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Sunlight permeability of an Anidolic daylighting system without compound parabolic collector

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Abstract
Light pipe is an effective way to channel outdoor daylight into the interior spaces of a building. Adding an anidolic concentrator at the entry port of the Light pipe will improve daylight capture ability and reduce the overall cost per unit of delivered daylight flux. This work numerically investigates the transmission of beam and diffuse daylight through an external collector, a tubular light funnel, an internal regulator, and finally a tubular Light pipe. The regulator is used to adjust the behaviors of the light at the exit port in accordance to how the exiting light is to be used. The aim of this work is to investigate the influences of various parameters on the overall luminous performance of the daylighting system. According to current simulation results, the sunlight at an incidence angle as large as 60° can still transmit through the device. To ensure better overall performance, the size of the collector should be smaller than that of the regulator. Furthermore, if the collector is much larger than the regulator, the sunlight will be rejected by the device. Also, the reflectivity of the funnel should be kept as high as possible. Semi-spherical regulator performs better if the sunlight is more properly aligned. Otherwise, spherical one is more preferable.

Keywords: anidolic daylighting systems, sky illuminance, daylight collector, daylight regulator, tubular light pipe, raytracing simulation

1. Introduction

In a dense urban environment, sky obstruction caused by high rise buildings leads to minimal daylighting for interiors on lower floors and in deep interior spaces. To remedy this, the use of innovative daylighting systems can enhance otherwise inaccessible or dimly lit places using available natural outdoor daylight [1]. In general, these systems have four key aims: to increase daylight levels deep within rooms, to improve daylight uniformity, to control direct sunlight, and to reduce glare. Among these, lightguides and Light pipes are mainly used to channel daylight.

Sweitzer [2] has discussed three daylighting technologies available in 1993. These less conventional technologies made use of the Light pipes, prismatic panels, and electrochromic glazings. They concluded that office and corridor ceiling heights, configurations, and finish surfaces were critical to the performance of the lighting technology.

In 2005, ARTHELIO, a European research project, had examined the possibility of guiding day-light into deeper building interiors using light guides. In two different test sites, daylight was successfully collected by the heliostats and was guided along the Light pipes before entering the destination space. Even if lightguides were characterized by important losses, Rosemann and Kraase [3] had confirmed that the transport of outdoor daylight through the light guides combined with heliostats is viable. In the same year, Oakley *et al*. [4] have monitored the performance of six Light pipes in a workshop, a residential landing, and a small office. Their results showed that Light pipes were proficient to introduce daylight into buildings. They concluded that straight and short Light pipes with low aspect ratios and large diameters are the most effective ones.

Mohelnikova [5] presented a theoretical description of light rays transport inside a straight tubular lightguide. Their mathematical model was comparable with actual light measurement. Also, they were able to evaluate the functioning of the lightguide system and determinate the design requirements based on their mathematical model. Then, Kocifaj *et al*. [6] had successfully derived a light transmission model through a bended hollow lightguide. Unlike the straight lightguide system, the analytical solution corresponding to a bend lightguide system had to be solved in a semi-analytical manner. Later, Darula *et al*. [7] considered the performance of a bend Light pipe when its external collector was set on a sloped roof. Similar to Kocifaj *et al*. [6], they also agreed that some additional light losses and distortions of the propagated light inevitably took place in bended tubular lightguides. Nevertheless, the bended lightguide system was still more effective than straight vertical lightguide system if to be installed on a sloped roof.

Taengchum *et al*. [8] had applied analytic approach to trace the rays through a Light pipe system. Under some conditions, the concentrator attached to the Light pipe might reject rays when their incidence angles were greater than the acceptance half-angle of the concentrator. Therefore, they concluded that there was a need to design alternative configurations if more uniform transmitted daylight was to be concentrated and brought into the interior spaces.

Garcia-Hansen and Edmonds [9] examined the feasibility of using vertical Light pipes to bring and distribute equal amount of natural daylight into the dark central core of a multilevel building. The daylight channeled through the partially reflecting cones within the transparent sections of the pipes at each floor level. Based on their theoretical formulation, they were able to estimate the partial reflectance necessary to provide equal light extraction at each level. The performance of the system was assessed with mathematical simulation and by observations made in a five-level building under clear sky conditions.

Kontadakis *et al*. [10] had very recently developed a sunlight redirection system consisted of a number of sun-tracking mirrors installed on a light shelf. The sunlight was reflected and then projected towards a specifically targeted area on the ceiling of a building. Five cases corresponding to various shading system configurations were examined. While they system generally increased daylighting levels in the space, there was a slight increase in daily primary energy consumption due to solar radiative heating.

The subject of current work is a system consists of an external collector, a funnel, a regulator, and a light pipe. The aim of this work is to investigate how different parameters affect the overall luminous performance of the system.

2. Methodology

Rays are the paths of the photons travel from the light source to its destination. The method to render the photon paths is called ray tracing. Ray tracing based simulation has nowadays been a valuable aid to predict the performance of daylighting systems. There are two ray tracing techniques, namely the forward and the backward ray tracing techniques. The former technique follows the photon in direction that light travels whereas the latter technique starts tracing the ray from the image and trace backwards until the ray finds a light source. Since backward ray tracing technique has been known for its inefficiency with many specular reflected indirect light rays, current work employed an in-house C++ program based on the principles of geometrical optics. This program allows the authors to perform the ray tracing technique and to calculate the direct daylight entering the Light pipe system and its transmission to the end of the Light pipe. Since a tubular Light pipe was considered in this study, only 3D geometries of the system were constructed and 3D simulations of various conditions were performed. The capturing effect and transmission of sunlight through the light pipe were then analyzed.

The schematic diagram of the problem is shown in Figure 1. The device consists of an external collector, an internal regulator, a light funnel, and a Light pipe. The external collector accepts parallel light from the solar ray emitted infinitely far away at an incidence degree θ. The internal regulator can be used to diffuse the daylight for immediate lighting or to compress the daylight for further transport. The light funnel refers to the part that connects the collector and the regulator. The Light pipe is an optional component of the system. It serves to guide the light exiting the regulator further downstream. The parameters investigated in this study included the incidence angle θ, the size of the external collector, the sizes and geometries of the intermediate regulator, and the light funnel.

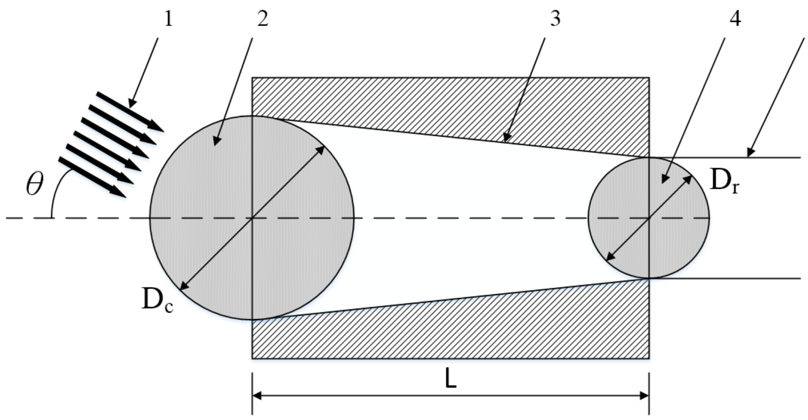

Fig 1: The schematic diagram of the device: (1) sunlight; (2) collector; (3) funnel; (4) regulator; and (5) Light pipe.

3. Results & Discussion

For ease of discussion, the size ratio between the collector and regulator was defined as $D^* = D_c/D_r$, where D_c and D_r represented the diameters of the collector and the regulator, respectively. Figures 2 show how the relative sizes of the collector and regulator influence the quality of light at the exit port. Both the collector and the regulator were assumed made of glass (n = 1.544). The color of the light path in the figures indicates the intensity of the light. The red lines imply that the light maintains 90%-100% of its original light intensity, the blue lines are 60%-90%, while the green lines are less than 10%. The quality of the light depended heavily on the incidence angle of the sunlight. When the collector was smaller than the regulator, i.e., $D^* < 1$, sunlight that entered the collector would reach the regulator through the funnel and eventually exit the system successfully. If $D^* > 1$, i.e., the collector was larger than the regulator, the amount of light successfully made its way through the system evidently became very limited unless the incidence angle θ was sufficiently small enough. When θ = 0°, the light rays were more concentrated and intensified at the center of the exit port. As the incidence angle θ increased, the rays at the exit port were more evenly distributed, but at a much lower intensity level. It is remarkable to point out that the above observation was misleading because this phenomenon was actually periodic in nature.

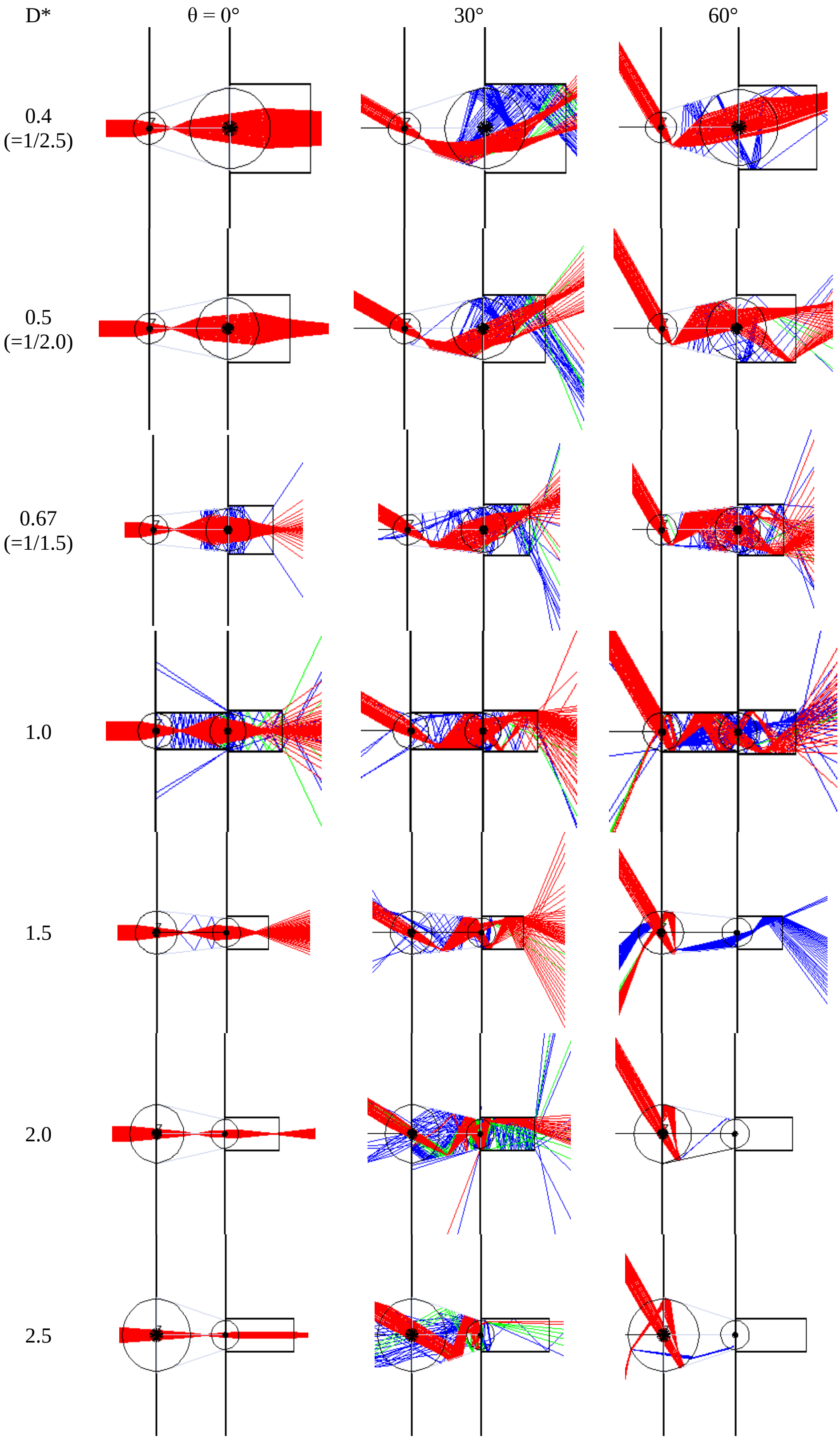

Fig 2: Lightpath in the system for different collector and regulator sizes.

Figures 3 show that the light coming out of the straight Light pipe if a semi-spherical regulator was used instead of a spherical one. The rays were somewhat less uniformly distributed in comparison with those displayed in Figures 2. In these cases, the flat portion of the regulator was facing outward. In additional to the span of the emitted light, the overall direction of the light had also changed at various sunlight incidence angles. Although this half-spherical configuration was less favorable in general, it did produce a more concentrated light beam when θ = 0°. Therefore, the use of a semi-spherical regulator was believed to yield a much higher efficiency if it was used along with a sun position tracking system which aligned the incidence sunlight properly with the system.

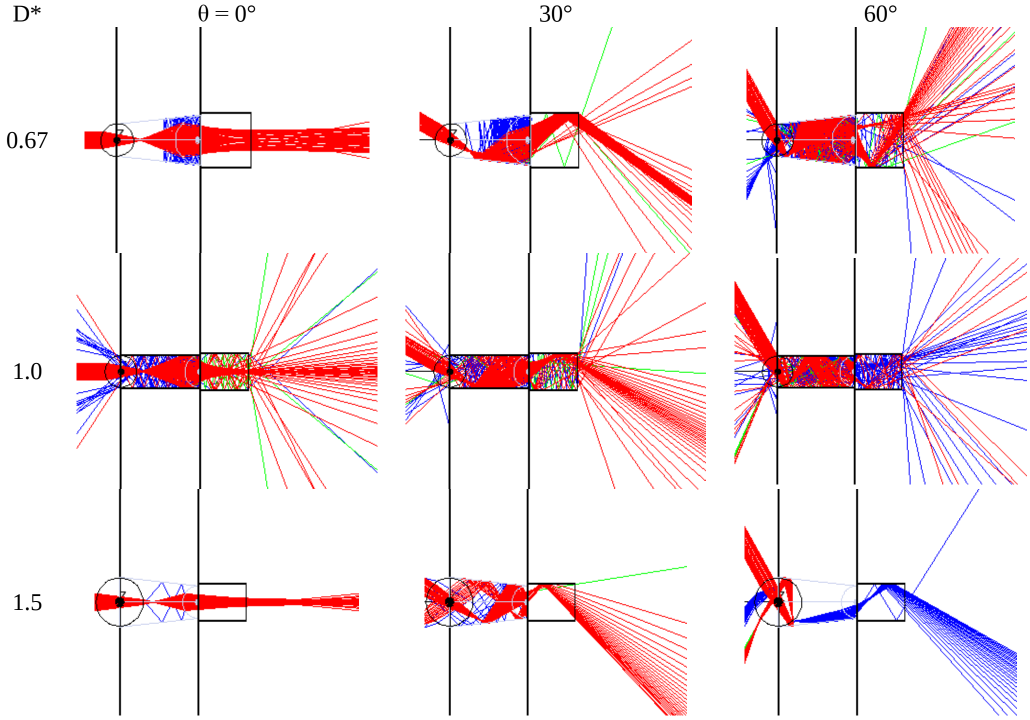

Fig 3: Light path in the system corresponding to a semi-spherical regulator for different values of D*.

Figures 4 show the influence of the length of the light funnel on the behavior of the light at the exit port if D* = 1.5. Since the inner surface of the funnel was assumed to be mirror-like, the reflectivity of this surface was hence assumed 1.0. The length of the funnel was normalized by the diameter of the regulator Dr, i.e., $L_r^* = L/D_r$. Apparently, the light had to go through more reflection as the length of the funnel increased. As long as the inner reflectivity of the funnel was kept greater than 90%, the length of the funnel basically improved the quality of the emitted light in terms of light uniformity and span. Based on other simulations whose results were not presented here, it was found that a straight funnel performed much better than both concavely or convexly shaped funnels in this regard.

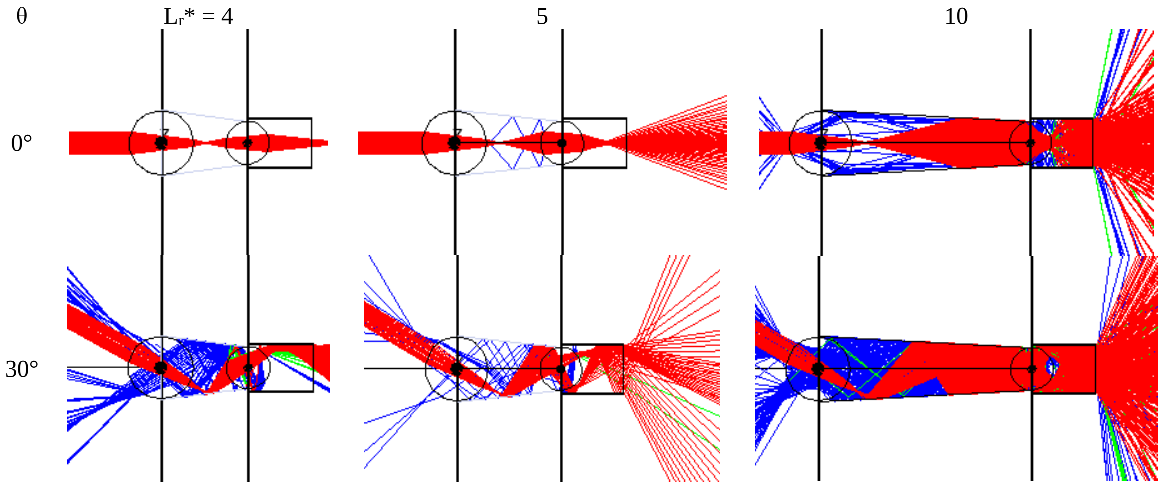

Fig 4: Light path in the system for different lengths of light funnel for D* = 1.5.

A series of similar studies for D* = 0.67 is displayed in Figures 5. For the sake of comparison, the length of the light funnel is now characterized as $L_c^* = L/D_c$. In this case, the size of the collector was only 2/3 of the size of the regulator. The scenarios studied here could easily achieved by simply swapping the left and right of the device considered in Figures 4. In these cases, the diameter of the Light pipe had to be adjusted to fit the size of the regulator. Similar to those shown in Figures 4, sunlight at θ = 0° yielded very good light transmission. However, it was discovered that the focal point of the light emitted from the regulator was further from the device when compared to those shown in Figures 4. As L_c^* increased, the focal point moved towards the regulator. For lighting purposes, a funnel long enough would rule out the possibility of fire hazard due to ignition by concentrating sunlight when the focal point was located within the regulator. For the sunlight at θ = 30°, all cases shown in Figures 4 and 5 disclosed the fact that light might be partially rejected by the device through the entry port after light was inverted in the regulator. However, this situation had been greatly suppressed when D* < 1.

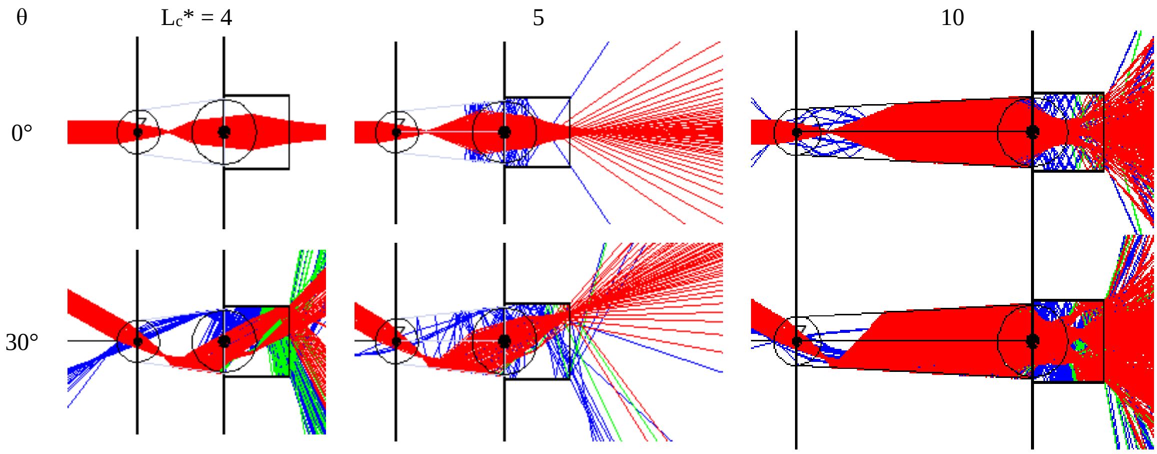

Fig 6: Light path in the system for different lengths of light funnel for D* = 0.67.

4. Conclusions

This work has studied the performance of a daylighting device. The results of current simulations suggested that:

1. The combination of a small collector with a large regulator helped guiding sunlight into the device and consequently promoted its rays traveling through the device successfully.
2. Spherical regulator was generally more preferable. However, a semi-spherical regulator would produce a more concentrated light beam if the sunlight was properly aligned with the device.
3. The reflectivity of the inner surface of the light funnel was critical. If the reflectivity was high, the length of the light funnel increased the span of the light as well as made the light more uniform.

5. References

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