Daylighting characteristics and experimental validation of a novel concentrating photovoltaic/daylighting system

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Abstract

Daylight plays an important role on the environmental comfort level for buildings. As for the energy consumption in the building, lighting is one of the main contributors. However, traditional building integrated solar utilization systems such as flat photovoltaic or concentrating photovoltaic systems can only supply the heat or the electricity for buildings. Thus, a novel concentrating photovoltaic/daylighting window is proposed as a strategy to effectively generate the renewable electricity for the domestic use while providing a better daylight performance. The indoor experiment and ray tracing simulation are both conducted to identify the effect of the "daylighting window" on the optical performance of the concentrator. The annual daylight performance of a typical office building installed with the concentrating photovoltaic/daylighting window at various installation angles, window-to-ceiling ratios and under different climate conditions is investigated through RADIANCE. The accuracy and confidence of the simulation model is validated through the outdoor experiment, and the deviation between the experimental and simulation results is as low as 8.7%, which is indicated by the coefficient of variation of the root mean squared error. The simulation results show that the concentrating photovoltaic/daylighting window provides a good daylight performance on the working plane of the office room: the percentage of the working hours under daylight that lies in the useful range (100–2000 lx) can be up to 92.00%. It also achieves a homogenous distribution of daylight within the internal working space and effectively reduces the possibility of glare. Through the simulation results under different climate conditions, besides of the solar irradiance, the latitude also has an obvious effect on the annual daylight performance. So for the application in different latitudes, it's highly recommended to be installed with the inclination angel near the local latitude for a higher annual electricity output and better annual daylight performance.

Keywords: Concentrating photovoltaic/daylighting window; Optical efficiency; RADIANCE; Daylight performance

Nomenclature

C

geometric concentration ratio of the lens-walled CPC

C_V (RMSE)

coefficient of variation of the root mean squared error

CPV/D

Concentrating Photovoltaic/Daylighting

DA

Daylighting Autonomy

DF

Daylighting Factor

UDI

Useful Daylight Illuminance

$I_{sc}^{without}$ (A)

short circuit of the non-concentrating PV

I_{sc}^{with} (A)

Short circuit current of the concentrating PV

LWCPC

Lens-walled compound parabolic concentrator

Greek symbols

θ (°)

incidence angle

$\eta_{daylighting}$

daylighting efficiency

η_{opt}

optical efficiency

$\eta_{opt,ac}$

actual optical efficiency of the concentrator

1 Introduction

It has been reported that the building sector is more than 40% responsible for the world total energy demand (Omer, 2008), which is still in the increasing trend with the rapid development of the society. In this regards, it was noting that the lighting is one of the main contributor to the building energy consumption. It was estimated by the Energy Information Administration (EIA) that the consumption of the electricity for lighting for the residential and commercial sectors in 2016 is 279 billion kWh, which was around 10% of the total electricity consumption by these sectors and around 7% of the total electricity consumption in the United States (EIA, 2017). Thus, it’s of great importance to introduce the renewable energy technology into buildings (Lv et al., 2017). What’s more, combining the natural daylighting with the exist renewable energy technologies such as PV, PV/T (Photovoltaic/Thermal) or CPV, CPV/T (Concentrating Photovoltaic/Thermal) would be a more efficient way to use the solar energy for buildings. In addition, It was highlighted by Wong that although artificial lighting has being used as supplementary lighting resource in the interiors of buildings for a long term, many reports suggested the negative effects of artificial lighting on human health (Wong, 2017). On the contrary, it offers a lot of benefits to the human health and it can even cure some of the medical ailments by using natural light (Hraska, 2015) and it can also reduce psychological sadness related to the Seasonal Affective Disorder (Sapia, 2013).

Speaking of combing the natural daylighting with the PV system, compared with the traditional flat PV module, the concentrating PV technology offers more design imaginations, for the concentrators are usually made of the transparent material such as polymethyl methacrylate (PMMA). The traditional plat PV module will block the sun rays from entering the room which make it inefficient to add the function of the daylighting. On the contrary, the CPV module made by the transparent material which would allow a portion of "escape" sun rays into the room for daylighting. By means of "escape", it represents the sun rays that can't reach the PV cell for the electricity generation. It's worth noting that the key component of the CPV module is the concentrator, a device usually makes use of geometrical optics in the design of reflective and/ or refractive types of concentrating devices to focus the solar flux onto a receiver module where the PV cell is attached (Abu-Bakar et al., 2015; Xu et al., 2016). Due to the fact that the high geometric concentration ratios needs additional tracking systems and high cost optical materials, it would not be suitable for the building application (Feng et al., 2015). In contrast to that, the compound parabolic concentrator (CPC) is more suitable for building integration because it can work as a static concentrator, which has also been paid a lot of attention since it was first invented in the U.S in 1970s (Rabl et al., 1980; Winston, 1974).

In the research area of the low concentration concentrator for building application, the work done by ~~professor~~Professor T.K. Mallick should be highlighted. Since the beginning of the 21st century, T.K. Mallick et al. have designed several low concentrators for building application which are suitable for the installation on the building rooftop and façade. These concentrators included the traditional compound parabolic concentrator besides its optimization structure, new-style concentrator and so on. T.K. Mallick et al. designed a novel asymmetric concentrator and outdoor experimental results indicated that the concentrator can increase the maximum power by a factor of 62% as compared with the non-concentrating solar cell (Mallick et al., 2004). Furthermore, based on the same outer contours, they further proposed the second generation asymmetric concentrator i.e. dielectric asymmetric concentrator that adopts the total internal reflection to collect sun rays, which was proved to be a more efficient energy collection way. The experimental results showed that the second-generation concentrator delivered a power ratio of 2.01 when compared to a similar non-concentrating system (i.e. increase the maximum power by a factor of 103%) (Mallick and Eames, 2007). For this same asymmetric structure, Sharma et al. used the phase change material to enhance the electrical performance of it, and an increase in the relative electrical efficiency by 1.15% at 500 W m^{-2}, 4.20% at 750 W m^{-2} and 6.80% at 1200 W m^{-2} was observed (Sharma et al., 2016). Muhammad-Sukki et al. proposed a mirror symmetrical dielectric totally internally reflecting concentrator (MSDTIRC) (Muhammad-Sukki et al., 2014), the structure of which was first calculated in the software Matlab® and then transferred into 3-D modelling software to plot the final structure. And their experimental results showed that the MSDTIRC-PV structure was capable of providing a maximum power concentration ratio of 4.2× when compared to a similar cell without the concentrator (Muhammad-Sukki et al., 2013). Baig et al. presented a low concentrator photovoltaic system with thermal (LCPV/T) extraction, and an increase in power of 141% (power ratio 2.41) was found through the experimental test compared to the analogous non-concentrating counterpart (Baig et al., 2018). Reddy et al. designed an Elliptical Hyperbolic Collector (EHC) and carried out the experimental investigation of trapezoidal/concave cavity surface receiver (TSR) for it. Based on the experimental results, for the flow rate of 0.03 kg/min and 0.5 kg/min, the fluid outlet temperature is estimated to be 87 °C at 768 W/m^2 and 49 °C at 908 W/m^2 respectively. The corresponding instantaneous efficiency was calculated to be 9% and 40% respectively (Reddy et al., 2018). Baig et al. designed a building integrated concentrating photovoltaic (BICPV) system. The system under study are essentially composed of Symmetric Elliptical Hyperboloid (SEH) concentrating elements with the geometric concentration ratio of 6X (Baig et al., 2015). Lamnatou et al. conducted an life-cycle assessment for the dielectric-based 3D building-integrated concentrating photovoltaic modules and it was found that energy payback times ranges from 2.30 to 4.10 years (Lamnatou et al., 2017).

Besides of some existing novel designs of the low concentration concentrators, most optimization structures of the low concentration concentrator are derived from the traditional CPC, and the lens-walled compound parabolic concentrator (LWCPC) is one of the typical representatives. Su et al. proposed the first generation of LWCPC by rotating the outer contour of the traditional CPC with a certain angle (usually 3~~-~~–5°) to form the lens-walled structure (Su et al., 2012a, 2012b). The main purpose of the original LWCPC was to reduce the manufacture material thus to reduce the overall cost and weight of the concentrating PV systems and use the refraction to enlarge the acceptance range of the concentrator to make it more suitable for building application (Li et al., 2013). In order to further enhance the optical performance of the LWCPC, Li et al. proposed to adopt the total internal reflection by setting an air gap between the lens-walled structure and the mirror concentrator with the same structure, which we called as the second generation LWCPC (Guiqiang et al., 2014). In this way, the optical efficiencies at various incidence angles can be increased by more than 10% with a more uniform flux distribution on the receiver (Guiqiang et al., 2013) and it has been concluded that the uniform flux distribution is good for the PV output (Li et al., 2018b). A concentrating PV/T system with the use of the second generation LWCPC for building application was also built (Li et al., 2014). Outdoor experiment (Li et al., 2015a) and numerical simulation (Li et al., 2015b) results indicated a good concentrating PV/T performance which proved a good solution for BICPV or BICPV/T. Inspired by this and considering the fact that the concentrator in symmetric geometry is more suitable for the integration with the building roof, while due to different irradiation condition, the asymmetric structure might be a better choice for the building façade. Xuan et al. designed an asymmetric air gap lens-walled CPC for the integration with the building south wall (Xuan et al., 2017b), and the optical performance of it were detailed studied through the experiment and ray-tracing simulation (Li et al., 2018a; Xuan et al., 2017a). Considering that the sun rays near the base area for the LWCPC would escape out of the concentrator, it's feasible to add the function of the daylighting. Based on the first generation LWCPC, the outer surface near the base area isn't coated to set up the "daylighting Window", which we would like to call it as the third generation of the LWCPC, to achieve the multi-function of the electricity generation and daylighting. It's worth noting that setting up the "daylighting window" won't decrease the optical efficiency of the concentrator but achieve a transmittance of around 10% (Li et al., 2018c). In this way, a multifunction of the concentrating photovoltaic/daylighting (CPV/D) window can be formed. Compared with the traditional window, the CPV/D window offers the optimization potential for the energy consumption within the buildings. For instance, during the summer when the solar radiation is uncomfortably high will mostly be absorbed by the PV cells attached with the absorber of the concentrator in the generation of the renewable electricity and only allows a small portion of the solar radiation into the building for lighting. However in conventional designs, the high solar radiation is controlled by the shading device and therefore dissipate as heat; In the winter, light and heat preferentially pass through the system helping to offset heating and lighting energy demands (Li et al., 2018c).

The quantity, quality and distribution of daylight that passes through a window system and illuminates a space, plays an important role in energy efficiency and achieving a comfortable indoor environment. Thus, in this paper, the actual daylight performance when using the CPV/D window are detailed presented with the use of the dynamic daylight performance metrics. The software RADIANCE is used for indicating the daylighting performance of a CPV/D window installed on a typical office room. In the simulation, a cellular office room installed with different CPV/D windows is modelled with the actual weather data from EnergyPlus, and the illuminance distribution across the working plane is calculated for 1 h time-step through the course of a year. The predicted luminous environment during working hours were analyzed using advanced metrics (e.g. useful daylight illuminance (UDI)). The effect of the installation angles as well as the window-to-ceiling ratio has been detailed studied to match with the different building designs. The performance of the chosen CPV/D window has also been investigated under different climate conditions to provide an indication of how site-specific variables influence performance.

2 The description of the CPV/D window

As illustrated in Fig. 1 is the key component of the Concentrating Photovoltaic/Daylighting (CPV/D) window, i.e. the lens-walled compound parabolic concentrator (LWCPC), which has been widely studied in the previous studies (Li et al., 2015a, 2014). The detailed description of the formation process of the lens-walled compound parabolic concentrator has been detailed introduced in (Li, 2018). The lens-walled compound parabolic concentrator is coated on the outer surface to concentrate the solar radiation through the specular reflection. In order to achieve the function of the daylight, the lower part (near the base area) is not coated to set the “daylighting window”, which allows a portion of sun rays to reach the room (Fig. 1(c)).

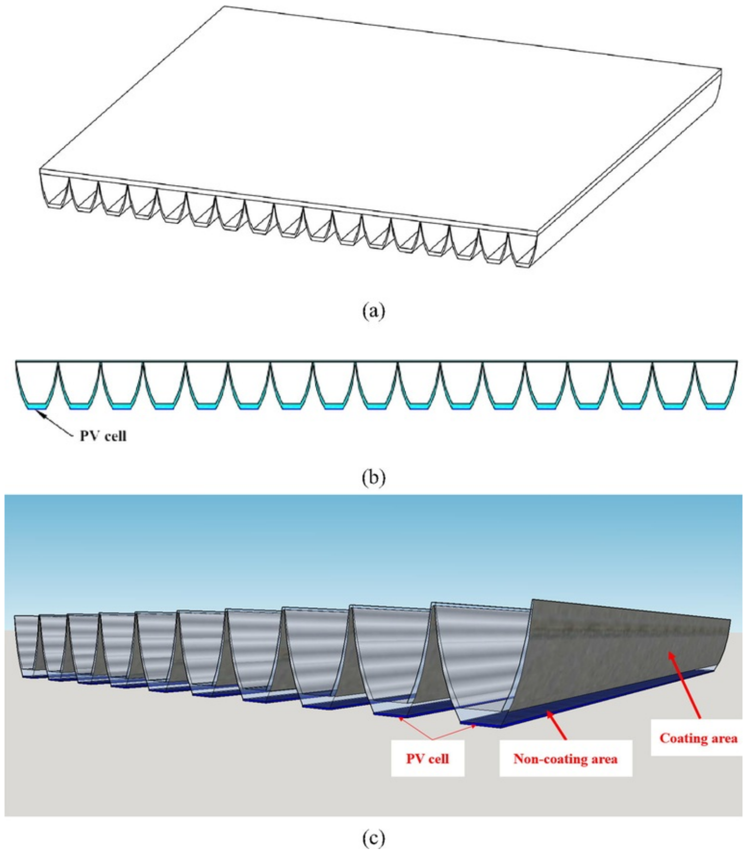


Fig. 1 (a) 3D view; (b) section view of the lens-walled CPC panel and (c) CPV/D window.

One major concern about the CPV/D window is that the optical efficiency might be decreased due to the "daylighting window". In order to address this issue, the optical performance of the lens-walled CPC with and without setting the "daylighting window" are studied through the ray tracing simulating and the indoor experiment. The optical efficiency and daylighting efficiency are defined as:

$$\eta_{opt} = \frac{\text{the solar radiation captured by the PV cell}}{\text{total incoming solar radiation}} \quad (1)$$

$$\eta_{daylighting} = \frac{\text{the solar radiation for dayligting}}{\text{total incoming solar radiation}} \quad (2)$$

And the actual optical efficiency of the concentrator can be investigated by:

$$\eta_{opt,ac} = \frac{1}{C}\frac{I_{sc}^{with}}{I_{sc}^{without}} \quad (3)$$

~~Where~~ where I_{sc}^{with} is the short circuit current of the concentrating PV; $I_{sc}^{without}$ is the short circuit of the non-concentrating PV. C is the geometric concentration ratio.

The optical simulation is conducted using the software Lighttools®. The geometric model of the CPV/D module and CPV module are first built in SolidWorks® and then transferred into Lighttools® for the ray tracing simulation. Detailed simulation parameters can be found in (Xuan et al., 2017a). In order to find out the actual optical performance of the CPV/D and CPV module, the prototype of the CPV/D and CPV module are manufactured and assembled as shown in Fig. 2. The material is selected as transparent Polymethyl Methacrylate (PMMA) with the refractive index of 1.49. Polymethyl Methacrylate is widely used for the construction of optical concentrators due to its high transmittance (92% per 10 mm) and good resistance to photo degradation. The evaporated aluminum coating technology was employed to process the mirror reflectors (with the specular reflectivity of around 85%). As illustrated in Fig. 2, is the indoor experiment test rig used to evaluate the electrical characteristics of the CPV/D and CPV module. Detailed description of the experimental test rig and how the tests are conducted can also be found in (Xuan et al., 2017a). The experiments are conducted under the standard test condition (STC, the solar simulator generates a ray intensity of 1000 W m^{-2} with the room temperature of 25 °C).

Fig. 2 The prototype of the CPV/D, CPV module and the indoor experiment test rig.

The simulation and experimental optical efficiency of the CPV/D and CPV module are presented in Fig. 3. From both simulation and experimental results, it can be seen clearly that the optical efficiencies of the CPV/D module at various incidence angles are basically consistent with that of the CPV module. So the concern towards the effect of "daylighting efficiency" can be expelled because the CPV/D module only uses the portion of sun rays that can't be used for the electricity generation for daylighting. Combined with the daylighting efficiency results at various incidence angles (Fig. 4), it can be concluded that setting "daylighting window" has no negative effect on the optical performance of the lens-walled compound parabolic concentrator but add the function of the daylighting to achieve a higher usage ratio of the solar energy which can also better suit with the building energy demands. The deviation of around 10% is observed from the simulation and experimental results, which can be caused by all kinds of errors (Li et al., 2018a).

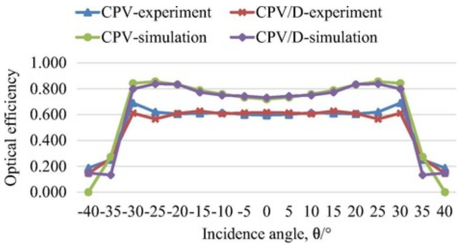


Fig. 3 Experimental and simulation optical efficiency comparison of the CPV/D module and CPV module.

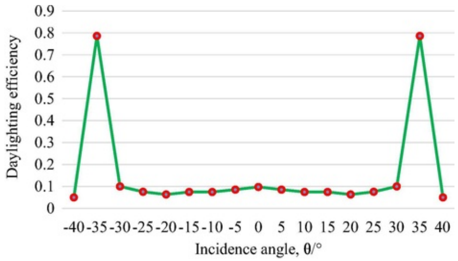


Fig. 4 Daylighting efficiency of the CPV/D module at various incidence angles.

3 Daylighting simulation and the validation of the model

3.1 Simulation method and daylight performance assessment metrics

In this study, a comprehensive daylighting model was built based on RADIANCE, which was developed by Lawrence Berkeley National Laboratory (LBNL), USA. RAIDANCE is a software tool based on a backward ray-tracing algorithm, which means that the rays are emitted from the point of interest and traced backwards until they either hit a light source or another object (Sun et al., 2017).

The annual simulation of a space that adopted the complex fenestration system, such as concentrating photovoltaic/daylighting window, would run into a lot of difficulties, because of the complicated internal multiple inter-reflections that occur within the concentrating photovoltaic/daylighting window. Thus in this paper, rather than simulate a specific daylight condition, the “three-phase method” was used to conduct the annual daylight performance prediction of the CPV/D window in an office. With the use of the “three-phase method”, flux transfer is broken into the following three phases for independent simulation (McNeil, 2010):

1. Sky to exterior of fenestration;
2. Transmission through fenestration;
3. Interior of fenestration into the simulated space.

A matrix is used to characterize each phase of light transport. The input condition, sky luminance, is a vector. The result, illuminance values or a rendering, is also vector. The result is achieved by multiplying the sun vector by each matrix representing each phase of flux transfer. This process is described by the following equation (McNeil, 2010):

$$i = VTDs \tag{4}$$

$$I = VTDS \tag{5}$$

where: i is point in time illuminance or luminance result; I is matrix containing time series of illuminance or luminance result; T is transmission matrix, relating incident window directions to exiting directions; V is view matrix and D is daylight matrix, which can be obtained through an embedded command in RADIANCE considering the model’s orientation, surrounding environment, geometry and surface properties of the indoor space; s is sky vector, assigning luminance values to patches representing sky directions; S is sky matrix, a collection of sky vectors. Sky matrices were obtained from CSTW weather data for different cities with different latitudes and climates. The transmission matrix for the CPV/D window systems was expressed using Bidirectional Scattering Distribution Functions (BSDFs). Detaile processes about how the BSDF files for the CPV/D window are got can be found in references (McNeil, 2010; Sun et al., 2017).

There are several metrics such as Daylighting Factor (DF), Daylight Autonomy (DA), Useful Daylight Illuminance (UDI), and Illuminance Uniformity Ratio (UR), etc. that are used for the dynamic daylight performance assessment (Reinhart et al., 2006). Sun et al. summarized the characteristics of these metrics (Sun et al., 2017). Daylighting Factor was a traditional metric that are mainly based on the rule of thumb with the simplified calculation algorithm, which also seems to be increasingly deemed inadequate for the more and more complex daylight equipment (Sun et al., 2017). Nowadays, Daylighting Autonomy and Useful Daylight Illuminance (UDI) are two commonly used metrics. These more sophisticated metrics are currently available from several free daylighting simulation software, such as RADIANCE (Reinhart and Andersen, 2006) and DAYSIM (Cheng et al., 2018). The metric of Daylight Autonomy was firstly proposed by the Association Suisse des Electriciens in 1989, which indicates the percentage of working hours in a year at a specific sensor point in which a minimum illuminance threshold could be achieved by daylight alone (Reinhart et al., 2006). However, the drawback of this metric is obvious, this metric only consider the minimum illuminance level but fail to consider strong glare effect under the excessive daylighting. In this case, Daylight Autonomy was modified with the metric of UDI (Nabil and Mardaljevic, 2006; Nabil, 2016), which is determined by classifying the simulated hourly illuminance at the sensor points into 3 bins:

(1) an undersupplied bin (illuminance value < 100 lx);

(2) a useful bin (100 lx < illuminance value < 2000 lx);

(3) an oversupplied bin (illuminance value > 2000 lx).

Thus UDI is an allaround dynamic metric that could avoid the potential of glare or too dark (Peng et al., 2015).

3.2 Model validation

The accuracy of the RADIANCE algorithm daylight coefficient method and Perez sky model have been analyzed for more than 10,000 sky conditions including overcast skies, clear skies and partly cloudy skies by Reinhart et al. (Reinhart and Andersen, 2006; Reinhart and Walkenhorst, 2001). The results of theirs proved that the RADIANCE is able to efficiently and accurately predict the annual indoor illuminance distribution of the buildings adopting the complicated daylighting elements based on the building geometry, optical properties of the surfaces and direct and diffuse solar irradiance. In this research, in order to display the annual prediction results for the actual office room with the CPV/D window more confidently and accurately, a CPV/D module integrated with the integrating box (Fig. 5) is manufactured and installed on the Engineering Building 2, University of Science and Technology of China, Hefei, China (31.86°N, 117.27°E). The photometric integrating box is a cubic box with its internal surface painted matt white so that light can be diffusely reflected to the internal sensor, which was proposed by the UK Building Research Establishment. The illuminances for the test rig were measured and compared with illuminances from simulation under the same conditions.

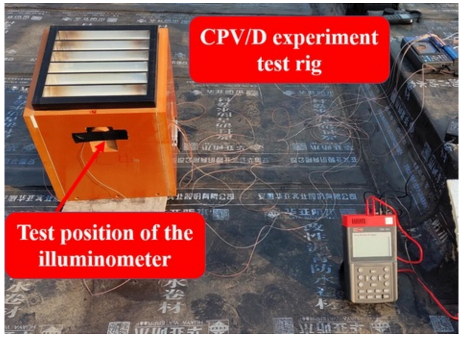


Fig. 5 The outdoor experiment test rig.

The measurements were taken on 10th August 2018 with the clear sky condition. The illuminance on the south wall of the box was measured by the illuminometer TES-1339R (with an accuracy of ±3%). The comparison of the simulation and experimental results was made as shown in Fig. 6. The picture of the experimental box which was taken during the experiment, and a simulated render image from the simulation are shown in Fig. 7. From the results, it can be seen clearly that the simulation results are basically consistent with the simulations despite small deviations. The deviations can be quantified by C_v(RMSE) (coefficient of variation of the root mean squared error) indicates the overall uncertainty in the prediction of simulation (Yun and Kim, 2013). A lower value means the better model accuracy:

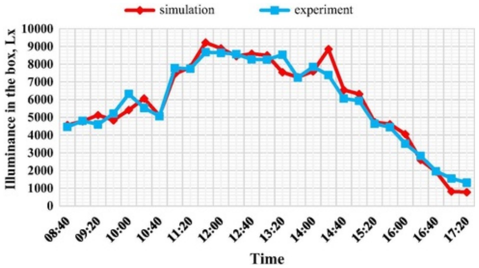


Fig. 6 Validation of the model.

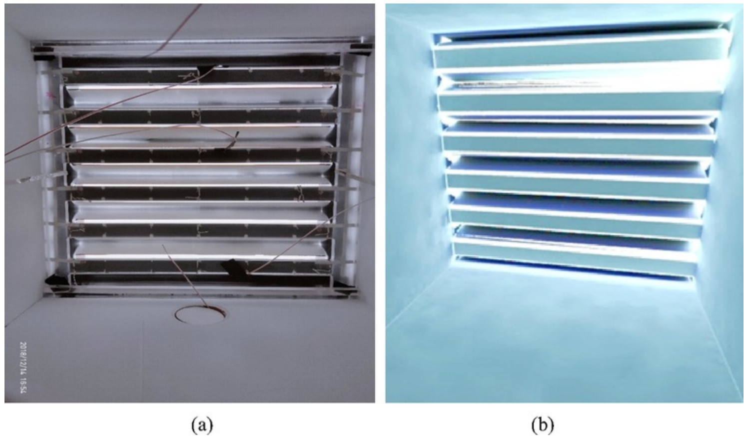


Fig. 7 (a) Photo of the box and (b) Rendered image.

RMSE is calculated by:

$$RMSE = \sqrt{\frac{1}{N}\sum_{1}^{N}(I_{sim,i} - I_{\exp,i})^2} \quad \textbf{(6)}$$

where N is the number of the time intervals, $I_{sim,i}$ and $I_{exp,i}$ are simulated and measured data respectively.

The mean of the measured data is calculated by:

$$A_{\exp} = \frac{\sum_1^N I_{\exp,i}}{N} \quad \textbf{(7)}$$

Then C_V(RMSE) is calculated by:

$$C_V\,(RMSE)\,(\%) = \frac{RMSE}{A_{\exp}} \times 100\% \quad \textbf{(8)}$$

After the calculation of the simulation and experiment results presented in Fig. 6, the value of C_V (RMSE) is 8.7%, which indicate the high level reliability in the use of the RADIANCE to predict the daylighting performance of the office room using the CPV/D window.

3.3 The description of the actual office modeling

After the validation of the CPV/D window in the RADIANCE, the model of the CPV/D window can be used to predict the annual daylighting performance of the actual office room (with the size of 4.0 m × 3.5 m × 3.3 m, Fig. 8(a)) integrated with the CPV/D window. A 12 × 18 analysis grid comprising 216 points are used to estimate the annual illuminance distribution on the working plane (usually 0.75 m above the ground level) as depicted in Fig. 8(b). A CPV/D window with the dimensions of 4.00 m (length) and 3.50 m (width) for the 100% window to ceiling installation ratio is located on the rooftop of the office room in the East - West orientation. The dimensions of the CPV/D windows for the 75% and 50% window to ceiling installation ratio are 3.46 m (length)/3.03 m (width) and 2.83 m (length)/2.47 m (width) respectively. The CPV/D window is tested to have a light transmittance of around 10%. The coordinate system presented in Fig. 8 is used to locate the analysis grid, which will be used in the Figures that illustrate the simulation results. The X-axis and Y-axis represent south wall and west wall respectively. In the simulation, illuminance distribution on the analysis grid is calculated for 1 h time-steps over the course of a year. The predicted luminous environment during working hours were analyzed using the advanced metric, i.e. UDI. The results are given as the proportion of the working hours in an entire year at the location points (Fig. 8(b)) generates a desire illuminance level (100 ~~to~~ –2000 lx). For example, the value of 0.85 at a specific point means that 85% of a year's time at this point can maintain the desire illuminance level of 100 ~~to~~ –2000 lx.

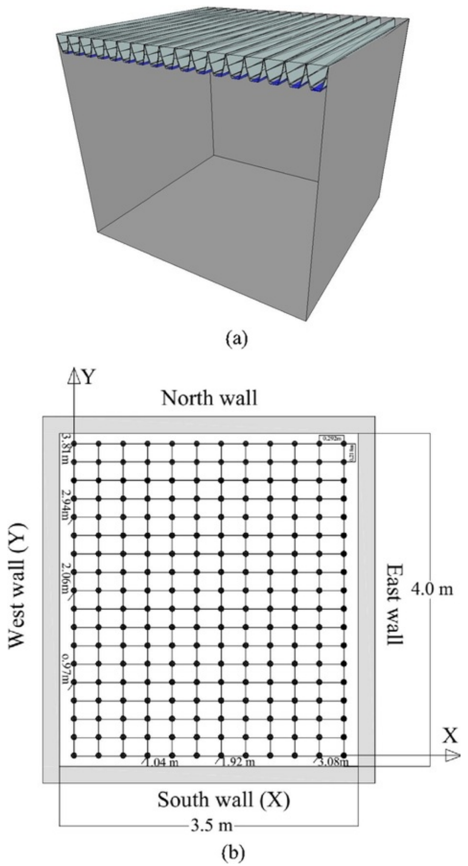


Fig. 8 (a) Simulation model; (b) Selected points for evaluating illuminance distribution on the working plane of the office.

3.4 Locations and weather data

In order to study the performance of the CPV/D window under different geographical and weather conditions, five different cities are chosen: Haikou (20.02°N, 110.20°E), Lhasa (29.39°N, 91.08°E), Hefei (31.86°N, 117.27°E), Beijing (39.90°N, 116.40°E), Harbin (45.44°N, 126.36°E). The weather data files of these cities are gotten from EnergyPlus. The simulations are run at 1-h time step for the entire year with the CSTW weather file.

4 Results and discussions

For the concentrating devices, duo to the restriction of the acceptance range of the concentrator and sun motion, the local latitude and installation angle have a great impact on the annual performance of them (Li et al., 2018c). Thus, in this section, the simulations are conducted for the CPV/D window with different installation angles (i.e. 0°, 10°, 20°, 30°, 40°), and the effect of the CPV/D window to ceiling ratio is also detailed analyzed. For the analysis of effect of these two factors, the office is assumed to be located in Hefei. At last, five different cities in China with the latitudes from low to high are selected to identify the performance of the CPV/D window under different geographical and weather conditions.

4.1 The effect of the inclination angle

As described by Li et al. (2018c) that the CPV/D window is designed to be installed on the building rooftop as an alternative to the skylight, thus it must suit with the building rooftop inclination angle by means of changing the installation angle (inclination angle). The figures presented in Fig. 9 are UDI bins for the office room with the different CPV/D inclination angles and the colorful contour represents the percentage of working hours at the test points generate a desire illuminance level of 100 to 2000 lx. As the inclination angle of the concentrator changes, the actual incidence angles (defined as the angle between the sun ray and the normal of the base of the concentrator) will change as well, which finally leads to change of the daylighting efficiency and optical efficiency. The five cases with 0°, 10°, 20°, 30° and 40° inclination angles will be called as Case0, Case10, Case20, Case30, Case40 in the following interpretation.

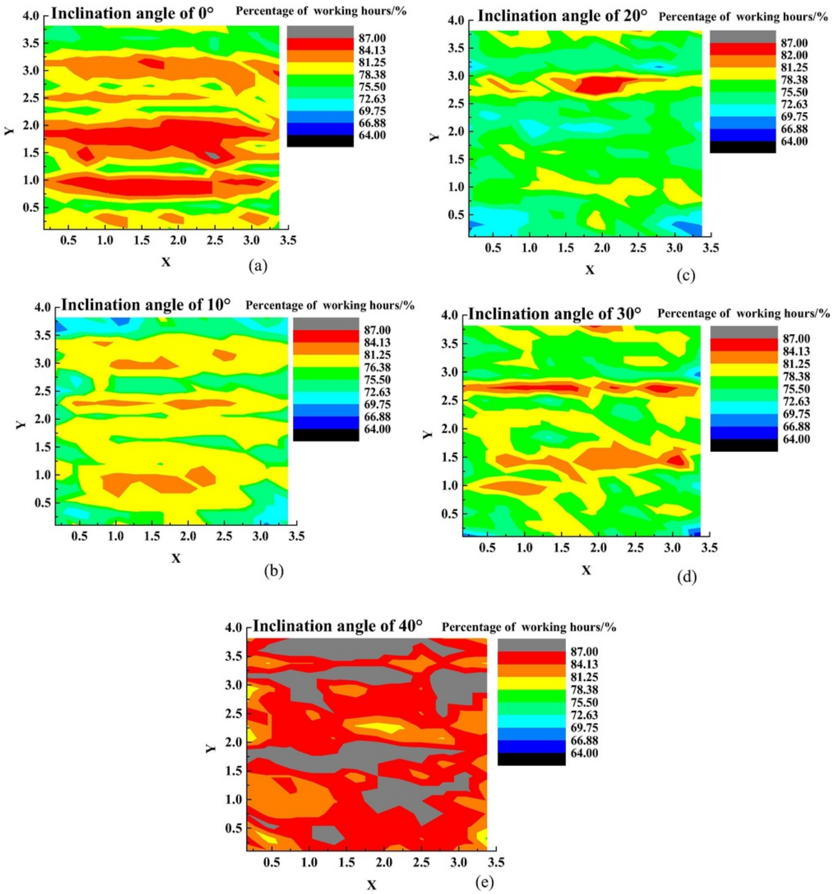


Fig. 9 $UDI_{100-2000}$ bins for the office room with the different CPV/D inclination angles: (a) 0°; (b) 10°; (c) 20°; (d) 30°; (e) 40°.

From the results, the effect of the inclination angle of the CPV/D window on the UDI bin is obvious. For the overall comparison by means of the comparison of the average value from 216 sensor points, the $UDI_{100-2000}$ values from Case40 are highest among five cases, while the results from Case10, Case20, Case30 are almost at the same level, which are 6%-10% lower than that from Case40. It’s no wonder that the solar energy utilization systems including the concentrating device is better to be installed at the inclination angle around the local latitude, which can capture more solar energy annually. The average $UDI_{100-2000}$ values on the 216 points for five cases are 80.52%, 76.98%, 76.00%, 77.99% and 85.57% and the medians of these values are 81.00%, 77.00%, 76.00%, 78.00% and 86.00% respectively. To investigate the non-uniformity factor of the $UDI_{100-2000}$ results for each case, the following equation is used (Xie et al., 2016):

$$U = \frac{UDI_{100-2000}^{\max} - UDI_{100-2000}^{\min}}{UDI_{100-2000}^{\max} + UDI_{100-2000}^{\min}} \times 100\% \quad (9)$$

where $UDI_{100-2000}^{\max}$ and $UDI_{100-2000}^{\min}$ are the maximum and minimum values displayed in Fig. 9. Thus the non-uniformity factors for five cases are 8.46%, 11.26%, 10.53%, 15.23% and 8.24%. The non-uniformity factors of the $UDI_{100-2000}$ results are all not very high across the analysis grid for five cases, which indicate a relatively uniform illumiance illuminance level distribution on the working plane. Therefore, draw from the yearly prediction results, it can be concluded that around 80% of working hours on the working plane of the office room with different CPV/D window installation angles can attain the desire illuminance level, which proves that the CPV/D window can suit with different rooftop slope angles thus provides a wider application scope.

4.2 The effect of the window to ceiling ratio

The contour data of $UDI_{100-2000}$ for the office room on the working plane of 0.75 m with different window to ceiling ratio (WCR) is presented in Fig. 10. The window to ceiling ratios of 50%, 75% and 100% are selected to be studied in this section. As it can be seen from the results that with the increase of the window to ceiling ratios from 50% to 100%, the $UDI_{100-2000}$ values across the analysis grid experience an obvious increase. The average value increases from 69.00% to 80.00%. The maximum values for three cases are close, which all exists in the middle area of the room. However, the minimum values varies a lot, which are 74.00%, 61.00% and 48.00% for WCR-100%, WCR-75% and WCR-50% respectively and these values are all close to the wall area. The main reason for this is that, the CPV/D window are installed at the center area of the rooftop, which shows little effect on the center area of the office room, but will influence the daylighting level near the wall significantly. However, for the actual human daylily life, the use rate of the area near the wall is much lower than that of center area in the same office room, not to mention that the area near the wall is also close to the window on the wall. In this case, it can be concluded that although the decrease of the window to ceiling ratio decrease the $UDI_{100-2000}$ on the analysis grid, the effect on the actual human activity is rather small. It should be noted that the analysis of the effect of the window to ceiling ratio also emphasize the feasibility of installing the CPV/D window on rooftops with different conditions just like the analysis of the effect of the inclination angle, which also provides the basic design reference for the actual engineering.

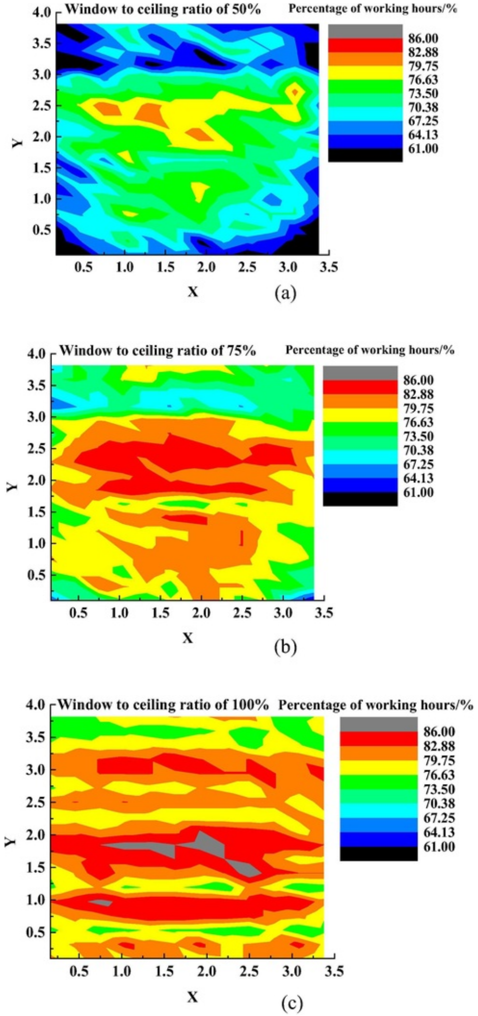
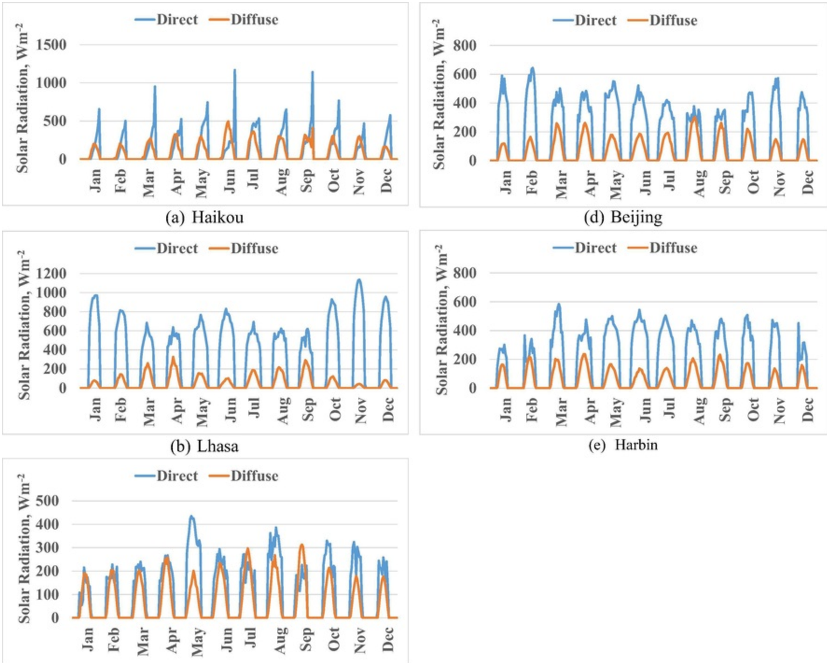


Fig. 10 $UDI_{100–2000}$ bins across the analysis grid for different WCR: (a) 50%; (b) 75%; (c) 100%.

4.3 The application of the CPV/D window in different climates

In this section, the performance of the CPV/D window under different climate conditions in China, i.e. Haikou, Lhasa, Hefei, Beijing and Harbin, which span a latitude range from 20.02° to 45.54° that covers most latitudes of Chinese area. The diurnal average direct and diffuse solar radiation from the CSWD weather files for these five cities are shown in Fig. 11. The characteristics of the weather condition for them can be described as: Haikou has a tropical monsoon climate, and the annual solar radiation is very strong here. Sometimes the diffuse solar radiation is a little larger than the direct solar radiation; Lhasa has a plateau mountain climate, and it has very strong annual direct solar radiation which is much larger than the diffuse solar radiation; Hefei has a subtropical monsoon climate and the annual direct solar radiation is approximately equal to the diffuse solar radiation; Beijing has a temperate monsoon climate and it has very strong direct solar radiation in winter, skies diffuse in summer; Harbin also has a temperate monsoon climate but unlike Beijing, it has stronger direct solar radiation than diffuse solar radiation throughout the year. The CPV/D window is installed in the East-West orientation and for a more comprehensive and reasonable comparison, the CPV/D window for five cities are all installed with no inclination angle. The distribution data of the UDI bins selected to quantify the performance for five cities across the analysis grid are presented in Figs. 12 and 13. The analysis far in this research mainly focused on the metric of $UDI_{100–2000}$ bins, however it is defined by China Standard for daylighting design of buildings (MOHURD, 2013) that the minimum acceptable illuminance level for the office building is 450 lx. Thus, in this section, the desired UDI range of 100–2000 lx is further divided into two

UDI bins: a sub-desired range of 100–450 lx ($UDI_{100–450}$) and a desired range of 450–2000 lx.



(a) Haikou

(d) Beijing

(b) Lhasa

(e) Harbin

(c) Hefei

Fig. 11 The diurnal average direct and diffuse solar radiation from the CSWD weather files for: (a) Haikou; (b) Lhasa; (c) Hefei; (d) Beijing; (e) Harbin.

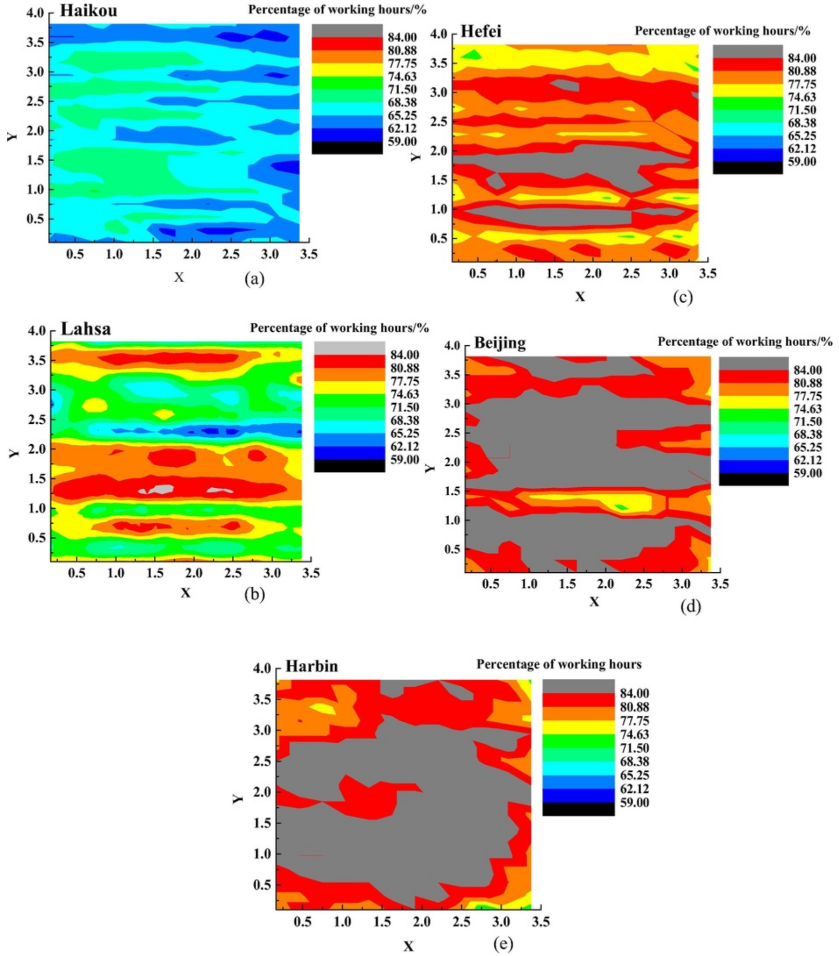


Fig. 12 $UDI_{100–2000}$ bins across the analysis grid for five cities: (a) Haikou; (b) Lhasa; (c) Hefei; (d) Beijing; (e) Harbin.

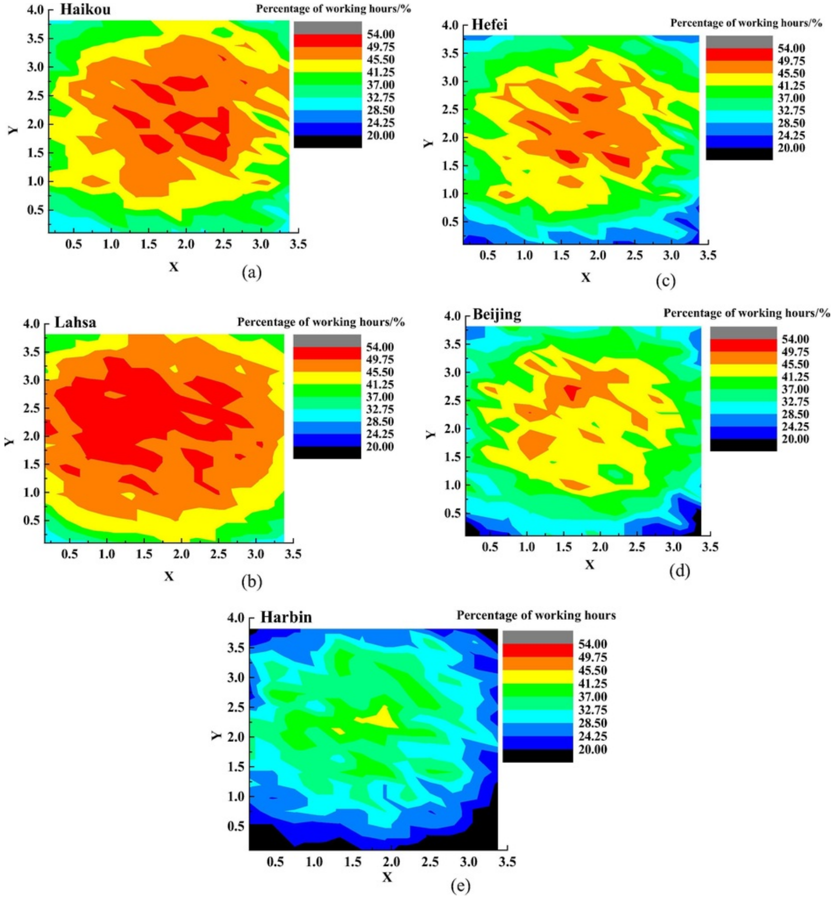


Fig. 13 $UDI_{450–2000}$ bins across the analysis grid for five cities: (a) Haikou; (b) Lhasa; (c) Hefei; (d) Beijing; (e) Harbin.

Fig. 11 shows the $UDI_{100–2000}$ values across the analysis grid for Haikou, Lhasa, Hefei, Beijing and Harbin. From the annual prediction results, it can be seen clearly that despite the difference of the annual solar radiation for five cities, with the increase of the local altitudes, the overall daylighting performance of the CPV/D window also increases. The main reason for this might be: on the one hand, the distribution percentage of the diffuse solar radiation has a great influence on the daylighting performance of the CPV/D window, for that the transmittance of the CPV/D window within the acceptance range of the concentrator for the direct solar radiation is around 10%, but this value for the diffuse solar radiation can be higher. This is why the latitudes of Hefei and Lhasa are almost at the same level, but the annual daylighting performance in Hefei is better than Lhasa, because although the annual direct solar radiation of Lhasa is larger than that of Hefei, the diffuse solar radiation in Hefei is larger. On the other hand, with the increase of the latitude angle, the equivalent incidence angle for the concentrator increases as well and combined with the results shown in Fig. 4, it’s obvious that the larger incidence angles are corresponding with the higher daylighting efficiency especially when the incidence angles are out of the scope of the acceptance range of the concentrator.

The averages values of the $UDI_{100–2000}$ bins for five cities are 66.00%, 75.00%, 81.00%, 84.00% and 84.00% respectively, with the non-uniformity factors of 9.09%, 17.48%, 8.64%, 9.20% and 11.25%. The larger values of $UDI_{100–2000}$ bins are all basically falls in the middle area of the working plane for five cities.

The $UDI_{450–2000}$ values for Haikou, Lhasa, Hefei, Beijing and Harbin across the analysis grid are shown in Fig. 13. Different from results of $UDI_{100–2000}$, the values of $UDI_{450–2000}$ from Lhasa and Haikou are highest among five cities (the average values are 46.00% and 43.00%) while those from Harbin are lowest, and $UDI_{450–2000}$ values from Hefei and Beijing are almost at the same level. This means that, although the results of $UDI_{100–2000}$ from Haikou and Lhasa are lowest, the illuminance level of them is relatively higher than that of other cities. Harbin has the highest $UDI_{100–2000}$ values on the working plane, but in the most time of the year, the illuminance level is within the range of 100–450 lx. From the $UDI_{450–2000}$ bins results for five cities, it can be seen clearly that the larger values across the analysis grid tend to be close to the center area more obviously, so the CPV/D window has an advantage of redirecting the sun rays to the center area of the office room, which make the natural daylighting more efficient.

5 Conclusions

This research displays a novel concentrating photovoltaic/daylighting window with the optimization lens-walled CPC. The annual daylight performance of a cellular office room installed with different concentrating photovoltaic/daylighting windows is modelled with the actual weather data from EnergyPlus for a range of different sites and window installation angles using RADIANCE. The following conclusions can be drawn:

(1) The indoor experiment and ray tracing simulation are both conducted to identify the effect of the “daylighting window” on the optical performance of the concentrator. From simulation and experimental results, it can be seen clearly that the optical efficiencies of the CPV/D module at various incidence angles are basically consistent with that of the CPV module, which can be concluded that setting “daylighting window” has no negative effect on the optical performance of the concentrator but add the function of the daylighting to achieve a higher usage ratio of the solar energy which can also better suit with the building energy demands.

(2) The daylighting simulation model for the concentrating photovoltaic/daylighting window integrated with the typical office room is validated through the outdoor experiment, and the deviation between the experimental and simulation results is as low as 8.7%, which is indicated with the coefficient of variation of the root mean squared error. Thus the accuracy and confidence of the simulation model is proved.

(3) The concentrating photovoltaic/daylighting window offers a good annual daylight performance in term of Useful Daylight Illuminance (UDI). The percentage of working hours when the UDI lies in the range of 100–2000 lx is between 60.00% and 89.00% for different geographical sites and weather conditions. This value can be up to 92.00% with the change of installation angles.

(4) The installation angles has the effect on the annual daylight performance of the concentrating photovoltaic/daylighting window, but this effect is not so obvious, which indicates that the concentrating photovoltaic/daylighting window can suits with different building designs.

(5) The application of the concentrating photovoltaic/daylighting windows at different latitudes suggest that with the increase of the latitude, the percentage of working hours when the UDI lies in the range of 100–2000 lx across the working plane decreases despite the difference of the yearly solar radiation. And it’s found that the diffuse solar radiation has an more obvious effect on the daylight performance of the concentrating photovoltaic/daylighting window: the latitudes of Hefei and Lhasa are close and the annual solar radiation in Lhasa is stronger than that in Hefei, but the concentrating photovoltaic/daylighting window shows a better daylight performance in Hefei rather than in Lhasa. The main reason for this is that the diffuse solar radiation in Hefei is larger than that in Lhasa and transmittance of the diffuse solar radiation is much larger than that of the direct solar radiation.

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Highlights

- The design of a novel CPV/D window based on the lens-walled CPC.
- The comparison of the optical performance was made for the CPV/D and CPV module experimentally.
- The daylighting simulation model in RADIANCE was experimentally validated.
- The daylight performance of the CPV/D window was investigated.

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