Performance Analysis of a Hybrid Solar Chimney with DC Fan under Polycarbonate Roofing in Tropical Climate Conditions

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Abstract

This study investigates the performance of a hybrid solar chimney ventilation system integrated with a solar-powered DC fan for controlled cooling in small-scale buildings with polycarbonate roofing under tropical climate conditions. The proposed system combines passive buoyancy-driven ventilation with active airflow enhancement powered by a 20 W photovoltaic module equipped with a maximum power point tracking (MPPT) controller, enabling efficient energy utilization under variable solar conditions. Experiments were conducted using two identical test houses (volume: 4.275 m^3) under real outdoor conditions in Thailand. Key parameters, including temperature distribution, air velocity, solar radiation, and heat flux, were continuously monitored throughout the day. The results show that sub-roof temperatures reached 75–78 °C, generating temperature differences exceeding 40 °C, which significantly enhanced buoyancy-driven airflow and stack effect. The hybrid system increased airflow velocity to 4.5 m/s, resulting in a substantial improvement in air change rates (ACH) compared to natural ventilation. Consequently, indoor temperatures were reduced by up to 12 °C, while heat flux decreased from approximately 330 W/m^2 to 210 W/m^2, corresponding to a maximum reduction efficiency of 12.1%. These results demonstrate that the proposed system can simultaneously enhance airflow, reduce thermal load, and improve indoor thermal conditions under high solar radiation. The integration of a solar-powered fan further enables energy self-sustained operation, making the system a practical and sustainable solution for mitigating heat accumulation in buildings in tropical climates.

Keywords: Polycarbonate, Hybrid Solar Chimney Performance, DC Fan

Introduction

Buildings in tropical regions are exposed to high levels of solar radiation, which leads to significant heat accumulation, particularly through roofing systems. Polycarbonate materials are widely used in building envelopes due to their lightweight properties and high light transmittance. However, these materials also absorb and transmit substantial solar heat, resulting in elevated indoor temperatures and thermal discomfort (Baskaran et al., 2024). Passive cooling strategies, such as natural ventilation and solar chimney systems, have been extensively investigated as energy-efficient approaches to mitigate heat accumulation in buildings (Bejan, 2013). These systems rely on buoyancy-driven airflow induced by temperature differences between indoor and outdoor environments. Despite their advantages, their performance is highly dependent on environmental conditions, particularly solar radiation intensity and temperature gradients, which limits their effectiveness under transient or low-driving-force conditions. To overcome these limitations, active ventilation systems using mechanical fans have been introduced to enhance airflow. However, such systems typically require continuous external energy input, thereby reducing overall energy efficiency and sustainability. Consequently, recent studies have proposed hybrid ventilation systems that integrate passive and active mechanisms to improve thermal performance while maintaining energy efficiency. Nevertheless, a critical research gap remains. While several studies have examined solar chimney performance under controlled or simulated conditions, there is a lack of experimental investigations conducted under real tropical outdoor environments, where solar radiation, ambient temperature, and airflow conditions are highly dynamic. Furthermore, limited research has focused on buildings incorporating polycarbonate roofing, which exhibits high solar heat gain and presents unique thermal challenges compared to conventional roofing materials. In particular, the combined effects of airflow balance, heat flux reduction, and ventilation efficiency in hybrid systems under such conditions have not been comprehensively quantified. Therefore, this study aims to experimentally investigate the thermal performance of a hybrid solar chimney system integrated with DC fans under polycarbonate roofing in a tropical climate. In addition, an empirical model is developed to predict airflow rates, and key parameters influencing ventilation performance, including heat flux and airflow balance, are systematically analyzed.

Literature Review

This study is grounded in fundamental engineering principles, including heat transfer, fluid flow, natural ventilation, and solar energy transfer in small-scale buildings with transparent polycarbonate roofing. Heat transfer within the roofing system and indoor air occurs through three primary mechanisms: conduction, convection, and thermal radiation, which form the basis of thermal energy analysis (Incropera et al., 2017). Conduction refers to heat transfer through a material due to temperature differences and is described by Fourier's law: $Q_{cond} = kA\frac{\Delta T}{L}$. Convection is the process of heat transfer between a surface and the surrounding fluid: $Q_{conv} = hA(T_s - T_{air})$. Thermal radiation is the transfer of energy through electromagnetic waves and can be described by the Stefan–Boltzmann law: $Q_{rad} = \epsilon\sigma A(Ts^4 - Tsky^4)$. Solar energy is the primary driving force for temperature rise in translucent roofing systems. The transmitted solar heat gain through the material can be expressed as: $Q_{solar} = \tau IA$ (Duffie & Beckman, 2013).

The stack effect is a ventilation mechanism driven by air density differences caused by temperature gradients, resulting in vertical airflow through building openings (Etheridge & Sandberg, 1996). In translucent roofing systems, solar radiation increases the air temperature within the roof cavity, generating buoyancy forces that induce upward airflow, similar to a solar chimney (Kalogirou, 2006). The solar chimney mechanism consists of: Solar heat absorption, Air temperature rise, Density difference, Buoyancy-driven airflow. Recent experimental studies have demonstrated that hybrid ventilation systems, which combine natural convection with mechanical assistance, can significantly enhance airflow and thermal performance compared to purely passive systems. For instance, Bansal et al. (2020) and Khanal and Lei (2011) reported that solar chimney systems improve ventilation rates under high solar radiation; however, their performance declines under low temperature gradients. More recent experimental investigations have further highlighted the effectiveness of hybrid systems. Gan (2018) and Li et al. (2021) showed that integrating low-power fans with solar chimney configurations can stabilize airflow and improve ventilation efficiency under fluctuating environmental conditions. Similarly, Zhang et al. (2022) experimentally demonstrated that hybrid solar-driven ventilation systems can reduce indoor temperature by 5–10°C compared to passive systems alone, particularly in hot climates. Despite these advancements, most previous studies have been conducted either under controlled laboratory conditions or in large-scale buildings. Experimental validation in small-scale buildings under real tropical outdoor conditions remains limited, particularly for roofing systems with high solar transmittance such as polycarbonate materials. Furthermore, the interaction between heat flux, airflow balance, and hybrid ventilation performance has not been fully quantified in such configurations. To overcome the limitations of passive systems, this study adopts a hybrid ventilation approach combining natural convection with mechanical assistance: $Q_{total} = Q_{natural} + Q_{fan}$. The use of a fan enhances airflow, particularly when buoyancy forces are insufficient, thereby improving overall cooling performance (Heiselberg, 2002). Furthermore, integrating a solar-powered DC fan enables sustainable operation without external energy input: $P = V \times I$. The photovoltaic system directly regulates airflow, allowing adaptive response to environmental conditions (Kalogirou, 2014).

Based on these principles, the experimental configuration (Fig. 1) demonstrates natural and hybrid ventilation in small-scale buildings with transparent polycarbonate roofing combined with reflective insulation. The sub-roof region experiences significantly higher temperatures than indoor conditions, with temperature differences exceeding 48–50 °C during March in Thailand. This large temperature gradient provides strong buoyancy forces and also presents potential for thermal energy utilization. Conduction refers to heat transfer through a material due to temperature differences and is described by Fourier's law.

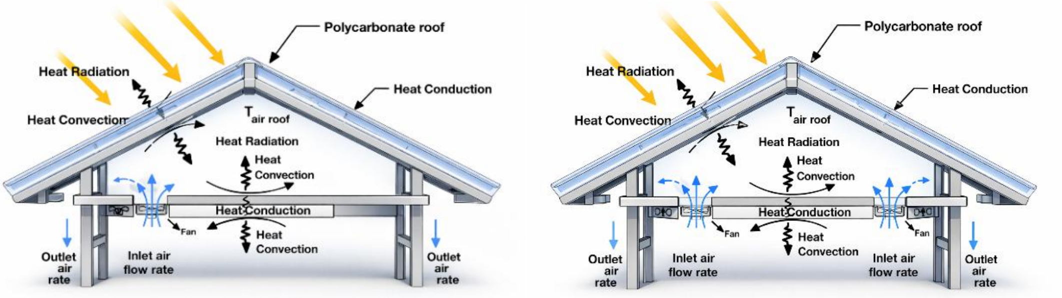

Figure 1 Schematic of natural heat transfer through the roof into the experimental house, illustrating configurations with one and two ventilation grille openings combined with one and two DC fans (Incropera et al., 2017, Preeda Chantawong , 2009).

Research Methodology

Two identical model houses were constructed and tested in a residential area in Phattharin Village, Khu Bang Luang, Lat Lum Kaeo, Pathum Thani, Thailand (as shown in Fig. 2). The study investigates solar chimney ventilation and compares its effectiveness in reducing heat gain under natural climatic conditions. Each house had dimensions of 1.5 × 1.5 × 1.9 m, corresponding to a volume of 4.275 m³. The first configuration was equipped with a single ventilation grille opening (10 × 10 cm, 0.01 m²) integrated with one DC brushless fan (FW-12VDC). The second configuration included two identical ventilation openings combined with two DC brushless fans. The system was powered by a 200 W photovoltaic panel (Model JC-DS20250520-1614) with an MPPT solar charge controller (SUOER), charging a 12V, 7.2

Ah sealed battery (Kung Long, Model WP7.2-12). Thermal insulation consisting of 10 mm thick cross-linked closed-cell polyethylene was installed between the roof and ceiling, above SCG Smartboard panels (flat edge, cement finish; 120 × 240 × 0.6 cm). The roof structure was designed as a gable roof, with the sub-roof space divided into two layers. The outer layer consists of a 2 mm thick transparent polycarbonate sheet to enhance natural light transmission, while the inner layer is constructed from a flat Smartboard panel with a thickness of approximately 6 mm. The structural frame is made of black steel square tubes (2 × 2 inches, 3 mm thickness), with joints connected by welding. The walls are constructed from SCG Smartboard panels (flat edge, cement finish) with dimensions of 120 × 240 × 0.6 cm, and the floor is made of Viva Board panels (cement finish) with dimensions of 120 × 240 × 1.0 cm. As shown in the table below.

Table 1 Table presents the key parameters and experimental configurations of the two test houses.

Category	**Parameter**	**House 1**	**House 2**	**Unit**
Building Geometry	Length × Width × Height	1.5 × 1.5 × 1.9	1.5 × 1.5 × 1.9	m
	Building volume	4.275	4.275	m^3
	Roof type	Gable roof (double layer)	Gable roof (double layer)	-
	Roof area (solar exposure)	4.275	4.275	m^3
Roof Material	Outer layer	Polycarbonate (clear)	Polycarbonate (clear)	-
	Thickness (outer)	2	2	mm
	Inner layer	Smart board	Smart board	-
	Thickness (inner)	6	6	mm
Insulation	Type	Cross-linked PE	Cross-linked PE	-
	Thickness	10	10	mm
Ventilation System	Vent opening size	10	10	cm
	Vent area per opening	0.01	0.01	m^2
	Number of vents	1	2	-
	Total vent area	0.01	0.02	m^2
Fan System	Fan type	DC brushless fan	DC brushless fan	-
	Number of fans	1	2	
	Power source	Solar PV 20W	Solar PV 20W	W
	Solar radiation	Pyranometer ML-020V	Pyranometer ML-020V	W/m²
	Temperature	Thermocouple type K	Thermocouple type K	°C
	Air velocity	Testo 425	Testo 425	m/s
	Heat flux	EKO MF-180	EKO MF-180	W/m²
	Controller	SUOER MPPT	SUOER MPPT	-
	Battery	Model WP7.2-12	Model WP7.2-12	-
Data Acquisition	Data logger	Hioki 8400-20	Same	-
	Sampling interval	10	10	min

	Measurement period	07:05–19:05	Same	hr.
Environmental Conditions	Climate	Tropical (Thailand)	Same	-
	Max solar radiation	~1000	~1000	W/m²

Figure 2 Photograph of the experimental house used for data collection in the evaluation of the system's thermal performance.

This study experimentally evaluates and compares the thermal performance of the system in reducing heat gain within the model houses. The analysis includes variations in ambient temperature and solar radiation intensity, measured using a pyranometer (Model ML-020V, sensitivity: 7.2 µV/W/m²; range: 0–2000 W/m²). Indoor air temperature, ceiling temperature, and roof surface temperature were monitored for both configurations. House 1 was equipped with a smooth, transparent polycarbonate roof with one ventilation grille opening (10 × 10 cm, 0.01 m²) integrated with one DC brushless fan (FW-12 VDC), while House 2 had two identical openings combined with two DC brushless fans. Temperature measurements were conducted using Type K thermocouples (range: 0–1250 °C, accuracy: ±0.5 °C). Air velocity inside and outside the houses was measured using a Testo 425 (range: 0–20 m/s, accuracy: ±5%). Heat flux through the roof was measured using an EKO heat flow meter (Model MF-180, range: −30 °C to 120 °C, accuracy: ±2%). All data were recorded using a data logger (Hioki, Model 8400-20, accuracy: ±0.8%) at 10-minute intervals from 07:05 to 19:05, for a total duration of 12 hours.

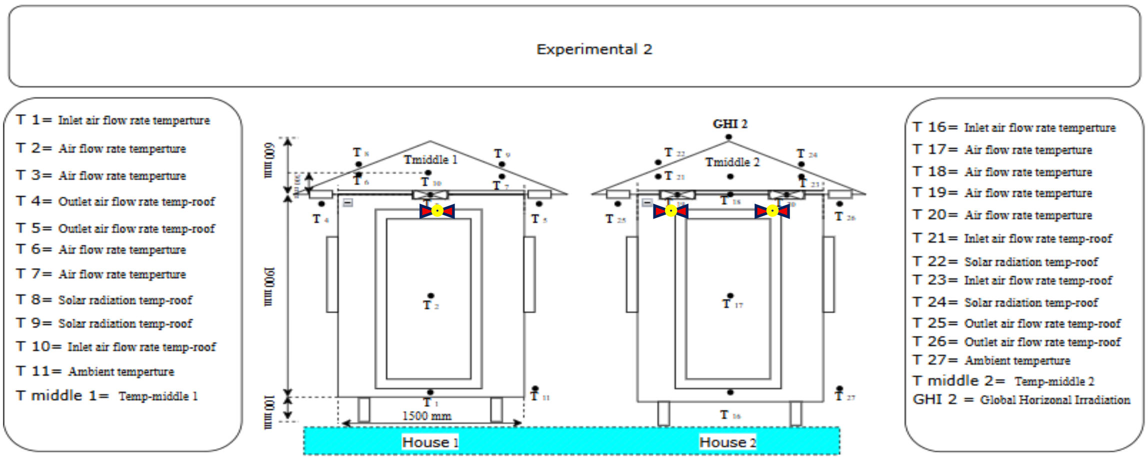

Figure 3 Schematic showing the locations of measurement instruments installed for evaluating the thermal performance of the system.

Result

The results were analyzed and presented graphically to evaluate the ventilation performance of a solar-driven thermal chimney in small-scale buildings with transparent polycarbonate roofing over a 12-hour period (07:05–19:05). As shown in Fig. 3, the findings indicate that the installation of a single DC fan enhances airflow and improves cooling performance compared to natural ventilation alone. However, the system remains insufficient under peak thermal conditions, where roof temperatures exceed 70 °C. Although indoor temperatures were reduced by approximately 2–5 °C, heat accumulation persisted. This suggests that the use of a single DC fan provides only partial improvement in ventilation performance.

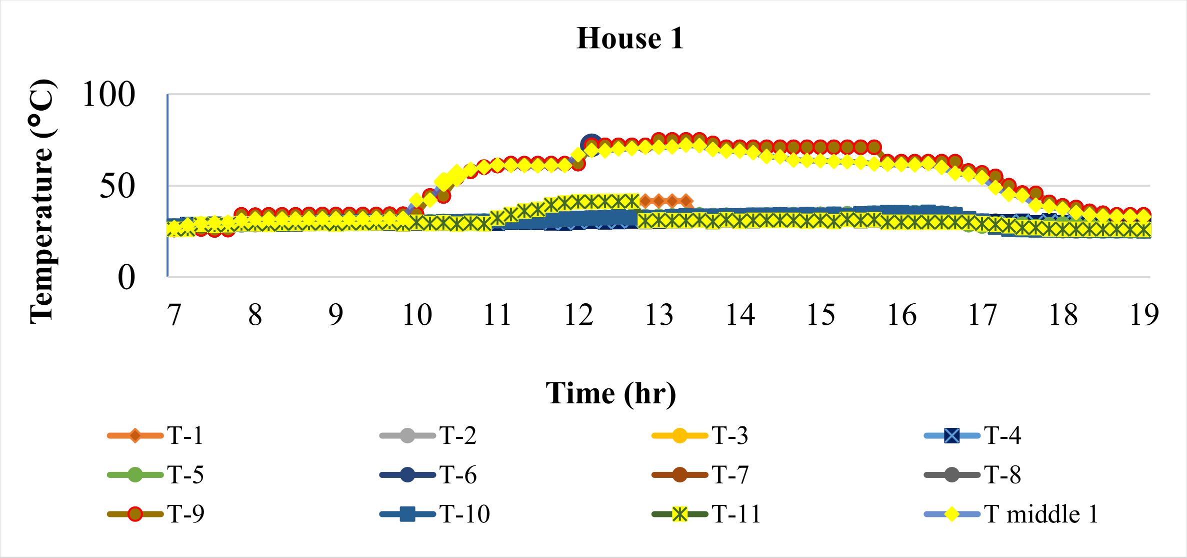

Figure 4 Temperature profile showing natural heat transfer between the sub-roof space and indoor environment in the experimental house with a single ventilation grille opening combined with one DC fan.

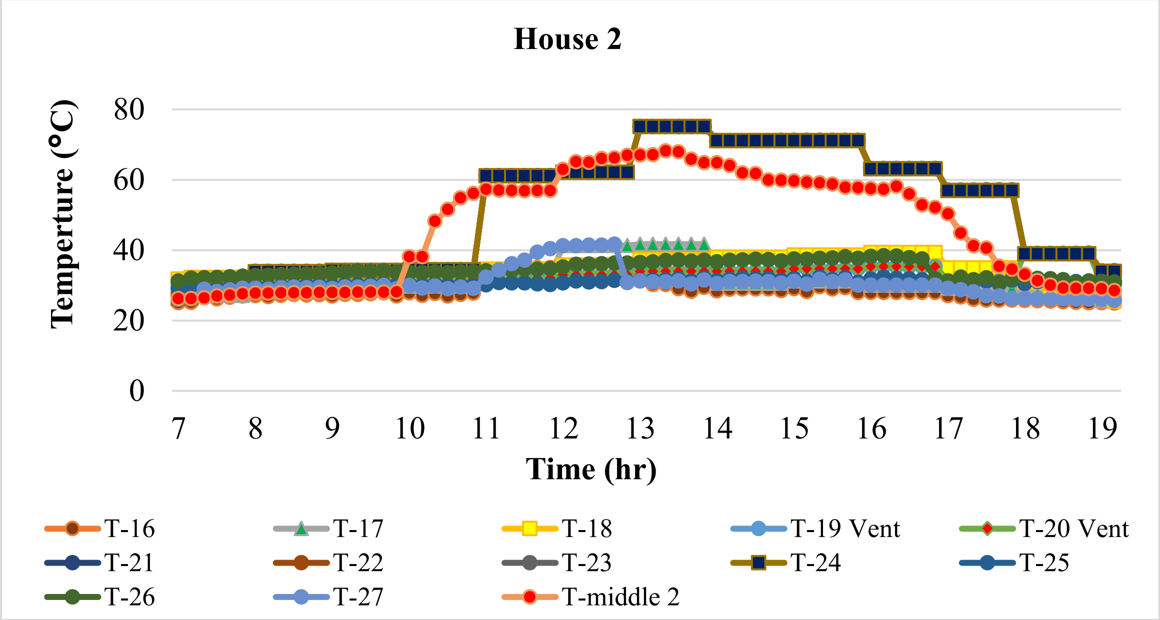

Figure 5 Temperature profile showing natural heat transfer between the sub-roof space and indoor environment in the experimental house with two ventilation grille openings combined with two DC fans.

As shown in Fig. 5, the results indicate that the hybrid ventilation system with dual DC fans significantly improves cooling performance compared to the single-fan configuration. Although the roof temperature remains similar (approximately 75 °C), the indoor temperature is reduced to 30–35 °C, indicating more effective heat removal. The presence of two ventilation openings and enhanced airflow leads to a more balanced system, reducing heat accumulation and improving overall ventilation performance. In contrast, Fig. 6 presents the airflow measurements, which reveal a significant imbalance between inlet and outlet air velocities, with outlet velocities reaching up to 4.7 m/s. The inlet air velocity remained relatively constant at approximately 1.6 m/s and 4.2 m/s.

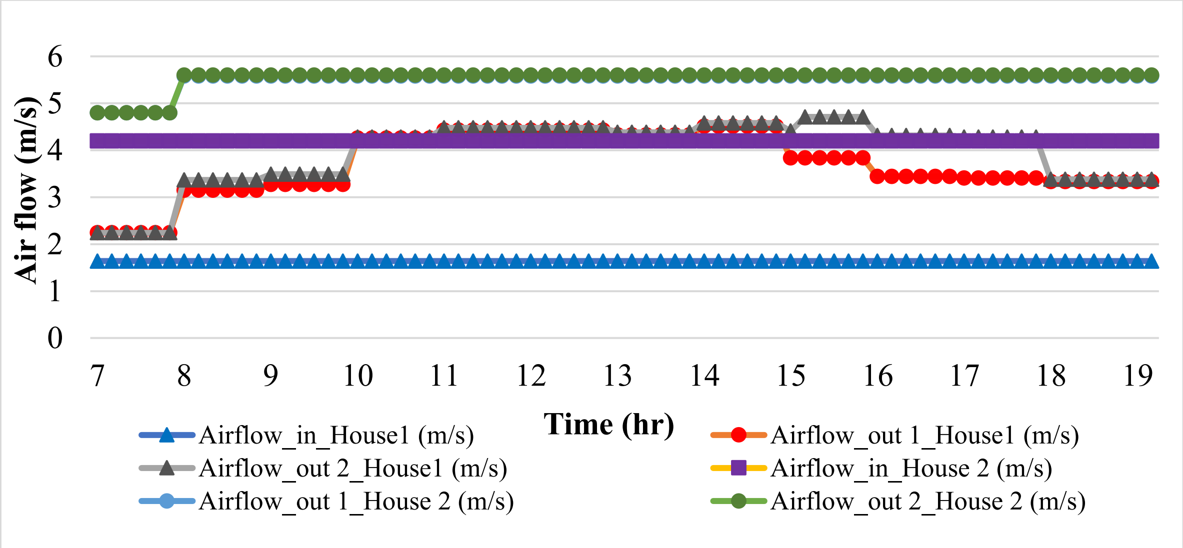

Figure 6 Comparison of air velocity variations between the experimental houses (House 1 and House 2).

This imbalance indicates flow restriction at the inlet, leading to negative pressure conditions within the system. Although the use of fans enhances airflow, the limited inlet area reduces overall ventilation efficiency. In contrast, airflow measurements in House 2 show stable and nearly constant flow throughout the experimental period. The inlet and outlet air velocities are comparable, indicating a well-balanced ventilation system with minimal flow resistance. Unlike the single-fan configuration, the dual-fan system provides more uniform airflow that is less sensitive to temperature variations, resulting in improved cooling performance and more uniform air distribution.

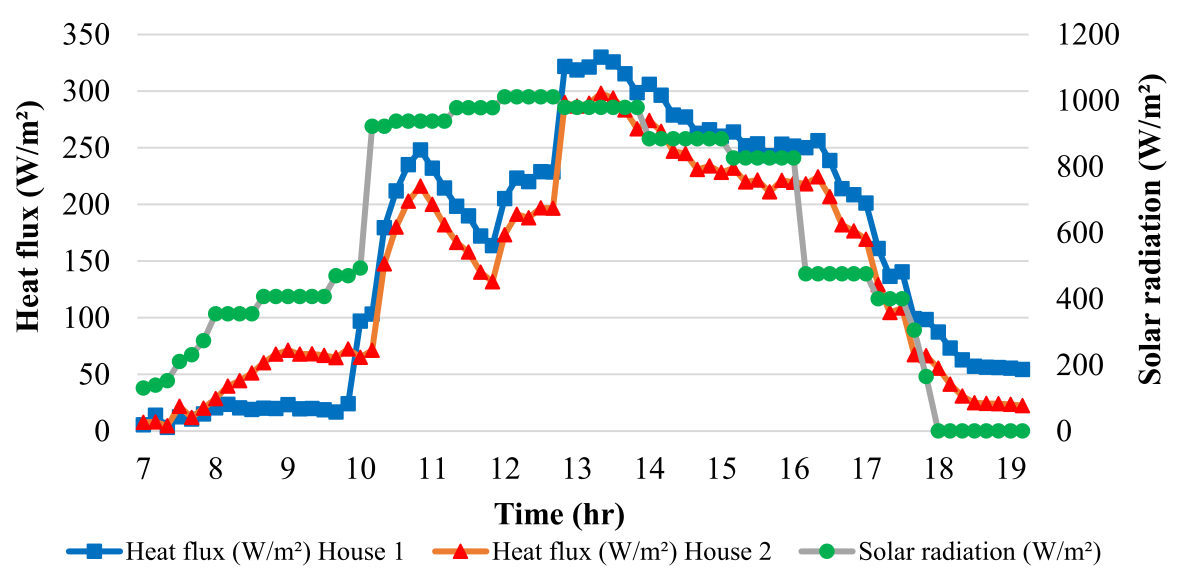

Figure 7 Comparison of natural heat transfer through polycarbonate-roof experimental houses (House 1 and House 2) integrated with DC fans.

As shown in Fig. 7, the results indicate that House 2 consistently exhibits lower heat transfer compared to House 1, despite being exposed to the same solar conditions. This demonstrates that the improved ventilation system in House 2 is more effective in removing heat and reducing heat accumulation beneath the roof. The enhanced airflow balance and increased ventilation capacity play a crucial role in minimizing heat transfer into the indoor space. As shown in the table below.

Table 2 Table presents the performance indicators.

Category	**Parameter**	**House 1**	**House 2**	**Unit**
Performance Indicators	Heat flux (peak)	~330	~290	W/m²
	Heat flux reduction	-	~12	%
	Indoor temperature reduction	Baseline	Reduce 8–12	°C
	Airflow performance	Unbalanced	Balanced	-

Discussion and conclusions

The experimental results demonstrate that solar radiation is the primary driving force influencing thermal behavior in polycarbonate roofing systems. The roof temperature reached up to 70–78°C under peak solar conditions, generating a significant temperature difference that drives buoyancy-induced airflow. This observation is consistent with classical heat transfer and natural convection theory (Bejan, 2013), as well as previous studies on solar chimney systems (Khanal & Lei, 2011). The airflow analysis revealed a clear distinction between the two configurations. In House 1, the system exhibited an imbalance between inlet and outlet airflow, resulting in localized heat accumulation and temperature stratification. In contrast, House 2 demonstrated a balanced airflow system with nearly equal inlet and outlet velocities, leading to improved air mixing and uniform temperature distribution. These findings are in agreement with previous experimental studies. For example, Bansal et al. (1993) reported that ventilation performance in solar chimney systems strongly depends on airflow balance and opening configuration. Similarly, Gan (2018) highlighted that insufficient inlet area can limit airflow effectiveness, even when buoyancy forces are strong. The present study confirms these observations under real tropical conditions, where solar radiation is significantly higher and more variable. Furthermore, the integration of DC fans in the hybrid system significantly enhanced ventilation performance. The results show that House 2 achieved a reduction in heat flux of approximately 10–12% compared to House 1, along with a decrease in indoor temperature of 8–12°C. These results are consistent with more recent studies on hybrid ventilation systems. Li et al. (2021) reported that hybrid systems can improve airflow stability and reduce indoor temperature by 5–10°C, while Zhang et al. (2022) demonstrated that fan-assisted solar ventilation systems provide more consistent airflow under fluctuating environmental conditions. However, the present study extends previous work by providing experimental validation under real tropical outdoor conditions using polycarbonate roofing, which exhibits higher solar heat gain compared to conventional materials. Unlike many previous studies conducted under controlled environments or simulations, this study captures the dynamic interaction between solar radiation, heat flux, and airflow in real conditions.

In addition, the results show that higher heat flux values observed in House 2 during peak periods are associated with improved heat removal rather than increased heat gain. This phenomenon aligns with the findings of Heiselberg (2002), who emphasized that enhanced ventilation increases heat transfer rates and reduces thermal accumulation within buildings.

Overall, the findings confirm that hybrid ventilation systems can significantly improve thermal performance, particularly when airflow is balanced and sufficient ventilation capacity is provided. The agreement between the present results and previous studies strengthens the validity of the conclusions and highlights the applicability of hybrid solar chimney systems in tropical climates.

This study investigated heat transfer behavior and hybrid ventilation performance using solar-powered DC fans beneath polycarbonate roofing in two experimental model houses under the climatic conditions of Pathum Thani, Thailand. The results demonstrate that the hybrid solar chimney system integrated with DC fans significantly enhances ventilation performance and effectively improves cooling in small-scale buildings.

Suggestion

Based on the experimental results, a single fan provides moderate performance, while two fans significantly enhance ventilation efficiency. Therefore, increasing the number of fans is recommended for larger spaces. In addition, selecting high static pressure fans and optimizing their placement according to airflow direction are important for improving system performance. Future research should focus on energy-saving analysis and further development of hybrid ventilation systems.

Acknowledgements

The author would like to express sincere gratitude to the advisor and all faculty members for their valuable guidance, constructive suggestions, and academic support throughout this research.

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