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Experimental Comparative Analysis of the Photovoltaic Water Flow Window and the Conventional PV Window for Solar Energy Utilization#

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ABSTRACT

Enhancing the performance of transparent building envelopes is a key strategy for improving building energy efficiency. This study presents a photovoltaic liquid flow window (PV-LFW) as an innovative building-integrated photovoltaic/thermal (BIPV/T) solution. Compared to a conventional single-layer cadmium telluride (CdTe) photovoltaic window (SPV), the PV-LFW not only reduces glazing temperatures under intense solar radiation but also enables full-spectrum solar energy utilization, thereby lowering energy consumption for both air conditioning and hot water systems. The research details the conceptual design and working mechanism of the PV-LFW, followed by a comparative experimental evaluation of its thermoelectric performance against the SPV. Results demonstrate that the PV-LFW effectively functions as a solar thermal collector, achieving an approximate 10°C reduction in CdTe solar cell layer temperature and a 14°C reduction in innermost glass temperature at noon. While the PV-LFW offered only marginal improvements in photovoltaic power generation—due to the low temperature sensitivity of CdTe cells—it exhibited high thermal efficiencies (46.1–61.2%), resulting in overall PV/T efficiencies of up to 68.8%. These findings confirm the potential of PV-LFW for integrated solar energy harvesting and its promise for advancing energy-efficient building envelope technologies.

Keywords: BIPV/T window; Liquid cooling; CdTe PV window; Solar energy utilization; Building energy saving

NONMENCLATURE

Abbreviations	
BIPV	building integrated photovoltaic
BIPV/T	building integrated photovoltaic and thermal
CdTe	cadmium telluride
LFW	liquid-flow window
PV	photovoltaic
PV/T	photovoltaic and thermal
SPV	single PV glazing
STC	standard testing conditions
WFW	water flow window
Symbols	
A	Area, m^2
Q	Heat energy, W
T	Temperature, ^oC
Abbreviations	
ADAPEN	Advances in Applied Energy
Symbols	
n	Year

1. INTRODUCTION

Buildings account for approximately one-third of global energy consumption and over 40% of CO_2 emissions [1]. Windows, as essential components of building envelopes, play a vital role in ventilation, daylighting, and external connections. However, they also contribute significantly to energy loss, accounting for 20–40% of a building's total energy consumption [2]. To address this issue, integrating renewable energy, particularly solar energy, into window designs is crucial for reducing overall energy demand and achieving net-zero energy buildings [3,4]. Various solar energy-harvesting window technologies, including solar thermal and photovoltaic systems, have been developed to support these goals [5,6].

Among the different window technologies for solar photovoltaic (PV) applications, PV windows, which are integrated into the building envelope as part of building integrated photovoltaic (BIPV) systems, are the most prevalent. PV windows generate clean, renewable energy by converting sunlight into electricity and reduce solar heat gain due to the shading effect of the PV glass. As a result, PV windows not only contribute to electricity generation but also help lower building cooling loads [7,8]. CdTe thin-film solar cells, in particular, can be designed in various colors and shapes, enhancing the

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aesthetic appeal of buildings [9]. CdTe also demonstrates superior corrosion resistance compared to silicon and gallium arsenide solar cells, making it highly competitive in the photovoltaic industry with significant potential fordevelopment. Therefore, PV glass incorporating CdTe thin-film solar cells is a primary focus of this study. Tan et al. [10] reviewed vacuum-integrated PV glazing systems with various solar cells and developed a daylight-electrical-thermal coupling model to evaluate their performance. With an optimized design, the vacuum-integrated CdTe PV glazing can achieve 67% zero-energy hours over a year. Uddin et al. [11] assessed the energy conservation potential of three configurations of semi-transparent CdTe windows (single PV glazing, PV insulated glazing unit, and PV ventilated DSF) in office buildings under climate conditions of Bangladesh, demonstrating significant energy savings and electricity generation potential. Sorgato et al. [12] evaluated the technical and economic feasibility of CdTe BIPV systems in commercial buildings across six Brazilian cities. The results showed that a four-story office building net annual energy demand could be met using this CdTe BIPV system in all selected cities.

However, none of the aforementioned window designs fully utilize the entire spectrum of solar energy. Developing windows that integrate both photovoltaic and thermal (PV/T) functions offers a promising solution for more efficient solar energy harnessing in the future. Currently, ventilated PV DSFs represent one such PV/T design, but they have limitations, including insufficient cooling of the glass during summer and the potential to exacerbate the urban heat island effect due to heat emission. In winter, PV shading can also increase indoor heating demands [13–15]. To further mitigate overheating risks and enhance heat dissipation from the PV glass, this study proposes a liquid-cooled PV glazing as an alternative PV/T window. This design features a larger contact area between the working fluid (such as water) and the PV glass pane (CdTe in this study), a simpler structure, and more flexible operational modes.

This study employs an experimental approach to investigate the performance of an innovative liquid-cooled CdTe window (also referred to as a photovoltaic liquid flow window, PV-LFW). The primary objective of this study is to explore the potential of building integrated photovoltaic and thermal (BIPV/T) windows for efficient solar energy utilization, thereby contributing to sustainable building development.

2. EXPERIMENTAL STUDY

2.1 Description of the CdTe glazing prototypes

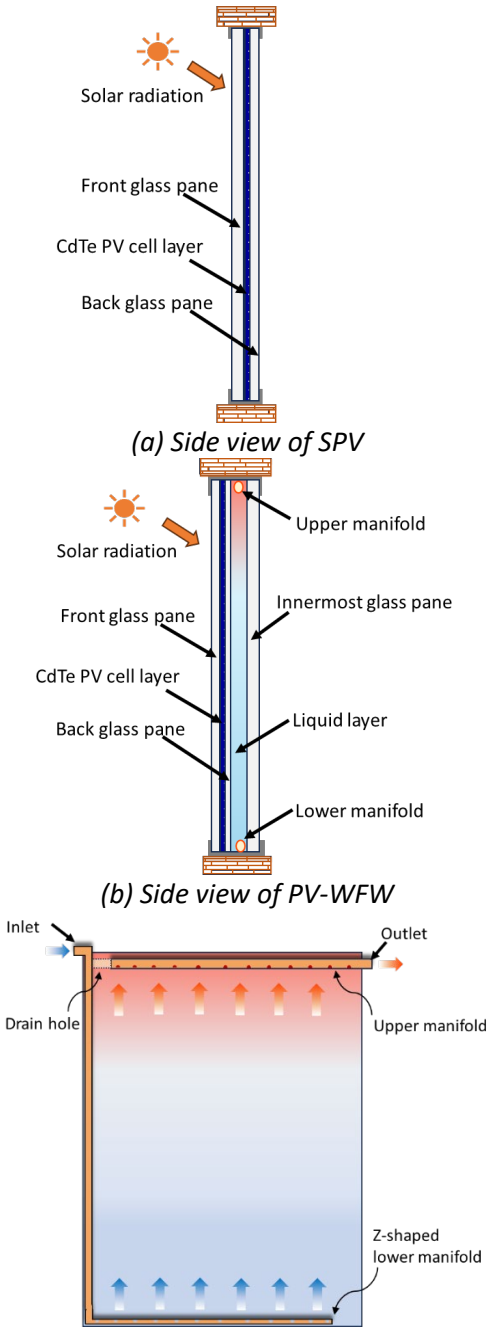
This section provides a detailed description of the design and functionality of the traditional single photovoltaic window (SPV) and photovoltaic water flow window (PV-WFW) prototypes introduced in this research. Fig. 1(a) displays the side view of the SPV prototype, which is constructed as a sandwich structure. Fig. 1(b) and (c) depict the side and front views of the PV-WFW prototype, which features a double-window design with a CdTe PV glazing and an additional glass pane. This design creates a cavity for water flow, with water entering and exiting through a specially designed Z-shaped lower manifold and an upper manifold. This arrangement minimizes the risk of leakage by avoiding openings at the bottom of the cavity, where liquid pressure is highest. These manifolds are seamlessly integrated into the window frame, preserving the aesthetic and visual appeal. The CdTe PV glazing used in these prototypes was obtained from the market.

When sunlight reaches the window, a portion of it passes through the outermost glass pane of the CdTe PV glazing and reaches the CdTe thin-film solar cell. Here, wavelengths ranging from visible light to near-infrared (0.3–0.9 μm) are converted into electrical energy through the photovoltaic effect. The CdTe layer absorbs some of the remaining radiation and converts it into thermal energy, while the rest of the solar radiation passes through the CdTe PV glazing and reaches the water layer. As a result, the PV-WFW functions similarly to traditional SPVs by providing shading during intense solar exposure while maintaining indoor illumination levels comparable to those of a standard PV window. This is because the water layer does not significantly affect visible light transmission.

In addition to directly absorbing solar radiation, the flowing water in the PV-WFW also gains heat from the adjacent CdTe PV glazing and the glass pane facing the indoor environment through convection, provided the incoming water is cooler than the glass surfaces. This process preheats the water, which can be used directly for household purposes or further heated by an auxiliary heater to the desired temperature, thereby reducing energy consumption for hot water systems.

For the indoor environment, solar energy contributes to room heat gain through two main pathways: direct transmission of short-wave infrared radiation and convective and radiative heat transfer between the glass surfaces and the indoor space due to temperature differences. Effective solar control of both short-wave and long-wave infrared radiation is essential in glazed buildings. This control is achieved through the flowing water in the PV-WFW cavity, which helps reduce indoor heat gain, particularly during the summer

months, thus lowering the energy demand for air conditioning systems. Additionally, the amount of solar radiation reflected back to the outdoor environment is minimized, contributing to a reduction in the urban heat island effect.



(a) Side view of SPV

(b) Side view of PV-WFW

(c) Front view of the PV-WFW

Fig. 1 Schematic Illustrations of the SPV and PV-WFW Prototype Designs

2.2 Experimental setup

The testing was performed in a full-scale environmental chamber situated in Foshan City, Guangdong Province (22.80°N, 113.30°E, 5 meters above sea level), which falls within China's hot summer and warm winter climatic region. The SPV and PV-WFW prototypes were mounted on the south-facing openings of the chamber. The experimental data acquisition setup includes a temperature monitoring system, an outdoor meteorological data collection system, a circulating water system, and a photovoltaic measurement system, as shown in Fig. 2.

Fig. 2 The environmental chamber with prototypes(① pyranometer ② weather station ③ T-type thermocouples)

2.3 Evaluation indicators

Given that SPV is a variant of BIPV and PV-WFW is a type of BIPV/T design, evaluation metrics such as water heat gain, thermal efficiency, power generation, and photovoltaic efficiency are utilized to assess their performance comprehensively.

The water heat gain of the PV-WFW, denoted as Q_{th} in W/m², can be calculated using the following formula:

$$Q_{th} = c_w \dot{m} (\bar{T}_{out} - \bar{T}_{in}) / A_g \quad (1)$$

Here, c_w represents the specific heat capacity of water, $\dot{m}$ is the mass flow rate of the water, $\bar{T}_{out}$ and $\bar{T}_{in}$ are the average outlet and inlet temperatures of the water, respectively, and A_g is the gross area of the PV-WFW.

The corresponding average thermal efficiency η_{th} is defined as the ratio of the total water heat gain to the total solar radiation received over the same time period:

$$\eta_{th} = \frac{\sum Q_{th} \Delta t}{\sum G_{tt} \Delta t} \quad (2)$$

In this equation, Δt is the time interval, and G_{tt} is the total solar radiation in W/m².

Based on the first law of thermodynamics, the overall performance η_{pvt} of the PV-WFW, as a semi-transparent PV/T panel, can be derived as follows:

$$\eta_{pvt} = \eta_{th} + \eta_{pv} \quad (3)$$

Here, η_{pv} represents the photovoltaic efficiency of the window.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The study was carried out in October 2024 to evaluate the energy performance of the proposed PV-

WFW by comparing it with traditional SPV using data collected over five consecutive days. As illustrated in Fig. 3, the ambient temperature follows a diurnal cycle, peaking in the afternoon before declining at night, with recorded values ranging from 23.8°C to 38.4°C. Both horizontal and vertical solar irradiance exhibit similar daily trends. On the horizontal plane, irradiance consistently exceeded 750 W/m² across all five days, whereas the vertical window surface received peak irradiance values above 510 W/m² daily. The cumulative daily solar radiation on the vertical surface varied between 10.6 and 13.2 MJ/m². These parameters—solar irradiance and ambient temperature—critically influence PV window temperatures, indoor thermal loads, and power generation efficiency.

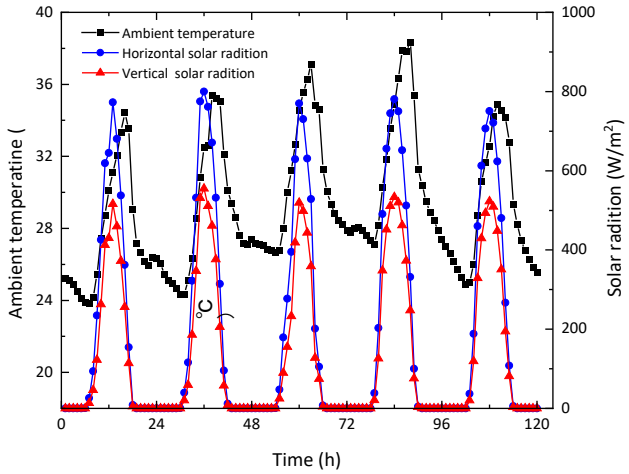


Fig. 3 Meteorological Conditions from 4th to 8th, Oct, 2024

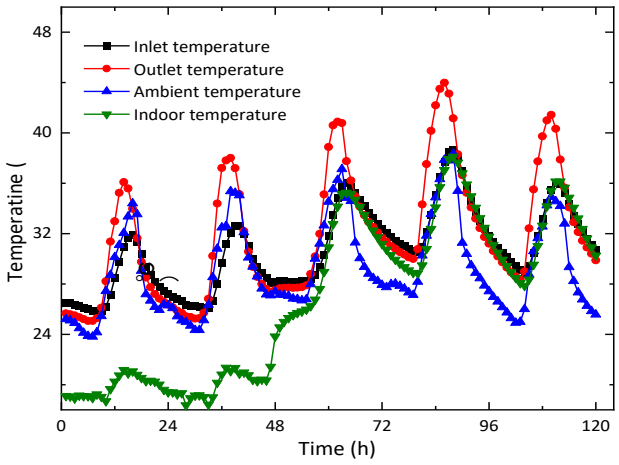


Fig. 4 Fluctuations in the inlet and outlet temperatures over the experimental days

During the five-day experimental period, the PV-WFW system maintained a constant feedwater flow rate of 0.5 L/min. The feedwater, supplied directly from the municipal network without active temperature control, exhibited temperature variations at the inlet and outlet, as illustrated in Fig. 4. While the indoor temperature remained stable, the inlet temperature generally followed ambient temperature trends, albeit with minor fluctuations. The outlet temperature consistently exceeded the inlet temperature, confirming effective solar thermal absorption—particularly during peak daylight hours. Temperature differentials between the inlet and outlet reached maxima of 5.5°C, 7.5°C, 7.1°C, 7.1°C, and 6.5°C on successive days, demonstrating the capability of the PV-WFW to function as an efficient solar thermal collector.

Fig. 5 presents a detailed comparison of the thermal behavior of the outermost and innermost glass panes for both the SPV and the PV-WFW over a five-day testing period. Overall, the glass temperatures exhibited significant diurnal fluctuations, peaking during the afternoon due to solar radiation and ambient temperature, and declining at night with ambient cooling. During the experiment, the outermost glass temperature of the SPV ranged from 22.4°C to 55.7°C, whereas the PV-WFW recorded a narrower range of 24.6°C to 45.4°C. The lower peak temperatures observed in the PV-WFW underscore the cooling effect of the circulating feedwater. Notably, at noon each day, the feedwater cooling in the PV-WFW reduced the CdTe solar cell layer temperature by approximately 10°C, effectively mitigating overheating, improving power generation efficiency, and extending the operational lifespan of the PV glazing.

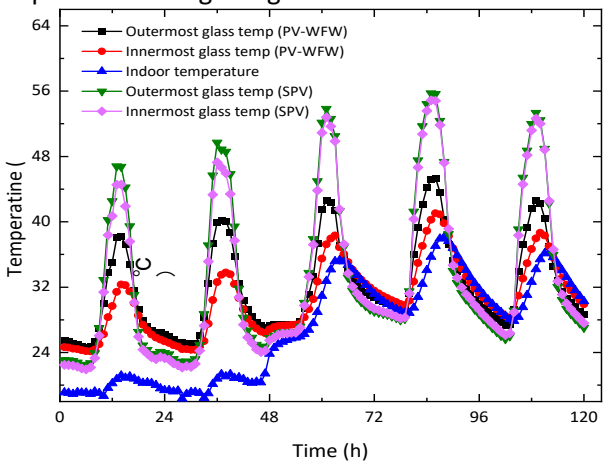


Fig. 5 Thermal Fluctuations of the Outermost and Innermost Glass Panes Across the Testing Period

The environmental chamber was operated without air conditioning, maintaining a stable indoor temperature significantly lower than the glass pane temperatures. The innermost glass pane temperatures generally mirrored the outermost patterns. Peak innermost glass temperatures were 44.6°C, 47.3°C, 52.8°C, 54.9°C, and 52.6°C for the SPV, compared to 32.3°C, 33.8°C, 38.3°C, 41.0°C, and 38.6°C for the PV-WFW. Owing to the relatively thin construction of the SPV, the temperature difference between its outermost

and innermost panes was minimal. In contrast, the PV-WFW system achieved an approximate 14°C reduction in the innermost glass temperature at noon, thereby significantly decreasing the indoor cooling load.

Overall, the data demonstrate that the PV-WFW system effectively moderates temperature fluctuations through water-flow cooling, maintaining lower temperatures across both glass surfaces compared to the SPV, particularly during peak solar radiation periods.

In hot summer and warm winter regions of China, cooling demand remains high even in late autumn. However, at night, the high inlet water temperature led to heat release into both indoor and outdoor environments, potentially reducing the energy-saving benefits of the air conditioning system. Therefore, regulating the nighttime inlet temperature of the flowing feedwater is essential to prevent unnecessary heating loads or to stop the flow during the night. Additionally, in this experiment, the water supply temperature was not controlled and remained relatively high—closely following outdoor temperatures during the day but exceeding indoor temperatures at night. This suggests that maintaining a sufficiently low feedwater inlet temperature is crucial for effective indoor cooling, especially in climates where buildings require air conditioning throughout the day.

Table 1 summarizes the electrical and thermal performance of the SPV and PV-WFW systems over five days of testing (8:00–17:00). The daily-averaged electrical efficiency of the SPV ranged from 7.2% to 7.5%, while that of the PV-WFW ranged from 7.3% to 7.6%. The PV-WFW also exhibited thermal efficiencies between 46.1% and 61.2%, resulting in overall PV/T efficiencies of 53.7% to 68.8%. These results indicate that the PV-WFW provides only marginal improvements in electrical efficiency compared to the conventional SPV, largely due to the low temperature sensitivity of the CdTe photovoltaic cells. Nevertheless, the ability of PV-WFW to reduce PV glazing temperatures offers significant advantages, including extended system lifespan and reduced energy consumption for air conditioning. Furthermore, by functioning as a solar thermal collector, the PV-WFW enables full-spectrum solar energy utilization within a BIPV/T framework, highlighting its strong potential for integrated solar energy applications.

Table 1 Daily Energy Performance Comparisons Between SPV and PV-WFW During the Experiment

		SPV		PV-WFW				
	G_{tt} (MJ/m^2)	E_{pv} (MJ/m^2)	η_{pv}	E_{pv} (MJ/m^2)	η_{pv}	Q_{th} (MJ/m^2)	η_{th}	η_{pvt}
Day 1	10.8	0.65	7.5%	0.66	7.6%	5.0	46.1%	53.7%
Day 2	12.0	0.70	7.3%	0.72	7.5%	6.9	57.4%	64.9%
Day 3	10.5	0.63	7.5%	0.64	7.6%	6.4	61.2%	68.8%
Day 4	13.1	0.75	7.2%	0.77	7.3%	7.6	57.8%	65.1%
Day 5	12.5	0.72	7.2%	0.74	7.4%	6.9	55.5%	62.9%

4. CONCLUSIONS

This study introduces a novel liquid-cooled CdTe photovoltaic window (PV-WFW), designed to integrate photovoltaic and thermal energy collection within building envelopes. A comparative experimental analysis against traditional SPV was conducted. The results show that the PV-WFW significantly reduced glazing temperatures through continuous water-flow cooling, maintaining both outermost and innermost glass temperatures substantially lower than those of the SPV, particularly during peak solar radiation hours. Specifically, the PV-WFW achieved an approximate 10°C reduction in the CdTe solar cell layer temperature and a 14°C reduction in the innermost glass temperature at noon, thereby substantially decreasing the indoor cooling load. Although the PV-WFW offered only marginal improvements in electrical efficiency over the SPV—due to the low temperature sensitivity of CdTe cells—it exhibited high thermal efficiencies (46.1–61.2%), leading to overall PV/T efficiencies between 53.7% and 68.8%. These findings confirm the PV-WFW's effectiveness as a solar thermal collector and its potential to enable full-spectrum solar energy utilization within a BIPV/T system.

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