Effect of dividing daylight in symmetric prismatic daylight collector

Shih-Chuan Yeh¹*, Ju-Lin Lu², and Yu-Chin Cheng¹

¹ De Lin Institute of Technology, Taiwan
² Taipei Municipal Wenhua Elementary School, Taiwan

*E-mail: yehshch@gmail.com

Abstract. This paper presented a symmetric prismatic daylight collector to collect daylight for the natural light illumination system. We analyzed the characteristics of the emerging light when the parallel light beam illuminate on the horizontally placed symmetric prismatic daylight collector. The ratio of the relative intensities of collected daylight that emerging from each surface of the daylight collector shown that the ratio is varied with the incident angle during a day. The simulation of the emerging light of the daylight collector shown that the ratio of emerging light is varied with the tilted angle when sunshine illuminated on a symmetric prismatic daylight collector which was not placed horizontally. The integration of normalized intensity is also varied with the tilted angle. The symmetric prismatic daylight collector with the benefits of reducing glare and dividing intensity of incident daylight, it is applicable to using in the natural light illumination system and hybrid system for improving the efficiency of utilizing of solar energy.

1. Introduction

Energy saving and using renewable energy are the most important issues of reducing energy consumption and slow down the pace of global warming. The Energy Performance of Building Directive highlights that the importance of reducing the emerging consumption in building [1]. And the energy consumption by artificial lighting system is a major portion of the total energy consumption in a building, it could account for 30% of the total electrical energy consumption in commercial buildings [2]. Utilization of efficient artificial lighting, such as LED, can reduce the electrical energy consumption [3-5]. An excellent design of interior natural light illumination would contribute to a lower consumption of electrical energy [6].

Solar energy is one of the renewable energies that now providing the lowest cost options for economic and community development in rural regions around the globe. Utilization of solar energy, in addition to the use of solar cell by photovoltaic effect, and solar thermal application, indoor daylight illumination is also an important access to solar energy. Due to the difficulty towards the full implementation of renewable energy, energy saving is crucial for global development. The windows of a building allow the penetration of daylight into a room for illumination; meanwhile, the energy consumption of artificial lighting is reduced. However, the daylight glare probably cause uncomfortable illumination. Kostantzos et al. study daylighting glare probability by simulation and experiment with an HDR camera in office space with dynamic window shades [7]. The perceived level of visual discomfort may vary with time of day, Altomonte et al. study the relationships between visual task difficulty and glare response [8]. The possibility of visual discomfort is likely to arise due
to the uncontrolled daylighting. Fasi et al. investigated the energy and visual; performance for different types of glazed windows, which including the impact of glare index and daylighting factor [9]. Hee et al. studied the role of window glazing on daylight illumination and energy saving [10]. Huang et al. analyzed the thermal and daylighting performance of glazing and shading design on office building, the results of simulation shown that the performance of windows design on the south orientation getting better as the latitude risen [11]. A natural light illumination system which is compounded by a daylight collector, guiding part and indoor natural light emission part. This system bring daylight into a building as a lighting source not only with the benefits of energy saving and reduced the glare, but also lead to a comfortable working environment and it has the potential to improve human health, mood, performance and productivity [12-16]. The energy conversion efficiency of commercially photovoltaics is about less than 20% at present. The natural light illumination system directly use daylight for indoor illumination which without the loss of conversion in different forms of energy. The possibility of controlling direct daylight by optical designed systems for comfort illumination or energy conservation has been reported by many authors in the past. Daylight is varied with time of day, climate, latitude and the orientation of buildings. One of the challenges of natural light illumination is the difficulty in getting a uniform illuminated condition during a day. For the purpose of getting visual comfort and energy saving, the concept of daylight linked controls which combined with the sensors is also presented [17]. Borisuit et al. proposed a camera like light sensor to monitor luminance and circadian weighted radiance and simulated the potential impact light on non-visual functions on daylight optimization in buildings [18]. Boscario et al. developed a simulation environment and daylighting control strategy for energy efficient lighting while providing desired lighting level for LED-based [19]. High energy performance building concepts have proposed, combines energy saving and energy recovery from local renewable resources [20], the natural light illumination system can provide part building energy demand. The hybrid systems of natural light illumination coupled with artificial light source or solar cells are also developed for advanced illuminated condition and energy consumption [21-23].

The detailed analysis of transmitted light of daylight collector can improve the performance of natural light illumination systems and aid in the design of hybrid natural light illumination systems. Mohelnikova calculated the light rays transported inside a straight, tubular light guide and their distribution at the output of the light guide. Wittkopf et al. analyzed the luminous intensity distribution curves of anidolic daylighting systems based on the ray tracing model [24, 25]. Prismatic elements, which with the characteristics of re-directing the propagate direction and the potential of dividing the energy of incident light, can be part of a daylight illuminate system located on the roof or facade of buildings and can be used as collectors to collect and guide daylight to reduce glare and save energy. The characteristics of the light emerging from a passive prismatic canopy, which is composed of right-angled prisms have been presented for daylight incident on it at different incident angles over the course of a day based on a mathematical matrix model [26, 27]. It has been shown that these methodologies, which are based on redirecting daylight, can save energy and produce natural light illumination when they are used as daylight guiding systems. The structure of symmetric prisms with the benefits of simple manufacture and dividing intensity of transmitted light more effectively. This paper present a natural light illumination system that is composed of a symmetric prismatic canopy as well as daylight collector, a reflector for re-directing daylight into the room and an indoor reflector as illustrated in figure 1. We analyzed the characteristics of dividing intensity and direction of transmitted light based on the optical theories.

2. Methodology

The symmetric prismatic daylight collectors are made of PMMA, which with refractive index 1.4906. Fig. 2 is the photography of a symmetric prismatic daylight collector with a 60° apex. An illustration of the symmetric prismatic daylight collector is shown in Fig. 3. The characteristics of transmitted light when sunshine illuminating onto the symmetric prismatic daylight collector are analyzed in both of geometric optical calculation and optical package program.
The intensity and propagate direction of transmitted light is calculated based on optical theory when parallel light incident onto the upper surface of the symmetric prismatic daylight collector. The ratio of the area which corresponding to the transmitted light would intersect to the surface left, SL and which would intersect to the surface right, SR of the prismatic daylight collector are obtained by Eq. (1) to Eq. (3), the parameter \( w \) is the width of the prismatic unit, \( h \) is the height of the prismatic unit, \( \phi_2 \) is the propagate direction of ST, \( \phi_{NT} \) is the normal incident direction of ST, and LSL and LSR are the relative areas that the transmitted light would intersect to SL and SR, respectively. The ray trace is obtained by the law of reflection and Snell’s law, and the transmitted intensity is determined by Fresnel’s equations.

\[
\frac{L_{SL}}{L_{SR}} = \frac{W - L_{\delta}}{W + L_{\delta}}, \\
L_{\delta} = h \cdot \tan \delta \\
\delta = \phi_2 - \phi_{NT}
\]

Where, 
\[
W = \frac{L_{d}}{2}
\]

Figure 1. An illustration of a room with a natural light illumination system.

Figure 2. The photography of a symmetric prismatic daylight collector with a 60° apex.

Figure 3. An illustration of the symmetric prismatic daylight collector.

Figure 4. The simulated result of the parallel light incident to a symmetric prismatic daylight collector.

Figure 5. The illustration of the definition of direction of ray.
3. Results
In this paper, we simulated the parallel light incident a symmetric prismatic structure at different angle. Fig. 4 is the simulated result of the parallel light incident to the surface of the symmetric prismatic daylight collector, which with a 60° apex at 30° incident angle. It illustrated the property of dividing intensity of transmitted light when the parallel light incident to the surface of the symmetric prismatic daylight collector. Fig. 5 is the illustration of the definition of direction of ray.

The transmitted light of the top surface, ST of the symmetric prismatic daylight collector would be incident to the left surface, SL and right surface, SR of the bottom of the prismatic unit when light illuminated onto the top surface of the symmetric prismatic daylight collector, and the ratio of LSL and LSR is varied with the incident angles. Due to the distribution of emerging light would impact to the design of natural light illumination system, we calculated the transmittance and direction of emerging light that from SR and SL when parallel light incident to the prismatic unit at different direction for improving design the natural light illumination system more efficiently. Surface Right 1, SR1 and Surface Right 2, SR2 which corresponding to the light emerging out from SR, the ray trace of SR1 means the transmitted light from ST and then emerged out from SR; the ray trace of SR2 means the transmitted light from ST and then intersect to SL, and emerging out from SR by the totally internal reflective at SL. Surface Left 1, SL1 and Surface Left 2, SL2 which corresponding to the light emerging out from SL, the ray trace of SL1 is transmitted light from ST and then emerged out from SL; the ray trace of SL2 is transmitted light from ST and then intersect to SR, and emerging out from SL by the totally internal reflective at SR. Fig. 6 is the calculated results of the transmittance and direction of the light which is emerging from SR1 and SL2 by the transmitted light intersect to SR when a parallel light beam incident onto the ST of a horizontally placed symmetric prismatic daylight collector with a 60° apex. The upper part of this figure shown that the main emerging light is transmitted from SR when sunshine illuminated the symmetric prismatic daylight collector at the region of $295^\circ < \phi_1 < 360^\circ$, which is corresponding to the time interval during afternoon. Due to the direction of main emerging light is smaller than the direction of light which parallel to the surface SR, it can illuminate to space directly, which $\phi_{SR}$ equals to $330^\circ$ for a horizontally placed symmetric prismatic unit with a 60° apex. And the other part of this figure shown that the transmitted light from SR by totally internal reflected on SR where inside the prism at the region of $\phi_1 > 295^\circ$. However, the direction of emerging light is smaller than $\phi_{SL}$, which light would re-incident to SL. Fig. 7 is the calculated results of the transmittance and direction of emerging light that the transmitted light intersect to SL. This figure shown that the main emerging light is transmitted from directly transmitted from SL when sunshine illuminated the symmetric prismatic daylight collector at $\phi_1 < 242^\circ$.  

![Figure 6. The transmittance and direction of emerging light that the transmitted light intersect to SR.](image-url)
Figure 7. The transmittance and direction of emerging light that the transmitted light intersect to SL.

Fig. 8 is the combination of the emerging light which from SR and SL when the parallel light beam incident to the symmetric prismatic daylight collector. It shown that the transmittance of the emerging light which from SR and SL is varied with the direction of incident light beam, and the intensity is symmetric to $\phi_1=270^\circ$. The result shown that the natural light illumination system would be improving the efficiency of utilizing solar energy by use the symmetric prismatic daylight collector, due to the structure with the potential of dividing emerging light.

Figure 8. The combination of the emerging light which from SR and SL.

The direction and intensity of daylight beam that incident to the collector is varying with time when sunshine illuminate the collector. A daylight collector that is placed at an applicable tilted angle not only can reduce the glare, but also can increase the efficiency of utilizing of solar energy. Fig. 9 and Fig. 10 are the simulated results of the normalized intensity of emerging light when sunshine illuminate on the symmetric prismatic daylight collector which with the tilted angle $15^\circ$ and $30^\circ$, respectively.
It shown that the ratio of the normalized intensities which from SR and SL are varied with the tilted angle, due to the relative incident angle of incident daylight beam is varied with the tilted angle of the collector. Fig.11 is the calculated result of integrated intensity at the region $270^\circ < \phi_1 < 360^\circ$, which is refer to afternoon of a day. It shown that the integration of normalized intensity of emerging light from SL is increasing with increasing tilted angle of the symmetric prismatic daylight collector, and the integration of normalized intensity of emerging light from SR is not obviously vary with the tilted angle of the symmetric prismatic daylight collector, which is at a value of 2.2–2.4.

Figure 9. The simulated result of the normalized intensity when sunshine illuminated on the symmetric prismatic daylight collector which with the tilted angle 15°.

Figure 10. The simulated result of the normalized intensity when sunshine illuminated on the symmetric prismatic daylight collector which with the tilted angle 30°.

Figure 11. The calculated result of integrated intensity during afternoon.

4. Conclusion
In this paper, we detailed analyzed the characteristics of emerging light when parallel light beam illuminate on the symmetric prismatic daylight collector. The simulation of the parallel light beam incident to a horizontally placed symmetric prismatic daylight collector with a 60° apex shown this structure of daylight collector, symmetric prismatic unit can improve the efficacy of dividing intensity of a hybrid natural light illumination system, due to the ratio of main emerging light which from the SR and SL is varied with the incident angle of the incident beam. The calculated results shown that the transmittance of the emerging light which from SR and SL is varied with the direction of incident light beam, and the intensity is symmetric to $\phi_1 = 270^\circ$. The normalized intensity of emerging light shown that the ratio of the integration of normalized intensity of emerging light from SR and SL is varied with tilted angle of the collector when sunshine illuminate on the symmetric prismatic daylight collector which is placed at a tilted angle. A daylight collector that is placed at an applicable tilted
angle not only can reduce the glare, but also can increase the efficiency of utilizing of solar energy. The symmetric prismatic daylight collector can improve the efficiently utilizes solar energy for indoor natural light illumination, decrease the discomfort of glare and the application of hybrid natural light illumination system due to the benefits of reducing glare and dividing intesity of incident daylight.

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