Journal of Smart Technology Applications
Vol.1, No.1 (2020), pp.7-12
http://dx.doi.org/10.21742/jsta.2020.1.1.02

A Basic Study on the Development of PV Module Applying Building Envelope Technology for Energy Reduction

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Abstract

Recently, energy consumption in the building sector continues to rise, and many studies are being conducted to address this problem. In particular, building envelopes are the largest sources of heat loss in buildings, so the demand for related studies is increasing to improve its performance. Building envelopes are composed of element technologies related to insulation, daylighting, shading, and concentrating light. However, each technology has pros and cons, making it unsuitable for saving building energy. Therefore, the purpose of this study is to build basic data for building envelopes by proposing and validating the performance of a building envelope that can simultaneously concentrate light and perform daylighting. For this purpose, this study validated the effectiveness of saving building energy through a full-scale testbed. The main findings are as follows. 1) This study integrated a curved light shelf (daylighting system) with a PV module (to concentrate light) and proposed attaching the PV module to the bottom of the light shelf to solve issues that reduce PV generation efficiency. 2) The optimal angle of a flat light shelf for saving lighting energy during summers was 30° and based on this, the amount of lighting energy used to satisfy the optimal indoor illumination (400 lx) was 0.144 kWh. 3) The optimal angle of the curved light shelf with a PV module proposed in this study is 30° and based on this, 0.129 kWh of lighting energy was used to satisfy the optimal indoor illumination of 400 lx. The curved light shelf with a PV module can also produce energy through the PV module, so it can save building energy by 16.6% compared to a conventional flat light shelf considering the energy produced by the PV module.

Keywords: *Building envelope, Photovoltaic, Performance evaluation, Energy saving*

1. Introduction

According to the data by the Korea Energy Agency in 2017, energy consumption in the building sector accounted for 26% of the total use of energy, and this figure is expected to increase gradually. Therefore, various studies and technological developments are being pursued to reduce energy consumption in the building sector [1]. The building envelope is an important factor in determining the energy efficiency rating of a building in terms of protecting the indoor space from the external environment and is also the most vulnerable area to the heat loss in the indoor space [2]. Therefore, improving the performance of building envelopes is an important aspect to save building energy. Among the element technologies of building envelopes, the light shelf saves lighting energy by introducing outdoor natural light

Article history:
Received (July 15, 2020), Review Result (August 18, 2020), Accepted (September 14, 2020)

deep into the room, and many studies have been conducted in recognition of its efficiency [3]. A recent study focused on saving building energy by attaching a PV module, another building envelope technology, to the light shelf [4]. However, most previous studies on light shelves combine PVs on top of the reflector, which acts as a disadvantage because the efficiency may be degraded by soiling due to accumulated dust on the PV surface [5]. Flat light shelves are also unsuitable for maximizing daylighting efficiency because they reflect natural light in the form of mirror reflection [6]. Therefore, the purpose of this study is to build basic data in related fields by proposing a building envelope technology that can simultaneously increase the daylighting performance of light shelves and the concentration performance of PV modules and examine its performance.

2. Consideration of building envelope technologies and comfortable indoor environment standards

2.1. Consideration of building envelope technologies

Building envelopes primarily divide the indoor and outdoor areas and create a comfortable indoor environment from outdoor environmental factors. Building envelope element technologies include systems related to insulation, daylighting, and shading. The light shelf, as shown in [Figure 1], is a building envelope element technology that can efficiently save lighting energy by introducing external natural light deep into the room through reflection. The variables that determine the performance of light shelves include the width of the reflector, angle, height, and reflectivity. Recently, a wide variety of studies have been conducted on light shelves by diversifying the shape of the reflectors or by integrating IT technologies [7][8]. The shape of the reflector is important because light shelves perform daylighting by reflecting outdoor natural light. Conventional light shelves are generally flat and perform daylighting by mirror reflection, but this study applies a light shelf with curvature.

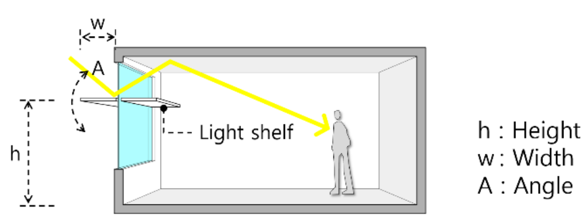

Figure 1. The concept and application of light shelves

A PV module is a system that consists of multiple PV cells to convert solar energy into electrical energy. PV generates electricity by the photoelectric effect when light is incident to the metal and semiconductor surface or the p-n junction of semiconductors. The types of PV cells include selenium, copper sulfate, silicon, and thin-film photovoltaic cells. PVs are composed of N (negative) type semiconductors and P (positive) type semiconductors that have different electrical properties. When PVs receive sufficient light energy, the electrons inside become free electrons and move from the positive P-side to the negative N-side. This movement creates an electric current and generates electricity [9].

2.2. Consideration of comfortable indoor environment standards

This study considered the relevant comfortable indoor environment standards to evaluate building energy performance. In particular, this study focused on the light environment among the comfortable environment factors of indoor space in terms of developing an envelope technology based on light shelves. The optimal light environment standards for indoor space vary by country, spatial characteristics, and activity. Therefore, this study was based on the standards presented by the Illuminating Engineering Society in the US and set the optimal indoor illumination to 500 lx (the standard for general work) to evaluate the performance of the building envelope [10].

3. Building envelope technology development & performance evaluation

3.1. Building envelope technology proposal

This study focused on the light shelf and PV in terms of building envelope technologies and comprised the following steps to efficiently perform the main functions of concentrating light and daylighting by applying the light shelf and PV. First, a curved reflector was applied to the light shelf with a PV module. The reason why this study chose a light shelf with a curved reflector is that, unlike a flat light shelf, it induces diffused reflection in the process of reflecting external natural light to improve the daylighting performance. Second, this study attached a PV module to the curved light shelf and suggested that the PV should be attached to the bottom of the reflector instead of the top. This is because the PV is vulnerable to soiling, but this problem can be solved by installing the PV to the bottom of the light shelf. In addition, when the PV is attached to the bottom of the curved light shelf, it can simultaneously concentrate light and perform daylighting depending on the angle of the light shelf and further contribute to saving building energy.

3.2. Performance evaluation environment and method

This study built a full-scale testbed as shown in Table 1 to evaluate the performance of the building envelope developed in this study. The size of the testbed was 4.9 m (width) x 6.6 m (depth) x 2.5 m (height), and the area of the window where the light shelf was installed was 2.2 m (width) x 1.8 m (height). This study also built a chamber outside the window to create an external environment and installed an artificial solar irradiation apparatus in the chamber. The artificial solar irradiation apparatus was capable of simulating the brightness and altitude of the sun but could not simulate the azimuth. As shown in [Figure 2], a total of four illuminance sensors were installed to analyze the indoor illumination of the testbed, where each illuminance sensor was connected to the lighting to provide lighting control. This study evaluated the performance of the proposed building envelope according to the following method. First, to validate the energy-saving performance of the PV-applied light shelf, which is the proposed building envelope technology in this study, it was compared to a conventional flat light shelf. The height and width of the light shelf were 1.8 m and 0.6 m, respectively. The height of the light shelf was set by considering the view of the window, and the angle was changed from 0° to 30° in increments of 10° considering movement. Second, this study calculated the consumption of lighting energy to validate the effectiveness of saving lighting energy in the cases set above. This was performed by calculating the lighting dimming control level and consumption of lighting energy for each case that satisfies the optimal indoor illumination (400 lx). In Case 3, which applies a PV module, the amount of energy generated by concentrating light was also monitored. Third, the lighting control to maintain the optimal indoor illumination (400 lx) was only performed when the illuminance sensor was

400 lx or less, in which the dimming level of the lighting connected to the illuminance sensor showing the lowest value was raised sequentially. The lighting control ended when all of the illuminance sensors satisfied 400 lx during this process and the consumption of lighting energy at this point was monitored. Fourth, this study limited the performance evaluation to summer, which is a limitation of this study.

Table 1. Testbed Overview

Room Size / Reflexibility	4.9 m (w) × 6.6 m (D) × 2.5 m (H) / Ceiling: 86%, Wall: 46%, Floor: 25%
Window	Size: 1.9 m (W) × 1.7 m (H), Type: Pair Glass 24 mm, Transmissivity: 80%
Illuminance Sensor	Sensing Element: Silicon Photo Sensor, Detection Range: 0 lx ~ 200,000 lx
Meridian Altitude	Summer: 76.5°

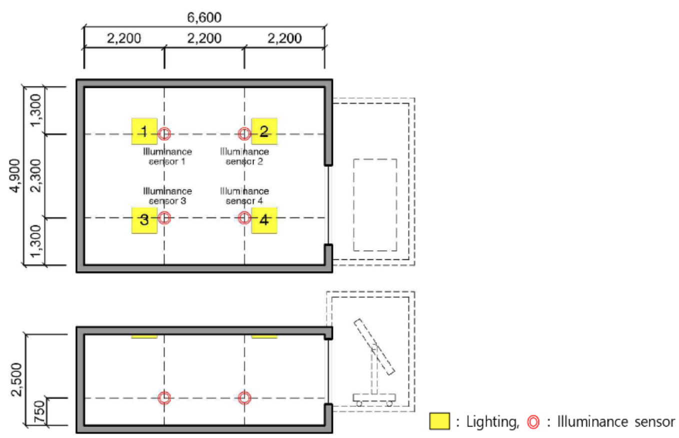

Figure 2. Testbed specifications and location of illuminance sensors for performance evaluation

3.3. Performance evaluation results and discussion

This study developed a building envelope technology that combines a light shelf with a PV module and evaluated the performance of saving building energy. The results are as follows.

First, [Table 2] shows the performance evaluation results according to the angle of a conventional flat light shelf, where the increase in the light shelf angle was advantageous for saving lighting energy. This is because the amount of light entering the room increases as the light shelf angle increases as shown in [Figure 3]. In particular, during summer, although the consumption of lighting energy may be high because of the small amount of natural light entering the room due to high altitude, this problem can be solved by installing a light shelf. The optimal angle of the flat light shelf to reduce building energy was 30°, and the amount of lighting energy used to satisfy the optimal indoor illumination (500 lx) was 0.144 kWh.

Table 2. Performance evaluation results of a flat light shelf during summer

Light shelf angle	Illumination (lx)		Lighting dimming control: Light ID (dimming level)	Electricity consumption (kWh)
	Min.	Avg.		
0°	65.0	342.1	1(8)+3(8) +2(8) +2(2)	0.171
10°	68.1	362.9	1(8) +3(8) +2(8) +2(1)	0.165
20°	76.9	377.7	1(8) +3(8) +2(8)	0.120
30°	80.4	382.0	1(8) +3(8) +2(7)	0.144

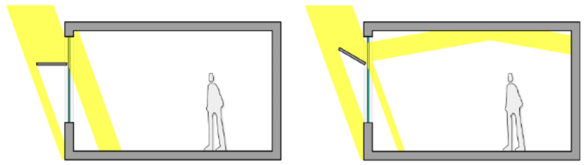

Figure 3. The inflow of natural light according to the light shelf angle during summer

Second, [Tables 3, 4] show the performance evaluation results of the curved light shelf with a PV module, which is the building envelope technology proposed in this study. The optimal angle of the curved light shelf with a PV module to reduce indoor lighting energy was 30° and based on this, the amount of lighting energy used to satisfy the optimal indoor illumination (500 lx) was 0.129 kWh. This proves the effectiveness of the curved light shelf by reducing the lighting energy by 10.4% compared to the flat light shelf. As shown in Table 4, the curved light shelf with a PV module can also produce energy through the PV module attached to the bottom, and the optimal light shelf angle was 30° even when considering the energy produced by the PV module. Considering both daylighting and light concentration, the curved light shelf with a PV module can save building energy by 16.6% compared to a conventional flat light shelf. This proves the effectiveness of the curved light shelf with a PV module in terms of saving building energy.

Table 3. Performance evaluation results of the curved light shelf with a PV module during summer

Light shelf angle	Illumination (lx)		Lighting dimming control: Light ID (dimming level)	Electricity consumption (kWh)
	Min.	Avg.		
0°	87.4	396.8	1(8)+3(8) +2(6)	0.140
10°	91.3	407.0	1(8) +3(8) +2(6)	0.140
20°	94.1	405.0	1(8) +3(8) +2(5)	0.136
30°	99.8	370.3	1(8) +3(8) +2(4)	0.129

Table 4. Performance evaluation results of the curved light shelf with a PV module during summer

Light shelf angle	Electricity consumption (kWh) A	Power produced (kWh) B	Net energy consumption (kWh) $\sum A - B$
0°	0.140	0.003	0.137
10°	0.140	0.005	0.135
20°	0.136	0.006	0.130
30°	0.129	0.009	0.120

4. Conclusion

This is a basic study on the development of building envelope technology by integrating two representative building envelope element technologies to solve related problems and maximize energy savings. The main findings are as follows. First, this study integrated a curved light shelf (daylighting system) with a PV system (for concentrating light) to propose a building envelope to efficiently reduce building energy. The PV module was attached to the bottom of the light shelf to solve problems related to reducing PV generation efficiency. Second, the optimal angle of the flat light shelf for saving lighting energy was 30° during summer, and the increased light shelf angle during summer increases the amount of natural light entering the room, thus improving the efficiency of saving indoor lighting energy. Based on the optimal angle of the flat light shelf, the amount of lighting energy used to satisfy the optimal indoor illumination (500 lx) was 0.144 kWh. Third, the optimal angle of the curved light shelf with a PV module, which is the building envelope technology proposed in this study, was 30°, and based on this, the amount of lighting energy used to satisfy the optimal indoor illumination (500 lx) was 0.129 kWh. This proves the effectiveness of the curved light shelf with a PV as it can save lighting energy by 10.4% compared to the conventional flat light shelf. The curved light shelf with a PV module can also produce energy through the PV module. As a result, it can reduce building energy by 16.6% compared to the conventional flat light shelf considering the energy produced by the PV module.

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