Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 57 (2014) 1951 – 1960
Energy Procedia

2013 ISES Solar World Congress

Core Sunlighting System, A New Approach to Daylighting in Buildings

Sepideh Khosravi*, Michele A. Mossman, Lorne A. Whitehead

University of British Columbia, Vancouver,V6T1Z1, Canada

Abstract

The building industry recognizes the importance of incorporating daylighting into the illumination of buildings to improve energy performance and lighting quality. There are several well-known methods that building designers use to increase the daylighting level in buildings, including windows and skylights. However, these methods are usually not capable of illuminating the core of the building, and may increase the energy usage of the building due to reduced insulation. There are other systems designed for illuminating the core of buildings with daylighting, but all have some limitations that have impeded widespread adoption.

An alternate daylighting system described here offers a novel approach to illuminating the core of buildings. This system consists of active and passive optical components that capture sunlight outside multi-floor buildings and transfer it to the dark core. Active sunlight redirectors, mounted at roof level on the edge of the building, track the sun throughout the day and redirect the sunlight towards building façades at a certain angle. Passive concentrator elements mounted on the façades of the building capture and concentrate the light and direct it into light guides. The sunlight is then distributed within the building via interior light guides to efficiently illuminate the building.

Selection and/or peer-review under responsibility of ISES.

Key words: Core sunlighting system; daylighting

1. Introduction

One of the challenges for building designers and lighting engineers is to illuminate the interior of buildings in a manner that uses less energy, while also achieving high color quality and lighting uniformity. To achieve this, designers often incorporate daylighting strategies, such as windows, atria, skylights [1], and solar lighting systems [2, 3, 4, 5]. Windows are the most common and conventional method to bring daylight into a building, but they can only provide natural lighting for the perimeter spaces in the building, and the core of the building often still requires electric lighting. To increase the penetration depth of light, architects sometimes design buildings with narrow floor plates, high ceilings, and high glazing ratios [6]. However, these methods are not always applicable or economically justifiable. In some cases, daylighting may result in increased electrical energy use for cooling and heating [7], because of the solar heat gain and lack of adequate insulation provided by the glazing area [8, 9]. Moreover, increasing the glazing area could lead to an uncomfortable glare and require expensive shading systems, which also reduce daylight penetration [6]. The core sunlighting system introduced in this paper offers a novel approach to daylighting that has overcome many of these limitations.

* Corresponding author. Tel.: +1-604-822-1954.
E-mail address: sepideh@phas.ubc.ca

Selection and/or peer-review under responsibility of ISES.
doi:10.1016/j.egypro.2014.10.059

2. Core sunlighting system

Core sunlighting systems provide an alternative method for illuminating the building core. In contrast to a building with large glazing area, where daylight can only illuminate the perimeter of the building, a core sunlighting system is capable of capturing the light at the perimeter or roof of the building and transferring it to the core. There are a number of different types of core sunlighting systems, such as those using façade and roof-mounted collectors [10, 11, 12].

One existing design of a core sunlighting system, abbreviated here as the “CSLS”, consists of two main components: a sunlight collector that tracks the sun with a motorized component and redirects and concentrates the sunlight to the desired location, and light guides that distribute the light throughout the building [12]. The collectors are installed above the windows on each floor on the façade where sunlight exposure is greatest. This façade-mounted system has shown that it is capable of offsetting a portion of the electricity used for illumination, but it has some limitations, which are overcome in the alternate design described here.

2.1. Limitations of the façade mounted system

Mounting the light collector on the façade of the building imposes some limitations. In this system, light is only captured on the most sun-facing façade (i.e. the South façade in the Northern hemisphere). This limits the operation of the system to the time that the sun is shining on that façade. Further, because the light guides are fed from one side of the building only, it is difficult to get natural daylight to the opposite side of a large building. This makes the system more applicable to buildings whose largest facades run East-West. Furthermore, the intensity of light hitting the façade and the light collectors changes with the solar azimuth angle which can further decrease the amount of captured light. In addition, in denser areas, shadowing from neighbouring buildings can further decrease the efficiency of the system if the sunshine does not reach the entire facade.

Additionally, the design of the redirector component in this CSLS had some problematic inefficiencies. The redirector unit consists of vertical arrays of mirrors that are reoriented in unison using two motors to track the sun and steer sunlight toward the redirecting mirror. These mirrors then concentrate light efficiently so that light can enter the interior light guide. This system works efficiently for some sun positions but when the solar altitude angle is high, the top mirrors shade the bottom ones. This reduces the intensity of captured light thus reducing the efficiency. This especially affects the performance of the system in low latitude locations during late spring and early summer days when the sun is very high during the central portion of the day.

2.2. New approach to the core sunlighting system

In our new approach to the CSLS we made key changes in the design of the system in order to improve the overall performance. First, sunlight redirectors are mounted at the roof level all around the building. They redirect sunlight at a predetermined angle to the exterior façades of the building, or the walls of an interior atrium, such that the whole façade is bathed by sunlight distributed uniformly between multiple floors, as shown in Figure 1. The concentrator components mounted on the façade of the building capture a portion of the sunlight at each floor, concentrate it and then recollimate it. The concentrator has two main components: a lens assembly which is installed outside the building beneath the window of the floor above, and an enclosure containing a separate lens and mirror assembly that protrudes only 15 cm from the façade. The enclosure can be installed either inside or outside of the building, between the windows of adjacent floors. The impact on the building appearance is therefore minimal.

In this design, light is captured from all sides of the building, and all facades are equally bathed with sunshine. Thus, it is easier to transport light to all regions of the building and to have a more uniform light distribution across the building plate, even for large buildings. Since the building geometry and orientation have less influence on the distribution and uniformity of light, this core sunlighting system can be applied to a wider variety of buildings.

The light collector component has been redesigned for this CSLS model. The vertical array of mirrors was replaced by a new rotating redirector unit that can operate in two different modes based on the solar elevation, in order to achieve higher efficiency at high solar altitudes. Since the redirectors are mounted at roof level, the amount of light that they can capture will not be significantly affected by the azimuthal movement of sun. In the following sections, all components will be described in detail.

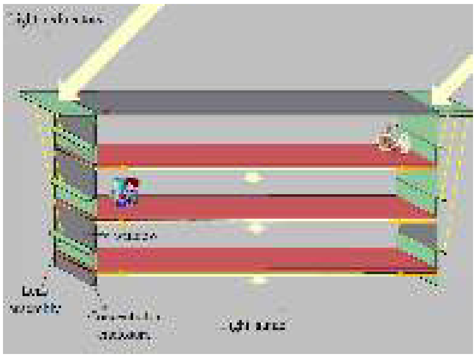


Fig. 1. Core sunlighting system from the side view, capturing light at roof level from both sides of the building

3. System Design

3.1. Rotating redirector component

In order to achieve relatively constant efficiency throughout the day, we use a rotating assembly in the redirector canopy. This assembly consists of parallel sets of reflective slats confined inside a ring, Figure 2. The whole assembly is mounted on the roof oriented horizontally such that it protrudes from the edge, as shown in Figure 1. The specific design of the redirector allows two independent rotations; one rotation about the assembly axis that follows the solar azimuth angle, and the other about the individual slat axes that follows the altitude angle. For each sun position, the slats can be rotated in unison about these axes such that incident sunlight will be redirected at the desired angle. The ability to rotate the entire assembly of mirrors, rather than only individual slats, makes it possible to get almost constant intensity of the redirected sunlight for any solar azimuth angle.

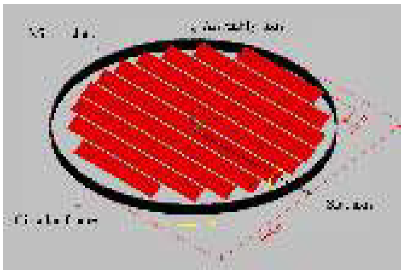
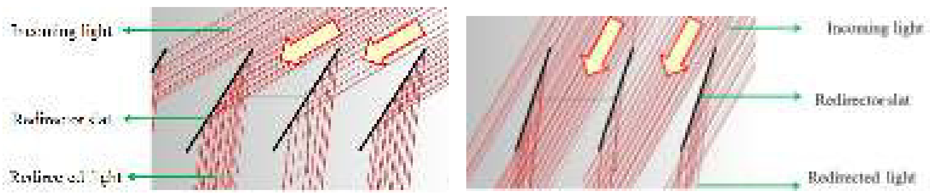


Fig. 2. Rotating redirector assembly

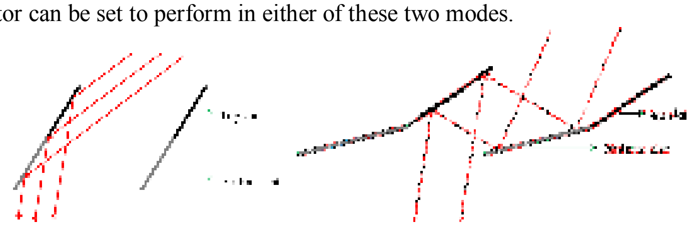
The parallel slats can also move in a similar fashion to the slats in a Venetian window blind. The reflective slats can be positioned using two inexpensive actuators, to a pre-determined orientation depending on the solar position, such that they reflect light to the desired angle. For some sun positions, this results in efficient redirection of most incoming rays, as shown by the ray diagram in Figure 3(a). However, for high solar altitudes, a large portion of the light passes between the slats rather than interacting with them, as shown in Figure 3(b). As a result, the intensity of captured light is reduced.



(a) (b)

Fig. 3. Rotating redirector slats from the side view (a) at low solar altitude; (b) at high solar altitude

To overcome this limitation, each slat set in the new design consists of two slats that can be independently positioned to optimize the amount of redirected light. At low solar altitudes, the redirectors will perform in single reflection mode, in which the two slats are co-planar, depicted in Figure 4(a). At high solar altitudes, the slats are repositioned at specific angles such that the sunlight undergoes double reflection and redirects light to the desired angle, depicted in Figure 4(b). This allows more light to be captured at higher solar altitudes. Depending on the solar altitude angle, the redirector can be set to perform in either of these two modes.



(a) (b)

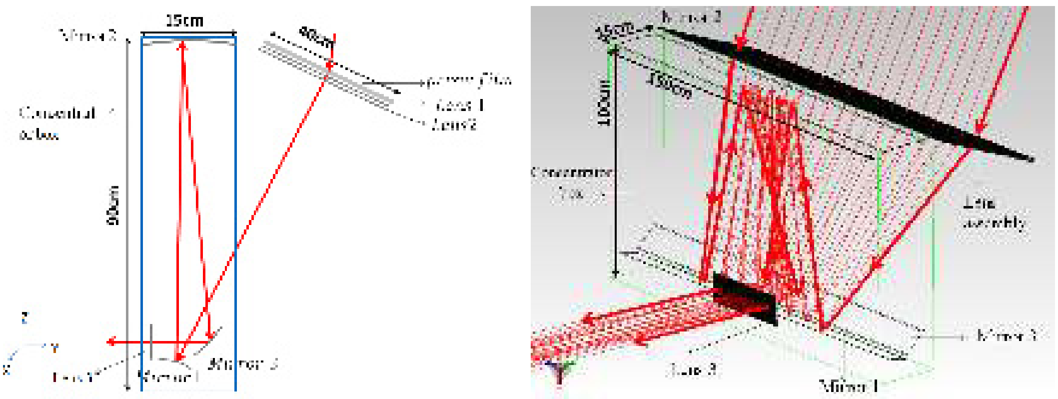
Fig. 4. Bi-valve rotating redirector assembly side view (a) Single reflection mode at low solar altitude; (b) Double reflection mode at high solar altitude

3.2. Concentrator unit

The concentrator unit mounted on the façade of the building concentrates light in both x and y directions, then recollimates it before it reaches the light guide. Each concentrator unit is 1.5m long (in the x direction) and 0.4m wide (in the y direction). Since the concentrator feeds one light guide that has a 30cm by 7cm cross section, this means the concentrator unit must enable a concentration factor of 5, where the concentrator factor is the ratio of the input aperture size to the output aperture size, to be within our design goal of +/-2.5°. Since sunlight has an approximate intrinsic divergence of +/- 0.25° (or half-angle), the output light will have a minimum half-angle of $C \times 0.25°$ [13], where C is the concentration factor. In principal, this system can achieve a half-angle of 1.25°. However, there are other factors that will increase the divergence, such as aberration caused by the lenses and mirrors. Using a lens with lower *f*-number, where *f*-number is the ratio of the focal distance to the lens aperture, increases this aberration. To maintain highly collimated light, it is important to use a lens with a reasonably high *f*-number and concentrate the light more slowly over a longer distance. The unique optical design is such that it allows the light to be concentrated over a long path distance as it travels vertically along a folded optical path inside the enclosure. This allows the half-angle of the concentrated light to be within our design goal of +/- 2.5°.

The concentrators interact with the sunlight to redirect it toward the building façade at a glancing angle, for example 7° . In order for the sunlight to strike Mirror 1 inside the enclosure, shown in Figure 5(a), the light must be further redirected to a steeper angle, for example 25° in this design. A customized prism film placed above the Fresnel lenses 1 and 2, changes the angle of incoming light to the desired angle. The Fresnel lenses and the prism film are installed inside the lens assembly, and the entire structure is positioned at 25° from the horizontal direction, so that the light passing through the prism film is perpendicular to the lenses. To minimize the system's visual impact on the buildings appearance, it is desirable to make the enclosure thin in the y direction, whereas in the x direction, the enclosure can be as wide as the Fresnel lens. This allows the use of two linear Fresnel lenses with different powers in x and y directions rather than a circular lens. The main advantage of linear Fresnel lenses is that light is concentrated in line rather than at a point. In this design, the power of each lens is different, thus the concentration does not happen at the same location. This also avoids generating a region of intensely focused sunlight, which can be a safety concern.

Lens 1, which is a linear Fresnel lens in the x direction with an *f*-number of 1.6, concentrates light slowly in the x direction, Figure 5(b). The light then hits Mirror 1 and travels upward inside the enclosure to shine on Mirror 2. It then travels downward and will be concentrated before hitting Mirror 3. These mirrors are flat in the x direction and are used to increase the distance that light can travel within the enclosure. This allows light to be slowly concentrated over the total path length. The concentrated light then hits Mirror 3, and is redirected towards Lens 3. Lens 3 is a linear Fresnel lens which collimates the concentrated light in the x direction.



(a) (b)

Fig. 5. Concentrator unit, (a) side view, (b) isometric view

As previously mentioned, the enclosure needs to be thin in the y direction. Thus a higher optical power lens must be used in this direction to narrow the beam enough so that all the light strikes Mirror 1. A linear lens with an *f*-number of 2.6 was used in x direction to concentrate light. To slow down the concentration, such that light can travel the same distance as in y direction while maintaining the desired special and angular characteristics, a convex mirror in the y direction, Mirror 1, was used, Figure 5(a). Light will then hit Mirror 2, which is a concave mirror in the y direction. This mirror causes the light to be focused at the focal point of Mirror 3 which is another concave mirror. Mirror 3 then collimates light in y direction and redirects it to the proper angle to be fed to the light guide. Since Lens 3 is a linear lens in the x direction, it will not affect the optical pathway of light in the y direction. The combination of all these components allows us to concentrate light in both directions independently and maintain the collimated light to within a half-angle of 2.5°.

3.3. Light guide

After the light has been redirected and concentrated, it is fed into the light guides, distributed uniformly throughout the building, and delivered to the working area using overhead luminaires. In this case, the light guide is a hollow rectangular pipe used for transferring light. The side walls and top of the inner surface of the guide are covered with highly specular reflective material, and the bottom light transmitting surface is made out of prismatic micro-structured optical film which has dual functionality. If the angular deviation of incident light from the axial direction of the guide is less than a critical angle, where this critical angle depends on the refractive index of prismatic film, the light undergoes total internal reflection and will be reflected such that it continues to propagate along the guide. Otherwise, it is transmitted through the prismatic film and exits the pipe [12]. In order to transport light along the guide, the incident angle of most of the rays needs to be smaller than the critical angle so that they are within the acceptable range of the prismatic film. For polycarbonate prismatic film, the critical angle is 28°, which is much greater than our solar input half-angle. All materials used in the light guide are commercially available.

Although the material used in the light guide is highly efficient, each time light hits the reflective walls or prismatic optical film, there is a small amount of absorption. It is therefore desirable to minimize the number of wall reflections as the light travels down the guide. For any given length of light guide, this can be achieved either by using a guide with a larger cross section, or using more highly collimated light. In this case, since the output of the concentrator component is highly collimated, we were able to use a relatively thin guide (7cm measured vertically), and transfer light much further down the guide at the same time. The feasible penetration depth of the guide is thus increased to 15 meters in this design.

To be able to extract light uniformly along the guide, an escape mechanism was introduced to the system. This is achieved via an extractor sheet that is installed inside the guide [14]. The extractor is a light diffuser material that scatters light rays to random angles, usually outside the acceptable range of the light guide. The light rays that hit the diffuser, have a high probability of escaping the light guide. To get uniform output from the light guide, the size of the extractor must increase further down the guide, since the intensity of light drops gradually as more light is extracted. The light guides are integrated with dimmable electric lamps inside which are programmed to supplement daylighting if needed, in order to maintain the desired level of illumination [12].

4. Performance modelling and efficiency calculation

4.1. Redirector component

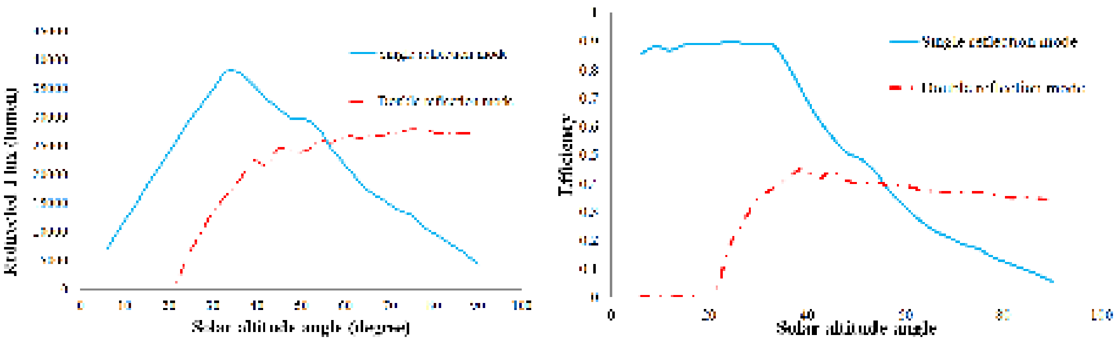
The performance and efficiency of each component have been carefully calculated using a raytracing software called “TracePro” [15]. The redirector is a key component in the core sunlighting system. To optimize the performance of CSLS, it is important to maximize the efficiency of the redirector, where the efficiency of the redirector (E_R) is the ratio of captured light by the redirector (L_R) to the light hitting the top surface of redirector (L_0).

$$E_R = \frac{L_R}{L_0} \quad (1)$$

If the illuminance of a light source is I_0 , the luminous flux of the light that hits the surface of redirector, L_0 , is:

$$L_0 = I_0 \times A_{eff} \times \sin(\alpha) \quad (2)$$

Where A_{eff} is the effective area of the surface and α is the incident angle of the light. For one unit of redirector with the diameter of 1m, the effective area is 0.785 m^2, and the incident angle is the solar altitude angle. To capture the maximum amount of light with one unit of the redirector, all variables of the redirector, such as slat size and distance between slats, have been precisely calculated to optimize the efficiency. The luminous flux of captured light and efficiency of the redirector is shown in the Figure 6 for the single and double reflection mode.

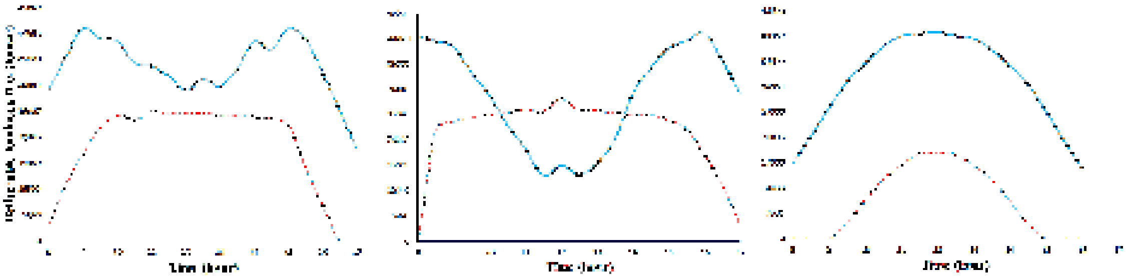


(a) (b)

Fig. 6. (a) Luminous flux of captured light by redirector; (b) efficiency of redirector, versus solar altitude angle for single reflection and double reflection modes (for solar azimuth angle= 180°)

As shown in the graphs, the efficiency of the redirector in the single reflection mode drops dramatically for high solar altitudes. This can especially affect the system in places located at low latitudes. In these locations, the solar altitude can be very high during a large portion of day in spring and summer days. The double reflection mode has better performance at higher solar altitudes. By combining these two modes, we can maintain the captured luminous flux at 25,000 lumens for a longer portion of day. This luminous flux value is required in this system to illuminate a 22.5m^2 office area at 500 lux. The system will switch between the two operating modes depending on the sun position to maximize the amount of sunlight that is redirected by the assembly. Raytracing simulations show that the variation in efficiency over the solar azimuth angle movement is less than 15%, and that the amount of captured light is almost identical for all four facades.

Using a series of ray tracing simulations, the efficiency of the redirector was calculated for different solar altitudes and azimuth angles. Using a standard sun position calculation and efficiency chart, we can predict the luminous flux captured by the redirector for any location at any time of the day throughout the year. For example, the reflected luminous flux at 30°N is shown in Figure 7 during the equinoxes and solstices (spring equinox and autumn equinox are identical). There are a few hours during spring and summer days where the flux of captured light in the single reflection mode drops below 25,000 lumens. Switching to the double reflection mode during those hours will boost the performance of the system. In fall and winter days, the CSLS can work only in single reflection mode. For locations of latitudes higher than 40°, the system only needs single slat redirectors, because the solar altitude never gets high enough to warrant the efficiency of the double reflection mode.



(a) (b) (c)

Fig. 7. Luminous flux of light captured by the redirector at (a) spring equinox; (b) summer solstice; (c) winter solstice, values are averaged for four sides of the building. (Solid line: single reflection mode, dashed line: Double reflection mode)

4.2. Concentrator component

The next component that light travels through is the concentrator section. It is important that the concentrator captures most of the light that reaches it, and collimates it as much as possible. The properties of the components, such as the focal distance of the lenses and mirrors as well as their exact locations and orientations, have been calculated to reach the maximum efficiency and collimation at the same time.

To test the design performance, we modelled the system with a light source that resembles a solar light source with a half-angle of 0.25°. The efficiency of the system is about 95%, where efficiency is the ratio of output light to the light that hits the lens assembly. Moreover, 96% of the output light has less than a 2.5° half-angle. As mentioned earlier, the collimation of the output light is important for transferring light to a longer distance in the light guide.

4.3. Light pipe

The light coming from the concentrator will be fed into the light guide previously described. To extract the maximum amount of light from the guide and to have the highest spatial uniformity along the guide, the size and shape of the extractor must be determined as a function of position along the guide. A 15m long pipe with a 7cm by 30cm cross section was modelled in our simulation. The width of the extractor is 17cm at the entrance and gradually increases along the pipe because the intensity of light drops and more rays need to be diffused and extracted. The resultant light output is uniform along the pipe and the light intensity has only a $\pm 15\%$ fluctuation. Moreover the variation of light happens slowly along the pipe, which is important for visual comfort.

To calculate efficiency, real properties were applied to materials in the light guide. Simulations showed that 77% of light can be extracted from the pipe and 3% will return to the entrance and exit the pipe. The remaining 20% will be absorbed by materials in the pipe, such as reflective walls, prismatic optical lighting film and diffusers.

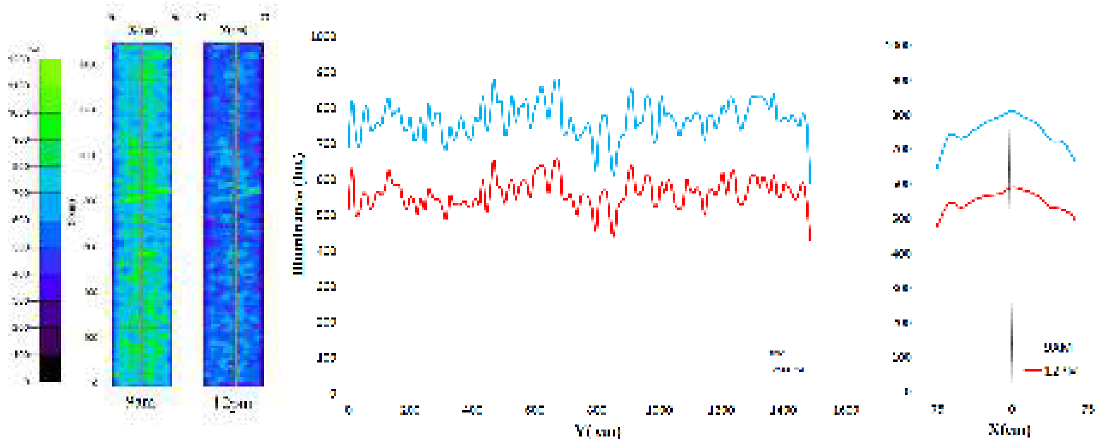
4.4. *Lighting module*

The next step was to calculate the amount of daylighting that could be provided by the CSLS at the work plane inside the building. In a typical office, luminaires are separated by about 1.5 to 2m. In order to simulate an office environment, we positioned the light guides 1.5m apart. Since offices highly vary in size and shape, we simulated the light distribution inside a smaller module which would resemble a slice of the building. Each lighting module is illuminated with one light guide, thus it is chosen be 1.5m wide. The module is 15m long, which is the maximum distance that the CSLS would typically be expected to provide sunlight within the building. The module parameters are set such that it represents a portion of the building, and side-by-side modules simulate the light distribution in a larger area. It is assumed that no window is involved in the module, since the size of the windows and orientation of the module will affect the result. In a real building, the effect of windows needs to be considered, since light intensity is higher near windows. The extractor needs to be modified such that it extracts less light near windows to keep the lighting level uniform along the module.

To make this module a realistic representative of a larger office area in the building, a particular reflectance characteristic should be applied to the surface in the simulated model. We estimated the walls to have 85% specular and 10.5% diffused reflectance and 4.5% absorption. The specular reflectance component represents an open space where light will be contributed from the neighbouring modules. The other two components represent a typical white wall with reflectance of 70% and absorption of 30%. The ceiling is assumed to be 80% diffused reflective, similar to a ceiling in a typical office, and the floor is 20% diffuse reflectance and 80% absorptive.

The reflectance of the surfaces in the room has a large impact on the coefficient of utilization, CU, which is the effectiveness in which the luminous flux provided by the luminaire can be delivered on to the work plane [16]. The value of CU also depends on the angular distribution of the light source, and the geometry of the room. In most cases, the CU is less than 1, but for a room with very high reflectance, where light undergoes many reflections before being absorbed, it is possible to have a CU value bigger than 1. Using the described module, we simulated the light distributions inside the office area and calculated the delivered luminous flux at the workplane. The coefficient of utilization, the ratio of delivered luminous flux at the workplane to the output of light guide, was calculated to be 1.16 in this module.

Large variations of the light intensity over a short distance across the work plane can be unpleasant. The simulation results showed that such variation is not a problem is this system. The variation of light intensity across the module was calculated to be 17.6% across the module and 12.6% along the module, which is virtually unnoticeable. The light distribution pattern is independent of the orientation of the module and the variation in the illuminanc level is very small (less than 5%) for different orientations. The illuminance distribution at the work plane in the module is shown in Figure 8 for 30°N during summer solstice at both 9:00am and noon (the illuminance map at 3:00pm is identical to 9:00am, so it is not shown here). The illuminance distribution within the module remains quite constant during the course of the day, and the only thing that changes slowly is the average illuminance level.



(a) (b) (c) (d)

Fig. 8. Illuminance map at the work plane in the lighting module at 30 °N at summer solstice, (a) at 9:00am (average illuminance: 740lux); (b) at noon (average illuminance: 543 lux); (c) line scan of illuminance along the Y axis ; (d)line scan of illuminance along the X axis.

Combining all components, we were able to calculate the overall efficiency of the system, which is the fraction of the light captured by the redirector that can be delivered to the room at the work plane, Figure 9. The effective efficiency of the system is the multiplication of efficiency of each component.

$$Eff = A_C \times E_c \times E_P \times CU \qquad (3)$$

Where, A_C is the ratio of light that will hit each unit of the concentrator, I_1, to the light that is redirected by the redirector, I, E_C is the efficiency of the concentrator, $\frac{I_2}{I_1}$, E_P is the efficiency of light guide, $\frac{I_3}{I_2}$, and CU is the coefficient of utilization , $\frac{I_4}{I_3}$. Multiplying all these values, the overall efficiency of the system is expected to be 30%.

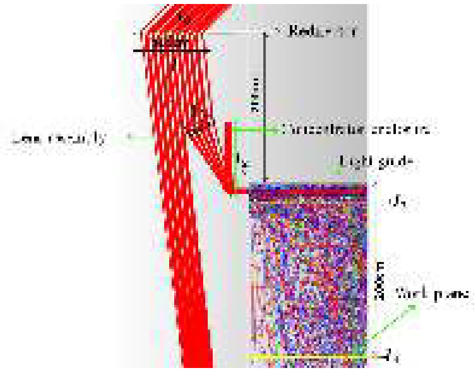


Fig. 9. The core sunlighting system captures light at roof level, concentrates it and delivers it on to the work plane in the building

5. Energy saving calculation

Sunlight is a free and renewable source of energy, but its availability varies with location and time. As we mentioned earlier, using the solar geometry calculation, the luminous flux captured by redirectors can be calculated at any time of the day for any place. To calculate delivered luminous flux in the light module, we multiplied the luminous flux of the captured light by the redirector by the overall efficiency of the system. We calculated the average available illuminance at the work plane, which is total luminous flux delivered to the module divided by the area of the module. In Figure 10, average illuminance level is shown for 30° N during equinox and solstices.

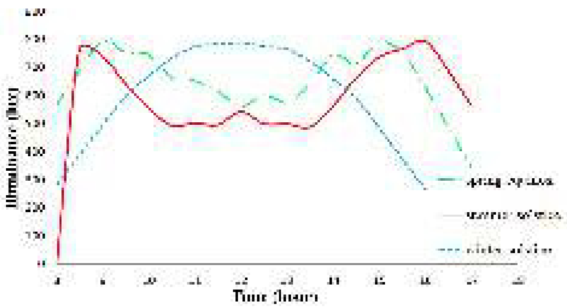


Fig. 10. Available illuminance at work plane at equinoxes for 30°N (spring and autumn equinoxes are identical)

It is desirable to keep the level of illumination at 500 lux in office areas [17]. As shown in Figure 10, there will be enough light to illuminate buildings with only daylighting on sunny days during spring and summer. During autumn and winter, the level of daylighting is enough for a portion of day, and it can be supplemented with electrical lighting during the rest of the day to maintain a constant level of lighting.

As shown in Figure 9, the captured light by the redirectors is distributed uniformly between floors. In this specific design, the redirector unit is 1m wide, which provides enough light for 2 floors. In many installations it would be practical to have a 3m wide redirector positioned at the roof edge, which would provide light for 6 floors of the building. Considering the fact that about 50% of commercial buildings in the US are 2-9 floors [18], this core sunlighting system can serve a significant portion of commercial buildings.

The calculations shown above are for unobstructed sunlight. However, weather conditions and sunshine probability affect the performance of the system. Moreover, the core sunlighting system can only work under direct sunshine, since diffused light cannot efficiently be concentrated by the system, thus electrical lighting is needed in overcast conditions. To calculate how much energy can be saved on average each month in a specific location, the sunshine probability of that city at that time of the year needs to be considered as well.

It is premature to calculate exactly how much a CSLS unit will cost in volume production, but since the system uses standard components we are confident that it is possible to make this system at a reasonable cost. Further analysis could be done to compare the performance of this model of the core sunlighting system and other core sunlighting systems, but as mentioned earlier, we were able to overcome the limitations in the existing models which will improve the performance of this model in comparison to existing ones.

Conclusion

The use of daylight for the illumination of the buildings is well known in the building industry. The new core sunlighting system design has a novel approach to the problem. Its ability to capture light at roof level, equally from all sides of a building, makes it an efficient method for delivering sunlight to the dark core of a building. Raytracing simulation results show that this core sunlighting system has potential to provide useful illumination most of the time. The impact of this system on the appearance of buildings is minimal and it can be readily into existing buildings.

Acknowledgements

The authors wish to thank the Natural Sciences and Engineering Research Council of Canada and the Sustainable Building Science Program at the University of British Columbia for providing financial support for this research project.

References

[1] M. Navvab, *Daylighting Techniques: Skylight as a Light Source*, Arch. Light 2 (8), 45-47, 50, 1988.
[2] J. Callow, L. Shao, *Air-clad Optical Rod Daylighting System*, Lighting Res. Technol. 35, 31-38,2003.
[3] Jeff Muhs, *Design and Analysis of Hybrid Solar Lighting and Full-Spectrum Solar Energy System*, American Solar Energy Society's SOLAR 2000 Conference
[4] R. McCluney, *Advanced Fenestration and Daylighting Systems*, International conference on daylighting technologies for energy efficiency in buildings, 1998.
[5] L. M. Fraas, W. R. Pyle, P.R. Ryson, *Concentrated and Piped Sunlight for indoor illumination*, Applied Optics, 22 (4), 578-582, 1983.
[6] K. Robertson, *Daylighting guide for Buildings*, The Alberta Association of Architecture, Web, http://www.aaa.ab.ca/website/AAA/The_AAA/AAA/The_AAA.aspx
[7] L. Whitehead, D. Yen, R, Salikan, *Core Sunlighting Technology offering a new approach to green building*, Journal of Construction CANADA: 53(5),48-56, 2011
[8] OakRidge National Laboratory, *Wall R-value Calculator for Whole Building Energy Simulation*, Web, http://www.ornl.gov/sci/roofs+walls/AWT/InteractiveCalculators/rvalueinfo.htm
[9] U.S. Department of Energy, *Typical Thermal Performance of Residential Windows, by Type*, Web, http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=5.2.8
[10] A. Rosemann, G. Cox, P. Friedel, M. Mossman, L. Whitehead, *Effective Dual Function Solar/ Electric Light Guide to Enable Cost-effective Core Daylighting*, Leukos 3 (4), 259-276, 2007
[11] A. Rosemann, M. Mossman, L. Whitehead, *Development of a Cost –effective Solar Illumination System to Bring Natutal Light into the Building Core*, Solar Energy 82, 302-310, 2008.
[12] L. Whitehead, A. Upward, P. Friedel, G. Cox, M. Mossman, *Using Core Sunlighting to Improve Illumination Quality and Increase Energy Efficiency of Commercial Buildings,* ASME 4th International Conference on Energy Sustainability, ASME2010.
[13] G. N. Tiwari, *Solar Energy, Fundamentals, Design, Modeling and Applications*, Alpha Science, 251-254, 2002.
[14] L. Whitehead, K. Hoffman, *New Simplified Design Procedures for Prism Light Guide Luminaires,* J. of Illuminating Engineering Society, 27(2), 21-27, 1998
[15] Lambda research corporation, *Trace pro software,* web: http://www.lambdares.com/
[16] Illuminating Engineering Society of North America, *Lighting Handbook Reference and Application*, ninth edition, New York: IESNA, 8-12, 2000.
[17] Illuminating Engineering Society of North America, *Lighting Handbook Reference and Application*, ninth edition, New York: IESNA, 10-18, 2000.
[18] US department of Energy, *Number of floors and type of ownership, as of 2003, commercial sector characteristics*, Web, http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=3.2.3