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Heat gain reduction using solar chimney window driven by pv-powered fan

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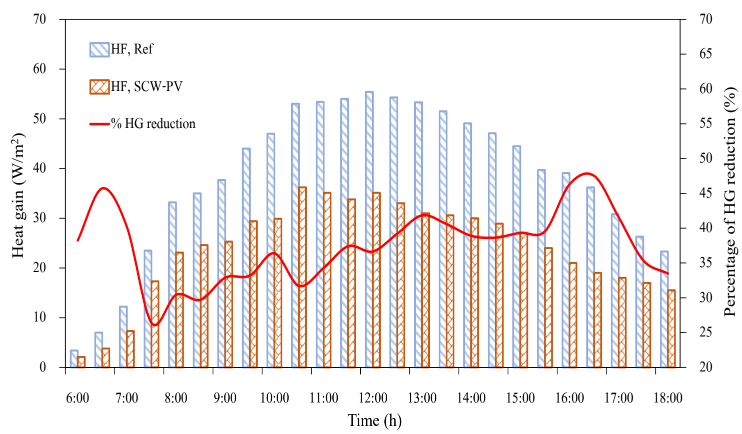
Abstract



This study investigated the performance of a solar chimney window equipped with a PV-powered fan (SCW-PV) in reducing heat gain and improving ventilation in buildings. The research methodology involved comparative testing of two houses: one with a common glazed window (reference) and the other with the SCW-PV installed. The SCW-PV consisted of two glass layers with an aluminum frame, vents at the top and bottom, and a DC fan connected to a PV panel without a battery. This field test investigated the variables of temperature and heat transfer reduction, with data collected during daytime hours on clear-sky days. Temperature, heat flux, and air velocity sensors were calibrated and recorded the data. Results showed that the SCW-PV effectively lowered the room space temperature compared to the common glazed window, reducing window heat gain by 10-20 W/m^2 (15-55% reduction). The ventilation rate through the SCW-PV ranged from 15-50 m^3/h, corresponding to 5.2-17.4 air changes per hour (ACH) in the 2.88 m^3 room. The findings suggest that the SCW-PV is a significant tool for reducing window heat gain, minimizing heat accumulation in room spaces, and improving indoor thermal comfort. Therefore, the SCW-PV is recommended for implementation in buildings to enhance energy efficiency and occupant comfort.

Keyword: Solar chimney window; PV-powered fan; Heat gain; Ventilation rate; Number of air change

1. Introduction

The significance of interior comfort and building services, together with the growing worldwide population, have led to a major growth in the context of energy utilization, the construction sector accounts for a substantial portion of worldwide energy consumption [1]. Under the present global carbon neutrality targets, the significance of sustainable development in the construction industry cannot be emphasized, since buildings have historically contributed significantly to overall energy consumption. According to the data, buildings consume 40% of the energy produced worldwide. In addition, current data indicates that over 50% of the world's yearly energy usage is attributed to the heat, ventilation, and air conditioning (HVAC) systems found in ordinary buildings [2].

In 2023, Thailand's final energy consumption reached 83,068 kilotonnes of oil equivalent (ktoe), with electrical energy consumption at 18,378 ktoe, accounting for 22.1 percent—an increase of 3.6 percent compared to 2022. The residential buildings sector consumed 9,969 ktoe of electrical energy, representing 12.0 percent and a 2.5 percent increase from 2022 [3]. This highlights the critical need to enhance the thermal performance of building envelopes, particularly windows, which are among the most energy-inefficient components [4]. Studies have shown that improving building envelope efficiency is essential for reducing energy consumption and enhancing occupant comfort, especially in high rise buildings within hot and humid climates [5]. Researchers have proposed various solutions, such as multi-functional windows with ventilation and solar blinds to reduce energy consumption and improve indoor air quality [6].

These investigations underscore the influence of solar radiation and wind on indoor environmental conditions, the correlation between window dimensions and energy efficiency, as well as the ideal dimensions for window ventilation systems. Similarly, solar radiation is instrumental in facilitating natural ventilation systems, especially in hot and humid climates. For example, solar chimneys can significantly improve buoyancy-driven ventilation by elevating the temperature of the air within the chimney, which subsequently ascends and establishes a pressure differential that draws in cooler external air [7].

However, the efficacy of such systems is contingent upon the architectural design and climatic conditions of the building. In tropical climates, where wind velocities are typically minimal, buoyancy-driven ventilation methods, such as solar chimneys, may prove to be more advantageous than wind-driven systems [8]. Wind-driven ventilation is significantly influenced by external wind speeds and the configuration of the building. The incorporation of transom windows and buffer zones can substantially improve indoor air velocity and thermal comfort [9]. Likewise, cross-ventilation approaches utilizing opposing windows have demonstrated a remarkable enhancement over single-sided ventilation, achieving improvements in natural ventilation rates of up to 62.5% [10]. Furthermore, solar radiation exerts an influence on thermal comfort by elevating indoor temperatures via windows.

In tropical climates, the thermal comfort range has been updated to 29.3°C to 31°C, reflecting the need for designs that minimize solar heat gain while maintaining natural ventilation [11]. The implementation of shading mechanisms and strategically positioned window orientations can effectively reduce excessive solar gain while simultaneously facilitating natural light and ventilation [12]. The window-to-wall ratio (WWR) serves as a pivotal element in assessing energy efficiency. Research conducted in subtropical monsoon climates, such as Bangladesh, has demonstrated that elevated WWRs result in increased solar heat gain, which can substantially escalate cooling energy consumption [13]. The dimensions and positioning of windows are vital, as they significantly affect air flow rates and overall ventilation efficiency.

The implementation of a solar chimney window (SCW) represents an innovative approach to enhancing indoor thermal comfort and energy efficiency through natural ventilation and solar energy. Al Touma et al. found that combining a solar chimney with a passive evaporative cooler lowered window temperatures by 8–12% under certain conditions, reducing heat gain and air conditioning dependence [14]. Ahmed highlighted the significance of computational fluid dynamics (CFD) simulations in optimizing solar chimney designs to improve airflow and thermal performance for better indoor conditions [15]. Advancements like the double-pass inclined design have demonstrated enhanced natural ventilation by optimizing solar exposure and airflow. Faouzi et al. revealed that this approach effectively utilized solar heat to ensure continuous airflow, thereby reducing reliance on mechanical ventilation systems [16].

Over the past decade, various studies have explored solar windows and related technologies in Thailand to reduce energy consumption, especially in Bangkok's tropical climate. Tanachaikhan et al. analyzed daylighting in non-air-conditioned buildings, developing a daylighting algorithm suited to tropical conditions that demonstrated significant energy conservation potential [17]. Ratanachotinun et al. executed a feasibility study on glass solar chimney walls (GSCWs) in Bangkok, finding that GSCWs could lower indoor temperatures and reduce air conditioning energy consumption by 5-14% depending on the season [18]. Chimres et al. reviewed the status and challenges of solar energy in Thailand, emphasizing the need for policy and infrastructure improvements [19]. Chaianong et al. and Chaianong highlighted the prospects and challenges for promoting solar photovoltaic rooftops, identifying high capital costs and low public awareness as major barriers to adoption [20,21]. These findings motivate further research on integrating advanced window systems, such as smart windows, PV technologies, and shading optimization, into energy-efficient building designs. There is potential for enhancing occupant comfort while simultaneously reducing energy consumption.

Previous studies consistently emphasized the importance of mitigating heat transfer within building envelopes to reduce energy consumption. This study focuses on heat transfer through building envelopes, investigating a solar chimney window integrated with a photovoltaic-powered fan (SCW-PV) to reduce heat gain and enhance ventilation within buildings. The incorporation of a solar chimney within a window system can substantially reduce the heat gain through windows, which are generally a principal contributor to excessive heat in structures. This system not only lessens the cooling demand but also enhances airflow, positioning it as a sustainable solution for contemporary architecture.

2. Materials and Methods

Research objectives

The primary objectives of this research are to investigate and analyze the reduction of heat through a solar chimney window (SCW) integrated with a photovoltaic (PV) system. Specifically, the study aims to examine the effect of heat transfer through the SCW-PV system and assess the performance of ventilation fans powered by the electrical energy generated from the PV system. By focusing on these key areas, we can gain a deeper understanding of the potential benefits and applications of utilizing solar energy for heat reduction and ventilation systems.

Research methodology

This experimental design compares the heat gain reduction of a solar chimney window equipped with a PV-powered fan (SCW-PV) system to that of a common glazed window which thickness of 0.7 centimeters. The experiment involves two small houses, each measuring 3.4 cubic meters. Both houses are constructed with lightweight brick walls and have roofs angled at 30 degrees, adorned with double-layered corrugated blue tiles. Furthermore, the positioning of the windows has been strategically aligned to face south, as illustrated in Fig. 1. The SCW-PV, measuring 1 meter in width and 1.2 meters in height, is installed in one house, with an air gap of 10 centimeters. This design allows for a controlled comparison between the two houses, as they are identical in size and construction, except for the type of window. This setup helps isolate the effects of the SCW-PV on energy usage, temperature regulation, and potential energy generation.

The solar cell ventilation system comprises a 25 Wp solar cell panel, a solar charge controller, and two 4.8 W DC electric fans specifically designed for ventilation purposes, all interconnected in the configuration illustrated in Fig. 2 This setup ensures efficient airflow and proper functioning of the system.

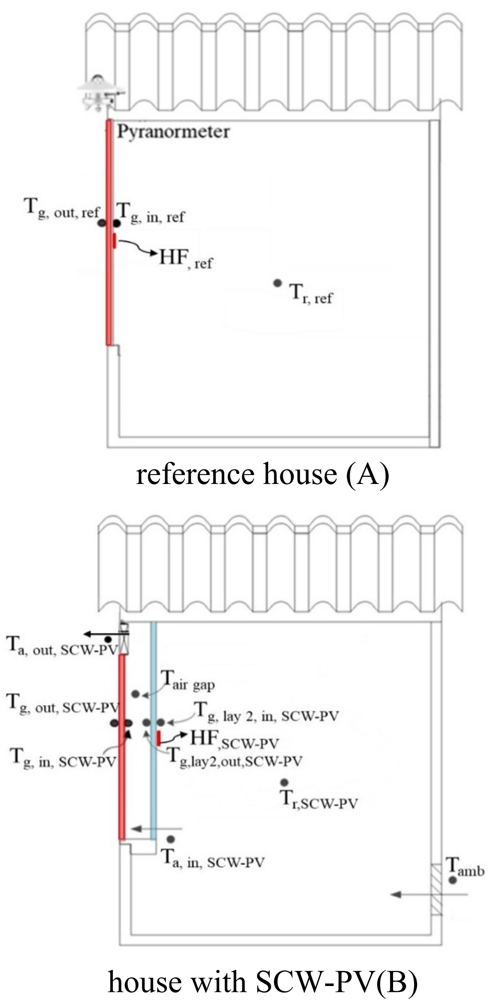


Fig. 1 Figure shows reference house (A) without ventilation system and test house with SCW-PV (B)

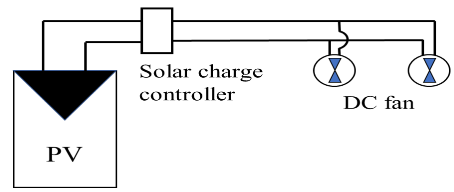


Fig. 2 Figure shows SCW-PV diagram

Research instruments and data reduction

The instrumentation employed in the experiment comprises a pyranometer (Kipp and Zonen: CMP11, operational range: 310-2800 µm, uncertainty <2%) that was positioned on the rooftop to quantify solar irradiance. Type K thermocouples (temperature range 0-1250°C, accuracy ±0.4°C) were interfaced with a data logger (Hioki: LR8422-20, accuracy ±0.7%) to monitor temperature variations. Additionally, a heat flux sensor (OmegaHFS-3, measurement range 1-1400 W/m², error ± 0.5%) was utilized to assess thermal gain, as illustrated in Figure 1. Window orientation is directed towards the south. The experimental period lasted for 30 days during the summer, and the data acquired from the collection process were scrutinized, selecting information from climatic conditions characterized by a clear sky. Data acquisition occurred from 6:00 to 18:00, with recordings taken at one-minute intervals. Two small-scale test structures were constructed on the rooftop of the Faculty of Architecture and Design at Rajamangala University of Technology Rattanakosin, Thailand (latitude 13°47'41.3"N and longitude 100°17'56.7"E).

The air flow rate through a ventilated SCW-PV system can be calculated from

$$Q = A_C v \quad (1)$$

When

A_C = air flow area, m^2

v = Speed of air through the SCW-PV, m/s

Number of air change in the test house installed with SCW-PV, which is calculated from

$$ACH = \frac{Q}{V} \quad (2)$$

When

Q = ventilation rate, m^3/hr

V = Volume of test house, m^3

3. Results and Discussion

This study investigated the reduction of heat transfer through a solar chimney window equipped with a PV-powered fan (SCW-PV), aiming to improve heat transfer efficiency by utilizing the solar cell ventilation system. As illustrated in Fig. 3, fluctuations in solar intensity and ambient air temperature were monitored throughout the testing phase. It was noted that an elevation in solar intensity corresponds with a rise in ambient air temperature. The solar intensity peaked at approximately 600 W/m², while the minimum recorded value was about 120 W/m². Likewise, the ambient air temperature (T_{amb}) fluctuated from a maximum of around 35°C to a minimum of approximately 17°C, demonstrating a direct correlation between solar intensity and temperature changes. These findings are consistent with earlier research indicating that increased solar radiation directly impacts air temperature, thereby influencing the overall heat transfer mechanisms in advanced window systems.

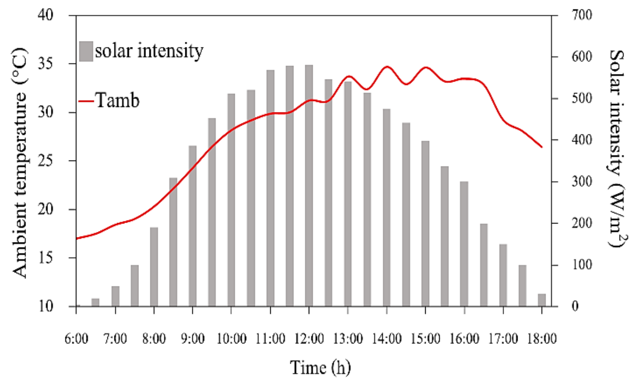


Fig. 3 Hourly variation of ambient temperature and solar intensity (Vertical plane)

Fig. 4 illustrates the air temperature at the inlet ($T_{a, in, SCW-PV}$) and outlet ($T_{a, in, SCW-PV}$) of the solar cell ventilation system (SCW-PV). The temperature difference between the inlet and outlet ranges from 2°C to 14°C. A larger temperature difference correlate with periods of high solar irradiance and optimal airflow rates, reflecting enhanced convective heat removal.That indicates more effective heat transfer to the environment, thereby reducing the amount of heat transferred through SCW-PV into the house. This phenomenon will be further explained in the subsequent figure.

Fig. 5 portrays the room temperatures of two test houses, one with a solar cell ventilation system installed ($T_{r, SCW-PV}$) and the other without any ventilation ($T_{r, Ref}$). It is evident from the graph that the house equipped with the solar cell ventilation system exhibits lower room temperatures compared to the unventilated house. The temperature difference ranges between 1°C to 3°C. This temperature reduction can be attributed to the ventilation's role in diminishing heat transfer through SCW-PV, which will be elaborated upon in the forthcoming figure. Furthermore, the implementation of SCW-PV has the potential to enhance the effectiveness of lowering the room temperature via window glass in comparison to analogous systems [14].

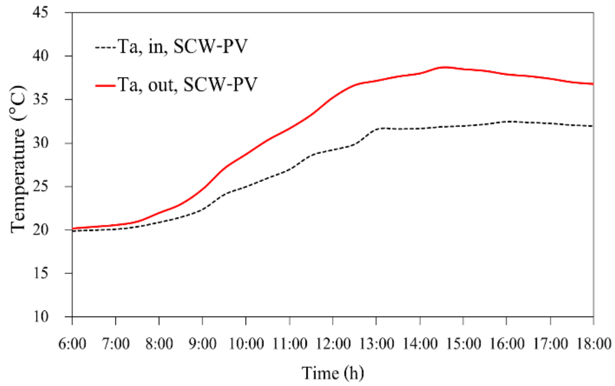


Fig. 4 Hourly variation of inlet and outlet air temperatures

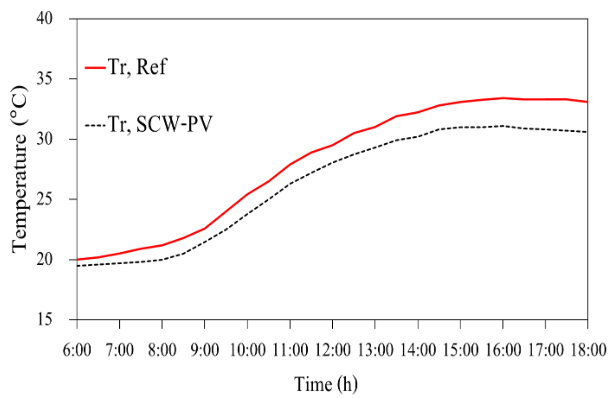


Fig. 5 Hourly variation of room temperature

Fig. 6 is presented to visually represent the ventilation rate (Q_{vent}) throughout the day. In the test house equipped with SCW-PV, the ventilation rate ranged between 15-50 m^3/h, with a maximum rate of 50 m^3/h. The calculation of the air change (ACH) in the SCW-PV installed test house is done using Equation (2).

The ventilation rate through the SCW-PV system indicates that the air passing through the double-glazed window chimney inside the test house is replaced by the air outside. As a result, the air inside the test house undergoes changes, preventing heat accumulation caused by heat transfer into the house. Figure 6 also shows the number of air changes in the test house ventilated by the SCW-PV system. The air change ranges from 5.2-17.4 air changes per hour (ACH) in the 2.88 m^3 room. This observation coincides with the temperature variations inside the test house room depicted in Fig. 5.

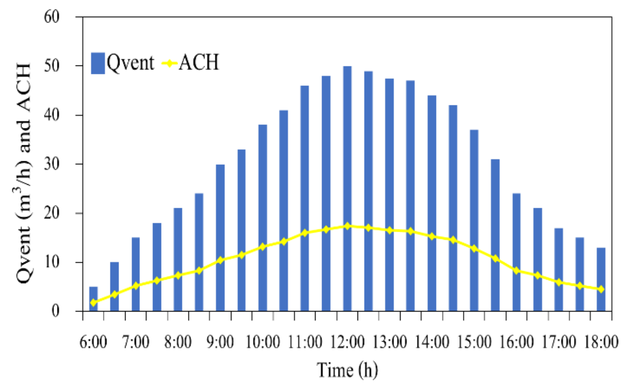


Fig. 6 Hourly variation of volume flowrate and air change

Fig. 7 depicts the hourly fluctuation of heat gain through the SCW-PV (HF_{SCW-PV}) system compared to the reference house (HF_{Ref}), highlighting variations in heat transfer values corresponding to solar radiation for both types of houses. The unventilated houses (HF_{Ref}) demonstrate heat transfer values ranging from 15 to 55 W/m² through the glass windows, while the SCW-PV ventilated test houses (HF_{SCW-PV}) exhibit heat transfer values ranging from 8 to 35 W/m² through the double-glazed windows. Notably, the hourly fluctuation of heat gain through the SCW-PV system falls within the range of 10 - 20 W/m², underscoring the system's effectiveness in maintaining consistent heat transfer. Furthermore, Fig. 8 visually represents the percentage decrease in heat transfer ($\%HG_{reduction}$) values achieved by implementing the SCW-PV system compared to houses without ventilation, with reductions ranging from 10% to 30%. These results align with the ventilation rates and room temperatures discussed in the preceding sections of this comprehensive study**.** Moreover, the findings reveal the SCW-PV's potential to reduce heat gain though building and lower cooling loads, thereby increasing the efficiency of air conditioning systems. This has profound implications for energy management in buildings.

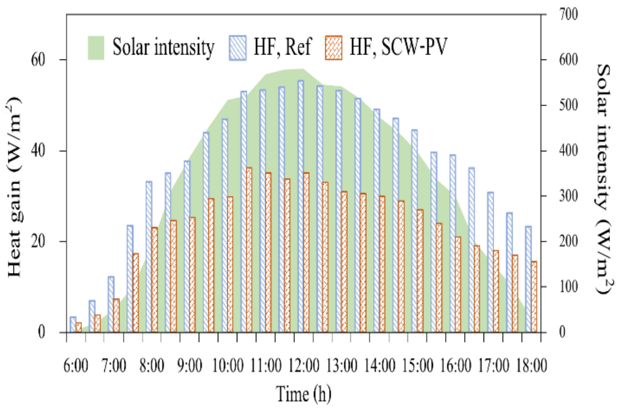


Fig. 7 Hourly variation of heat gain and solar intensity

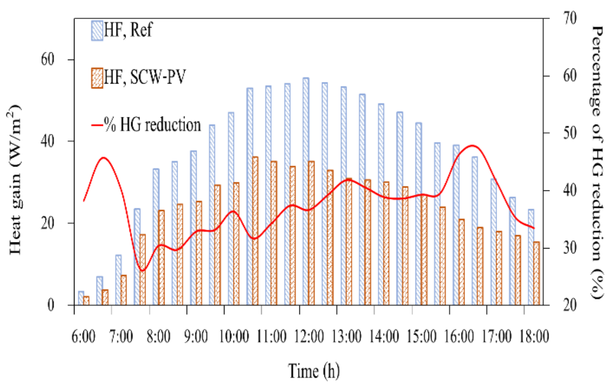


Fig. 8 Hourly variation of heat gain and percentage of heat gain reduction

4. Conclusion

The SCW-PV system exhibited a temperature reduction of 1–3°C in indoor environments compared to areas lacking ventilation, thereby affirming its efficacy in active cooling solutions. By utilizing enhanced ventilation rates (15–50 m³/h) and air exchange rates (5.2–17.4 ACH), the system proficiently alleviates heat buildup through convective removal by reliance on mechanical cooling methods. The PV-powered fan serves as a notable example of the effective incorporation of renewable energy within building systems. Driven by solar energy, the ventilation process harmonizes energy production with thermal management needs. This dual-purpose functionality underscores the capability of building-integrated photovoltaics (BIPV) to promote sustainability while catering to specific cooling requirements. Heat influx through the SCW-PV system was reduced by 5–20 W/m² (in contrast to 15–55 W/m² observed in reference buildings), resulting in a notable reduction of 10–30%. This empirical evidence contests conventional static models, highlighting the dynamic adaptability achievable with advanced glazing systems. Correlation Between Solar Irradiance and System Performance The system's efficiency reaches its zenith during elevated solar irradiance (up to 600 W/m²), at which point ventilation rates and temperature differentials (2–14°C) are optimized. This self-regulating mechanism ensures enhanced cooling efficacy during periods of peak thermal influx, which is crucial for tropical climates. A decrease in heat ingress contributes to reduced cooling demands, allowing air conditioning systems to function with enhanced efficiency. The incorporation of SCW-PV technology into architectural designs has the potential to substantially lower energy consumption, thereby supporting climate-responsive design and the attainment of net-zero energy objectives.

5. Suggestions

Despite its promising attributes, the scalability to larger structures and the long-term durability of the system remain to be fully validated. Future research endeavors should investigate hybrid systems (such as SCW-PV combined with phase-change materials) and perform lifecycle assessments to ascertain cost-effectiveness and environmental repercussions.

6. Acknowledgement

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