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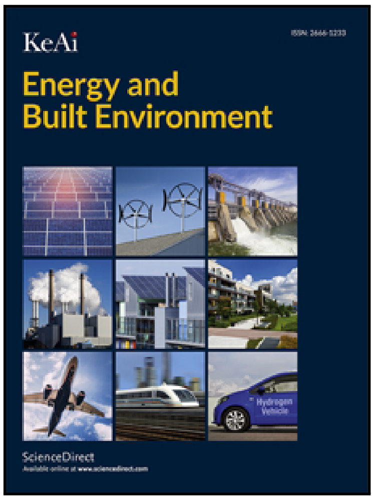

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PII: S2666-1233(25)00032-7
DOI: https://doi.org/10.1016/j.enbenv.2025.04.004
Reference: ENBENV 392

To appear in: *Energy and Built Environment*

Received date: 27 January 2025
Revised date: 13 April 2025
Accepted date: 14 April 2025

Please cite this article as: Aamir Sohail , Muhammad Waseem , Mohd Syakirin Rusdi , Mohd Zulkifly Abdullah , Sakhr M. Sultan , Numerical Analysis of Counter-Flow Converging Channels for Uniform Temperature Distribution in PV Panels to Enhance Energy Conversion Efficiency, *Energy and Built Environment* (2025), doi: https://doi.org/10.1016/j.enbenv.2025.04.004

HIGHLIGHT

- Counterflow converging channels enhance PV cooling efficiency.
- Most converging channel cut temperature by 23.73 K at 1050 W/m^2.
- Standard deviation fell from 1.7944 K to 1.1131 K in optimized design.
- Higher convergence improves uniformity, reducing temperature variation.

Numerical Analysis of Counter-Flow Converging Channels for Uniform Temperature Distribution in PV Panels to Enhance Energy Conversion Efficiency

Aamir Sohail[1,2], Muhammad Waseem[3], Mohd Syakirin Rusdi[1*], Mohd Zulkifly Abdullah[1], Sakhr M. Sultan[4]

1 School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia

2 Department of Mechanical Engineering, University of Engineering and Technology Taxila, 47050, Taxila, Pakistan

3 International Renewable and Energy Systems Integration Research Group (IRESI), School of Business, Maynooth University, Co. Kildare, Ireland

4 Solar Energy Research Institute, Universiti Kebangsaan Malaysia, Bangi, 43600, Selangor, Malaysia

* Corresponding author (syakirin@usm.my)

Abstract

Effective thermal management is crucial for enhancing photovoltaic efficiency, especially under high solar irradiation. Traditional water-cooling methods, including serpentine tubes and parallel channels, face challenges like temperature inhomogeneity. Recent innovations, such as porous cooling channels, fin turbulators, and converging geometries, improve temperature uniformity and photoelectric conversion efficiency. While limited research exists on converging channels, no studies have explored counter-flow converging channels for PV cooling. This study employs Ansys Fluent 2024 R2 to assess counter-flow converging water channels as an alternative cooling method. The impact of various convergence angles on temperature reduction is analysed under irradiation levels from 600 W/m² to 1050 W/m², demonstrating significant improvements over uncooled PV panels. Findings demonstrate that channels with larger convergence angles consistently exhibit enhanced thermal performance compared to those with smaller angles. Under an irradiance of 600 W/m², the channel with a 1.28° convergence angle achieved a temperature reduction of 13.24 K, surpassing the 11.45 K decrease observed in the straight channel. This disparity became more pronounced under higher irradiance conditions, such as 1050 W/m², where the maximum convergence angle channel achieved a temperature drop of 23.73 K, compared to 20.55 K for the straight channel. Furthermore, increasing the convergence ratio improves temperature uniformity across the solar cell, as indicated by lower standard deviation values at higher angles, which helps reduce thermal stress and enhance the panel's operational stability. However, increasing the convergence ratio also raises the pressure drop, leading to higher pumping power requirements and operational costs. The optimal channel design must balance thermal and hydraulic efficiency to maximize cooling effectiveness while minimizing energy consumption.

Keywords: Water cooling; Counter-flow; Converging water channels; CFD simulations; PV thermal management

Abbreviations:		**Nomenclature:**	
PV	Photovoltaic	τ	Transmissivity
PVCE	Photovoltaic conversion efficiency	α	Absorptivity
TI	Turbulence intensity	ε	Emissivity
PVSFs	Perforated V-shaped fins	γ	Thermal coefficient
LCPV	Low-concentrator photovoltaic	η	Efficiency
Re	Reynolds number	h	Heat transfer coefficient
CFD	Computational fluid dynamics	V	Velocity
EVA	Ethylene vinyl acetate	k	Thermal conductivity
		G	Solar Irradiance
Subscripts:		ρ	Density
s	solar	μ	Dynamic viscosity
t	top		
b	bottom		
c	cell		
ref	reference		
g	glass		
out	output		

1 Introduction

The swift initiatives to facilitate the energy transition depend on advancements in the adoption of renewable energy technology, particularly solar photovoltaics (PVs). Solar photovoltaic technology is an economical, low-maintenance, and sustainable method for advancing clean energy. Moreover, it exhibits intermittent characteristics that necessitate supplementary energy storage devices for reliable power consumption and to mitigate load curtailment. As augmenting energy storage systems is not always feasible, optimizing solar power generation by ensuring the solar PV panel operates at peak efficiency is the preferred approach [1]. 13–20% of solar irradiance is converted to electric power by commercially available PV panels [2], [3]. The residual absorbed radiation is converted into thermal energy, resulting in a significant boost in the temperature of the solar cell [4]. Nonetheless, the operational temperature of solar panels is a crucial determinant of their total photovoltaic conversion efficiency (PVCE) [5].

Research studies unequivocally demonstrate that temperature severely impacts the efficiency deterioration of photovoltaic panels, exceeding all other factors [6], [7], [8]. The rise in temperature of solar panels affects their longevity due to thermal cycling induced by massive temperature fluctuations. At elevated temperatures, the elevated thermal energy in the semiconductor material intensifies electron excitation, resulting in random electron movement, which boosts electrical resistance and diminishes voltage output [9]. Consequently, the overall efficiency of the photovoltaic cell drops as the temperature increases [10]. Therefore, appropriate cooling systems must be integrated with photovoltaic panels to manage thermal energy, thereby enhancing the effective operating PVCE [11], [12]. The temperature distributions on the PV panel are remarkably impacted by the features of the adopted heat dissipation system [13]. Several researchers have insinuated various approaches and cooling solutions to improve the efficiency of photovoltaic panels by dropping the cell temperature near their standard temperature.

The selection of a cooling fluid for heat dissipation in photovoltaic panels plays a crucial role in enhancing system performance [14]. Water, being widely available and highly effective in heat removal, is commonly utilized, significantly improving the efficiency of solar systems by mitigating excess thermal buildup. Techniques such as water piping and cooling channels enhance the management of temperature and system efficiency by efficiently dispensing heat from photovoltaic systems [3], [15], [16], [17]. Experimental and numerical investigations were performed to cool polycrystalline photovoltaic panels utilising a flowing water layer on both the front [18] and rear surfaces [19]. The findings showed how cooling the solar panels resulted in superior power output. Alktranee et al. [20] investigated the influence of deionized water cooling on PVCE through experimental and computational studies. The initial uncooled efficacy of the PV module was reported at 5.75%, which later increased to 6.3%. Salem et al. [21] assessed the productivity of a photovoltaic system integrating straight and helical channel aluminium cooling plates. Their research proved that advancing the flow velocity of the cooling water results in a decline in the temperature of the PV system. The PVCE of the straight channels increased from 17.7% to 31.1%, while the helical configurations increased from 20% to 38.4% compared to the uncooled solar panel.

Solar panels are very sensitive to temperature, and their efficiency decreases significantly under thermal stress. To date, conventional water-cooling systems have been extensively employed for cooling solar panels, including designs such as serpentine tubes [22], spiral tube arrangements [23], water film cooling methods [24], and parallel channel heat exchangers [25]. These usually cause problems with temperature inhomogeneity, especially at the leaving points. The limitation common to all these techniques is the one-way and constant area flow of water within the cooling channels. As water enters the system, absorbing thermal energy from the solar panel, it cools the surface at the beginning. Water accumulates heat as it moves further downstream, and its temperature rises gradually. This results in a continuous reduction of the cooling capability of the fluid along the flow path. Therefore, the cooling effect is noticeable in the near region of the inlet, and an area nearer to the outlet end suffers due to insufficient cooling, which brings an overall non-homogeneous temperature. The temperature gradient creates the thermal hotspot with which the performance and life expectations of the panel go down. Further, thermal stresses resulting from this hot spot might degrade the photovoltaic cells and diminish their maximum power output or shrink the systems' total service life. This problem is further exacerbated by the deteriorating efficiency of the cooling fluid with more prolonged exposure to harsh sunshine, especially in regions with high solar irradiation. Fig. 1 illustrates the dispersed patterns of irregular temperature resulting from different water-based PV cooling methods.

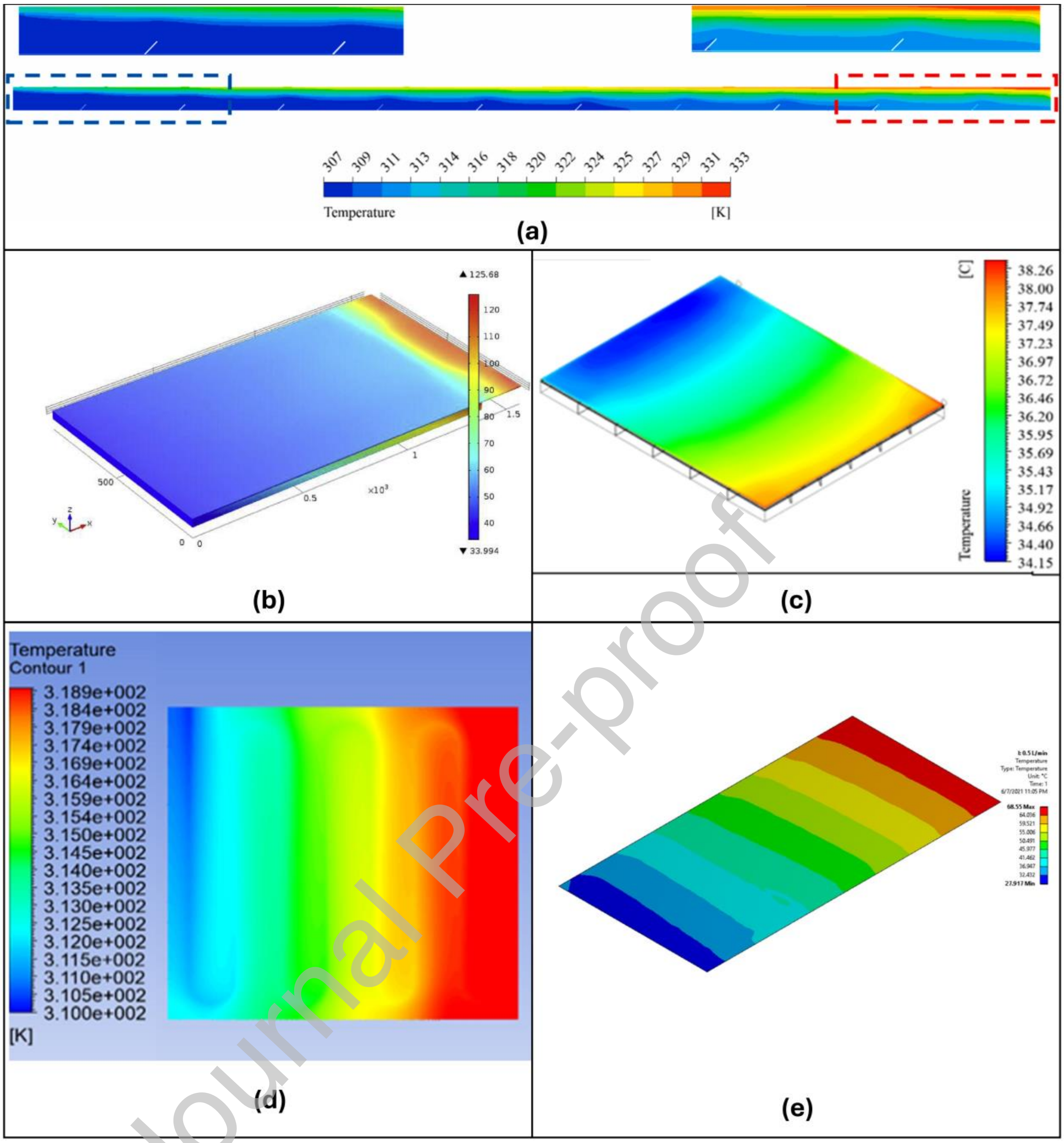

Figure 1: Uneven temperature distribution observed in various water-cooling strategies for photovoltaic systems: (a) Single-channel cooling PV system incorporating baffles demonstrating thermal imbalances [26] (b) Parallel plate flow channel operating under typical climatic conditions in Malaysia [27] (c) Water cooling channels with fins [28] (d) Serpentine channel with absorber plate [22] (e) Box heat exchanger [29]

In contrast to traditional water-cooling channels, researchers are progressively exploring novel channel designs to enhance temperature uniformity in PV panels. These advanced designs aim to minimize thermal gradients across the panel surface, reducing efficiency losses caused by localized hotspots. Zhang et al. [30] examined porous cooling channels utilised in solar systems to enhance the inefficient heat transfer observed in traditional channels. The findings indicated that non-uniformly distributed holes near the cooling water outflow enhanced the cooling effect, with a hole diameter of 0.005 m yielding optimal performance. The innovative cooling channel exhibited enhanced cooling performance relative to the traditional cooling channel, with an overall efficiency exceeding that of the conventional channel by around 4%. Selimefendigil and Öztop [31] conducted a comparative analysis of various cooling systems, demonstrating that channel cooling with a porous layer and wavy walls exhibited the highest cooling efficiency. This approach achieved a temperature reduction of 37.6 °C, surpassing the performance of hollow fin, flat fin, and conventional systems, which achieved reductions of 37°C, 33.6°C, and 29°C, respectively. Attia et al. [32] conducted a numerical investigation and comparative performance analysis of PV cooling systems utilizing both natural air and a TiO_2-water nanofluid across two finned and non-finned cooling channel configurations. The study evaluated the thermal efficiency of both cooling mediums, revealing that under a continuous TiO_2-water flow rate of 0.015 kg/s, the finned configuration achieved a thermal efficiency of 78.6%, whereas the non-finned counterpart exhibited a lower efficiency of 70.8%.

To improve the thermal regulation of PV systems, a series of innovative cooling modules were developed, featuring fin turbulators within a serpentine channel located on the rear side of the PV module [28]. These modules were explicitly developed to optimise heat dissipation, guaranteeing a more consistent temperature distribution and thereby improving PVCE. The incorporation of 30° angled fins yielded an increase in PVCE of roughly 0.9%-1.9% relative to traditional PV backside water channels without fins. Alqatamin et al. [33] evaluated the performance of novel water channels having perforated V-shaped fins (PVSFs), demonstrating significant improvements in cooling efficiency and PVCE. The PVSFs cooling system reduced solar cell temperature by 31.27% and achieved a maximum electrical efficiency of 18.79%, outperforming other configurations due to its innovative fin design and enhanced heat dissipation. Attia et al. [34] introduced a revolutionary cooling approach for photovoltaic systems, tackling surface temperature variability using an innovative zigzag cooling channel design. The suggested design, which segmented the cooling channel into uniformly spaced mini zigzag-plated tube sections, including multiple reciprocal inlets and outlets, exhibited enhanced thermal performance relative to a traditional straight zigzag channel. The findings indicated that the optimized design improves PVCE by 4% and 4.6% for water- and air-based PV systems, respectively, highlighting its potential for improving solar panel cooling performance.

Converging channels enhance heat transfer by increasing fluid velocity and turbulence, which improves convective heat transfer efficiency. This leads to lower surface temperatures and more uniform temperature distribution, making them effective for thermal management applications [35]. Baloch et al. [36] performed experimental and numerical analyses to assess the cooling effectiveness of PV-converging channel cooling systems, emphasising the reduction of average cell temperature and the attainment of uniform temperature distribution. A converging channel cooling system with a 2° angle exhibited superior thermal performance, reducing cell temperature by as much as 57.8% in June and 32.7% in December, hence enhancing power production by 35.5% and 26.1%, respectively. Radwan et al. [37] introduced a comprehensive photovoltaic thermal management strategy utilising a converging channel affixed to the rear of low-concentrator photovoltaic (LCPV) systems functioning at a concentration ratio of 3, employing experimental, statistical, computational, and optimisation techniques. Predictive models were developed to evaluate essential performance indicators, such as module temperature, thermal power, and net electric power. The research indicated that although multiple design elements considerably affect performance, the converging angle exerts the minimal influence on entropy formation. Alderremy et al. [38] incorporated a trapezoidal flow channel featuring a constant intake height and a variable exit height, sustaining an aspect ratio ranging from 0.4 to 1. The findings indicated a notable 37% decrease in cell temperature when the Reynolds number (Re) rose from 100 to 400 and a 1.8% decrease when the aspect ratio was reduced to 0.4. Furthermore, cell efficiency was enhanced by 8.4% as the Re escalated from 100 to 1000. Bhatnagar et al. [39] carried out investigations to assess the effectiveness of cooling photovoltaic panels using water circulating through V-shaped channels. At a volume flow rate of 0.3 L/min, a temperature reduction of around 12.7 °C was observed, resulting in a decrease of roughly 21.6% relative to the standard PV panel without cooling. The cooled panel also demonstrated an approximate 2.26% enhancement in PVCE at a volume flow rate of 0.5 L/min even under overcast conditions. Table 1 provides a thorough summary of studies on PV front and backside cooling using conventional and advanced channel configurations. Water flow cooling for photovoltaic modules enhances efficiency and longevity by flowing water to sustain ideal temperatures. It lowers the temperature of the photovoltaic module, particularly in hotter environments. Design issues involve efficient circulation, leak mitigation, water usage regulation, suitable infrastructure, and routine maintenance. These next-generation cooling channels aim to optimise thermal management and overall photovoltaic performance by integrating features such as converging-diverging geometry, varied cross-sections, and optimised flow distribution methods.

Table 1: Highlights of PV cooling using different channel configurations

Researchers [Ref.], Year	Cooling mode	Cooling channel	PV technology	Nature of research	Temperature reduced (°C)	Growth in performance (% PVCE)	Location
Alqatamin and Jinzhan [33], 2025	PV rear side	Water channel including perforated V-shaped fins	Poly-crystalline	Sim	30	18.79	Xi'an, (China)
Radwan et al. [37], 2025	PV rear side	Converging channel with LCPV module	Poly-crystalline	Sim. and Exp.	25.9	-	Sharjah (United Arab Emirates)
Alderremy et al. [38], 2024	PV rear side	Trapezoidal channel	Mono-crystalline	Sim	37 % (as Re increased from 100 to 400)	8.4 % (as Re increased from 100 to 1000)	-
Bhatnagar et al. [39], 2024	PV rear side	V-shaped channels	Poly-crystalline	Exp.	12.7 °C (for a flow rate of 0.3 L/min)	2.26 % (for 0.5 L/min flow rate)	Manipal (India)
Alktranee et al. [20], 2024	PV rear side	Serpentine tubes featuring a copper absorbent plate	Crystalline Silicon	Sim. and Exp.	3	9.56	Miskolc (Hungary)
Fakouriyan et al. [40], 2024	PV rear side	Aluminium conduits	Crystalline Silicon	Sim.	9.98	10.3	Tehran (Iran)
Firoozzadeh et al. [41], 2024	PV front side	Water film	Poly-crystalline	Exp.	30	37.6	Dezful (Iran)
Erdogan et al. [42], 2023	PV front side	Water layer	Poly-crystalline	Exp.	1.88	13.69	Ankara (Turkey)

Nabil and Mansour [43], 2022	PV rear side	Copper serpentine heat exchangers	Poly-crystalline	Exp.	2.46	4.5	Ismailia (Egypt)
Valiente-Blanco et al [19], 2022	PV rear side	Geothermal water-cooling system	Poly-crystalline	Sim. and Exp.	14	9.8	Alcala de Henares (Spain)
Sathyamurthy et al. [23], 2021	PV rear side	Copper spiral tube arrangement	Mono-crystalline	Exp.	11.3	8.45	-
Wu et al.[24], 2020	PV rear side	Single channel cooling	Mono-crystalline	Sim.	32	52	Jilin, (China)
Mah et al.[18], 2019	PV front side	Water film cooling	Crystalline Silicon	Exp.	28	15	Selangor (Malaysia)
Baloch at al. [36], 2015	PV rear side	Converging channel cooling	Mono-crystalline	Sim. and Exp.	45.1	27.5	Dhahran (Saudi Arabia)

Conventional cooling methods, particularly constant-area water channel cooling, often result in significant temperature variations along the length of the PV module due to progressive heat accumulation. A review of the existing literature reveals a critical gap in the application of counter-flow converging water channels for photovoltaic cooling, with most prior studies focusing on conventional water-cooling techniques that fail to achieve uniform temperature distribution. While previous research has explored diverse cooling strategies, including porous channels, fin turbulators, and zigzag geometries, the potential of counter-flow converging designs remains largely unexplored. The lack of studies on counter-flow converging water channels highlights the need for advanced cooling systems capable of maintaining consistent heat dissipation and reducing thermal non-uniformity. This research addresses this gap by systematically evaluating the effectiveness of counter-flow converging water channels using computational fluid dynamics (CFD) simulations. By analysing multiple convergence angles under varying solar irradiance levels, this research provides a comprehensive assessment of temperature reduction, thermal uniformity, and pressure drop, offering valuable insights into the feasibility of this novel cooling approach.

2 Mathematical model

The aspects that were considered in establishing the mathematical model are as follows:

- Three-dimensional incompressible laminar flow.
- Solar radiation is regarded as a steady thermal flux impacting directly on the surface of the photovoltaic panel.
- Each layer of the PV panel is in optimal contact with one another. Consequently, the thermal resistances between them are disregarded.
- The thermal characteristics of solid components are regarded as constant due to their negligible thickness.
- The posterior surface of the cooling system is treated as adiabatic.

The mathematical model was founded on the conservation of mass, momentum, and energy [44] in the fluid domain, as well as heat conduction in the solid domain [36]. The temperature distribution and flow pattern within the solar cell and PV cooling system under investigation were determined by solving the equations simultaneously using CFD software.

Continuity

$$\nabla \cdot (\rho \vec{V}) = 0$$

Momentum

$$\nabla \cdot (\rho \vec{V}\vec{V}) = -\nabla P + \nabla \cdot (\mu \nabla \vec{V}) + \rho g + S$$

Energy

$$\nabla \cdot (\rho \vec{V} h) = \nabla \cdot (k \nabla T)$$

where $\vec{V}$ characterizes the velocity vector, and P denotes the pressure.

The following equation was utilised to determine the quantity of solar radiation absorbed by the solar cell [45]. Thus, solar panel absorptivity and the efficiency of the PV panel references were not overlooked.

$$G_{\text{absorbed}} = G_s \tau_g \alpha_c (1 - \eta)$$

P_{out} is electrical power [46] and was determined by:

$$P_{\text{out}} = \eta_{\text{ref}} \left[1 - \gamma_{\text{ref}} \left(T_{\text{pv}} - T_{\text{ref}}\right)\right] A G_{\text{total}}$$

The variables η_{ref} and γ_{ref} denote the electrical efficiency and temperature coefficient at the reference temperature (T_{ref}). The corresponding values for η_{ref} and γ_{ref} are 0.13 [28] and 0.0045 $°C^{-1}$ [22], respectively.

The subsequent equation [47] was employed to calculate the heat transfer coefficient for the upper and lower walls of the PV panel as a function of wind velocity.

$$h_{\text{t}} = 2.9 + 4.1V\ (1 + 0.86TI)$$

$$h_{\text{b}} = 2.8 + 4.3V\ (1 + 0.43TI)$$

3 Materials and methods

The following section presents the operational and boundary conditions defined for the analysis, along with a description of the geometry, mesh, and computational model of the PV panel and water-cooling channels. This study used the ANSYS-FLUENT 2024R2 CFD solver. The principal equations utilised by computer models to investigate PV cooling are the continuity, momentum, and energy equations, which were employed to address fluid flow and heat transfer. A steady-state, pressure-based solver was employed, utilizing a high-resolution discretization approach to ensure accuracy in all simulations.

3.1 Physical model

This work numerically examined a counter-converging flow cooling system for a PV system. Fig. 2 illustrates the physical model of the system, comprising five layers of the photovoltaic panel (glass, ethylene vinyl acetate (EVA), PV cell, and Tedlar), together with counter converging flow channels through which cooling water circulates. Specifications and characteristics of the components are presented in Table 2 and Table 3. The thermal behaviour of a solar panel (250 W solar cell), which is comprised of a solid domain and a fluid domain (counterflow converging channels for cooling), was modelled using the ANSYS design modeller.

Table 2: Material properties of solar panel [27] and cooling water [22] used in the CFD modelling.

Attributes	**Glass**	**EVA**	**PV cell**	**Tedlar**	**Water**
Thermal conductivity [W/m.K]	2	0.311	148	0.15	0.607
Specific heat capacity [J/(kg.K)]	500	2090	700	1250	4180
Density [kg/m^3]	2450	950	2329	1200	997
Dynamic viscosity [kg/m·s]	-	-	-	-	0.00089
Thickness [mm]	3.00	0.80	0.10	0.05	-

Table 3: Specifications, size [27], and solar radiation characteristics [22], [28] of the PV system

Type	Polycrystalline silicon
Power	250 W
Size	1570 mm x 940 mm
Standard testing conditions	1000 W/m^2, 25 °C
Standard efficiency of the PV cell	13 %
Thermal coefficient (γ_{ref})	0.0045 /°C
Glass transmissivity (τ_g)	0.95
Glass emissivity (ε_g)	0.05
Absorptivity of solar cell (α_c)	0.91

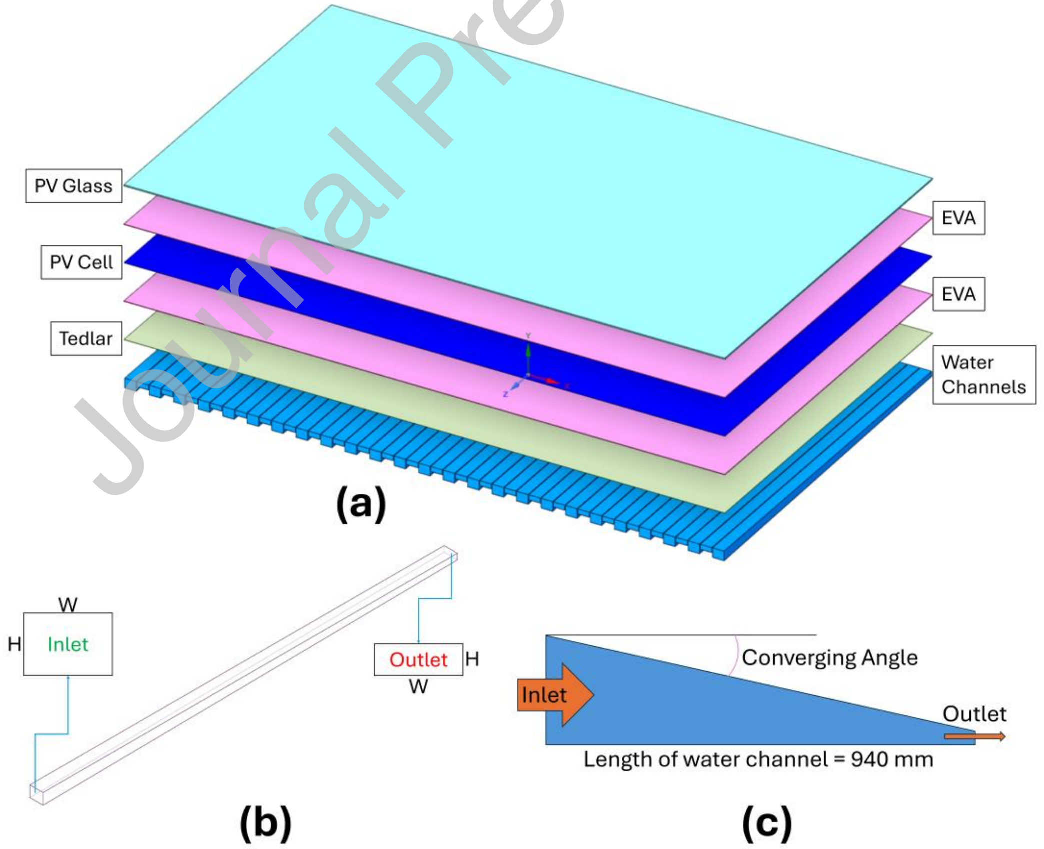

Figure 2: Geometric configurations of the PV and PV cooling channel designs(a) PV panel layers with cooling channels, (b) inlet, outlet, and converging channel, and (c) channel length and converging angle.

3.2 Numerical Method

Continuity, momentum, and energy equations are basic equations for fluid flow and heat transfer analysis, and these were solved numerically by a three-dimensional CFD model. These are critical equations that need to be solved to predict the correct amount of heat being distributed throughout the PV panel and how the water is flowing through the system. These equations, solved simultaneously in the simulation, captured the interactions between fluid motion and temperature distribution. The simulation was done using the ANSYS FLUENT program, version 2024R2 because it is robust and accurate for handling such complex simulations.

To ensure the accurate resolution of the problem, a high-quality computational mesh was generated using the ANSYS meshing tool. The meshing process involved subdividing the computational domain into smaller elements, facilitating a detailed numerical solution governed by the fundamental conservation equations. To enhance accuracy in regions with steep gradients, the mesh was selectively refined to an element size of 2 mm within the water flow channels. A highly stringent convergence criterion of 10^{-6} was employed, ensuring that the iterative solver continued until the residuals of the continuity, momentum, and energy equations fell below this threshold. This level of convergence guarantees the stability and precision of numerical results. The computational domain was discretized using 6,284,082 nodes and 5,668,200 elements, providing a resolution sufficient to capture all relevant physical phenomena. Fig. 3 presents the computational mesh, including both a full-view representation and a zoomed-in section. The full mesh visualization depicts the overall discretization, while the zoomed-in section demonstrates the adequacy of the mesh resolution for accurately capturing flow and thermal boundary effects.

A grid independence study was conducted to validate the accuracy and reproducibility of the numerical simulations. This assessment involved performing simulations with progressively refined meshes until the solution became independent of further refinement, ensuring that numerical errors due to insufficient grid resolution were eliminated. The objective was to achieve a balance between computational efficiency and accuracy while preventing discrepancies arising from grid dependency. Table 4 presents the results of this analysis, showing variations in key parameters such as solar cell temperature, water outlet temperature, velocity, and pressure loss across different mesh densities. As the mesh elements increased from 111,014 to 5,668,200, the solar cell temperature exhibited a decline from 315.852 K to 315.637 K, while the water outlet temperature rose from 311.007 K to 311.301 K, demonstrating a convergence trend. Likewise, the water outlet velocity stabilized at 0.000961555 m/s beyond 3,028,592 elements, and the pressure loss exhibited minimal variation, converging at approximately 0.0396152 Pa. The negligible difference observed between 5,668,200 and 5,749,400 elements confirmed that further refinement did not yield significant improvements. Consequently, a mesh resolution of 5,668,200 elements was selected to ensure numerical accuracy while optimizing computational resources.

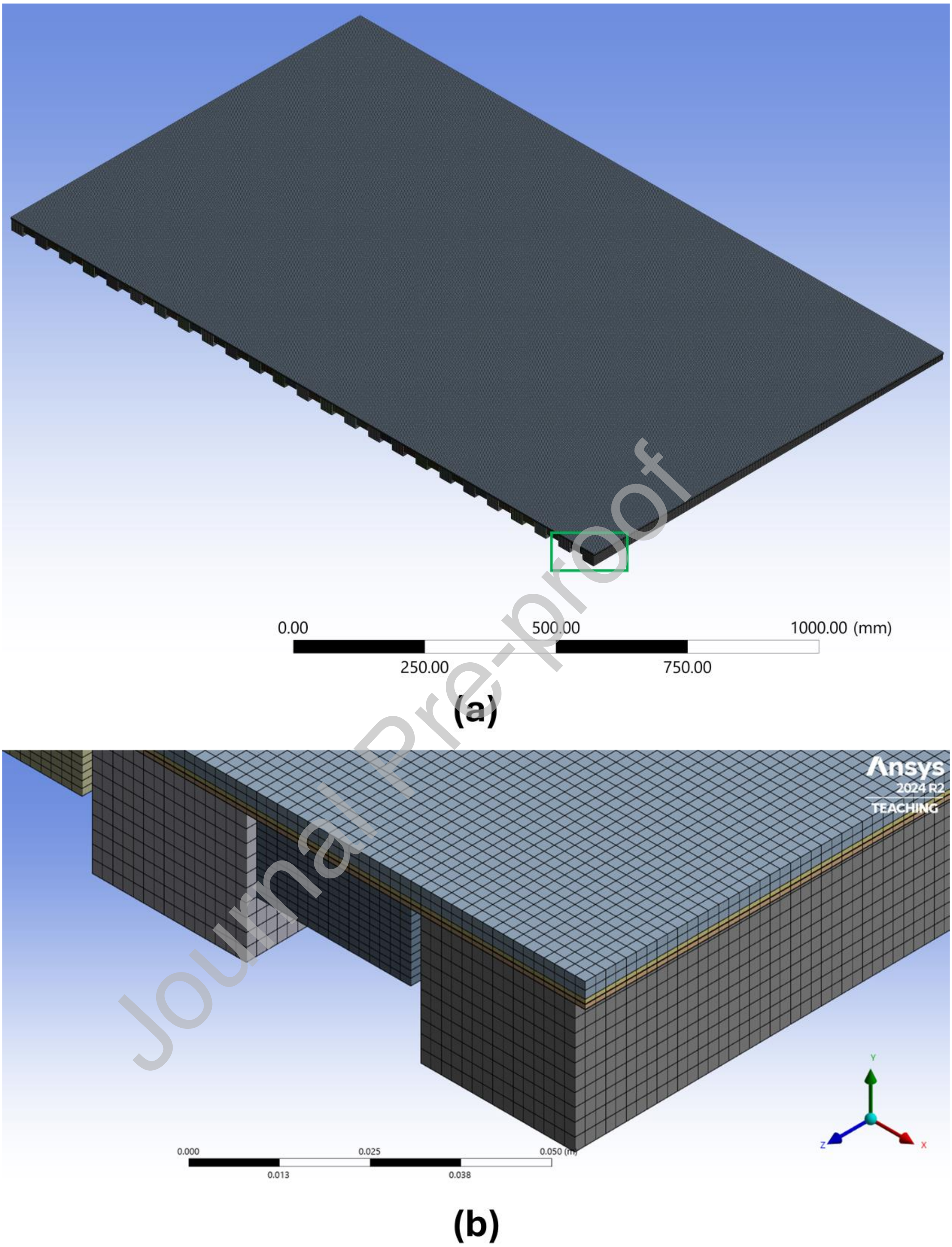

Figure 3: Mesh configuration of the photovoltaic panel and converging water channels. (a) Full view of the meshing across all computational domains, illustrating the overall discretization. (b) A detailed view of the meshing within the selected green box portion in (a)

Table 4: Mesh independence analysis.

Number of Elements	Solar Cell Temperature (K)	Water Outlet Temperature (K)	Water Outlet Velocity (m/s)	Pressure Loss (Pa)
111014	315.852	311.007	0.000961549	0.0245001
3028592	315.691	311.255	0.000961555	0.0386252
4347819	315.656	311.288	0.000961555	0.0393743
5668200	**315.637**	**311.301**	**0.000961555**	**0.0396152**
5749400	315.636	311.301	0.000961555	0.0396150

3.3 Boundary Conditions and Case Studies

The computational domain was subjected to suitable boundary constraints in accordance with the parameters of the photovoltaic system. The simulations were conducted under typical solar radiation conditions, with an incoming radiation intensity of 600-1050 W/m². This aligns with standard solar energy levels during clear, sunny weather; therefore, it is vital to analyse the thermal performance of the photovoltaic panel under realistic conditions. To ensure consistency in the simulation and to isolate the impact of the cooling system, both the ambient temperature and the cooling water inlet temperature were maintained at 300 K. This assumption permitted the maintenance of consistent external environmental conditions, hence ensuring an identical surrounding environment throughout all simulations for evaluating thermal management performance. The cooling water inlet flow velocity was sustained at 0.0005 m/s, indicative of a low flow rate. This will provide a laminar flow regime, which is crucial for comprehensive thermal study and effective heat transfer modelling. The selected flow rate can effectively replicate realistic cooling by circulating water at low velocities, hence optimizing cooling efficiency while reducing energy expenditure for pumping.

The baseline scenario was defined with a constant flow rate of 1.1 L/min, which was maintained across all examined cases. The inlet water temperature and environmental temperature were both 300 K, with a generated power of 250 W and an electrical efficiency of 13% under solar irradiation of 600-1050 W/m², considering the material and physical attributes of the solar panel and cooling water as detailed in Tables 2 and 3. Different converging channels were included in the simulation to analyse the impact of coolant flow on photovoltaic degradation due to high-temperature gradients. An analysis was conducted on the variation in the exit area of converging channels. Examining various cooling channels is pertinent, as the thermo-physical properties of the fluid (thermal conductivity, density, specific heat capacity, dynamic viscosity, convective heat transfer) significantly influence heat transfer efficiency and, consequently, the ultimate temperature distributions within the cell. This study analysed 8 water channels, as shown in Table 5, which examines the differences in the outflow area and the converging angle relative to the base case.

Table 5: Summary of all cases and water channels employed in this research.

Water channel number	Outlet (W x H mm^2)	Converging angle	Converging ratio	Outlet Re	Additional factors
1	30 x 25	0	1	15.28	Inlet: (W x H mm^2) 30 x 25 mm^2
2	30 x 22	0.183	1.13	16.16	Number of water Channels: 49
3	30 x 19	0.366	1.32	17.15	Flow rate: 1.1 L/min
4	30 x 16	0.549	1.56	18.26	Inlet water temperature: 300 K
5	30 x 13	0.731	1.97	19.54	
6	30 x 10	0.914	2.50	21.00	Free stream temperature: 300 K
7	30 x 7	1.097	3.57	22.71	Wind velocity: 1.5 m/s
8	30 x 4	1.28	6.25	24.71	Re at Inlet:15.28 Solar irradiation: 600-1050 W/m^2

4 Results

4.1 Validation

To validate the developed numerical model, the simulation results were compared with the experimentally obtained temperature reduction values reported by [25]. As shown in Fig. 4, the reliability of the developed numerical model was demonstrated through direct validation against the experimental data. The comparison revealed an excellent agreement between the simulation results and the experimental data, with an average temperature difference of only 0.1 K under the same conditions. Furthermore, it was observed that both the experimental and simulation results exhibited a consistent linear trend for changes in solar irradiance, further reinforcing the accuracy of the model in capturing the thermal behaviour of the system. This validation confirms that the numerical model reliably captures the key physical mechanisms and heat transfer processes under investigation, providing confidence in its predictive accuracy.

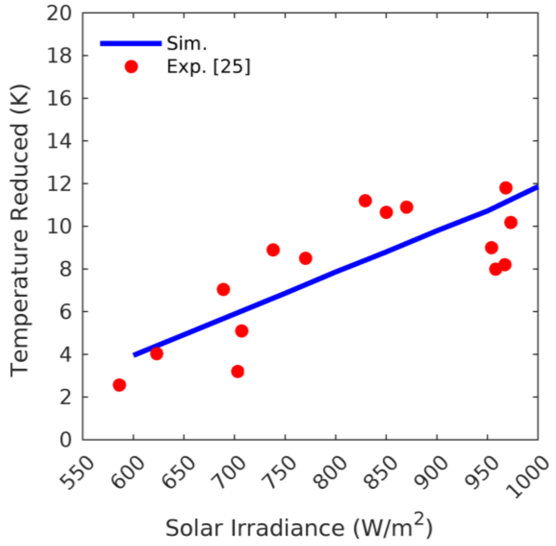

Figure 4: Comparison of simulation results for temperature reduction with the experimental results [25]

4.2 Impact of Counter-Flow Converging Channels on Coolant Temperature Dynamics

The counter-flow converging channels enhance the coolant temperature dynamics by promoting efficient heat exchange. In all examined scenarios, the inlet boundary condition for water temperature was maintained at 300 K; nevertheless, when the water flows, it absorbs heat from the solar panel, resulting in a surge in water temperature. Under a constant solar intensity of 1000 W/m² and equivalent operating circumstances, simulations indicated that the coolant temperature increased by 0.5 K compared to straight counter-flow channels. In a system with an intake coolant temperature of 300 K, converging channels can reduce the PV panel temperature to around 314 K. In contrast, constant area channels can decrease it to 317 K. While preserving the temperature differential using counterflow rules of behaviour, the exacerbated velocity in the converging channels enables the convective heat transfer coefficient to rise, providing enhanced heat dissipation and improved temperature stability. Fig. 5 illustrates the specific behaviour of cooling water temperature within converging channel 4. A comparable type of behaviour was noted in all cases examined for simulations.

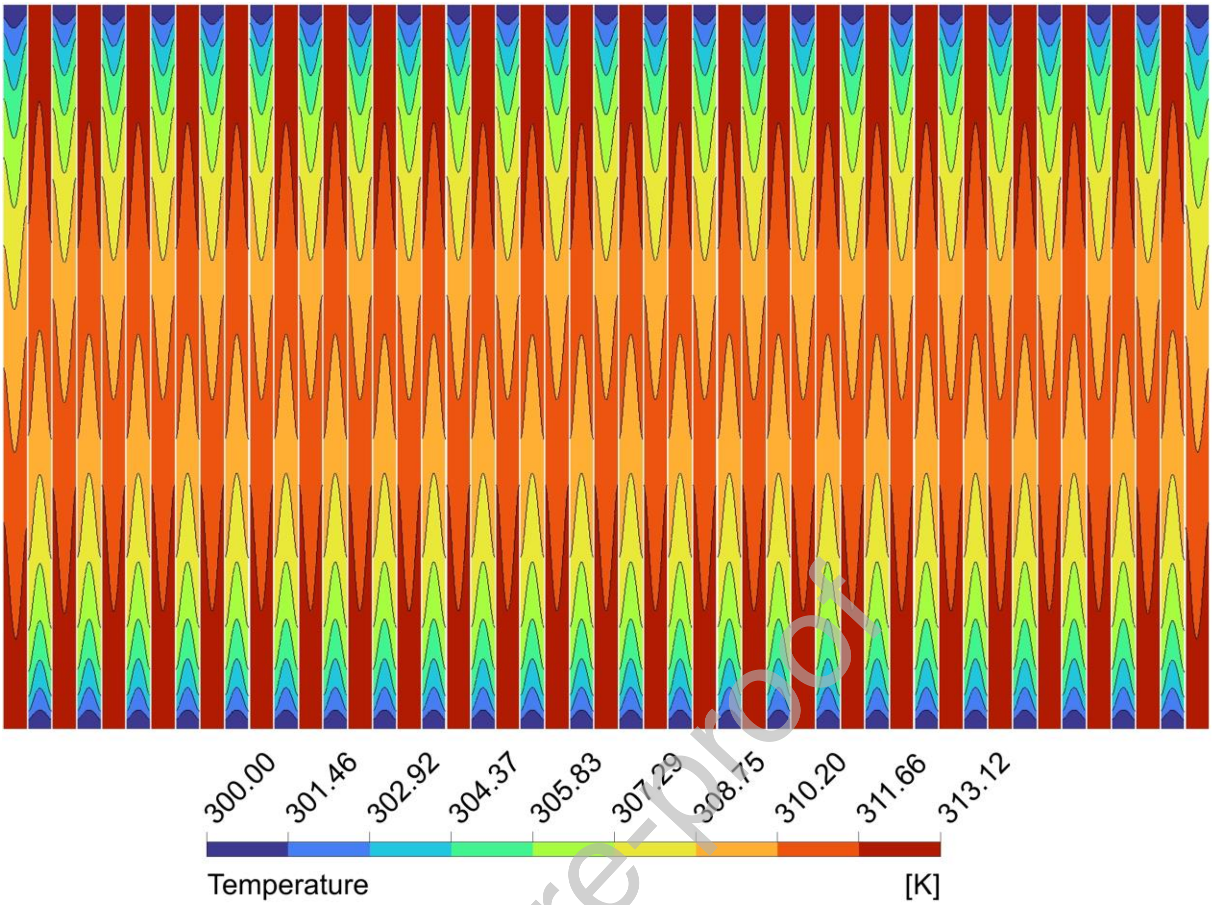

Figure 5: Water channel temperature contours for channel-4 at solar intensity of 1000 W/m^2

The study systematically evaluated 80 distinct scenarios to investigate the influence of counter-flow channel configurations on the thermal behaviour of the coolant within a photovoltaic cooling system. Eight different channel geometries were analysed under ten solar irradiance levels, ranging from 600 to 1050 W/m², to examine the combined effects of channel topology and solar intensity on cooling performance. Across all cases, the outlet water temperature varied between 306 K and 312 K, highlighting the significant role of channel design and irradiation intensity in determining cooling efficiency. A predominantly linear relationship was observed between outlet water temperature and solar irradiance, particularly within the 600–950 W/m² range, where the outlet temperature increased by approximately 0.5 K for every 50 W/m² rise in solar intensity. However, beyond 950 W/m², this rate of increase diminished to approximately 0.35 K per 50 W/m², indicating a shift in heat dissipation efficiency at higher irradiance levels. The observed trends, as detailed in Fig. 6, underscore the necessity of optimizing channel design to maintain effective thermal management across varying solar conditions.

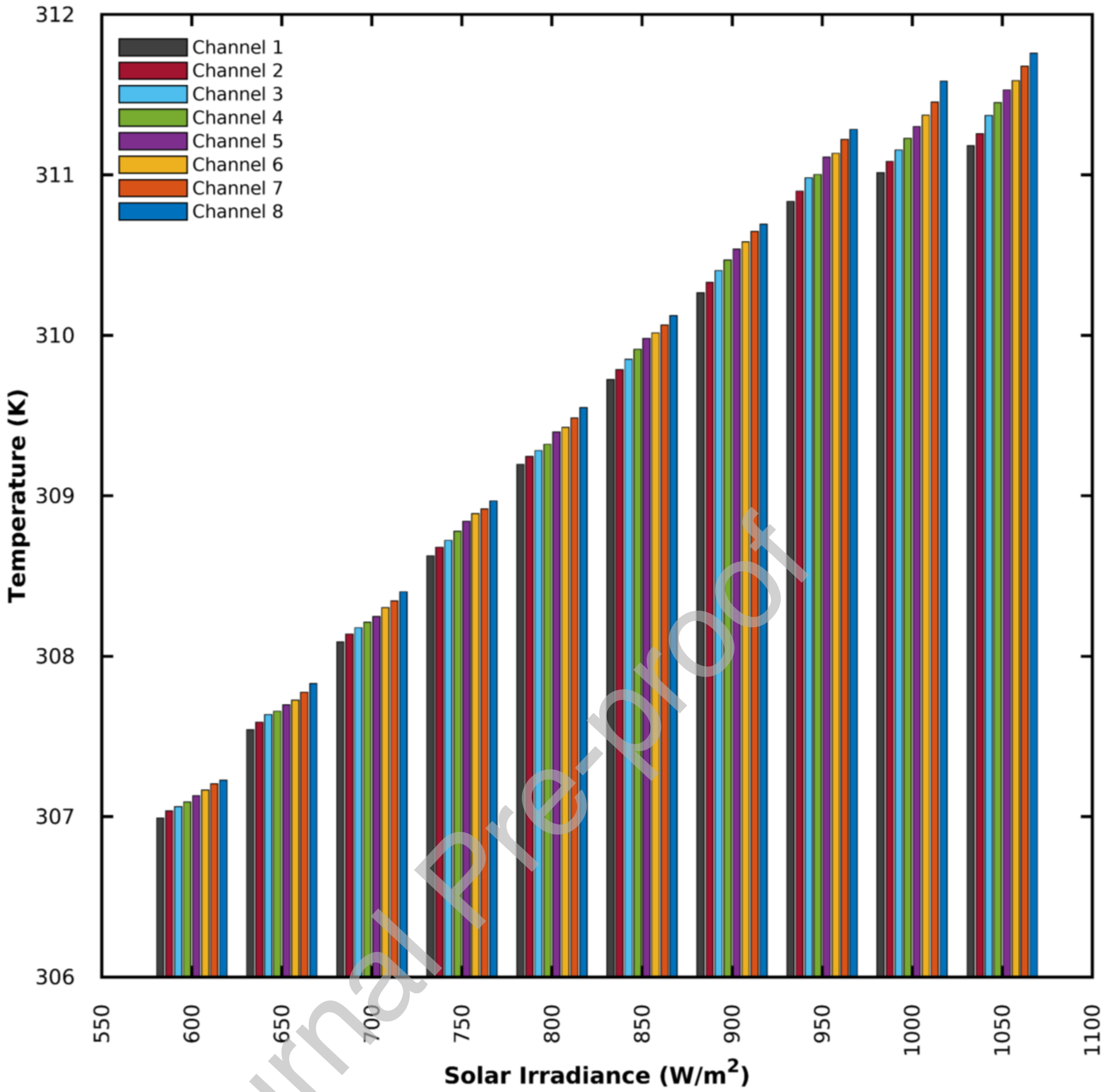

Figure 6: Coolant exit temperature for an inlet temperature of 300 K across all analysed cases.

4.3 Influence of Counter-Flow Converging Channels on Pressure and Velocity Profiles

The implementation of counter-flow converging channels significantly affects the pressure and velocity distributions within the cooling system. Computational analysis revealed that the coolant velocity could increase by up to sixfold compared to conventional uniform-section channels, reaching a peak of 0.003 m/s at the narrowest section, as opposed to 0.0005 m/s in non-converging designs. This velocity enhancement improves heat transfer efficiency but also induces a pressure drop of approximately 0.24 Pa. The overall pressure loss varies between 0.02 and 0.24 Pa, depending on the channel geometry and coolant flow rate. Proper adjustments are necessary to balance pressure loss and prevent excessive pumping power requirements while ensuring effective thermal performance. Fig. 7 presents the exit velocity and pressure loss for all eight water channel configurations. The plot illustrates how different channel geometries influence both velocity and pressure drop, highlighting the trade-off between enhanced heat transfer and increased pumping requirements.

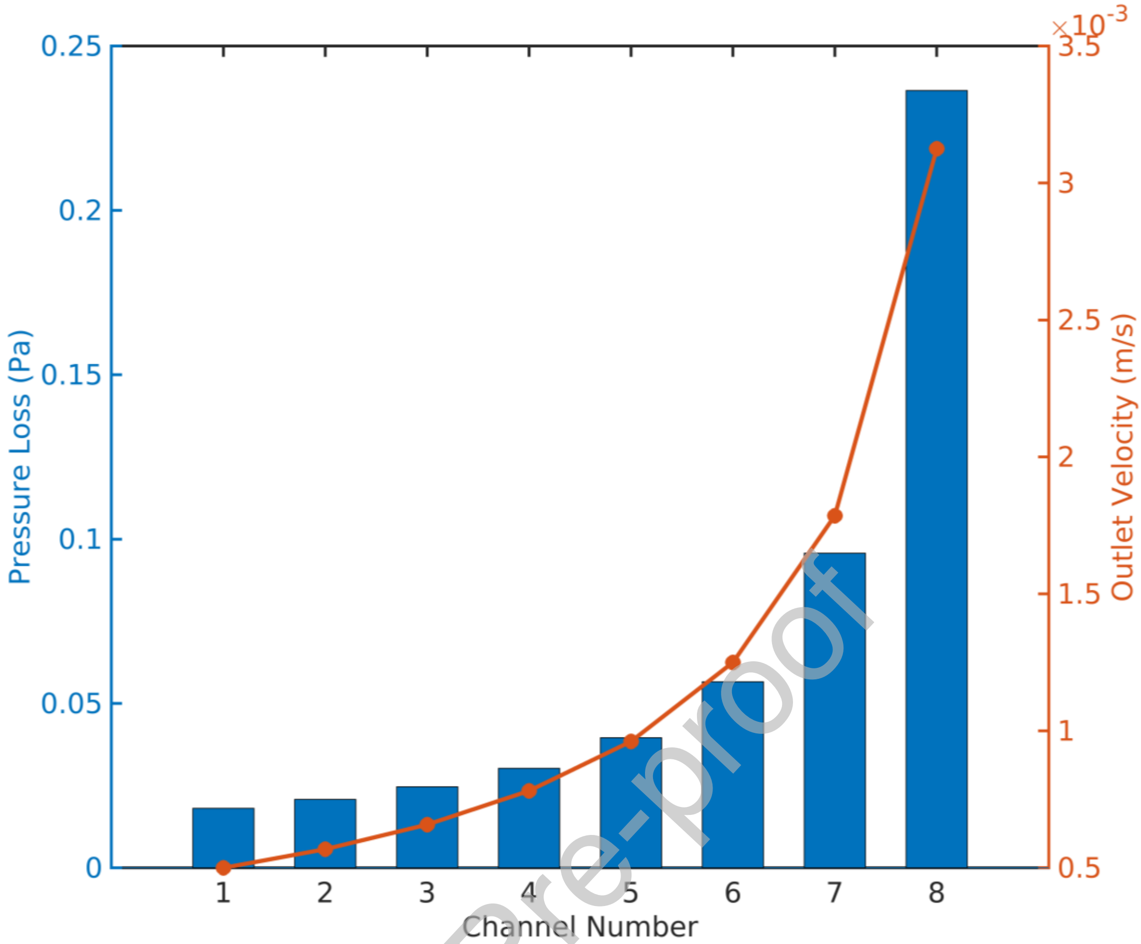

Figure 7: Outlet velocity and pressure loss for all eight types of water channels.

The impact of convergence ratios on pressure and velocity profiles illustrates a trade-off between heat transfer efficiency and pressure loss. For a 2:1 convergence ratio, the coolant velocity escalates from 0.0005 m/s at the intake to 0.0096 m/s at the end of the channel, with a pressure decrease of 0.04 Pa recorded across the channel. With a 6.25:1 ratio, the velocity substantially jumps to 0.003 m/s, leading to an improved heat transfer rate, however accompanied by a worsened pressure drop of 0.24 Pa. In comparison, a parallel-flow channel sustains a constant velocity of 0.0005 m/s and encounters a pressure decrease of merely 0.02 Pa. The results indicate that although elevated convergence ratios improve thermal and velocity profiles, they simultaneously augment the energy demand for coolant circulation. An optimal design must equilibrate these parameters to attain efficient thermal performance while maintaining feasible pumping power consumption.

The pressure drop across the cooling channels is a critical factor in determining the pumping power required to maintain adequate fluid flow. The results indicate that as the convergence ratio of the channel design increases, the pressure drop rises due to enhanced flow constriction. Designs with higher pressure drops require stronger pumps, leading to increased energy consumption and operational costs. Conversely, lower-pressure-drop designs reduce energy demand but may compromise thermal performance by limiting convective heat transfer. The selection of an optimal channel design involves balancing thermal and hydraulic performance. While designs with significant narrowing and increased flow acceleration can enhance heat transfer, excessive pressure drop can negate these benefits by increasing pumping energy demands. Thus, the ideal design should minimize pressure drop while ensuring sufficient cooling capacity, making it essential to consider both thermal and hydraulic efficiency in the design process.

4.4 Effect of Counter-Flow Converging Channels on Photovoltaic Temperature Regulation

The setting up of counter-flow converging channels in photovoltaic thermal management systems significantly enhances temperature regulation. Numeric comparisons indicate that PV panels cooled by these channels can achieve an average surface temperature drop of 3 K compared to those cooled by straight counter-flow designs. For example, at an incident solar irradiation of 950 W/m² and an ambient temperature of 300 K, the maximum panel temperature can be sustained at 313 K utilising converging channels, in contrast to 316 K with constant area cooling. A decrease in temperature enhances the electrical efficiency of the photovoltaic system by 1-1.5% and mitigates thermal stressors, hence prolonging the PV module's active lifecycle. Fig. 8 displays the cooling performance outcomes of several converging water channel types under solar intensities ranging from 600 W/m² to 1050 W/m². As solar intensity progresses, the PV temperature increases across all channel configurations, signifying that elevated solar irradiance results in enhanced heat absorption, necessitating more effective cooling systems. Channels exhibiting greater convergence angles consistently yield lower temperatures, indicating their enhanced cooling efficacy relative to channels with lesser convergence angles.

In all examined situations, the average temperature of solar panels ranged from 309 to 318 K. This temperature regulation of photovoltaic panels, facilitated by counter-flow converging channels, depends on the convergence ratio and velocity of the coolant. For a one-degree convergence angle at standard operating conditions, with 1000 W/m² solar irradiance and ambient temperature at 300 K, the maximum temperature of the PV panel drops to 314 K. Thermal stresses to the PV panel are drastically reduced, hence offering a longer lifespan and more reliability for the system. The variation in PV cell temperatures across all channels minimizes with a solar intensity of 600 W/m². Channels with reduced convergence angles demonstrate marginally elevated PV cell temperatures compared to those with greater convergence angles. Channels with lower convergence angles, for instance, demonstrate panel temperatures slightly exceeding 310.4 K. Still, those with greater convergence angles acquire temperatures nearer to 308.7 K. At decreased thermal loading, the performance variation among channel types is minimal, as indicated by the slight difference at this irradiance level.

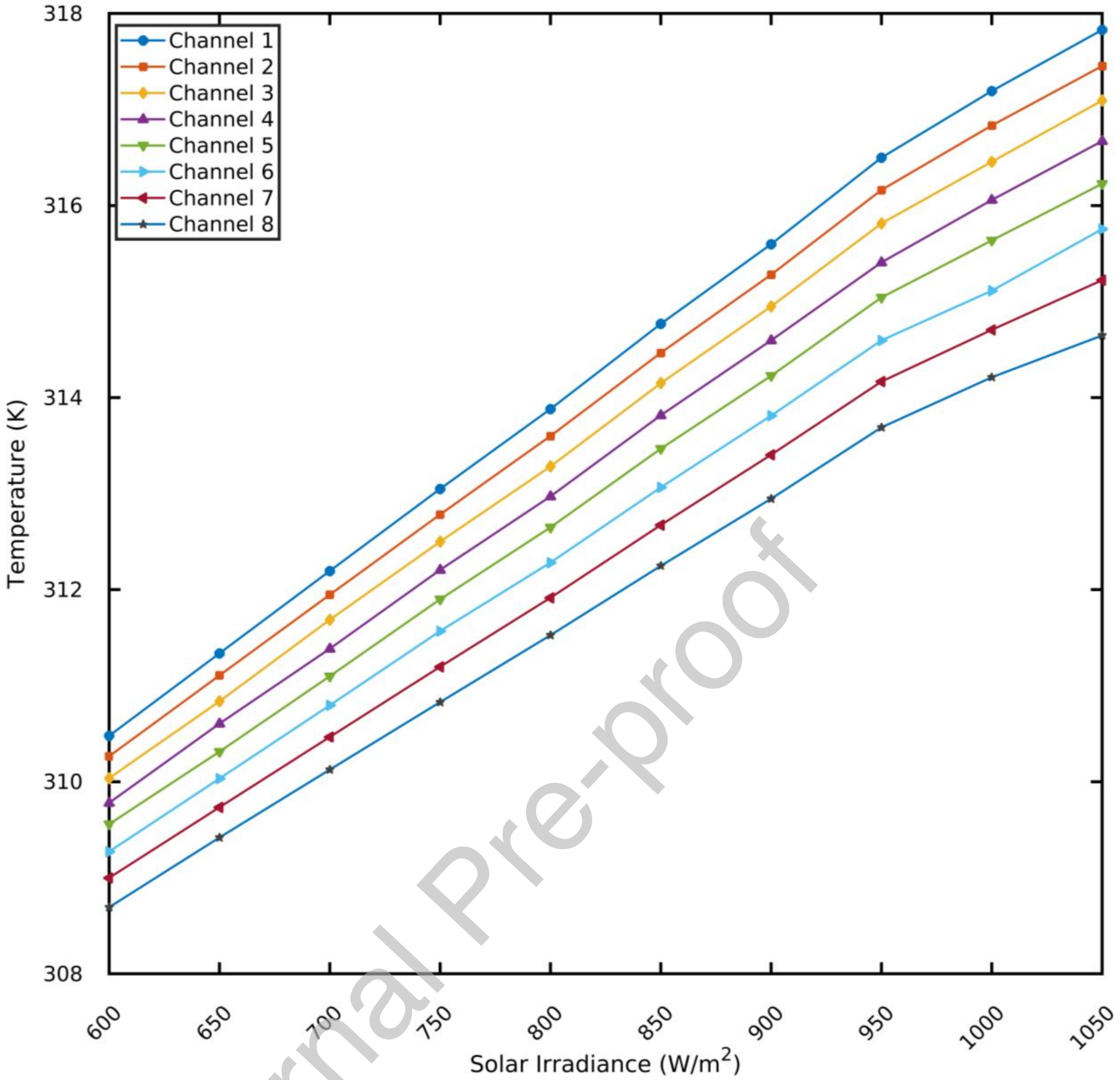

Figure 8: Temperature of the solar panel across various channel configurations and solar irradiation levels

The intermediate solar intensities (e.g., 800 W/m² and 900 W/m²) further reveal the trend, where higher convergence angle channels consistently exhibit better cooling performance. At 900 W/m², channels with reduced convergence angles achieve outlet temperatures of approximately 315.5 K, whereas channels with strong convergence retain considerably lower temperatures of about 312.9 K. The persistent superiority of higher convergence channels at all irradiance levels highlights their enhanced capacity for heat dissipation. The distinctions in cooling performance between channel types become noticeably prominent as the sun intensity rises to 1050 W/m². Channels that have lesser convergence angles document solar module temperatures surpassing 317 K, whereas channels with increased convergence angles sustain values nearer to 314.6 K. This indicates that greater convergence angles are more efficient in alleviating the effects of greater thermal loads, owing to their superior heat transfer properties. The increasing temperature disparities among channel types at elevated sun intensities emphasize the fundamental significance of channel design in thermal management amid extreme heat flux environments.

4.4.1 Temperature uniformity

Serpentine tubes, spiral tubes, water film cooling, and parallel channel heat exchangers are some of the water-cooling techniques that have seen widespread use in solar panel cooling. Temperature inhomogeneity issues, particularly near the exits, typically result from this, as shown in Fig. 1. All these technologies share the characteristic that the water flow within the cooling channels is unidirectional and/or parallel. The counter-flow converging water channel design addresses these problems by implementing a non-parallel flow configuration and a channel geometry that progressively shrinks. This novel method offers a strong remedy to the constraints of conventional cooling strategies. It facilitates the development of more effective thermal management systems for solar panel applications, especially in high-intensity regions. The temperature gradients inside the cooling system are markedly diminished, especially near the exits, where traditional systems often encounter difficulties. The comparative examination of findings utilizing eight channel types reveals that the most convergent channels attain the lowest temperatures and exhibit a high degree of temperature uniformity, as illustrated in Fig. 9, hence facilitating more effective and consistent cooling.

The standard deviation values of temperature across the solar cell (Table 6) reveal the impact of solar intensity and channel number on thermal uniformity. As solar intensity increases from 600 W/m² to 1050 W/m², the standard deviation also rises for all channels, indicating greater temperature variations. For instance, in channel 1, the standard deviation increases from 1.0696 K at 600 W/m² to 1.7944 K at 1050 W/m², reflecting a rise in non-uniformity. A similar trend is observed across other channels, although the magnitude of variation decreases with higher converging angles. Furthermore, the effect of the converging angle is evident, as higher angles exhibit lower standard deviation values, indicating improved thermal uniformity. For example, at 1050 W/m², channel 8 records a standard deviation of only 1.1131 K compared to 1.7944 K in channel 1, highlighting a significant reduction in temperature variation. The difference between successive channels is more pronounced at lower numbers, with channel 2 experiencing a 0.0911 K reduction compared to channel 1 at 1050 W/m², whereas the reduction from channel 7 to channel 8 is only 0.1043 K. This trend implies that increased converging ratio enhances temperature uniformity, which is crucial for minimizing thermal stress and improving the operational stability of the solar cell.

Table 6: Standard deviation values (in K) for temperature distribution across the solar cell.

Channel Number	Solar Intensity (W/m^2)									
	600	650	700	750	800	850	900	950	1000	1050
1	1.0696	1.1568	1.2439	1.3303	1.4088	1.5047	1.5843	1.6825	1.7447	1.7944
2	1.0182	1.1010	1.1838	1.2658	1.3407	1.4315	1.5074	1.6009	1.6575	1.7033
3	0.9649	1.0392	1.1223	1.1995	1.2681	1.3568	1.4290	1.5184	1.5686	1.6168
4	0.9070	0.9850	1.0547	1.1321	1.1966	1.2803	1.3484	1.4269	1.4780	1.5212
5	0.8553	0.9200	0.9896	1.0621	1.1228	1.2008	1.2647	1.3430	1.3822	1.4203
6	0.7958	0.8603	0.9252	0.9922	1.0463	1.1170	1.1779	1.2494	1.2777	1.3228
7	0.7405	0.7800	0.8593	0.9182	0.9722	1.0379	1.0960	1.1639	1.1921	1.2174
8	0.6823	0.7397	0.7942	0.8481	0.8976	0.9576	1.0097	1.0741	1.0990	1.1131

4.4.2 Reduction in photovoltaic panel temperature

To evaluate the efficacy of these unique cooling configurations, the temperature reduction relative to the uncooled panel was compared across all solar irradiation levels. Numerical analysis demonstrates the cooling efficiency of counter-flow converging water channels across different solar irradiation levels (600 W/m² to 1050 W/m²), as detailed in Table 7. At 600 W/m², channel 1 cuts the temperature by 11.45 K, while channel 8 achieves 13.24 K, showcasing the enhanced heat transfer properties of highly converging designs. As sun intensity reaches 1050 W/m², the disparity expands, with channel 1 decreasing the temperature by 20.55 K and channel 8 making a reduction of 23.73 K. At moderate irradiance levels of 800 W/m², channel 8 attains a thermal effect of 17.71 K, whereas channel 1 reaches 15.36 K, hence validating the scalability of cutting-edge convergence systems in handling elevated heat loads. The investigation indicates a 15–30% enhancement in cooling efficiency for the most converging channels, illustrating their capacity to diminish temperature inhomogeneity and manage substantial thermal loads proficiently. The results confirm the effectiveness of counter-flow converging channels in delivering enhanced and scalable thermal management, establishing them as a dependable solution for solar panel cooling in high-intensity settings, where conventional unidirectional cooling approaches frequently exhibit unsustainability.

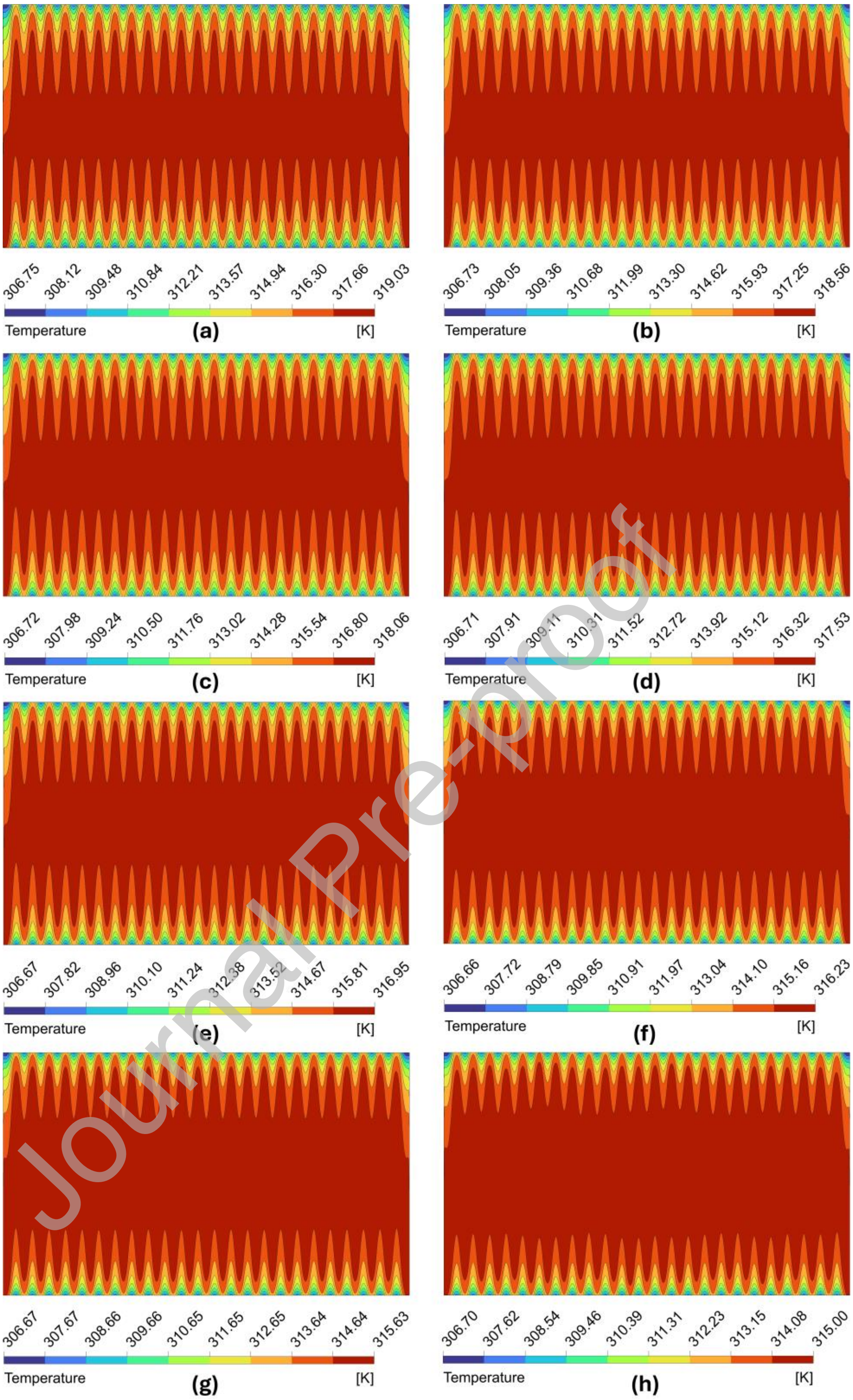

Figure 9: Contour of solar panel temperature at solar irradiation of 1000 W/m² for (a) channel-1, (b) channel-2, (c) channel-3, (d) channel-4, (e) channel-5, (f) channel-6, (g) channel-7, (h) channel-8

Table 7: Temperature reduction of photovoltaic panels by the utilization of water-cooled channels.

Channel Number	Solar Intensity (W/m^2)									
	600	**650**	**700**	**750**	**800**	**850**	**900**	**950**	**1000**	**1050**
1	11.45	12.42	13.39	14.36	15.36	16.30	17.29	18.22	19.36	20.55
2	11.66	12.65	13.64	14.63	15.64	16.60	17.61	18.56	19.72	20.92
3	11.89	12.92	13.90	14.91	15.95	16.92	17.94	18.91	20.10	21.28
4	12.15	13.15	14.20	15.20	16.27	17.25	18.30	19.31	20.50	21.70
5	12.37	13.44	14.48	15.51	16.59	17.60	18.67	19.68	20.92	22.15
6	12.66	13.72	14.79	15.84	16.96	18.00	19.08	20.12	21.44	22.62
7	12.93	14.02	15.12	16.21	17.32	18.39	19.49	20.55	21.85	23.15
8	13.24	14.34	15.46	16.58	17.71	18.82	19.95	21.03	22.34	23.73

5 Study Limitations

This study provides significant insights into the application of counterflow converging channels for the cooling of PV systems and the maintenance of temperature homogeneity. Nevertheless, numerous significant limitations must be recognized and rectified in subsequent research.

A primary limitation stems from the inherent variability of solar irradiance due to fluctuating weather conditions. The performance of the proposed cooling system, like all photovoltaic systems, is directly influenced by solar intensity, which is subject to variations caused by cloud cover, seasonal transitions, and geographical differences. While this study examined a range of irradiance levels through controlled simulations, real-world applications may experience periods of suboptimal performance due to these inconsistencies.

Additionally, to maintain computational feasibility and isolate the effects of the cooling mechanism, a uniform wind velocity of 1.5 m/s was applied across the PV panel surface. However, in practical conditions, wind speed and direction fluctuate dynamically, impacting convective heat transfer and altering the overall cooling efficiency. Future studies should incorporate non-uniform wind profiles to enhance the predictive accuracy of the cooling system under realistic atmospheric conditions.

Another key constraint lies in the fixed ambient and inlet water temperatures, both maintained at 300 K to ensure consistency in simulation results. However, environmental conditions such as extreme temperatures, humidity fluctuations, and precipitation events can significantly influence system performance. Elevated ambient temperatures may exacerbate thermal loads and reduce cooling effectiveness, whereas colder climates could enhance cooling efficiency but pose risks of freezing for the working fluid. A more comprehensive analysis of the system's adaptability under varying climatic conditions is necessary to establish its long-term feasibility.

Furthermore, this study does not account for additional real-world operational factors, such as variations in panel installation angle, shading effects from nearby structures or vegetation, and dust accumulation on the PV surface, all of which can influence overall efficiency. Future research should extend the scope of analysis to encompass these practical considerations and evaluate the system’s robustness over extended operational periods.

6 Conclusions

This study highlights the successful use of counterflow converging water channels as a thermal regulation solution for solar panels across different sunlight intensity levels. Numerical research indicates that channels with elevated convergence angles outperformed those with lower angles, resulting in enhanced temperature reduction and superior cooling uniformity. By addressing the limitations of traditional unidirectional cooling techniques, this method offers a resilient and energy-efficient alternative for cooling solar panels, especially in high-intensity conditions. The salient points of the investigations are as follows:

- Channels with elevated convergence angles regularly surpass lower angle designs, attaining superior temperature decreases across all solar irradiation levels.
- At 1050 W/m^2, the highest converging channel decreased the temperature by 23.73 K, whereas the straight counterflow channel dropped it by 20.55 K, demonstrating enhanced scalability and heat dissipation.
- A temperature reduction ranging from 11.45 to 23.73 K was obtained across various circumstances examined in this study.
- A proportional association was seen in PV temperature reduction and temperature homogeneity for the converging angle.
- The counter-flow design maintains a consistent temperature gradient, facilitating homogeneous cooling and preventing localised overheating.
- The standard deviation of temperature distribution across the solar cell increases with rising solar intensity, from 1.0696 K at 600 W/m^2 to 1.7944 K at 1050 W/m^2 for channel 1. However, higher converging channel numbers significantly reduce temperature variation, with channel 8 maintaining a lower standard deviation of 0.6823 K at 600 W/m^2 and 1.1131 K at 1050 W/m^2, demonstrating enhanced thermal uniformity.
- This approach addresses the limitations of traditional unidirectional cooling techniques and offers a robust and energy-efficient solution for high-intensity environments.

7 Future Recommendations

- Examine the impacts of differing convergence angles, flow rates, and channel dimensions in establishing the optimal layout.
- Investigate advanced materials with elevated thermal conductivity or nanofluids to improve heat transfer in cooling channels.

- Develop integrated thermal-photovoltaic systems that combine cooling with energy recovery for additional efficiency gains.
- Compare the effectiveness of counter-flow converging channels in a variety of environmental conditions, such as disparate ambient temperatures and wind speeds.
- Evaluate the energy usage of pumps and other system elements to confirm that the entire system stays economically and energetically efficient.
- Execute extensive implementations to assess the viability and financial effectiveness of incorporating this technology in solar farms.

These suggestions intend to promote the advancement of new cooling technologies, guaranteeing effective and sustainable thermal management for solar PV systems.

Acknowledgement

The authors express their sincere gratitude to the Malaysian Ministry of Higher Education for funding this study under the Fundamental Research Grant Scheme (Project Code: FRGS/1/2021/TK0/USM/03/9).

CRediT roles

Aamir Sohail: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing - original draft; **Muhammad Waseem**: Conceptualization; Methodology; Software; Visualization; Writing - review & editing; **Mohd Syakirin Rusdi:** Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Software; Supervision; Writing - review & editing; **Mohd Zulkifly Abdullah:** Conceptualization; Funding acquisition; Project administration; Resources; Software; Supervision; **Sakhr M. Sultan:** Conceptualization; Project administration;

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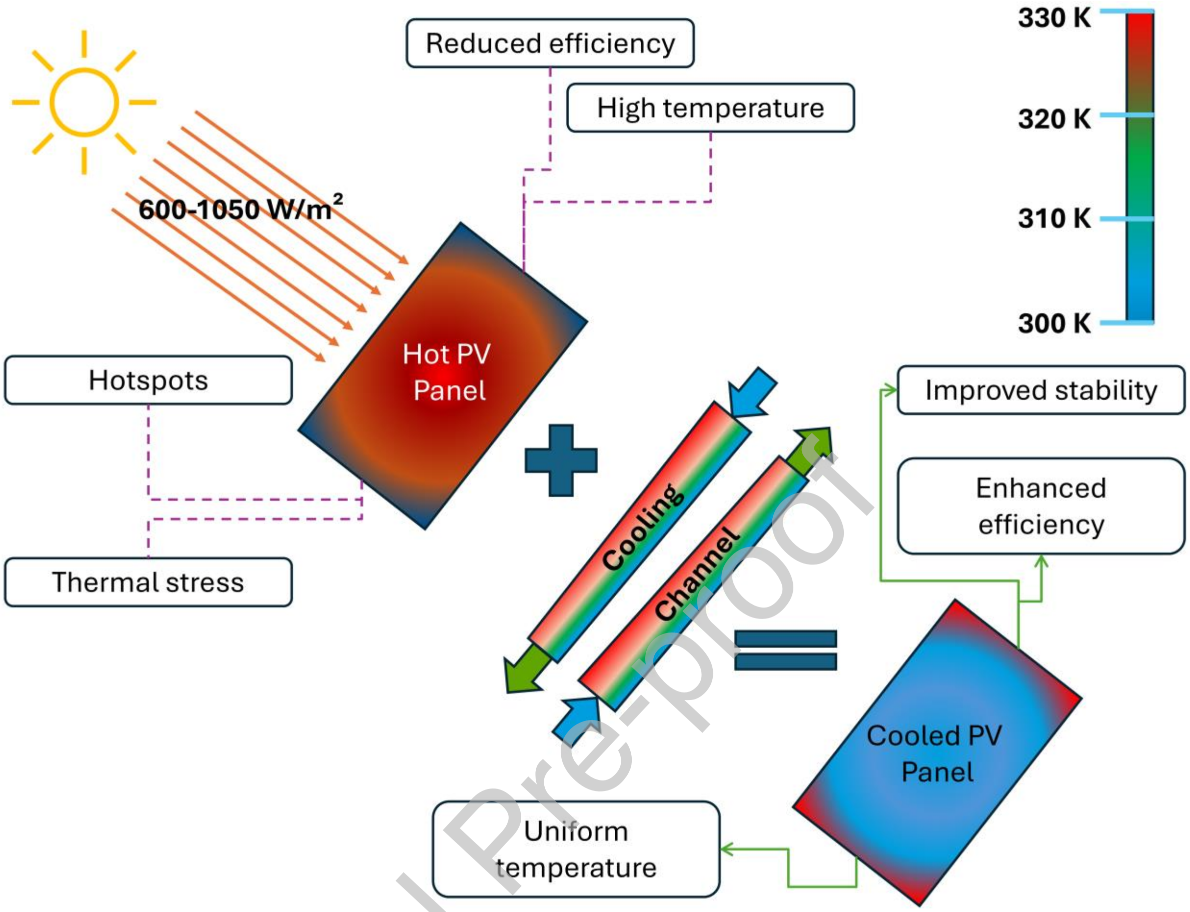
Graphical Abstract



Declaration of interests

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.