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Solar Photovoltaic Surface Cooling Using Hybrid Solar Chimney-Collector with Wavy Fins

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ABSTRACT

Elevated temperatures, frequently observed in regions characterized by high ambient heat, markedly diminish the operational efficiency and curtail the lifespan of Solar Photovoltaic (PV) panels. Consequently, it is essential to enhance the sustainability and operational performance of solar energy systems through the mitigation of surface temperatures of solar PV panels. The study investigates the impact of the number of fins on the panel's surface temperature and the airflow within the collector-chimney cavity. Computational Fluid Dynamics (CFD) simulations were employed to determine the optimal number of fins for maximum cooling efficiency. The results indicate that increasing the number of fins initially lowers the solar PV surface temperatures, but the improvements diminish due to increased airflow restrictions. The surface temperature reduction enabled by the fins up to 14.1°C at 50.99°C, which can help mitigate solar PV efficiency losses in hot climates. The CFD simulations accurately predicted the thermal-fluid behaviour and cooling capacity of the hybrid system, as validated against experimental data. The study concludes that the incorporation of optimized wavy cooling fins in a hybrid solar chimney-collector system shows strong potential for passively enhancing solar PV panel cooling and efficiency.

1. Introduction

A rapid population growth increases the dependency on electricity. Fossil fuels are heavily used for power generation, while their sources are dwindling each decade. Moreover, they emit hazardous emissions leading to global warming and adverse health impacts. New alternatives utilizing renewable energy sources such as solar, hydropower and wind can reduce reliance on fossil fuels, thereby mitigating the greenhouse effect resulting primarily from electricity generation [1].

Active and passive are the two main types of solar energy. Active solar technology involves the use of electrical and mechanical components to directly convert solar energy into heat and electricity through methods such as photovoltaic panels or solar thermal systems [2]. Equipment involved includes fans, pumps, and control systems that monitor and adjust the flow of captured sunlight for

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maximum efficiency. In contrast, passive technology entails collecting solar or thermal energy without converting its form, for instance, heating houses in winter using strategically designed windows to maximize natural heat gain while minimizing heat loss. Unlike other renewable sources, solar energy does not contribute to environmental pollution. Hence, it presents the most viable renewable solution to address global warming concerns.

Solar photovoltaic (PV) systems directly convert light energy from the sun into electrical energy via the photovoltaic effect [3]. Solar cells are categorized into first, second and third generation types [4-8]. First generation solar cells comprise crystalline silicon wafers manufactured from crystalline silicon. Second generation thin-film solar cells include amorphous silicon, copper indium gallium diselenide (CIGS), cadmium telluride and more. Of these generations, third generation single junction solar cells demonstrate the highest efficiency. Quantum dot, perovskite, organic and dye-sensitized CZTS solar cells fall under this category.

Typical PV system efficiencies range between 15-20% [5]; thus, maintaining high efficiency is crucial. Efficiency gradually declines as operational temperatures rise, owing to overheating of the PV panel surface from excessive solar irradiance and high ambient temperatures [6]. Excessive temperatures decrease PV panel efficiency by increasing solar cell temperatures and decreasing maximum power output [7]. While 35°C is the normal PV panel operating temperature, the maximum allowable limit is 45°C. Hybrid photovoltaic/thermal (PV/T) systems can mitigate such efficiency losses via integrated cooling mechanisms that circulate air or water around PV panels to maintain lower solar cell temperatures. According to Wu and Xiong [8], operating temperature significantly impacts PV panel efficiency. The choice of solar photovoltaic systems and their efficiency are crucial factors in addressing the global energy crisis. The aforementioned operating temperatures indeed have a significant impact on the efficiency of PV panels. However, it is important to delve deeper into the methods and technologies that can effectively mitigate these efficiency losses.

Solar cells have a temperature coefficient that measures how temperature changes affect their efficiency. Typically, for every degree Celsius increase above 25°C, there is a fixed percentage decrease in the panel's efficiency [9]. Solar panels operate optimally within a specific temperature range, usually around 25°C to 35°C. However, when temperatures exceed their ideal range and reach the maximum limit of around 45°C or higher, the efficiency can drop significantly.

Semiconductor materials, like silicon used in solar cells, change their electrical properties as temperature varies [10]. Higher temperatures can increase the internal energy of the charge carriers (electrons and holes), which may lead to higher rates of recombination and lower the voltage output of the cell [11]. With increased temperature, the output voltage of the solar PV cells decreases while the current only slightly increases or remains unchanged, leading to reduced power output [12]. This results in an overall reduction of power output from the solar panel. Verma *et al.,* [13] discuss the variations in PV panel surface temperature are influenced by factors such as differing sunlight intensity, wind direction, humidity, and dust accumulation. These elements contribute to the dynamic nature of PV panel temperatures.

To enhance efficiency and counter the negative impact of high operating temperatures on PV panels, a range of cooling mechanisms can be integrated into the system. Active and passive cooling systems are both used to address the challenges posed by high operating temperatures in solar photovoltaic panels [14]. Active cooling systems, such as water cooling or fan cooling, are more effective in enhancing photovoltaic performance, but they require an external power source. However, the power required for these systems is deducted from the power produced by the PV cells, reducing the net output power [15]. For instance, water cooling can reduce the solar panel surface temperature significantly, thereby avoiding overheating that can lead to the destruction of a PV cell [16].

On the other hand, passive cooling systems, such as heatsinks, rely on natural processes and do not require additional power [15,17]. These systems are characterized by their simplicity, low cost, and the absence of a need for an external power source. Passive cooling techniques include natural air cooling, heat pipes, and improved heat exchanger designs [15]. Despite being less effective than active cooling systems in terms of heat transfer rate, they are still beneficial in enhancing the photovoltaic performance to a certain extent.

Multiple studies have demonstrated that attaching cooling fins to the back of solar PV panels can effectively reduce the panel surface temperature. According to Kim and Nam [18], the addition of fins reduced the average PV module temperature by over 14°C. The number and geometry of cooling fins impacts the extent of PV panel cooling. Grubišić-Čabo *et al.,* [19] tested PV panels with no fins, 3 fins, 6 fins and 12 fins. They found that 12 fins provided the maximum temperature reduction of 16°C and PV efficiency improvement of 5.9%. This indicates diminishing returns with an increasing number of fins. Additionally, dimpled and perforated fins were found to promote turbulence and provide better cooling compared to plain fins [20]. The mechanism of PV panel cooling by fins relies on effectively dissipating heat into the passing air. As noted in [21], the cotton wick mesh and water-cooling method achieved a 23.55°C temperature drop. This highlights the importance of maximizing heat transfer area via fins to facilitate convection. Higher air flow velocity over the fins also improves heat transfer [20].

To improve energy efficiency, solar chimneys provide ventilation and temperature control. Solar chimneys constitute passive solar cooling and heating systems that leverage natural processes like convection, conduction and radiation [22]. They require no external energy input while maintaining functionality. Solar chimney materials are black or dark to maximize sunlight absorption and minimize reflection. Solar chimneys comprise solar collector areas, ventilation shafts and inlet/outlet openings. There are three solar chimney types: Trombe walls, roof solar chimneys and combined Trombe wall-roof systems. Solar chimneys simply utilize solar energy to enhance ventilation rates [23]. Hybrid photovoltaic solar chimneys (PV/SCs) integrate solar panels with traditional solar chimneys. Per studies, such hybrids fulfill solar-assisted air cleaning roles [24]. Hence, they not only improve solar PV efficiency but also ventilation.

Several researchs has been done on the use of solar chimneys to reduce the surface temperature of solar photovoltaic (PV) panels. Kalkan and Dagetkin [25] employed Computational Fluid Dynamic (CFD) fluently to design and analyze solar systems for specific climatic conditions. The paper by Ahmed *et al.,* [26] proposed a photovoltaic solar chimney design based on solar cells as an endothermic surface, which could reduce the average surface temperature of the PV panels. Another study by Jafari and Kalantar [27] explored a combination of wind-catcher, solar chimney, and water spray system to provide natural air circulation. The research done by Hasan *et al.,* [28], demonstrated that the efficiency of a new solar chimney design was three times that of a conventional one. Alkasrawi *et al.,* [29] investigated the potential of enhancing the efficiency of a standard solar chimney power plant (SCPP) by integrating it with photovoltaic panels. Lastly, Arunachala [30] reported a 13% reduction in surface temperature due to improved airflow over the PV module rear surface.

Previous studies have demonstrated that innovative methods have been employed to reduce the surface temperature of solar photovoltaic (PV) systems. These methods include the use of cooling fins to increase heat transfer rates on solar PV panels and the utilization of solar chimneys to promote passive ventilation through air buoyancy promotion. Recently, our laboratory has proposed the design of a hybrid solar chimney-collector with wavy fins to capitalize on the effect of the solar chimney-collector for improved airflow and wavy fins for extended surface area within a constricted space for better cooling effect. The primary objective of this research paper is to investigate the impact of incorporating wavy fins into a solar chimney-collector configuration on the cooling of solar photovoltaic (PV) panels. Specifically, the study aims to understand how these wavy fins, when placed on the back of the panel, influence the panel's surface temperature and the airflow within the collector-chimney cavity. To achieve this, the research employs Computational Fluid Dynamics (CFD) simulations to determine the optimal number of fins for maximum cooling efficiency.

2. Methodology

In this study, a hybrid solar chimney-collector with wavy fins on the back of the solar PV and solar collector is proposed to enhance the cooling of solar photovoltaic (PV) panels. The methodology phase includes the design description, CFD study, validation of the CFD study, and finally the discussion on the effect of fins on solar PV surface temperature distribution. The novel design incorporates wavy fin shapes to improve the cooling efficiency of the PV panels. Geometry and computational models are developed to analyze the fluid dynamics and heat transfer in the hybrid solar chimney-collector with fins, considering the relevant boundary conditions. The CFD study is validated by comparing the results with experimental data conducted in a prior study [31]. The discussion analyzes how the cooling efficiency of PV panels is affected by varying numbers of fins. It also compares the proposed hybrid solar chimney-collector with fins to non-cooled solar PV.

2.1 Design and Construction of Hybrid Solar Chimney-Collector with Fins

A hybrid solar chimney-collector with fins were developed and design to maximize their integration with PV panels (refer to Figure 1) and enables higher air flowrate and heat transfer achieved thru larger surface area and increased natural ventilation. The chimney is 1500 mm tall, 700 mm long, and 215 mm wide, engineered for efficient natural convection and airflow. Similarly aligned parallel to the panels, the wavy cooling fins as shown in Figure 1 measure 1450 mm in length, and 57 mm in height, with a thickness of just 1 mm. In addition to this setup, an absorber section includes a black-painted metal paired with a 1000 mm $\times$70 mm $\times$3 mm acrylic sheet selected for optimal heat transfer efficiency. Furthermore, the monocrystalline silicon photovoltaic panels used in the study measured at 1450 mm by 680 mm and boast a thickness of 300 µm demonstrate at an approximately 15% efficiency rate. The design of the 3D model aims to optimize natural convection and passive cooling through consideration of critical geometric parameters that integrate all components -PV panel, fins, chimney, and collector-in a single package.

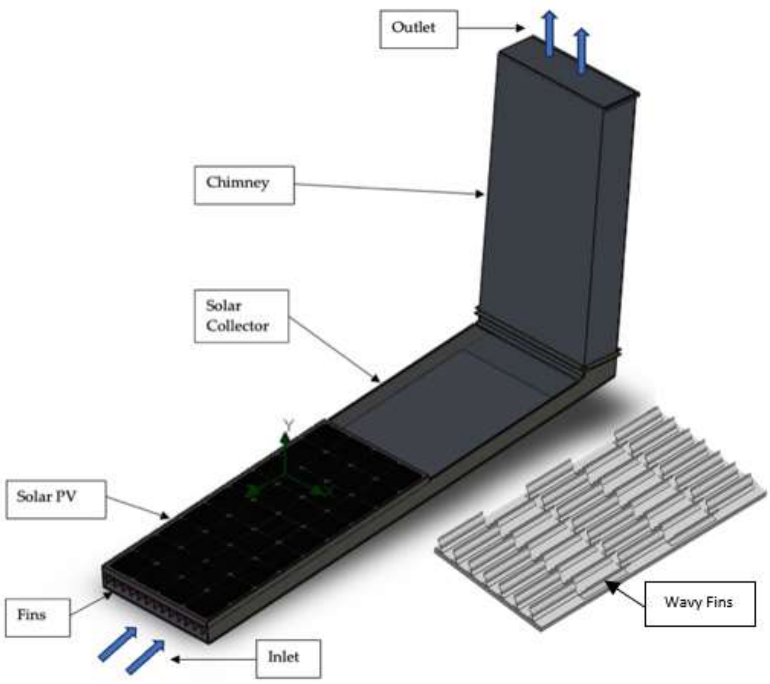


Fig. 1. Design of hybrid solar chimney-collector with fins for solar PV cooling

2.2 CFD Study

A CFD simulation study was conducted using ANSYS CFX software to visualize the flow and analyze the thermal behavior within the hybrid solar chimney-collector system with wavy fins for solar PV cooling. The study employed a 3D model of the system, as depicted in Figure 1. The flow domain, defined by the boundaries of the hybrid solar chimney-collector with fins, was discretized using a second-order upwind method and the SIMPLE scheme for pressure-velocity coupling. This discretization process enabled the solution of the Reynolds-averaged Navier-Stokes (RANS) equations using the realizable k-ε turbulence model.

Several assumptions were made in the CFD simulations to simplify the computational model while capturing the essential physics of the problem. The simulations assumed steady-state conditions, implying that the flow and temperature fields remain constant over time. The air was considered an incompressible Newtonian fluid with constant viscosity, a reasonable assumption for the relatively low velocities within the system. The airflow was assumed to be turbulent, and the realizable k-ε turbulence model was employed to capture the turbulent effects. The no-slip boundary condition was applied at the walls, assuming zero fluid velocity at the solid surfaces. The thermophysical properties of the materials were assumed to be constant within the operating temperature range. Radiation heat transfer between the surfaces within the system was considered negligible compared to the convective heat transfer. Lastly, the solar irradiance on the PV panel surface was assumed to be uniform, neglecting any spatial variations due to shading or other factors. The validity of these assumptions was assessed by comparing the simulation results with experimental data, as discussed in the validation section.

2.2.1 Governing equation

The model simulated fluid motion by solving three-dimensional, steady, incompressible Navier–Stokes energy, and k– ε turbulent equations.

Continuity equation:

$$\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)=0 \tag{1}$$

Navier-Stokes equations:

$$\begin{aligned}
\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)&=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)\\
\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)&=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\rho g\\
\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)&=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)
\end{aligned} \tag{2}$$

Energy Equation:

$$\rho C_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+S_E \tag{3}$$

k-ε equations :

$$\begin{aligned}
\frac{\partial}{\partial x_i}(\rho k u_i)&=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+G_k+\beta g_i\frac{\mu_t}{Pr_t}\frac{\partial T}{\partial x_i}\\
\frac{\partial}{\partial x_i}(\rho \varepsilon u_i)&=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+\rho C_1 S_\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}\left(C1\varepsilon\frac{\varepsilon}{k}C_{3\varepsilon}\beta g_i\frac{\mu_t}{Pr_t}\frac{\partial T}{\partial x_i}\right)+S_\varepsilon
\end{aligned} \tag{4}$$

In the given context, ρ denotes the air flow density, *Cp* signifies the specific heat of the air flow, *β* signifies the thermal expansion factor, and G_k signifies the turbulent kinetic energy generated. C_1, C_2 and $C_{3\varepsilon}$ are constants. The turbulent Prandtl numbers for k and ε are denoted as σ_k and σ_ε, respectively. The terms, S_k and S_ε represent the kinetic energy and dissipation source terms, respectively. The Reynolds averaged velocity, pressure, viscosity, and density are denoted by u,p,μ, and ρ in the equations above, respectively. The Reynolds stress tensor τ_{ij}, which represents the impact of turbulent velocity variations on the fluid flow, is defined as $\tau_{ij}=-\rho\dot{u}_i\dot{u}_j$.

2.2.3 Boundary conditions

The CFD simulations employ precise boundary conditions to guarantee precision. The ambient parameters consist of a pressure of 101,325 Pa and an initial temperature of 30°C. Turbulence is specified at a 0.10% intensity with a length scale of 0.007 m for increased accuracy in the results. The aluminum components are modeled as blackbody walls, and the simulation involves solar radiation input with a power density of 1024 W/m² to capture realistic environmental effects on heat transfer processes. The overarching objective for the simulation is to attain peak velocity and understand its impact on various aspects of the system, while comprehensive information regarding the thermal properties of the materials can be located in Table 1 for more detailed analysis.

Table 1
Material properties for boundary conditions

Component	Material	Material properties		
		Thermal conductivity (W/m*K)	Density (kg/m^3)	Specific heat (J/kg*K)
Collector cover	Acrylic	0.21	1200	1500
Body/Frame	Plywood	0.15	700	1420
Solar PV	Silicon	148	2330	700
Chimney/Fins	Aluminum	205	2688.9	897

2.3 Grid Independence Study

Grid independence testing was conducted to determine the optimal mesh density for computational analysis. Three mesh densities were evaluated under a solar radiation of 1024W/m^2 using CFX software. Surface matching between partial models was defined to enable subsequent setup, with surfaces named as follows: opening, inlet, sun-to-iron, iron-to-sun, iron-to-air, air-to-iron, air-to-plate, and plate-to-air. A base grid size of 0.1mm and maximum size of 15mm were utilized with a default growth rate of 1.20. Default CFX system values were applied for additional settings as outlined in Table 2. The elemental b distribution within the computational mesh is illustrated in Figure 2. There are 731,897 grids and 187,707 nodes in the model. This mesh configuration was selected through comparison of simulation results between differing mesh densities to quantify solution sensitivity to spatial discretization. The chosen mesh density of elements enables grid independent solutions within the defined tolerance.

Fig. 2. Wire mesh geometry of solar chimney-collector with fins for solar PV cooling

Table 2
Mesh configuration

Setting	Value
Use Advanced Size Fun.	On: Curvature
Relevance Center	Fine
Initial Size Seed	Active Assembly
Smoothing	High
Transition	Slow
Span Angle Center	Fine
Curvature	Default (18.0°)
Min Size	0.10 mm
Max Face Size	15.0 mm
Max Size	30.0 mm
Growth Rate	Default (1.20)
Minimum Edge Length	1.50 mm

2.4 Validation of Simulation Result

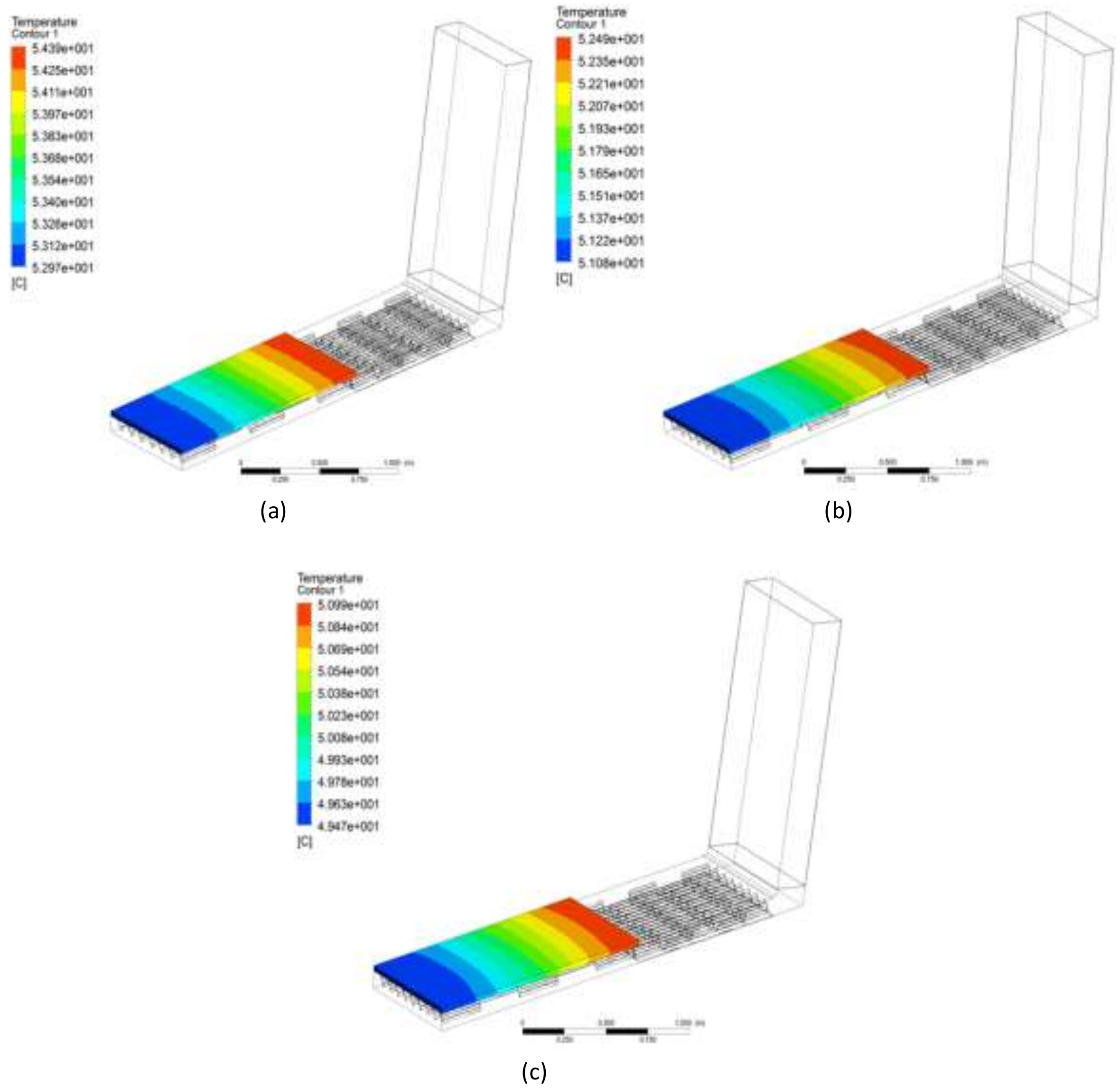
The validity of the simulation model was rigorously assessed through a detailed comparison with empirical data obtain from a previous study [31]. In the study, a similar construction of a Hybrid Solar Chimney-Collector system, incorporating fins, was fabricated, and subjected to experimental testing under actual conditions. The empirical approach involved recording the surface temperature of the solar photovoltaic (PV) panels at nine distinct points on the surface. This methodology was employed to meticulously analyze the variations in temperature across different levels of solar radiation. Thus, this comparative analysis primarily focused on the highest temperatures recorded in both the simulated and experimental setups, revealing a close concordance between the two datasets. Such alignment underscores the precision and dependability of the numerical model in forecasting the thermal dynamics of the hybrid solar chimney system, alongside its efficacy in cooling solar photovoltaic (PV) panels. Specifically, the experimental arrangement documented a peak temperature of 50.2°C at the central upper section of the solar PV panel, whereas the simulation model noted a slightly higher temperature of 50.8°C. This marginal discrepancy, indicative of the model's adeptness in capturing the thermal behavior, further substantiates its validation capabilities in accurately predicting the cooling capacity. The variance between these datasets was less than 1.18%, illustrating a robust correlation between the simulated and experimental outcomes. This evidence solidifies the numerical model's proficiency in precisely forecasting the cooling efficiency for solar PV panels within hybrid solar chimney systems, leveraging solar load and calculation tools.

3. Result and Discussion

Figure 3 illustrates the temperature contours within the hybrid solar chimney-collector system at the maximum incident solar radiation of 1024 W/m^2. Four system configurations were investigated, as outlined in Table 3. These configurations were selected in order to study the effect of number of wavy fins on the heat distribution and average temperature of the solar PV. Configuration 1 serve as benchmarked for configuration without any fins, collector or chimney. The average temperature for configuration 1 is obtained thru experimental measurement.

Table 3
Configurations of fins in hybrid solar chimney-collector system

Number of Fins	Configurations			
	1	2	3	4
Solar PV panels	-	14	16	18
Solar Collector	-	16	16	16
total	-	30	32	34



(c)

Fig. 3. Temperature contour inside the hybrid chimney solar collector (a) Configurations 2 (b) Configurations 3 (c) Configurations 4

At the inlet of the solar chimney, the air velocity is initially slow. As the air flows through the passage underneath the photovoltaic panel and solar collector, the velocity continually increases, reaching a maximum at the chimney outlet. This velocity increase complies with the principle of mass conservation, owing to the reduction in flow cross-sectional area. The number of wavy fins affects the velocity and mass flow rate inside the hybrid solar chimney-collector. As shown in Table 4, the mass flow rate attains a maximum for Configuration 4. This outcome potentially arises because the increased hot surface area of the fins behind the photovoltaic panel and solar collector elevates the air temperature within the constriction. The heightened air temperature intensifies the buoyancy effect, thereby promoting more rapid airflow [18].

The simulation results in Figure 3 offer a deeper understanding of how fins impact airflow and temperature distribution within the hybrid solar chimney-collector system. The analysis of four different system configurations in Table 4 shows a direct relationship between the number of wavy fins and the velocity and mass flow rate within the system, suggesting that more fins lead to improved airflow efficiency, which influences the cooling performance of the solar PV panels. However, increasing fin numbers also leads to reduced mass flow rate due to increased airflow restrictions and surface friction along the fins.

Table 4
Velocity and mass flow rate for different system configurations

Configuration	Solar PV panel inlet (m/s)	Mass flow rate (kg/s)	Deviation of mass flow rate (%)
1	-	-	
2	0.737	4.37	-
3	0.766	4.57	4.58
4	0.662	4.64	1.53

The addition of fins appears to enhance the heat transfer rate, leading to a decrease in the average surface temperature of the solar photovoltaic (PV) panel [18]. As illustrated in Figure 3, the surface temperature of the solar PV at the inlet is cooler and gradually increases towards the end near the solar collector section. This temperature gradient is likely due to the ambient air being progressively heated as it flows through the wavy fins. As the air approaches the end section of the solar PV, the heat transfer rate diminishes due to a reduced temperature difference between the fins. The temperature gradient across all configurations is relatively consistent, except for Configuration 1, which lacks fins. In this configuration, the surface remains consistently hotter compared to other configurations although there is a reduction in temperature from the inlet, followed by a gradual increase towards the end of the solar PV. The air continues to heat up in the solar collector area, enhancing the buoyancy effect and increasing the airflow rate. These findings show the effect that the addition of fins can have on reducing the surface temperature of a solar PV panel [18,32].

Figure 4 presents the average surface temperature of the solar panel at different number of fins. The lowest surface temperature is observed in Configuration 4, which has the highest number of fins (34), resulting in an average temperature of 50.99 °C. Configuration 3, with a surface temperature of 52.49℃, shows a significant decrease from Configuration 1's 65℃. This suggests that the modifications made in Configuration 3 were particularly effective at reducing the panel's temperature. However, the decrease to 50.99℃ in Configuration 4 is less significant, suggesting that further modifications or cooling may have diminishing returns. The number of fins seems to significantly impact the heat transfer rate and subsequently, the surface temperature of the solar PV. Nonetheless, there appears to be a limit to how effective adding more fins can be, as seen in the smaller temperature decrease from Configuration 2-3 to 3-4 with a deviation of 3.49% and 2.86% respectively. Other studies have also reported similar trends, indicating that the number of fins can lower the surface temperature of the solar PV panel. However, this outcome depends on the configurations and shapes of fins; different designs or configurations will yield varying numbers of fins [18,32,33].

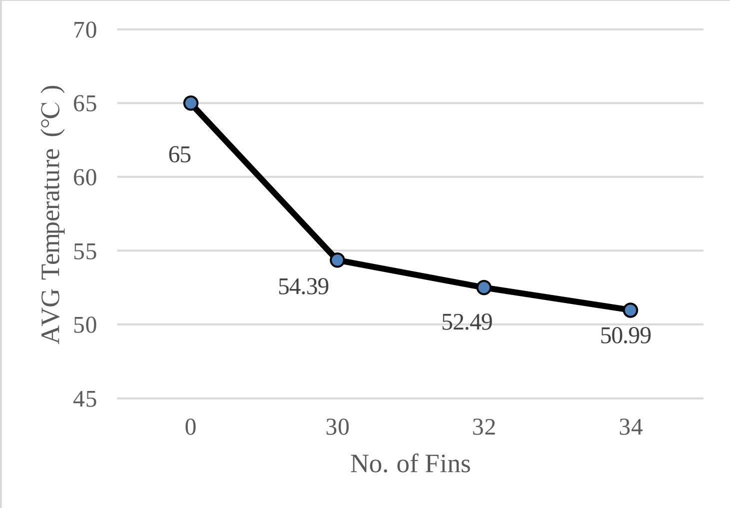


Fig. 4. Average temperature of solar PV at number of fins

4. Conclusion

The hybrid solar chimney-collector system with optimized wavy cooling fins demonstrates strong potential to passively improve solar PV panel cooling and efficiency. The fins enhance heat transfer and promote airflow via natural convection, thereby reducing panel surface temperatures. While additional fins initially further lowered temperatures, the benefits diminished due to increased airflow restrictions. Maximal cooling for presented configurations was achieved with 34 fins, enabling a 14.1°C reduction to 50.99°C. This can mitigate solar PV hot-climate efficiency losses. As validated against experiments, the numerical models accurately predicted the system's thermal-fluid behavior and cooling capacity with the simulated temperatures was less than 1.18% of the measured values. They can thus reliably optimize fin design and operating parameters. In summary, strategic incorporation of wavy cooling fins in the hybrid configuration shows promise for substantially boosting solar PV panel cooling and efficiency through customized design optimization.

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References
[1] Buonocore, Jonathan J., Hughes, Ethan J., Michanowicz, Drew R., Heo, Jinhyok, Allen, Joseph G., and Williams, Augusta. "Climate and health benefits of increasing renewable energy deployment in the United States." *Environmental Research Letters*, no. 4 (2019): 1-13. https://doi.org/10.1088/1748-9326/ab49bc

[2] Güney, Taner. "Solar energy, governance and CO_2 emissions." *Renewable Energy* 184 (2022): 791-798. https://doi.org/10.1016/j.renene.2021.11.124

[3] Abdul Karim, Nayab, Mehmood, Umer, Zahid, Hafiza Fizza, and Asif, Tahira. "Nanostructured photoanode and counter electrode materials for efficient Dye-Sensitized Solar Cells (DSSCs)." *Solar Energy* 185 (2019): 165-188. https://doi.org/10.1016/j.solener.2019.04.057

[4] Dambhare, Mugdha V., Butey, Bhavana, and S. V. Moharil. "Solar photovoltaic technology: A review of different types of solar cells and its future trends." *Journal of Physics: Conference Series* 1913 (2021): 1-16. https://doi:10.1088/1742-6596/1913/1/012053

[5] Saleem, Adeel, Mehmood, Kashif, and Rashid, Faizan. "The Efficiency of Solar PV System." Proceedings of 2nd International Multi-Disciplinary Conference (2019): 1-6.

[6] Lupu, A. G., Homutescu, V. M., Balanescu, D. T., and Popescu, A. "A review of solar photovoltaic systems cooling technologies." *IOP Conference Series: Materials Science and Engineering* 444 (2018): 1-24. https://doi:10.1088/1757-899X/444/8/082016

[7] Moharram, K. A., Abd-Elhady, M. S., Kandil, H. A., and El-Sherif, H. “Enhancing the performance of photovoltaic panels by water cooling.” *Ain Shams Engineering Journal* 4, no. 4 (2013): 869-877. https://doi.org/10.1016/j.asej.2013.03.005

[8] Wu, S., and Xiong, C. “Passive cooling technology for photovoltaic panels for domestic houses.” *International Journal of Low-Carbon Technologies* 9 no. 2 (2014): 118-126. https://doi.org/10.1093/ijlct/ctu013

[9] Ren, X., Li, J., Jiao, D., Gao, D., and Pei, G. “Temperature-dependent performance of amorphous silicon photovoltaic/thermal systems in the long term operation.” *Applied Energy* 275 (2020): 1-14. https://doi.org/10.1016/j.apenergy.2020.115156

[10] Zhao, B., Hu, J., Chen, W., Qiu, Z., Zhou, J., Qu, Y., and Ge, B. (2016, September 8). “Photothermal performance of an amorphous silicon photovoltaic panel integrated in a membrane structure.” *Journal of Physics D: Applied Physics* 49, no. 39 (2016). https://doi.org/10.1088/0022-3727/49/39/395601

[11] Dupré, Oliver, Vaillon, Radolphe, and Green, Martin. “Temperature Coefficients of Photovoltaic Devices.” *Springer eBooks* (2016): 29-74. https://doi.org/10.1007/978-3-319-49457-9_2

[12] Hou, Xin, Wen, Daoyuan, Li, Fangqin, Ma, Chuang, Zhang, Xiaotong, Feng, Haijun, and Ren, Jianxing. “Influence of light and its temperature on solar photovoltaic panels.” *E3S Web of Conferences* 118 (2019): 1-3. https://doi.org/10.1051/e3sconf/201911801047

[13] Verma, Shrey, Mohapatra, Subhashree, Chowdhury, Subhankar, and Dwivedi, Gaurav. “Cooling techniques of the PV module: A review.” *Materials Today: Proceedings* 38, no. 1 (2020): 253-258. https://doi.org/10.1016/j.matpr.2020.07.130

[14] Elias, M. A., Jais, R., Muda, N., and Hassan, N. “Advances of Solar PV System Output Improvement through Cooling Technologies in Malaysia.” *IOP Conference Series: Materials Science and Engineering* 884, no.1 (2020): 1-8. https://doi.org/10.1088/1757-899X/884/1/012076

[15] Sharaf, Mohamed, Yousef, Mohamed S., and Huzayyin, Ahmed S. “Review of cooling techniques used to enhance the efficiency of photovoltaic power systems.” *Environmental Science and Pollution Research* 29 (2022): 26131-26159. https://doi.org/10.1007/s11356-022-18719-9

[16] Taqwa, Ahmad, Dewi, Tresna, Kusumanto, RD., Sitompul, Carlos R., and Rusdianasari, R. “Automatic Cooling of a PV System to Overcome Overheated PV Surface in Palembang.” *Journal of Physics: Conference Series* 1500 (2020): 1-10. https://doi.org/10.1088/1742-6596/1500/1/012013

[17] Dewi, Tresna, Taqwa, Ahmad, Sitompul, Carlos R., Kusumanto, RD., and Rusdianasari, R.“Active and Passive Cooling Comparison of PV Panels Applied in Tropical City: Case Study Palembang, South Sumatra.” *IOP Conference Series: Earth and Environment Science* 709 (2021): 1-9. https://doi.org/10.1088/1755-1315/709/1/012005

[18] Kim, Jaemin, and Nam, Yujin. “Study on the cooling effect of attached fins on pv using cfd simulation.” *Energies* 12, no. 4 (2019): 1-12. https://doi.org/10.3390/en12040758

[19] Grubišić-Čabo, Filip, Nižetić, Sandro, Čoko, Duje, Marinić Kragić, Ivo, and Papadopoulos, Agis. “Experimental investigation of the passive cooled free-standing photovoltaic panel with fixed aluminum fins on the backside surface.” *Journal of Cleaner Production* 176 (2018): 119-129. https://doi.org/10.1016/j.jclepro.2017.12.149

[20] Ibrahim, Mohd Farith, Misaran, Mohd Suffian, and Amaludin, Nazrein Adrian. “Simulation of solar pv surface temperature with dimpled fin cooling.” *IOP Conference Series: Materials Science and Engineering* 1217 (2022): 1-6. https://doi.org/10.1088/1757-899X/1217/1/012015

[21] Agyekum, Ephraim Bonah, Praveenkumar, Seepana, Alwan, Naseer T., Velkin, Vladimir Ivanovich, and Shcheklein, Sergey E. “Effect of dual surface cooling of solar photovoltaic panel on the efficiency of the module: experimental investigation.” *Heliyon* 7 (2021): 1-9. https://doi.org/10.1016/j.heliyon.2021.e07920

[22] Jawad, Ahmed, Misaran, Mohd Suffian, Rahman, Md. Mizanur, and Ismail, Mohd Azlan. “Experimental investigation on the effect of divergent tower solar chimney on the theoretical power potential.” *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 81, no. 1 (2021): 140-149. https://doi.org/10.37934/arfmts.81.1.140149

[23] Tasnim, Rumana, Us Saleheen, Rezwan, Rahman, Mr. Mizanur, and Mahbub, Farhan. “Introduction to solar chimney and its applications.” Cold Inflow-Free Solar Chimney (2021): 39-52. https://doi.org/10.1007/978-981-33-6831-6_3

[24] Jawad, Ahmed, Rahman, Md. Mizanur, and Misaran, Mohd Suffian. “Study the effects of physical parameters on performance in the divergent solar chimney.” *Journal of Mechanical Engineering Research and Developments* 42, no.4 (2019): 249-253. http://doi.org/10.26480/jmerd.04.2019.249.253

[25] Kalkan, Naci, and Dagtekin, Ihsan. “Passive cooling technology by using solar chimney for mild or warm climates.” *Thermal Science* 20, no. 6 (2016): 2125-2136. https://doi.org/10.2298/TSCI150608168K

[26] Ahmed, Omer Khalil, Algburi, Sameer, Ali, Zaid H., Ahmed, Amer K., and Shubat, Hawazen N. “Hybrid solar chimneys: a comprehensive review.” *Energy Reports* 8 (2022): 438-460. https://doi.org/10.1016/j.egyr.2021.12.007

[27] Jafari, Sajedeh, and Kalantar, Vali. "Numerical simulation of natural ventilation with passive cooling by diagonal solar chimneys and windcatcher and water spray system in a hot and dry climate." *Energy and Buildings* 256, no. 1 (2022): 1-16. https://doi.org/10.1016/j.enbuild.2021.111714

[28] Hasan, Afnan A., Ahmed, Omer Khalil, and Fadhil, Ehsan. "Experimental Study of Performance of Solar Chimney." *IOP Conference Series: Materials Science and Engineering* 1094 (2021): 1-11. https://doi.org/10.1088/1757-899X/1094/1/012046

[29] Alkasrawi, Malek, Abdelsalam, Emad, Alnawafah, Hamza, Almomani, Fares, Tawalbeh, Muhammad, and Mousa, Aya. "Integration of solar chimney power plant with photovoltaic for co-cooling, power production, and water desalination." *Processes* 9 (2021): 1-17. https://doi.org/10.3390/pr9122155

[30] Chandavar, Arunachala Umesh. "Quantifying the performance advantage of using passive solar air heater with chimney for photovoltaic module cooling." *International Journal of Energy Research* 45 (2020): 1576-1586. https://doi.org/10.1002/er.5782

[31] Hafiz. "Effect of Wire Mesh on Solar Chimney Performance in a Solar PV Cooling Setup" Undergraduate Thesis, Universiti Malaysia Sabah, Malaysia. 2022.

[32] Popovici, Catalin-George, Hudișteanu, Sebastian Valeriu, Mateescu, Theodor Dorin, and Cherecheş, Nelu-Cristian. "Efficiency Improvement of Photovoltaic Panels by Using Air Cooled Heat Sinks." *Energy Procedia* 85 (2016): 425-432. https://doi.org/10.1016/j.egypro.2015.12.223

[33] Teo, H. G., P. S. Lee, and M. N. A. Hawlader. "An active cooling system for photovoltaic modules." *applied energy* 90, no. 1 (2012): 309-315. https://doi.org/10.1016/j.apenergy.2011.01.017