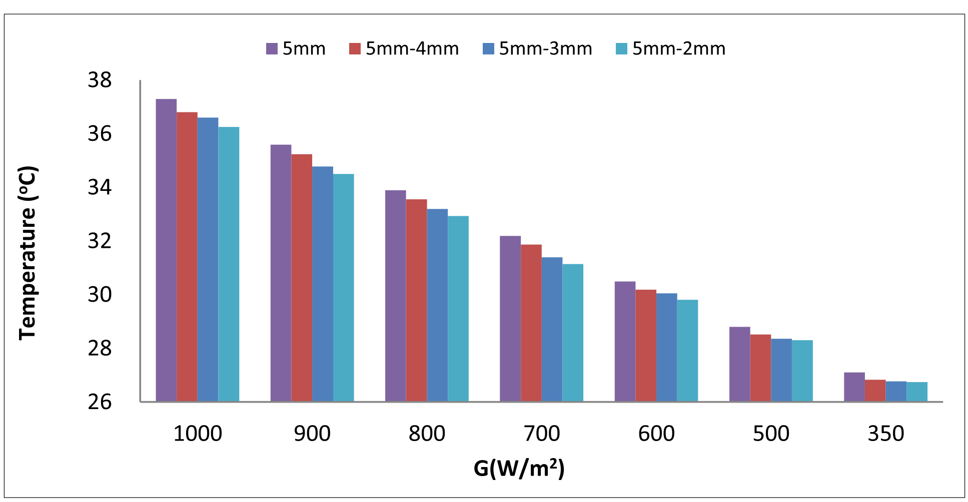


Fig. 19. Comparative analysis of cooling channel configurations and PV temperature variations with solar radiation levels.

- The effect of the porous media types

Fig. 24 highlights the significant influence of porous media selection on the maximum surface temperature of PV panels, particularly under a solar irradiation level of 1000 W/m^2. The study compares the cooling performance of various media types, including sandstone, flint, marble, and gravel, each exhibiting distinct temperature variations. Fig. 25 further illustrates the temperature differences in the PV panel based on solar radiation and the type of porous media used. Among the media types tested, sandstone demonstrated the most efficient cooling, resulting in the lowest maximum PV temperature of 35.66 °C. Flint followed closely, with a maximum temperature of 35.89 °C, while marble recorded 35.94 °C. Gravel, on the other hand, resulted in the highest maximum temperature of 36.6 °C. These findings suggest that all the materials tested can be adapted for PV cooling; however, sandstone proved to be the most effective choice. The variation in cooling performance among the porous media is primarily attributed to differences in their thermal conductivity. Materials with higher thermal

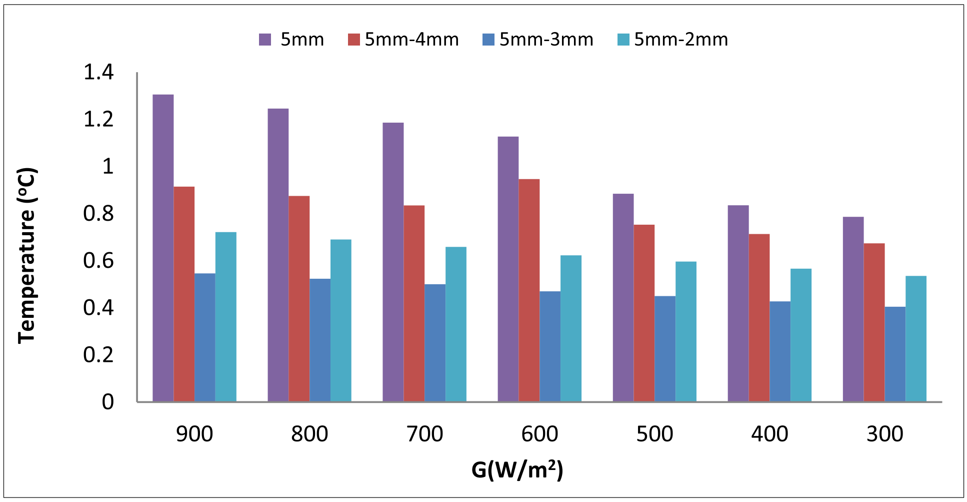


Fig. 20. Differences in PV temperature with the solar radiation for fixed inlet height and different outlet heights.

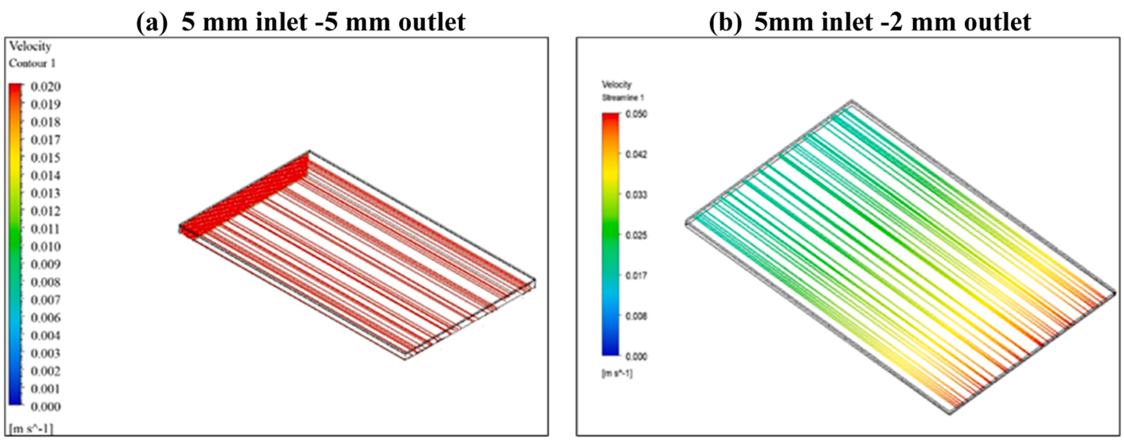


Fig. 21. Effect of outlet height on fluid velocity and flow dynamics within the cooling channel.

conductivity, such as sandstone, facilitate more efficient heat dissipation from the PV panel, leading to lower surface temperatures. In contrast, materials with lower thermal conductivity, like gravel, are less effective at transferring heat, resulting in higher PV temperatures. This relationship is critical for optimizing the thermal management of PV systems.

Porous media enhance cooling through a combination of conduction, convection, and radiation. The interconnected pores within the media increase the surface area available for heat exchange, improving the overall heat transfer efficiency. Additionally, the flow of coolant (e.g., air or water) through the porous structure further enhances convective heat transfer. The thermal conductivity of the media directly influences these mechanisms, making it a key parameter for selecting the most effective cooling material.

When selecting porous media for PV cooling applications, the following properties should be considered: (i) Thermal conductivity: Higher thermal conductivity enhances heat dissipation, leading to lower PV temperatures; (ii) Porosity and permeability: Optimal porosity and permeability improve fluid flow and heat transfer within the media; (iii) Mechanical stability: The media should be mechanically stable to withstand environmental conditions and long-term use; and (iv) Cost and availability: The material should be cost-effective and readily available for large-scale applications.

Future research could explore the development of composite porous media that combine materials with complementary properties. For example, a composite of sandstone and metal particles could enhance thermal conductivity while maintaining structural integrity.

In summary, selecting porous media with higher thermal conductivity is vital for improving the cooling performance of PV panels. Accordingly, higher thermal conductivity enhances heat transfer away from the panels, helping to maintain lower operating temperatures. This, in turn, improves the overall performance and extends the lifespan of the PV system.

Fig. 26a demonstrates that as temperature decreases, energy output from solar systems increases. This figure highlights the inverse relationship between temperature and energy production efficiency, showing that lowering the temperature improves solar system performance and boosts energy production. Similarly, Fig. 26b further illustrates the combined effects of temperature and solar irradiance on system efficiency. While higher solar irradiance levels generally increase energy production, the efficiency gains are significantly amplified in cooler environments. This is because lower temperatures reduce the internal resistance of solar cells, allowing them to convert a higher proportion of incident solar energy into electrical energy. The figure highlights that the optimal operating conditions for solar systems involve high solar irradiance coupled with low ambient temperatures.

These figures emphasize the importance of temperature control in optimizing solar system efficiency. Fig. 26 illustrates how favorable climatic conditions, particularly lower temperatures, can enhance performance and energy output. Fig. 26 further highlights the impact of environmental factors like temperature and solar irradiance, indicating that improved performance occurs with cooler temperatures and higher

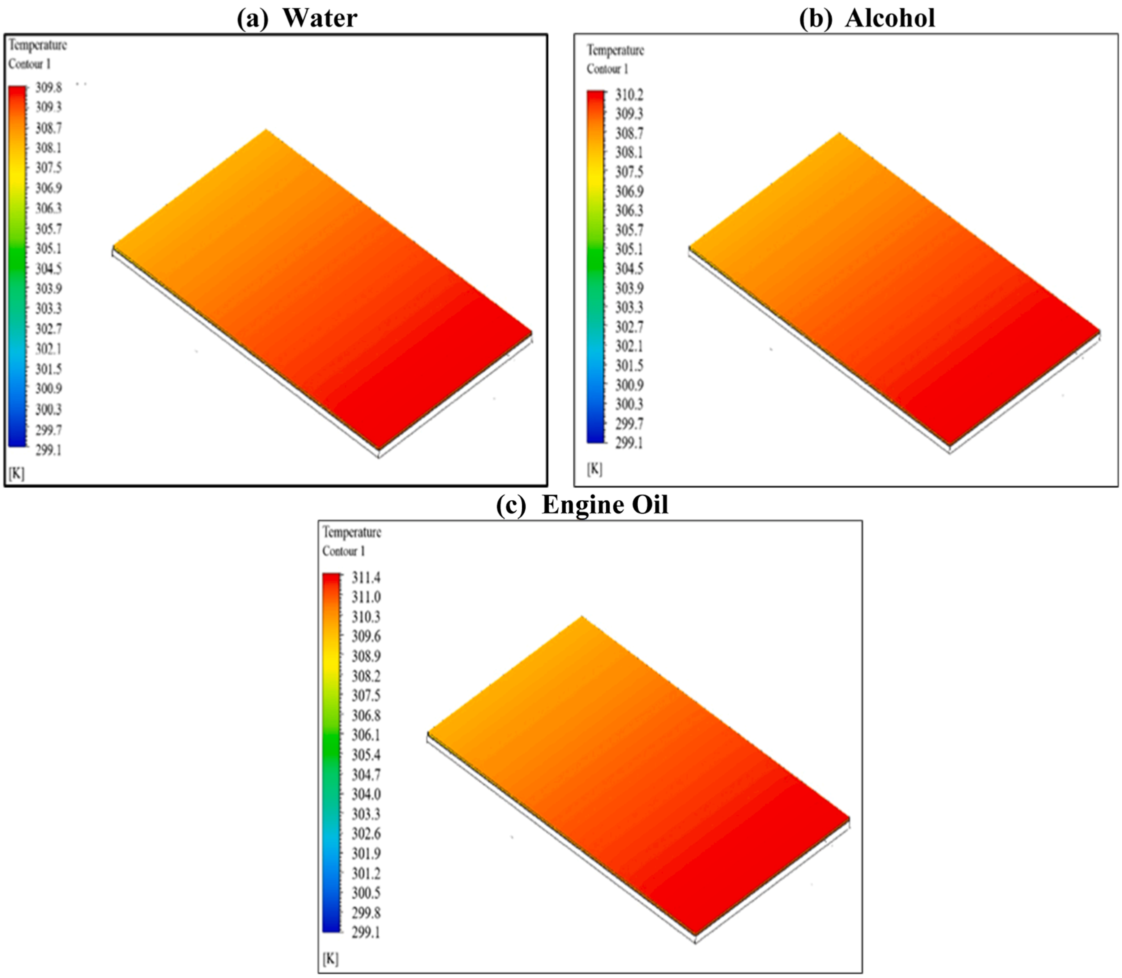


Fig. 22. PV temperature distribution for different coolant types.

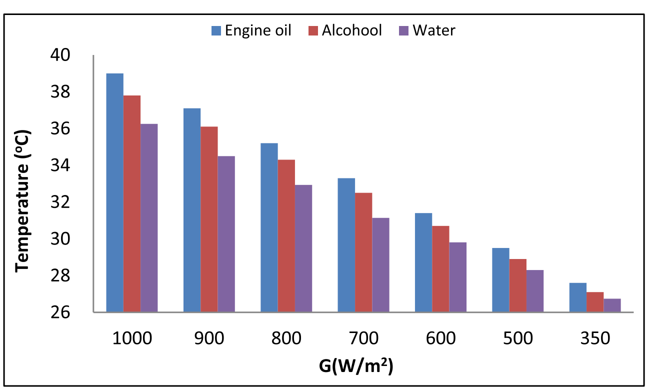


Fig. 23. PV temperature difference with solar radiation for different coolant types.

irradiance. The findings highlight that cooling solar systems effectively can significantly improve their efficiency and energy output. Future solar system designs should take temperature into account and explore innovative cooling methods to sustainably enhance system efficiency.

4. Comparison between current and previous studies

Table 6 presents a comprehensive comparison between the results of studies in the literature and the current research. The comparison highlights the superior performance of the current study in two key areas: temperature reduction and power output enhancement. Regarding temperature reduction, the current research achieved an impressive decrease of 22 °C, surpassing the best results from previous studies, which reported reductions between 15 °C and 19 °C. This improvement can be attributed to the innovative cooling techniques employed in the current study, which effectively mitigate the temperature rise in PV cells. The use of efficient cooling strategies has ensured lower PV temperatures, promoted optimal operating conditions and reduced the risk of performance degradation and efficiency loss. As a result, the electrical output remains stable and reliable over time.

In addition, the current study excels in boosting the output power of PV panels. By employing advanced technologies and precise thermal management techniques, the study has significantly enhanced the power output of solar panels. This improvement is critical, as it directly contributes to increased energy efficiency and more effective use of solar energy resources. The findings of this study are of particular significance for applications in residential, commercial, and industrial solar energy systems. Enhanced temperature regulation and increased power output lead to higher energy yields, making solar technologies more attractive and viable for widespread adoption.

It is important to note that advancements in technology, meticulous experimental approaches, and comprehensive data analysis have played pivotal roles in achieving the current study's outcomes. By comparing these findings with previous research, areas for further improvement have been identified, leading to the implementation of new strategies that overcome previous limitations and drive continued progress in the field.

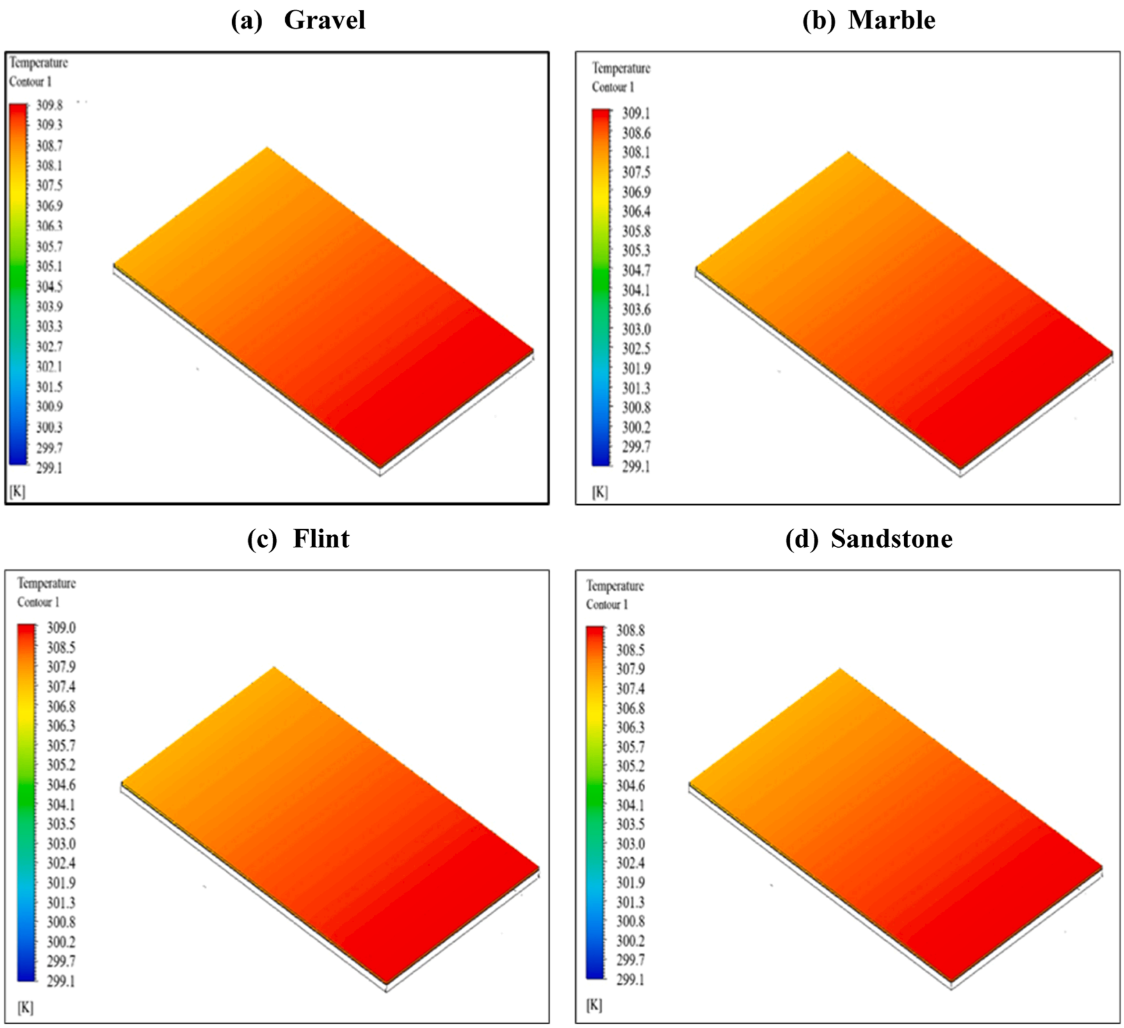


Fig. 24. PV temperature distribution for different coolant types; (a) gravel; (b) marble; (c) flint; and (d) sandstone.

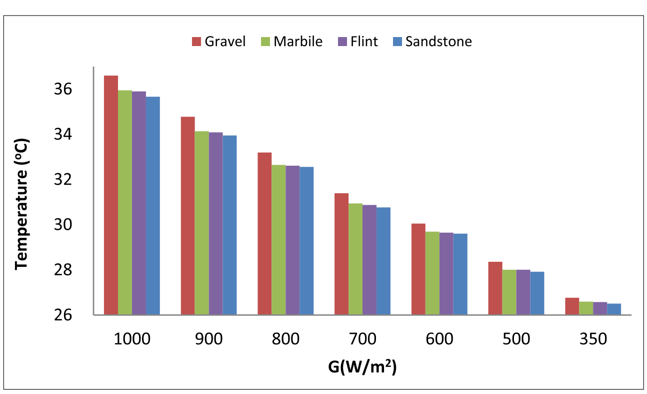


Fig. 25. Difference in surface PV panel temperature with solar radiation and porous media type.

5. Conclusions

This study aimed to explore the effectiveness of porous media cooling techniques in enhancing the performance of PV panels under real-world conditions. The objectives of the research were to evaluate the impact of cooling strategies involving porous media, identify optimal cooling parameters (such as porosity size, flow rate, and coolant types), and provide insights into cooling channel designs that maximize PV panel performance. A combination of experimental tests and numerical simulations using ANSYS software was employed to achieve these objectives. The experimental setups involved varying key parameters, such as porosity sizes (ranging from 0.35 to 0.5), flow rates (1 to 4 L/min), and coolants (water, chemical alcohol, engine oil).

ANSYS software was employed to examine the impact of various parameters on PV cooling using porous media. The parameters investigated included the height of the cooling channel, which varied between 50 mm and 5 mm, as well as the shape of the channel, achieved by adjusting the outlet height from 4 mm to 2 mm while keeping the inlet height fixed at 5 mm. The study also considered different coolants, as well as various types of porous media, including gravel, marble, flint, and sandstone. The key findings of this study are summarized as follows:

- The most effective cooling combination was found to be a porosity size of 0.35, a flow rate of 2 L/min, and water as the coolant. Under these conditions, surface temperatures decreased by 35.7 %, and power output increased by 9.4 %.
- The optimal cooling channel design included a channel height of 5 mm at the inlet and 3 mm at the outlet. This configuration, combined with the optimal porosity and flow rate, improved cooling efficiency.
- Temperature reductions of 35.7 °C, 34.8 °C, and 34 °C were observed for porosity sizes of 0.35, 0.4, and 0.48, respectively, with corresponding power gains of 9.4 %, 7.8 %, and 6.2 %.
- A flow rate of 2 L/min was identified as optimal, balancing temperature reduction and power output. Higher flow rates (3 L/min and

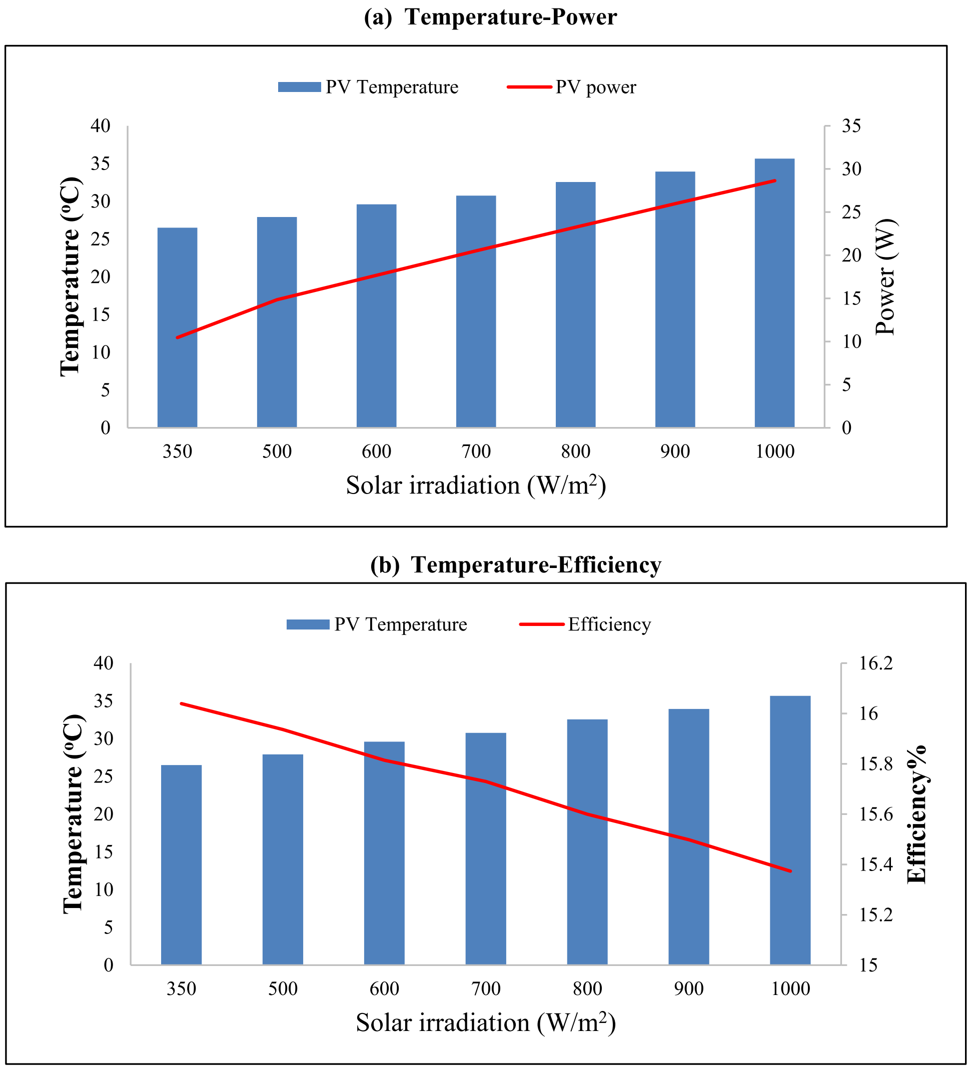


Fig. 26. Variation of PV panel (a) temperature and power, and (b) temperature and efficiency with solar radiation difference.

4 L/min) showed improvements, but with diminishing returns compared to 2 L/min.

- Numerical simulations conducted using ANSYS software were validated with experimental data, showing less than a 3 % deviation in temperature predictions, confirming the reliability of the simulation results.
- The results from the ANSYS simulation showed that the PV temperature was 36.6 °C, which was obtained with a cooling channel height of 5 mm at the inlet and 3 mm at the outlet, using water as the coolant and sandstone as the porous media. The optimized porosity size and volume flow rate were 0.35 and 2 L/min, respectively.

The findings of this study have significant practical applications for the design and optimization of PV systems, particularly in regions with high solar irradiance and elevated ambient temperatures. The key applications include:

- Implementing porous media cooling can significantly enhance energy output and system longevity, making large solar farms more efficient and economically viable.
- Cooling-enhanced PV systems can improve efficiency in urban environments, particularly in high-temperature regions where overheating is a concern.
- The passive cooling approach using porous media can be an effective solution for maintaining PV efficiency in remote areas with limited access to active cooling technologies.
- Integrating PV cooling with other renewable energy sources, such as solar-thermal hybrid systems, could lead to improved energy management and sustainability in smart grid applications.

Future research could focus on evaluating the performance of advanced porous materials, such as metal foams or aerogels, which may offer superior thermal conductivity and enhance cooling efficiency in PV systems. Additionally, integrating machine learning algorithms, like neural networks or support vector machines, with experimental and simulation data could help predict optimal cooling configurations for PV systems under varying operating conditions. Furthermore, combining machine learning with advanced optimization techniques, such as genetic algorithms, particle swarm optimization (PSO), or simulated annealing, could automate the identification of the most effective cooling strategies for PV systems. Another important avenue for future investigation is studying the long-term effects of porous media on the aging of PV panels, including potential impacts on panel degradation and efficiency loss over time.

CRediT authorship contribution statement

Ismail Masalha: Writing – original draft, Software, Methodology,

Table 6
Comparison of results from literature and the current study on effective cooling techniques for reducing surface temperature of PV panels.

Reference	Cooling Method/ Coolant	Reduction of temperature (°C)	Increase in output power (%)
Tang et al. (2010) [87]	Air	4.7 °C	8 %
Moradgholi et al. (2014) [88]	Methanol	13 °C	5 %
Smith et al. (2014) [89]	Water	11 °C	6 %
Micheli et al. (2015) [90]	Air	13 °C	7.7 %
Hasan et al. (2016) [91]	PCM	10 °C	6.6 %
Ebaid et al. (2018) [38]	Nanofluied	20 °C	9 %
Lin et al. (2019) [92]	Air	4 °C	7 %
Abdelrazik et al. (2022) [93]	NP-PCMs	3.9 % drop in Temperature	2.65 %
Aslfattahi et al. (2022) [94]	NP-PCMs	2.7 % drop in temperature	1.33 %
Ahmed et al. (2023) [95]	Water	–	7 %
Alsaqoor et al. (2023) [17]	PCM-PVT	20.5 °C	Up to 14 %
Al-Masalha et al. (2024) [96]	Water	7.7	7.4 %
Mahdi et al. (2024) [36]	Modified PVT-HAWSC system with PCM, porous media, and NF	28 °C	28.8 %
Current work	Porous media	22 °C	14.4 %

Investigation, Formal analysis, Conceptualization, Writing – review & editing. **Siti Ujila Masuri:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Omar Badran:** Writing – original draft, Investigation, Conceptualization, Validation. **Ali Alahmer:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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