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Increasing the Utilization of Solar Energy through the Performance Evaluation of Air-Based Photovoltaic Thermal Systems

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Abstract: Photovoltaic thermal (PVT) systems are attracting a significant amount of attention in research because they can generate electricity outside of daytime hours, unlike photovoltaic (PV) systems, and can increase efficiency and collect additional energy by reducing the temperature of PVT panels. However, a somewhat lower amount of collected energy is used in the summer than in the winter, and research on this issue is lacking. In this study, first, we experimentally evaluated the performance of PV and PVT systems by season and verified the improvement in the performance of the PVT system. Second, experiments were conducted to verify the enthalpy reduction via mist cooling and dehumidification, and the temperature and humidity control effect via mist cooling and dehumidification was verified. Based on our research findings, we propose a model that can be integrated with indoor ventilation systems to increase the solar energy utilization of PVT systems. Using the PVT system, we improved the panel power generation efficiency by up to 5.89% and generated up to a 38.0% higher collection efficiency than that of the PV system. The air that passed through the PVT system was then subjected to mist cooling and dehumidification to reduce its temperature and increase its humidity, resulting in a 23.2% reduction in enthalpy.

Keywords: solar energy; photovoltaic/thermal system; dehumidification; energy saving; power generation efficiency

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1. Introduction

In recent years, global warming has led to an increased interest in renewable energy. In this regard, global efforts have been underway since the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 [1] to limit the average increase in global temperature. The Intergovernmental Panel on Climate Change (IPCC) [2] has proposed the goal of reducing CO_2 emissions by at least 45% from 2010 levels by 2030 and achieving carbon neutrality by 2050 to limit the 1.5 °C increase in the global average temperature by 2100. Since 2016, several countries around the world have voluntarily committed to GHG reduction targets and agreed to develop and submit long-term low-carbon development strategies [3] and nationally determined contributions [4].

Solar energy has garnered more research attention than other renewable energies such as hydropower and wind power because it is an inexhaustible energy source, and the infrastructure needed to collect it is easier to install and maintain.

Systems that utilize solar energy can be broadly divided into photovoltaic (PV) systems and solar thermal systems. PV systems only utilize sunlight, whereas solar thermal systems utilize solar thermal energy. Despite their many advantages, PV systems can generate power only during the daytime and require expensive batteries to store excess power, making them difficult to employ in industrial sites such as construction sites. Another disadvantage is that the power generation efficiency of PV systems decreases as the temperature of the panels increases. Photovoltaic thermal (PVT) systems were designed to alleviate these shortcomings and have received an increasing amount of research attention because they can collect solar heat while generating electricity using sunlight. PVT systems have the advantage of suppressing the temperature rise in panels by passing a relatively low-temperature liquid or air behind them to increase the power generation efficiency and utilizing the heated fluid for hot water or to heat buildings. However, unfortunately, during the summer months, when the outside air temperature is high, the thermal energy that can be obtained from the PVT system is used less. Nazri [5] found that an air-assisted PVT system increased solar energy capture by 80.3% and was more efficient at power generation than conventional PV systems. Ozakin [6] found that passing air under a panel reduced the panel's surface temperature by about 10–15 °C and increased the efficiency by about 15% depending on the wind speed. Abdulla [7] found that the surface temperature of the panel of a liquid PVT system decreased by about 5 to 9 °C compared to that of a conventional PV system, and the system's power generation efficiency increased accordingly. Vittorini [8] showed that by supplying 2 L of cooling water per minute, the temperature rise of the PV panels was suppressed, resulting in an increase in power generation efficiency of about 33% compared to that of conventional PV systems.

Various studies have been conducted for performance evaluations and improvement measures of air-based PVT systems for building applications. Zogou [9] conducted an energy analysis for integrating solar panels into an office building in Central Greece. This study assessed the impact of solar panel integration on building energy efficiency, considering factors such as solar radiation, building location, and energy consumption patterns. Furthermore, another study by Zogou [10] focuses on flow and heat transfer within PVT collectors designed for buildings. This paper presents a method to optimize system performance by analyzing fluid flow and heat transfer phenomena within the PVT collector. Gholampour [11] conducted a combination of experiments and theoretical analyses to evaluate the performance and efficiency of PVT collectors. Their study investigated collector configurations and operating conditions and assessed the system energy efficiency through energy and exergy analyses. While these studies show the improved efficiency of PVT systems compared to PV systems [12,13], there is a lack of research on efficiency differences in each system between summer and winter when used in a climate with four distinct seasons.

Furthermore, various studies have been conducted on cooling systems utilizing solar energy. J. Ruiz [14] presented an analytical model and optimization method for a solar-driven cooling system enhanced with a photovoltaic evaporative chimney. Their study aims to improve the cooling efficiency of the system by utilizing solar energy and evaporative cooling techniques, proposing measures to enhance the performance and energy efficiency of the system. Fang'ai Chi [15] focused on regulating and optimizing the thermal performance of residential buildings by integrating radiative cooling and solar heating systems. Optimal control strategies were proposed to maintain indoor thermal comfort while minimizing energy consumption. Mehran Bozorgi [16] examined thermal comfort conditions using a phase change material-based solar desiccant cooling system hybridized with a heat pump. Through experimental investigations and performance analyses, an effective system was proposed to maintain thermal comfort conditions while reducing energy consumption. Mehran Bozorgi [17] also reviewed methods to enhance indoor thermal comfort and sustainability through a solar-driven desiccant cooling and adsorption chiller system. By evaluating the performance and environmental impact of the integrated system, the effectiveness of sustainable cooling solutions was demonstrated. Chong Zhai [18] proposed a compact modular microchannel membrane-based absorption thermal energy storage system for highly efficient solar cooling. Experimental testing and performance evaluations confirmed the effectiveness of the proposed energy storage system in enhancing the overall performance of solar cooling technologies.

However, these cooling systems often involve additional devices for cooling, leading to an increased scale and cost for system implementation. Therefore, there is a need to minimize the scale of systems applicable to small-scale buildings while still maintaining their cooling performance. In addition, Fahad Faraz Ahmad et al. [19] confirmed through experimental performance evaluations that mist cooling can be applied to lower the temperature of modules and enhance power production. Zafar Said et al. [20] demonstrated the effectiveness of combining mist with phase change materials (PCMs) to maintain the temperature of solar modules and improve power production. However, in these studies, the utilization of mist is primarily aimed at reducing the temperature of solar panels, and there is a lack of research on methods to introduce mist-cooled air indoors.

This study experimentally evaluated the performance of an air-based PVT system using air as a fluid to verify the performance improvement of the PVT system. We then verified the temperature and humidity control effect of the PVT system through mist cooling [21] and dehumidification. Based on the experimental data, this study proposes a model that combines a PVT system with an indoor ventilation system using mist cooling and dehumidification. After each operation mode is described, a system to increase the utilization of solar energy is proposed. The system proposed in this study can be used not only for power generation throughout the year but also for cooling, heating, and ventilation and is expected to be highly usable in small-scale buildings as its size is reduced compared to that of solar energy systems combined with existing HVAC systems.

2. Materials and Methods

The experiments were conducted on the rooftop of Kyonggi University's Lecture Hall No. 7 (latitude 37.30°, longitude 127.04°) in Yeongtong-gu, Suwon, Gyeonggi-do, Republic of Korea [22]. We examined the system performance improvement by reducing the temperature of the solar panel by passing air under the panel of an existing PV system and the collection efficiency through the increased temperature of the passing air. A conceptual diagram of the target panels used in this experiment is shown in Figure 1, and the actual installation is shown in Figure 2. The PV panels (Case 1) had insulation attached to the bottom of the typical panel, and the PVT (Case 2) panels had a space for air movement at the bottom of the panel. A fan was used to induce airflow. Both panels had the same output of 300 W. Both panels were installed at a 30° angle facing due south. In reality, the surface temperature of the panels varies due to external wind speeds. However, this study did not account for temperature changes caused by wind speed, as experiments comparing PV and PVT systems under identical conditions were conducted.

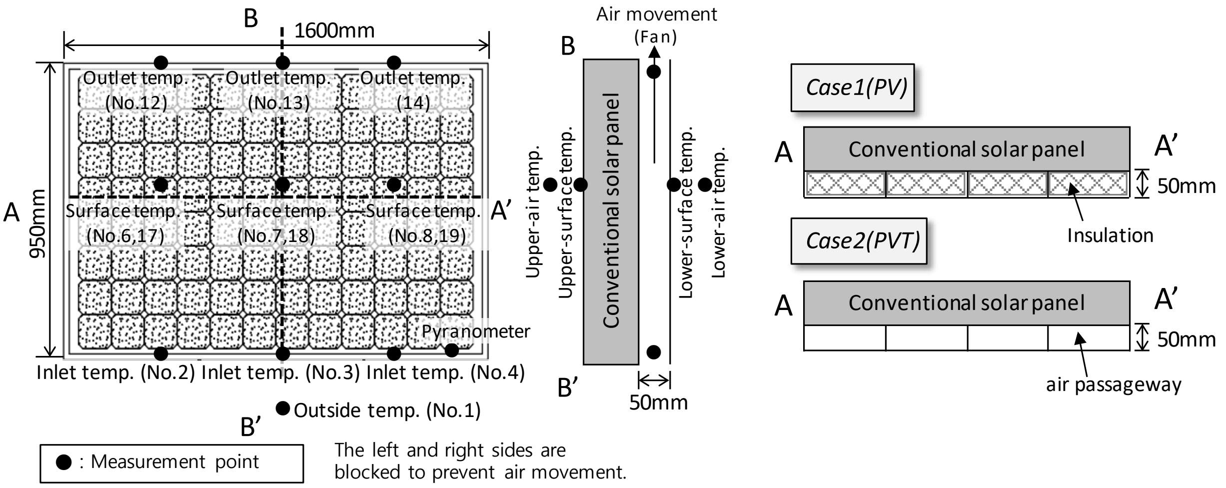

Figure 1. Schematic of the experimental arrangement.

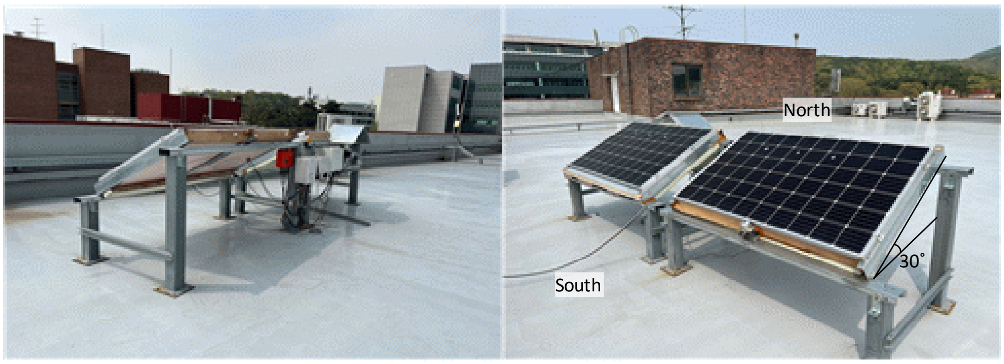

Figure 2. Installation view of the systems.

3. Results

The measuring instruments, items, and specifications of this experiment are shown in Tables 1 and 2. The measurements were taken at 1 s intervals, and the data were converted into 10 min average results to account for fluctuations due to external conditions. The experiment was conducted from 16 August 2021 to 31 March 2023, and the data were interpreted based on the results over approximately 3 days in the summer (2021.08.18~20) and 3 days in the winter (2022.12.31–2023.01.02). To evaluate whether the PVT system outperforms the PV system, a comparative analysis was conducted, maintaining consistent inlet temperature conditions while comparing the changes in outlet temperature and panel surface temperature. Subsequently, the power generation efficiency of both systems was compared based on the obtained results. Furthermore, the heat gain within the PVT system was quantified by analyzing the changes in inlet and outlet air temperatures as well as airflow. As a result, the seasonal heat gain efficiency of the PVT system was evaluated.

Table 1. Specification of measurements.

Classification	Equipment	Specification
Temperature	T-Type Thermocouple	Range: −200–250 °C, Resolution: 0.1 °C, Accuracy: ±0.5 °C,
Solar radiation	EKO MS-40 Pyranometer ISO 9060:2018 [23] Class C (Second class)	Range: 0–2000 W/m^2, Accuracy: ±0.2%
Electricity	Solar Volt/Current Unit	10 A/50 mV
Wind speed	Hot-wire anemometer	Range: 0–30 m/s, Accuracy: ±0.1–0.3 m/s
Data logger	Memory Hilogger	Resolution Temperature: 0.01 °C, Voltage: 500 nV

3.1. Performance Evaluation of PVT System

Figures 3 and 4 show graphs comparing the solar radiation and outside temperature reaching the panels by season. The amounts of solar radiation reaching the panel surface in the summer were 3350 Wh, 5617 Wh, and 4020 Wh on the three days, as shown in Figure 3, with an average of about 4329 Wh, and the outside temperature was measured as having a low of 24.7 °C and a high of 37.0 °C. The amounts of insolation reaching the panel surface for the three days in the winter were 5518 Wh, 4821 Wh, and 4139 Wh, respectively, as shown in Figure 4, and the average was about 4826 Wh. The outside temperature was measured as a low of −7.6 °C and a high of 15.0 °C. Although solar radiation is generally considered higher in the summer, this experiment showed that more solar radiation reached the panel surface in the winter because the installation angle of the panel was fixed at 30°. The south-central altitude in the summer is 76° on average, while that in the winter is 29° on average. Thus, the amount of solar radiation perpendicular to the panel surface was higher in the winter, but the sunlight hours in the winter were shorter than those in the summer, limiting the amount of solar radiation.

Table 2. Measurement items.

Number	Item	Number	Item
1	Outside temp.	15	Lower air temp. (Case 2)
2	Air inlet temp. 1 (Case 2)	16	Upper air temp. (Case 1)
3	Air inlet temp. 2 (Case 2)	17	Upper-surface temp. 1 (Case 1)
4	Air inlet temp. 3 (Case 2)	18	Upper-surface temp. 2 (Case 1)
5	Upper air temp. (Case 2)	19	Upper-surface temp. 3 (Case 1)
6	Upper-surface temp. 1 (Case 2)	20	Lower-surface temp. 1 (Case 1)
7	Upper-surface temp. 2 (Case 2)	21	Lower-surface temp. 2 (Case 1)
8	Upper-surface temp. 3 (Case 2)	22	Lower-surface temp. 3 (Case 1)
9	Lower-surface temp. 1 (Case 2)	23	Lower air temp. (Case 1)
10	Lower-surface temp. 2 (Case 2)	24	Pyranometer (30° angle facing due south)
11	Lower-surface temp. 3 (Case 2)	25	Current (Case 2)
12	Air outlet temp. 1 (Case 2)	26	Voltage (Case 2)
13	Air outlet temp. 2 (Case 2)	27	Current (Case 1)
14	Air outlet temp. 3 (Case 2)	28	Voltage (Case 1)

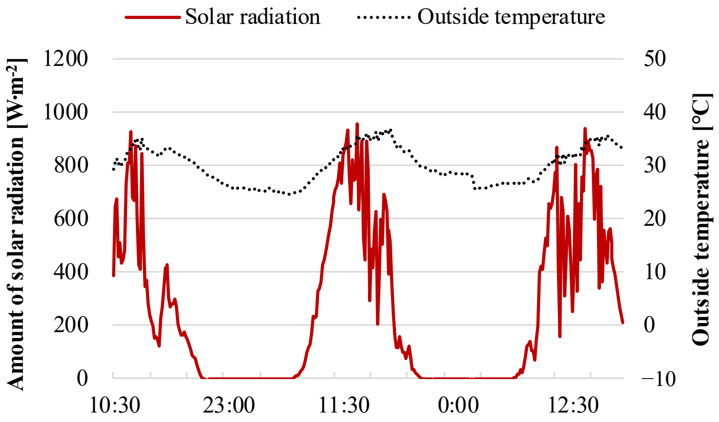

Figure 3. Insolation and outside temperature in the summer.

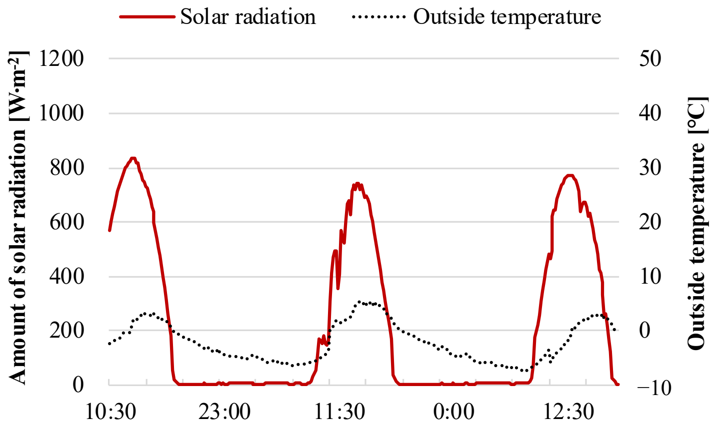

Figure 4. Insolation and outside temperature in the winter.

Figure 5 shows the average value of the inlet temperature of the PVT panel in the summer and the outlet temperature of the PVT panel at three points, and Figure 6 shows the inlet and outlet temperatures of the panel in the winter. Regardless of the season, the air temperature passing through the PVT panel increased through heat exchange with the panel, and the air heated by solar radiation increased by a maximum of 7.8 °C and an average of 3.6 °C in the summer, as shown in Figure 5, and a maximum of 3.3 °C and an average of 1.8 °C in the winter, as shown in Figure 6. To determine whether the increase in air temperature was caused by the difference in outside temperature or the difference in seasonal insolation, the correlation between insolation and the PVT outlet temperature was analyzed.

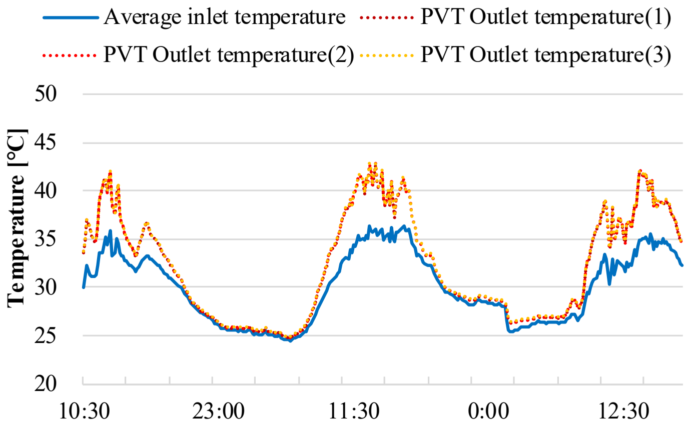

Figure 5. PVT panel inlet and outlet temperature in the summer.

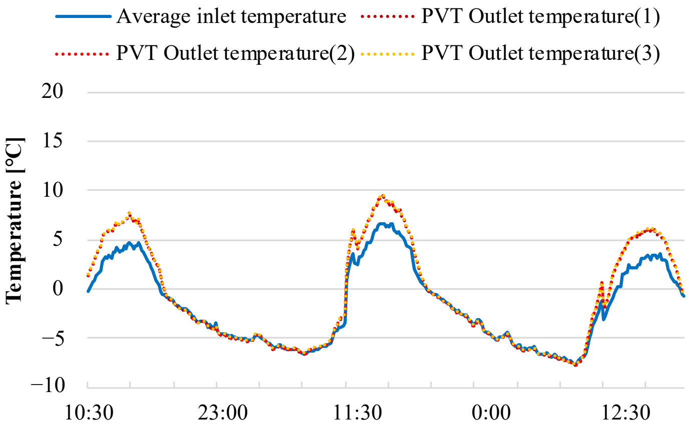

Figure 6. PVT panel inlet and outlet temperature in the winter.

As in the previous analysis, we correlated the solar insolation with the panel power generation by season to check whether the observed results were a result of the correlation with solar insolation. Figures 7 and 8 show the correlations of panel power generation with summer and winter insolation. The PVT system showed an approximately 4.9% and 6.3% improvements in power generation compared to that of the PV system in the summer and winter, respectively.

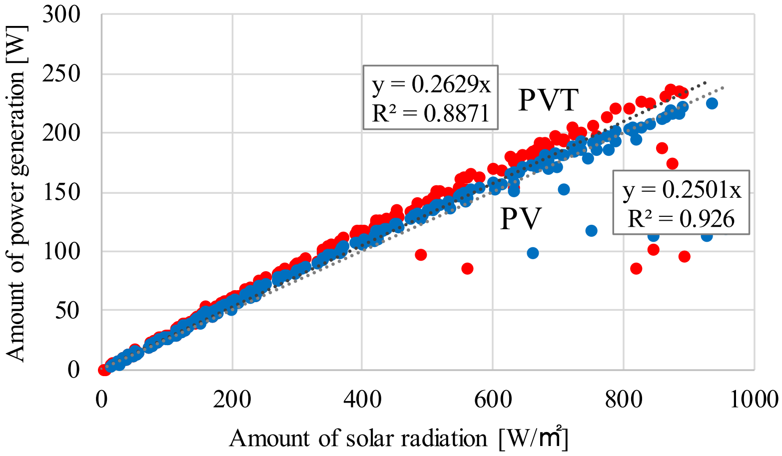

Figure 7. Correlation between solar insolation and power generation in the summer.

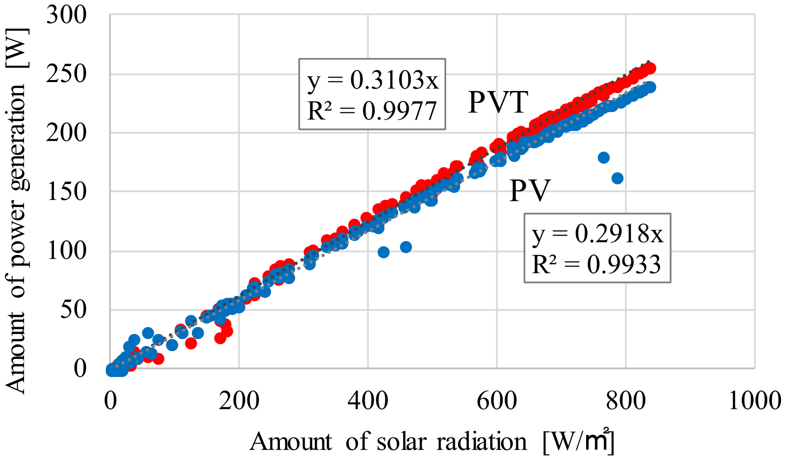

Figure 8. Correlation between solar insolation and power generation in the winter.

The PVT system has the advantage of being able to collect solar heat, unlike the PV system. The airflow rate of the fan applied in this experiment was 3.53 m^3/min (circular duct with a 90 mm diameter). The maximum amount of heat collected in the summer was 501.4 W with an average of 238.0 W, and the maximum amount of heat collected in the winter was 230.9 W with an average of 148.6 W. The air flow under the panels of the PVT system reduced the panel surface temperature, which increased the power generation and allowed additional thermal energy to be captured.

As shown in Figure 9, the PV system had a solar energy utilization efficiency of 17.97% in the summer, but the PVT system had a 5.89% performance improvement in terms of panel area power generation and an additional 38.0% solar collection efficiency, resulting in a total solar energy utilization efficiency of 57.07%. In addition, in the winter, as shown in Figure 10, the PV system showed a solar energy utilization efficiency of 17.03%, but the PVT system showed a performance improvement of 1.96% in panel power generation and an additional improvement of 17.42% in solar collection efficiency, resulting in a total solar energy utilization efficiency of 35.43%.

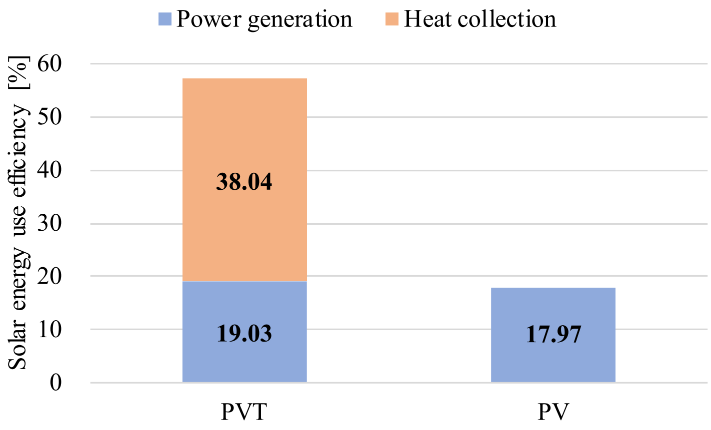

Figure 9. Solar utilization efficiency for each system in the summer.

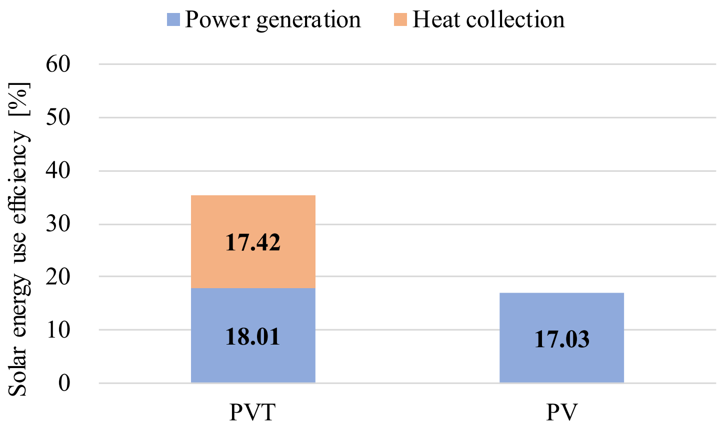

Figure 10. Solar utilization efficiency for each system in the winter.

3.2. Enthalpy Reduction through Mist Cooling and Dehumidification

In the previous experiments, we evaluated the performance of the air-type PVT system and confirmed the improved performance of the PVT system. In the summer, more heat energy can be collected than in the winter and the power generation efficiency of the panel is higher, but the utilization of the collected heat energy is limited because the outside air temperature is higher in the summer. In addition, the heat energy collected by the air PVT system is more rarely applied than that in the liquid PVT system because the heat capacity of air is lower than that of liquids such as water.

Air PVT systems can be used in parallel with ventilation systems to preheat the outside air, but this has the disadvantage of being difficult to use in the summer. To further compensate for this, mist cooling and dehumidification may be used to reduce the air temperature and, consequently, the enthalpy of the air; accordingly, we evaluated whether they can be used in ventilation systems in the summer.

Figure 11 is a schematic of a PVT system undergoing mist cooling and dehumidification. ① to ③ represent the measurement points in the duct through which the air passes. The instrument at ① measures the temperature and humidity of the air that passes through the PVT panel, that at ② measures the temperature and humidity of the air that passes through the mist humidification section, and that at ③ measures the temperature and humidity of the air that passes through the dehumidification process using a desiccant. The purpose of mist cooling and dehumidification using the air passing through the PVT system is to realize air conditioning in the summer when the outside temperature is high. Fans and ducts were installed to induce airflow (there was an average wind speed of 9.25 m/s and an airflow rate of 3.53 m^3/min in the ducts), and temperature and humidity sensors were installed at the measurement points to obtain data in the form of a CSV file using an app that allows real-time monitoring. In addition, the dehumidification section used silica gel, and the dehumidifier was placed in a certain section of the duct to reduce the humidity of the air humidified through the mist. The amount of silica gel was divided into two parts, one that was 1 kg and the other that was 2 kg, to check the effect of the amount of desiccant on the temperature and humidity after the dehumidification process.

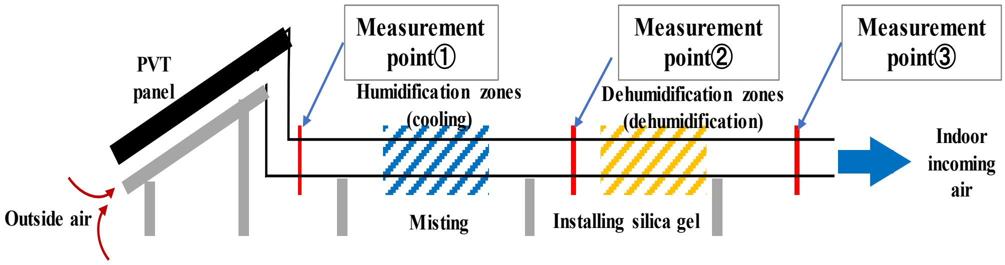

Figure 11. Experimental schematic of mist cooling and dehumidification process in PVT system.

The experiment was conducted at 2:00 p.m., when the outside air temperature was at its highest, with 30 min of misting and dehumidification and a total of three measurements were taken. Figure 12 shows the average temperature and humidity changes during the mist humidification of the PVT outlet air between the three measurements. Before the mist cooling, the PVT outlet temperature was as high as 19.5 °C and as low as 18.1 °C. After the mist cooling, the air temperature decreased by 12.3 °C to 7.2 °C. The humidity increased by 65%, reaching a maximum of 83% RH.

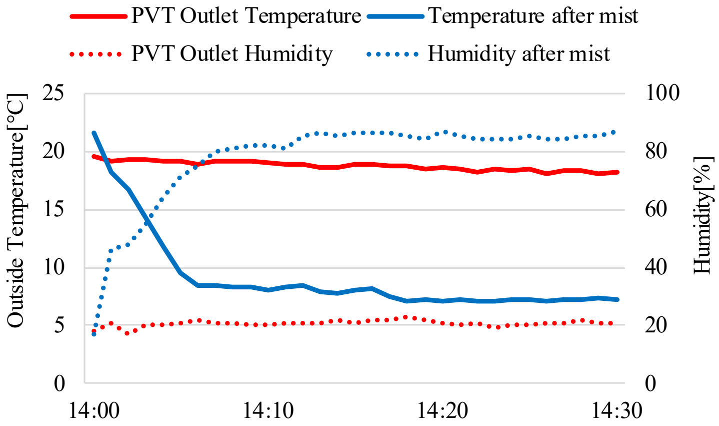

Figure 12. Changes in temperature and humidity during mist humidification cooling.

Figure 13 shows the change in the state of the air through the experimental process on a moisture airflow diagram. The air is shown in four different states: 1 is the outside air before entering the PVT system, 2 is the air that has been simply heated in passing through the PVT, 3 is the air that has been cooled and humidified by the mist, and 4 is the air that has been dehumidified by the desiccant. The air in state 1, which was the same temperature as that of the outside air, had a temperature of 17.53 °C and a humidity of 20.14% with an enthalpy of 24.04 kJ/kg. The air in state 1 passed through the PVT system and underwent a simple heating process. After this process, the air in state 2 was at 21.01 °C and 17.07% humidity, with an enthalpy of 27.79 kJ/kg, which was a 15.6% increase in enthalpy compared to that of the air in state 1. Next, the heated air in state 2 was humidified and cooled by mist cooling, which is shown in the upper left corner of the wet air line diagram. After the humidification cooling process, the air reached state 3, at which point the temperature decreased to 8.99 °C, and the humidity increased to 83.92%. The enthalpy was 24.07 kJ/kg, showing a slight decrease compared to that of the air in state 2. Finally, the humidified air was subject to dehumidification to remove excess moisture and reached state 4. The temperature of the air in state 4 was 9.03 °C, which is the same as the air in state 3, and the humidity was 51.97%, which is about 32% less than the previous state. As a result, the temperature and humidity of the air undergoing the experimental process changed from state 1 to state 4, and the corresponding enthalpy decreased from 23.94 kJ/kg of enthalpy for state 1 to 18.38 kJ/kg of enthalpy for state 4, which is about 23.2%, as shown in the graph in Figure 13.

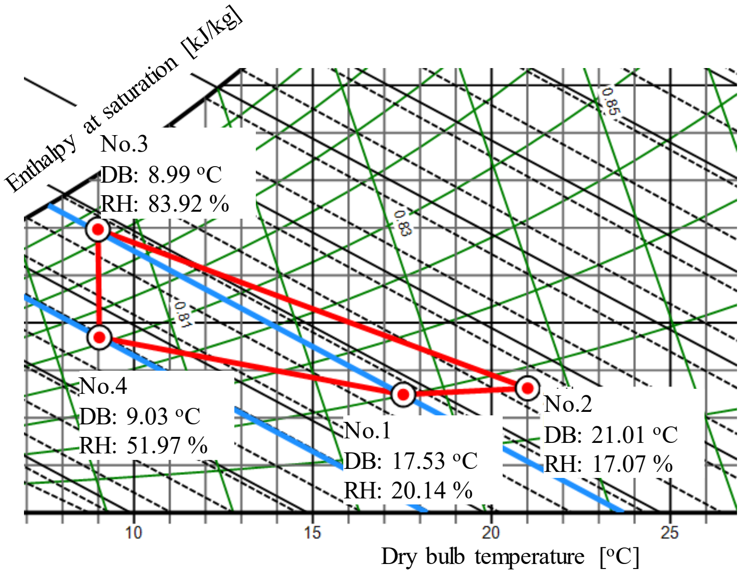

Figure 13. Changes in air condition due to mist cooling and dehumidification.

4. Discussion

The experiments discussed in Section 3.1 verified the performance improvement by applying the PVT system and temperature and humidity control through mist humidification and dehumidification. It was concluded that in step 1, the PVT system has superior solar energy utilization compared to the conventional PV system, and in step 2, it was found that the enthalpy of air can be lowered through the cooling effect of mist humidification and dehumidification.

However, previous studies have shown that in summer, the thermal energy acquired through PVT systems is less utilized and is often wasted without heat storage. Liquid-based PVT systems can be applied to hot water storage tanks in summer to supply hot water for space heating and domestic hot water in buildings, but research on how to improve the utilization of air-based PVT systems in summer is lacking. Therefore, this study proposes a system that can reduce the enthalpy of outside air introduced in indoor ventilation through mist cooling and dehumidification and increase the utilization rate of solar energy by using the thermal energy acquired from a PVT system to regenerate the dehumidifier. The system proposed in this study not only lowers the temperature of the PV surface by passing air through the rear of the PV during winter, thereby increasing the power generation efficiency, but also allows heated air to be introduced indoors for heating and ventilation purposes. Additionally, during summer, the external air can be mist-cooled and dehumidified before being introduced indoors, providing a cooling effect. The system, which integrates heating, cooling, and ventilation in this study, is anticipated to reduce the size and energy consumption of air conditioning units for indoor cooling and heating.

However, further research is needed on the timing of the mode changes because the point at which the desiccant in each line is saturated is likely to fluctuate depending on the enthalpy of the outside air, and the amount of mist sprayed significantly impacts the saturation of the desiccant. In addition, if the PVT system does not collect a sufficient amount of heat to regenerate the desiccant, the time required to regenerate the desiccant may increase. Thus, an optimized design method that controls the mode based on real-time measurements of the variables related to the mode change should be considered.

5. Conclusions

In this study, we aimed to verify the performance of a PVT system, a combined solar/thermal power generation system, through experiments to check the improvements in its solar energy utilization efficiency over that of a conventional PV system. In our literature review, we identified the features, advantages, and disadvantages of air PVT systems and liquid PVT systems and confirmed the use of air PVT systems in combination with ventilation systems. Our literature review also identified the problem of the relatively low utilization efficiency of the collected energy in the summer. To verify the performance of the air PVT system, we compared the PV system and the PVT system through experiments, finding that the power generation efficiency of solar energy increased by about 8.6% over the PV system, and the solar heat collection efficiency increased by 38.0% in the summer and 17.4% in the winter.

To solve the problem of utilization in the summer, a cooling system using mist humidification and a desiccant was applied to consider the parallel use of the air PVT system and a ventilation system. During the mist cooling process, the air temperature decreased and the humidity increased, while the air temperature was unchanged after dehumidification but the humidity decreased. However, the dehumidifying agent was eventually saturated, after which dehumidification could no longer be achieved. As a result, the air after the mist cooling and dehumidification process showed a decrease in enthalpy of up to 23.2% compared to that of the initial state. However, further research is needed on the timing of the changes in the operation model under different conditions when applying the proposed system. Moreover, the efficiency likely fluctuates depending on the wind speed control in the duct, the capacity of the PVT panel, and the amount and temperature of the mist that is sprayed, so the application location and environment must be reviewed before applying the system.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the author.

Conflicts of Interest: The author declares no conflict of interest.

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