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Experimental study on PPFD and electricity consumption for Hybrid Louver Lighting System(HLLS) in indoor vertical farms#

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ABSTRACT

This study developed a hybrid louver lighting system that combines daylighting using solar energy and LED to solve the problems of high electric consumption and heat load of LED used in vertical farm. This system can control the LED lamp according to the intensity of daylighting that changes in real time to meet the set target PPFD. The louver is composed of transparent vacuum glass and diffuser, and multiple horizontal slats installed air cavity in louver effectively transmit the daylighting to the indoor and distribute the required PPFD. The vent applied to the upper and lower of the louver discharges unnecessary heat generated from the LED lamp to the outdoor in summer and utilizes the required heat indoor in winter. The electric consumption of the hybrid louver lighting system and the indoor temperature due to the heat load were evaluated using a full scale mock-up facility.

Keywords: Hybrid louver lighting system, Daylighting, LED, PPFD, Energy saving

NONMENCLATURE

Abbreviations	
HLLS	Hybrid Louver Lighting System
PPFD	Photosynthetic Photon Flux Density
LED	Light Emitting Diode

1. INTRODUCTION

The entire world is focusing on urban smart farms due to climate change, environmental pollution issues, and food safety demands, and the smart farm industry size is expected to grow at a CAGR of 9.4% from 2023 to 2028 [1].

Urban smart farms include Rooftop Farm (RF), Rooftop Greenhouse (RG), Vertically-integrated Greenhouse (VIG), Vertical Farm (VF), and Shipping Container Farm (SC), and research and development are active [2]. However, urban smart farms use LED lamps instead of sunlight for crop cultivation all year round, and excessive energy is consumed for cooling due to heat generation (60~80℃) caused by the low efficiency of LED light sources installed indoors, and cooling accounts for 80% of total energy consumption [3]. Research using solar energy is actively being conducted to improve illumination and save energy by artificial light sources in buildings. Han, H.J., et al. analyzed that an active daylighting system combining sunlight and artificial light in a building can save 174 kWh of energy compared to an LED lamp with an efficacy of 17 lm/W [4]. Vu, D.T., et al. analyzed that hybrid daylighting system combining mirrors and plastic fibers in a high-rise building were improved optical efficiency by 63.7% and save annual energy by 46.5% [5]. Chen, H., et al. analyzed the solar shuttle system, which can change the slat angle according to the season and solar altitude, showed energy savings of 9.18 ~ 22.46 kWh in June, indoor illuminance of 450 ~ 2000 lx, and daylighting time of more than 50% [6]. Ullah, I. and S. Shin analyzed using optical simulation that a daylighting system combining parabolic concentrator, Fresnel lens, and optical fibers for daylighting in an office can reduce lighting electric consumption and improve indoor environment [7, 8].

Previous studies have few cases of utilizing daylighting in vertical farm and most studies have utilized daylight using expensive optical fibers for buildings. In this study, a hybrid louver lighting system was developed that can actively utilize daylighting in vertical farm and uses low-cost louvers, and its performance in terms of PPFD and electric consumption was verified.

2. PROPOSED HLLS

2.1 Material and method

HLLS consists of LED lamp, Slat, Diffuser, and Vent. LED is dimmed by the PPFD of daylighting. Slat is

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controlled by the angle by time schedule to meet the target amount of light according to solar radiation and solar altitude. Diffuser has the function of diffusing natural light, and vacuum glass and single-panel glass are applied to control the cooling load. Vent is opened or closed according to the outdoor conditions. The components of HLLS were developed to appropriately respond to solar radiation, solar altitude, and ambient. This paper analyzed the PPFD, electric consumption, and indoor temperature that affects the cooling and heating load of the HLLS system.

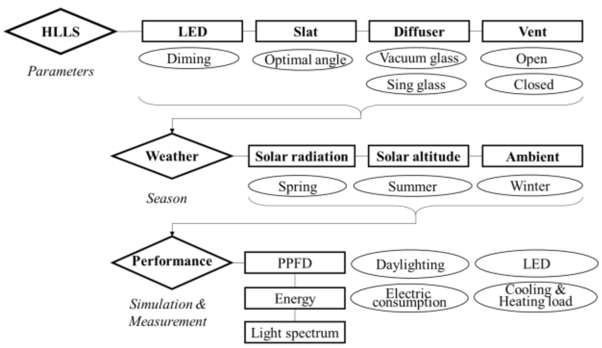

Figure 1 Schematic of experiment analysis

3. DESIGN OF HLLS

3.1 Concepts of HLLS

The operating principles of the cooling and heating season of HLLS are shown in Figure 2 In the cooling season, the vents on the top and bottom of the outer glass are opened to discharge the heated air in the air cavity to the outside, and the vents on the top and bottom of the inner glass are closed to block the heated air in the air cavity from entering the room. In the heating season, the vents are operated in the opposite direction to the cooling season, and the heated air in the air cavity is moved indoors to contribute to the heating load.

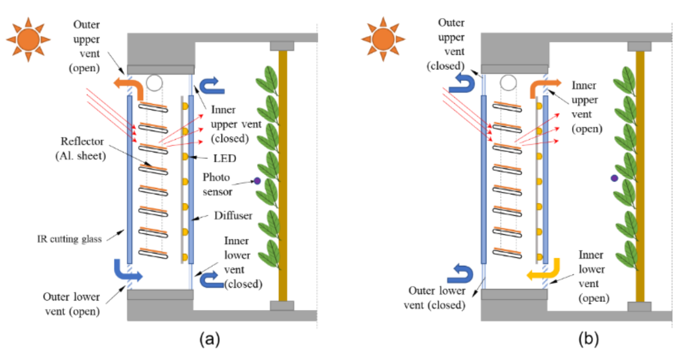

Figure 2 Section view and operating principle of the hybrid louver lighting system; (a) Cooling season mode, (b) Heating season mode

HLLS controls the PPFD setting value according to the solar radiation. The control is to turn on the LED 100%, operate the LED and daylighting mixed, or use daylighting 100% depending on the weather condition. As shown in Figure 3 on a clear day, daylighting can be used to the maximum, which greatly reduces the electric consumption of the LED lamp. At noon on a clear day, daylighting more than the setting value occurs. At this time, daylighting more than the setting value is blocked. Daylighting is also used to the maximum on a cloudy day.

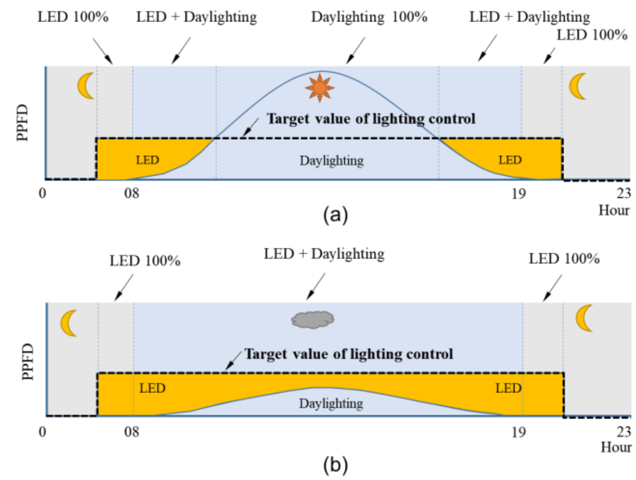

Figure 3 Control strategy of LED and daylighting according to weather condition; (a) Clear day, (b) Cloud day

3.2 Model of HLLS

The development model of HLLS and full scale mock-up facility that can achieve the optimal required light quantity through simulation analysis are shown in Figure 4. Room (1) applied the HLLS prototype, and Room (2) was constructed as a conventional vertical farm. The detail and specification of horizontal slats located in the air cavity of the louver are as shown in Figure 5. The PPFD was measured using a quantum sensor (Li-190R), the temperature of each part was measured using a thermocouple (Type 0.3), and the vertical solar radiation was measured using a Pyranometer (CMP21).

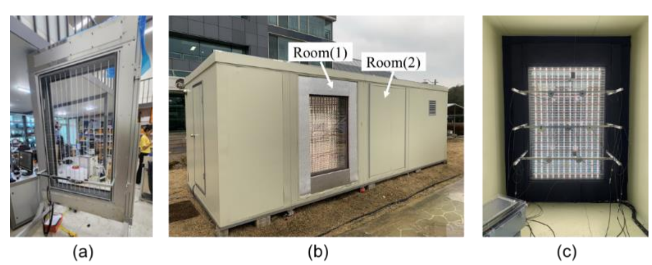

Figure 4 View of the mock-up facility applied prototype of the HLLS; (a) Prototype, (b) Outside view, (c) Inside view

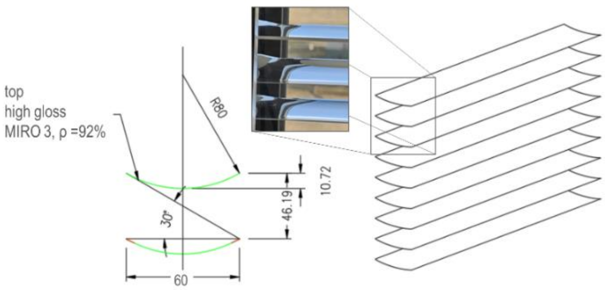

Figure 5 Detail and specification of horizontal slat

As shown in Table 1, each LED lamp has a capacity of 23W, and a total of 12 lamps were applied in 3 groups on the left, center, and right. The dimming strategy of the LED lamp is to appropriately control the distribution of daylighting distributed according to the azimuth of the sun.

Table 1 Specification of LED lamp

Items	Specification
Capacity	*23 W / 1bar*
Bar block	*1540 mm (5x5 mm)*
Rated voltage	*12 V*
Wide angle	*120 °*

4. RESULT AND DISCUSSION

4.1 Photosynthetic photon Flux Density

The required PPFD value differ depending on the plant. The standard for the general appropriate PPFD value is divided into low PPFD 150 μmol/m^{2}s, medium PPFD 200 μmol/m^{2}s, and high PPFD 250 μmol/m^{2}s.

In this study, an experiment was conducted to determine whether HLLS could reach the target PPFD of

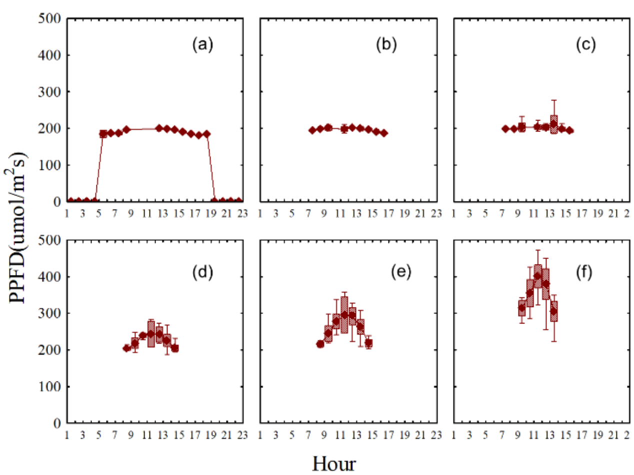

Figure 6 PPFD according to range of solar radiation; (a) under 200, (b) 200~300, (c) 300~400, (d) 400~500, (e) 500~600, (f) over 600

medium PPFD 200 μmol/m^{2}s. The experiment was conducted from March 15 to March 18, 2024, and data were collected (Lab View) every 5 seconds. The HLLS system was operated for 12 hours from 6:00 AM to 6:00 PM to actively utilize daylighting. When the solar radiation was less than 400 W/m^2, the target PPFD of 200 μmol/m^{2}s was met, but when it was over 400 W/m^2, the target PPFD was exceeded, and the PPFD increased in proportion to the intensity of the solar radiation.

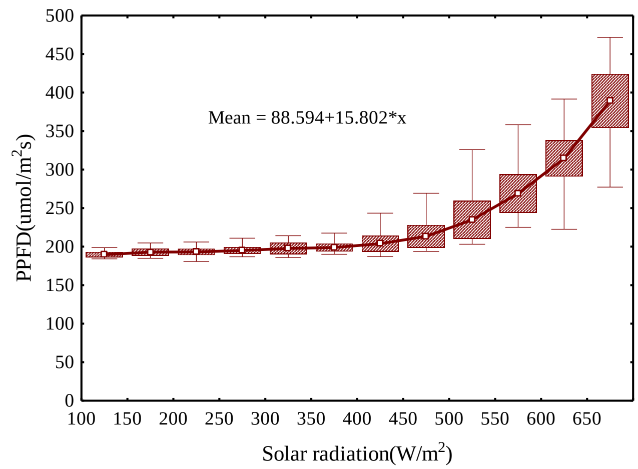

Figure 7 PPFD according to solar radiation

As shown in Figure 7, the PPFD increased rapidly when the solar radiation was 400 W/m^2 or higher, and when the solar radiation was 400 W/m^2, the average was 203.8 μmol/m^{2}s, the maximum was 243.1 μmol/m^{2}s, and when the solar radiation was 650 W/m^2, the average was 389.1 μmol/m^{2}s, the maximum was 471.6 μmol/m^{2}s. This experiment confirmed the PPFD distribution for HLLS system according to solar radiance.

This experiment was successful in confirming the change in PPFD distribution according to solar irradiance of the HLLS system. This study is currently in progress to improve slat specifications, LED lamp capacity, and control to meet the target PPFD even in high sections.

4.2 Electrical consumption and temperature

The results of comparing the electric consumption of the HLLS applied vertical farm Room (1) and the reference vertical farm Room (2) are shown in Figure 8. During the experimental period, the HLLS LED lamp consumed 10.5 kWh, while the reference LED lamp consumed 15.9 kWh. This resulted in a 33.8% reduction in electrical consumption for the HLLS system. The greatest reduction in electrical consumption occurred during noon hours when solar radiation intensity is high during the LED lamp operating hours. The indoor temperature during the operating hours when HLLS was applied was an average of 27.2 degrees Celsius, while the reference temperature was 29.7 degrees Celsius as in Figure 9. This temperature difference of 2.5 degrees Celsius was found to be caused by the heat from the LED lamp in air cavity of louver being discharged to the outside through the vent due to the influence of the HLLS system.

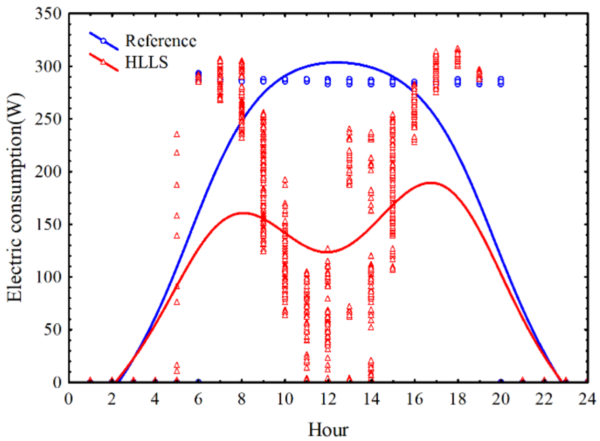

Figure 8 Electric consumption of LED lamp

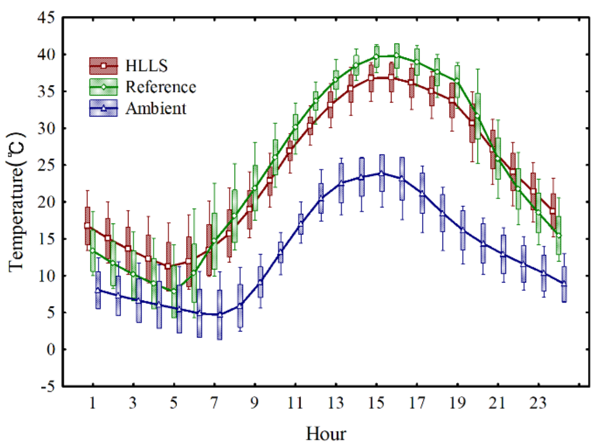

Figure 9 Room temperature of Room (1) installed HLLS and Reference Room (2)

5. CONCLUSION

This study developed a hybrid louver lighting system (HLLS) that combines daylighting and LED. The electric consumption and indoor temperature of the HLLS was evaluated using a full scale mock-up facility.

The electric consumption of the HLLS system was found to be 33.8% lower than that of the reference LED lamp when using daylighting, and the electric consumption was the greatest during the noon hours when the intensity of solar radiation was high the LED lamp operating hours. The HLLS system was shown to lower indoor temperatures by 2.5 degrees Celsius compared to a reference vertical farm during the experimental period.

This study is currently conducting research to improve the automation technology of the slat angle of the HLLS system to precisely reach the target PPFD and increase uniformity. In addition, this system will analyze the effect of indoor temperature distribution to verify the energy saving of the vertical farm.

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