A simulation study of air-type building-integrated photovoltaic-thermal system

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Abstract

The building-integrated photovoltaic-thermal (BIPVT) collector combines PV panels with solar thermal collectors that applies as a building envelope material to produce both thermal and electrical energy at the same time. The air based BIPVT system applied to buildings can be an outer layer to make building envelope double-layers, so that the thermal characteristics of a building with the envelope system could be different from normal walls due to the heat generated from PV panels. Therefore, the envelope of building with BIPVT system is different from that of existing building and may take different impact on the building energy loads. Also, the building energy performance varies according to the energy obtained from the system.

This study aims to evaluate the electrical and thermal performance of the air type BIPVT system, and to analyze the energy performance of building with the air type BIPVT system applied as the building envelope. For this study, building models with BIPV and BIPVT were compared through TRNSYS simulation results.

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Keywords: BIPVT(Building-Integrated Photovoltaic Thermal) system; building envelope; PV temperature; electrical efficiency; heating and cooling load

1. Introduction

The energy consumption in buildings has recently increased and in some countries, it reaches almost 40% of the total energy use. The building sector becomes one of the most important are to save energy for sustainable society.

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In this context, there are a lot of discussion on net zero-energy buildings (ZEB) which are buildings with reduced energy needs through energy efficiency measures and the energy supply from renewable technologies to maintain the balance of energy needs for building. In particular, PV systems that generate electricity can play an important role for zero energy buildings, as there are many ways to apply them into building.

The high temperature of PV modules reduces the efficiency of a PV system. In particular, BIPV systems appear to be more vulnerable to the PV module temperature, as they are attached to building surfaces. The extraction of heat from the space between the building envelope and the PV modules will increase the efficiency of the PV systems as it lowers the PV module temperature. It is also possible to utilize the extracted heat as a heat source for buildings. In addition to the improvement of the electrical performance of BIPV systems by the removal of heat, thermal collection through heating mediums such as air and water can be achieved with a device known as a photovoltaic-thermal (PVT) combined collector [1].

The air type BIPVT system functions as a building envelope and generates thermal energy and electrical energy simultaneously. The air type BIPVT system applied to buildings can be an outer layer that creates a building envelope that is double layered, and because of the generated heat source of its, their thermal characteristic such as U-value of the wall differ from that of the usual wall. Therefore, the envelope of building with BIPVT system is different from that of an existing building and may have a different impact on the building energy loads. Also, the building energy performance varies according to the energy obtained from the system. The PV module temperature of the air type BIPVT system is a significant factor in determining the energy performance of the system and the annual electricity generation. The PV modules temperature varies according to the PV cell type, PV module configuration, and other factors. In particular, the PV modules temperature of the BIPV system varies according to the installation method and other conditions of the building. Furthermore, the PV temperature influences the electrical performance of the BIPV system.

A considerable amount of research has been conducted regarding estimation of the heat transfer in double facades in buildings. Some papers focus on a specific configuration that may be related to an existing building facade concept, including PV facades. Brinkworth et al. [2] found that providing a ventilated air gap behind a PV panel is an effective way to limit increases in PV module temperature, which otherwise result in a decrease in electrical output. Yun et al. studied the effect of a number of parameters (i.e. climate, room depth, lighting loads, U-value, glazing device) on the overall energy performance of a ventilated PV facade, trying to optimize the ratio of transparent window area to the opaque PV modules area [3]. Mei et al. studied the thermal performance of a specific type of ventilated PV façade consisting of the PV panel, the air gap and the inner double glazing [4]. Solanki et al. report on the design, fabrication and performance assessment of a PV/T solar air heater [5]. The study of PV/T systems with TRNSYS was published by Kalogirou [6], dealing with the modeling and simulation of a hybrid PV/T system consisting of a normal PV panel at the back of which a heat exchanger is embedded.

This study aims to evaluate the electrical and thermal performance of the air type BIPVT system, and to analyze the energy performance of a building with the system applied as the building envelope.

2. Energy performance of BIPVT system

The BIPVT system, when applied to a building, influences the building energy load as well as the production of thermal and electrical energy from the system itself. In order to verify these factors in this study, the energy performances of a building with a BIPV envelope without ventilation and a building with ventilated BIPV envelope were compared through simulation modeling, and these cases were also compared with the energy performance of building.
For this study, a simulation model of an air type BIPVT system integrated into the building facade was designed as shown in Fig. 1, and the annual energy performance of the building with the air type BIPVT system installed on its envelope was analyzed through simulation modeling using the TRNSYS simulation program with the sub-models of Type 567 and Type 56[7]; results were compared with those from an existing building, a building with a BIPV envelope without ventilation and with ventilation. Four cases of BIPV and BIPVT system modeling are summarized in Table 1.

![Fig. 1. Building façade design with BIPV and BIPVT systems for simulation model](image1.png)

Table 1. Simulation model for building with BIPV and BIPVT system

<table>
<thead>
<tr>
<th>Name</th>
<th>Model Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Case</td>
<td>Building in which BIPV system is not installed</td>
</tr>
<tr>
<td>Case 1</td>
<td>Building in which BIPV system was attached to building envelope (without an air layer between PV panels and wall)</td>
</tr>
<tr>
<td>Case 2</td>
<td>Building in which force ventilated BIPV system was applied as building envelope (with 10 cm air layer between PV panels and wall, outdoor air inflow to air layer at a rate of 0.02 kg/s m²)</td>
</tr>
<tr>
<td>Case 3</td>
<td>Building in which BIPV-Thermal system was applied as building envelope (with 10 cm air layer between PV panels and wall, indoor air inflow to air layer at a rate of 0.02 kg/s m²)</td>
</tr>
</tbody>
</table>

For the simulation, a two-storey office building was modeled with three zones. The first floor has one zone (590 m²) and second floor has two zones (498 m² and 60 m²). It was assumed that the office building is located in Daejon, Republic of Korea (latitude 36.32N, longitude 127.38E). The hourly weather data of Daejon as TMY form was used. The zone temperature is controlled to 20 °C and 26 °C for the heating and cooling.

It was also assumed that BIPV or BIPVT system were placed on the south facade of the building model (Fig. 2) with 128 PV modules of a total rated power of 16 kWp over an area of 129 m². The air gap distance between BIPV modules and building wall surface was assumed to be 10 cm and the air flow rate of 9,310 kg/h. For the Case 3, it is controlled that the hot air from BIPVT system is exhausted to outside during the cooling season.
3. Results and discussion

Comparative results of the hourly simulation of the Reference building with Cases 1-3 are presented in Fig. 3-8.

The predicted PV temperatures of BIPV and BIPVT system for the three cases during a few days of the winter and summer in Daejon, Korea are shown in Fig. 3 and 4. It is observed in these figures that the PV temperature of Case 1 is the highest, followed by Case 3 and then Case 2. Therefore, it was obvious that the PV cooling effect is more enhanced for the lower temperature PV modules, as they are cooled by the forced ventilation for the BIPV and BIPVT systems in Case 2 and 3. For Case 1, PV temperature rose very high up to 46°C in spite of below zero ambient temperature in winter. This result indicates that the temperature of the BIPV module which was attached to building envelope without ventilation could be higher by solar radiation reaching on the module surface. On the other hand, the highest PV efficiency is expected with Case 2. In the case of the cooling season, the PV temperature of Case 1 is the highest, followed by Case 2 and Case 3, as shown in Fig. 4. However, the difference of the PV temperature for each case is relatively smaller than that of the heating season, which is believed to be due to lower solar radiation and higher ambient temperature in summer than in winter.

The predicted monthly electricity generation from the BIPV and BIPVT of the cases is also presented in Fig. 5. The annual electricity generation of Case 2 is the highest monthly, followed by Case 2 and the Case 1 is the lowest. It was analyzed that the electricity generation of Case 2 and 3 is higher annual 6% and 3% respectively due to PV module cooling of the BIPVT envelope than that of building with the BIPV envelope of the Case 1. These results indicate that BIPVT system certainly improves the electricity generation during the winter season, because the forced air flow significantly cools the PV modules. On the other hand, the BIPVT system that circulates the indoor air showed a lower increase in electricity generation compared to the BIPVT system with outdoor air inflow. Therefore, the BIPVT system with outdoor air inflow is more advantageous from a PV module cooling aspect; however, the BIPVT system that circulates the indoor air and runs the obtained heat source indoors is favorable in terms of building heating and cooling, along with overall energy, because the effect of the heating energy reduction is relatively greater than that of the electricity generation increase.
Fig. 6 shows the monthly heat gain and thermal efficiency for Case 2 and 3 of building with BIPVT system. The thermal efficiency of Case 2 and 3 are average 30% and 14% respectively in the winter season that solar radiation is higher than that of the summer. For the heat gain, Case 2 and 3 are average 3,900 kWh and 1,840kWh respectively. Therefore, the thermal performance of Case 2 is higher about 2 times than that of Case 3. From these results, it were analyzed that this is due to the temperature difference of inflow air from the outdoor ambient temperature.

![Graph showing monthly heat gain and thermal efficiency for Case 2 and 3 of building with BIPVT system.](image)

Fig. 3. PV temperature of the BIPV and BIPVT Cases in the heating season

![Graph showing PV temperature of the BIPV and BIPVT Cases in the cooling season.](image)

Fig. 4. PV temperature of the BIPV and BIPVT Cases in the cooling season
The temperature of building wall surface is one of the factors that decide the energy loads of a building, and is regarded as a boundary condition to calculate the heat loss of the building envelope. For the three cases, the wall surface faces the back side of PV modules of the BIPV and BIPVT systems, so that PV module temperature affects the wall surface temperature and in turn the heating and cooling loads of the building. Fig. 7 and 8 present the comparison of the predicted surface temperature of building wall during a few days of the typical heating and cooling season, respectively.

It is observed in these figures that the surface temperature of Case 1 rises up to 43°C in spite of below zero ambient temperature in winter (Fig. 7). On the other hand, the wall surface temperature of the reference model reaches up to 9°C, which results in a large temperature difference of 32°C compared to Case 1. In Case 2, the maximum wall surface temperature is about 7°C as cold air from outside came into the air space between the wall and PV modules, while the temperature of Case 3 goes up to 24°C. The
surface temperature of outside wall of Case 1 is the highest, followed by Case 3, Reference Case and Case 2. These results indicated that the wall surface temperatures of BIPV and BIPVT systems are higher than those of the reference building and the building with ventilated BIPV. Furthermore, the heating and cooling loads of the building could vary according to these outside surface temperatures.

In case of the cooling season (Fig. 8), the outside surface temperature of Case 1 is the highest that reaches to 43°C in spite of lower solar radiation in summer. And then it is followed by Case 2 and Reference Case; both have a similar temperature distribution with a slightly difference due to the forced circulation of outdoor air for Case 2. It also found that the temperature of Case 3 is the lowest. For Case 3, the inlet air temperature of BIPVT was set to the same temperature as the indoor cooling, so that outside surface temperature of Case 3 lower than that of Case 2 which circulated with outdoor hot air in summer.

The heating loads for the four cases are shown in Fig. 9. For Case 1, the building with the BIPV envelope showed a decrease in the annual heating load compared to the building of Reference Case, while Case 2, the building with BIPVT envelope showed an increase in the heating load because the building envelope cooled with the inflow of cold outdoor air. The heating load difference was analyzed and found that Case 1 and 2 to be insignificant at a level of 1%, as shown in Fig. 9. Therefore, the effects of the BIPV and BIPVT systems as the building envelope on the building heating loads were determined to be small. However, for Case 3, when the heat obtained from the BIPVT system was circulated into the building space, there was a significant difference; the heating load reduction is 27%, compared to Case 2. This should be attributed to the convection of the heated air from the BIPVT system.

Fig. 7. Wall surface temperature of Reference, BIPV and BIPVT Cases in winter
4. Conclusions

The air type BIPVT system applied to buildings can be an outer layer that creates a building envelope that is double layered; the characteristics of the envelope differ with its generated heat source. Therefore, a building envelope with the BIPVT system is different from that of an existing building and may have a different impact on the building energy loads. Also, the building energy performance varies according to the energy obtained from the system.

From the simulation analysis results, it was concluded that the building with the BIPVT system was able to prevent the efficiency decrease, in contrast to the building with the BIPV system without ventilation. In particular, the BIPVT system that ventilated with the inflow of outdoor air effectively prevented the efficiency decrease caused by the PV module temperature rise. Also, an installation of
BIPV at the building can slightly reduce the heating load compared to the building without BIPV installation on walls. On the other hand, for the building with BIPVT system that circulates the outdoor air, the heating load is slightly increased due to the cooling of the external wall by forced inflow of cold outdoor air. However, that is more advantageous from a PV module cooling aspect, and the effect on the cooling load of the building will be also of interest.

Through these study results, the BIPVT system was found to be more useful due to its increased electrical efficiency and heating energy conservation in winter in comparison with the BIPV system, which does not take into consideration the rear ventilation. Furthermore, the system is expected to operate at optimum levels through appropriate control of the electrical and thermal loads.

Acknowledgements

This work was supported by the Priority Research Centers Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No.2009-0093825) and by a grant from the Human Resources Development Project of the Korea Institute of Energy Technology Evaluation and Planning (No.20114010 203040) funded by the Korean Ministry of Knowledge Economy.

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