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# A study of transmission and illumination of light through rectangular light pipes with bends

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***Abstract:***
*Light pipes can bring daylight from the sky into deep interior spaces of a building. A pipe is often connected with a bend so as to orient the entry port in the direction that optimizes light reception and transmission. Another bend is connected before the exit port to optimize delivery of light into a room. This paper presents results of modeling, experiments, and simulation of transmission of beam and diffuse daylight through rectangular light pipes. Analytic method is used for tracing light rays from the source into the bend through to the straight section and through to the bend and then the exit port into the room, or forward raytracing method. The curve surface of the bend is modeled as a pie bend section. The interior surface of each section is specular but may have different reflectances. The algorithms of calculation are coded in MATLAB scripts and functions. The interior surfaces of the rectangular light pipe and bends are lined with a film of reflectance of 99%. A set of experiments was conducted indoor using an LED lamp as a point source. Results of calculation using the method match closely with those from experiments.*

***Keywords****: Daylighting; light pipe; bended pipes; sky luminance; sunlight*

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## 1. Introduction

Daylight in the tropical sky is voluminous and daylighting is attractive. One way of bringing daylight into the deep interior space of a building is to use light pipe, which is a tubular hollow pipe with highly specular and reflective interior surface comprising an inlet port and an exit port.

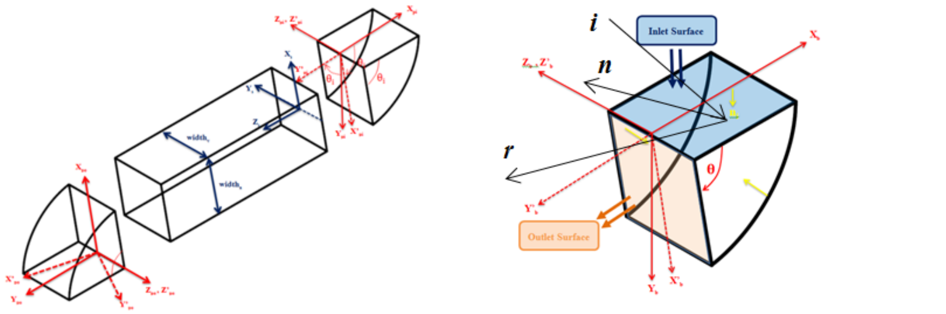
Zastrow and Wittwer (1986) considered transmission of light beam across cylindrical light pipes and offers a simple relationship for light transmission as a function of the length and diameter of the pipe, and the entry angle of the light beam. Swift et al. (2008) developed theoretical model of transmission of light through rectangular pipe for collimated rays and reported that results from the model agree well with experimental results. Kocifaj et al. (2008) developed a method called HOLIGILM for calculation of illuminance on an incremental area at the exit port of a circular light pipe by considering backward tracing of a light ray through the entry dome or port to a sky zone. Kocifaj et al. (2010) and Kocifaj and Kundacik (2011) extended the HOLIGILM method to the case where two straight pipes are connected to form a bend and consider the spread of light as it transmit through a pipe. Darula et al. (2010) applied the HOLIGILM method to study daylight transmission through a bended pipe on a roof. The authors concluded that effective design of bended tubular light pipe requires a study of interrelation between tube azimuth orientation and the angle of incidence of the sun beam. Samuhatananon et al. (2011) used forward raytracing in a study on daylight transmission through cylindrical pipes with and without torus bends. A number of publications report on the use of anidolic or non-imaging optics to concentrate captured daylight and transmit it through light pipe (Scartezzini and Courret, 2002; Molteni et al., 2000; Wittkopf 2006; Linhart et al., 2010). These studies use 'Photopia', a computer tool, to model capture and transmission of daylight from part of a sky dome through straight pipe and through an exit port. In order to capture daylight from a part of sky through a larger inlet port, concentrate it and let it pass through a smaller port. This paper reports a study on the application of raytracing to trace ray transmission through a spur light pipe that brings light to illuminate a space.

## 2. Ray tracing method and the computational algorithm

The method of forward raytracing employed in this paper is applicable for both façade mounted and roof mounted light pipes where a ray is traced along its path of travel from a daylight source and is specularly reflected when it encounters a surface. For the present work, the glazing elements at the entry and exit ports of a pipe are omitted in order to elucidate the mechanism of transmission of light rays through the pipe and to distinguish its features from the effects of transmission by the port elements.

Fig. 1(a) illustrates detailed configuration of the pipe with bends, and Fig. 1(b) the pie-shape bend. A coordinate is set up for each section of this pipe, which differs from that of other section. The position that each ray intersects with a surface is reference to its coordinate. In Fig. 1(a), ***i*** represents the incident vector of a ray on the surface, ***n*** represents the vector normal to the surface at the point of intersection and ***r*** represents the reflection vector. The three vectors are related in accordance with the law of optical physics as

$$\mathbf{r} = \mathbf{i} - 2(\mathbf{i}, \mathbf{n})\,\mathbf{n} \qquad (1)$$




(a) The three components of the light pipe. (b) The pie-shape bend.

**Fig. 1** The pie-shape bend light pipe.

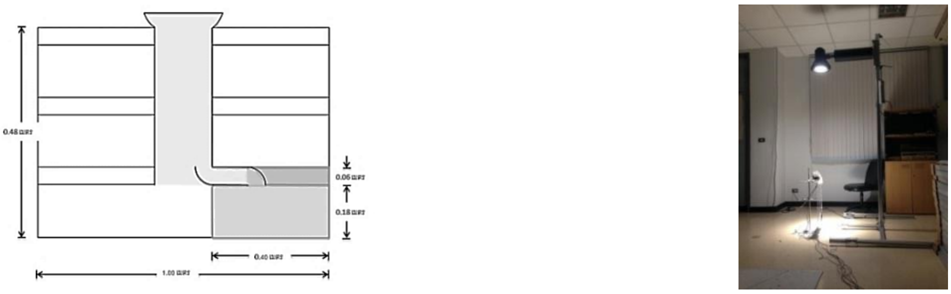
In the case where the point of intersection is the circular surface of the pie-shape bend the x and y coordinate of the point of intersection follows the following relationship, where $R$ is the radius of the bend,

$$x^2 + y^2 = R^2 \qquad (2)$$

When a ray intersects a point on a flat surface, the dot product of its vector with the normal of the surface takes on negative value. A ray with a given direction of travel is tested if it will intersect the exit or entry ports of a given section. If not, then it must intersect a surface of that section. The location of the intersection and reflection vectors is then computed, and the ray continues to travel. This is repeated until the ray intersects an entry or exit port of the given section. A counter is used to count the number of times a ray intersects the surface of each section. If the ray intersects the exit port of entry bend, it continues to travel into the straight rectangular pipe and enter into the coordinate of the pipe. A coordinate transformation is required when the coordinates between adjacent sections are not identical. When a ray leaves the exit port of the exit bend, its position on the port and the direction of travel are recorded. Such information is used in the calculation of the illuminance of light flux at exit, etc.

## 3. Calculation and experimental results

Fig. 2(a) illustrates the geometrical position of a light pipe connected with an anidolic concentrator installed in a building. The horizontal pipe with bends is supposed to extract part of the light flux from the main light pipe. The transmission of light flux through the horizontal pipe with bends is the main subject in this paper. Fig. 2(b) shows the configuration of an experimental setup where an LED lamp located at a distance more than five times the dimensions of the light source and the light pipe is treated as a point source that emanates parallel light rays into the entry port.



(a) The building model and light pipes (b) The experimental setup

**Fig. 2** The configuration of a main and a spur pipe and the experimental setup.

### 3.1 Calculation results

According to the calculation algorithm described, a ray is traced as it travels through each section of the pipe. The number of its reflections in each section is recorded. When it leaves the exit port its position and direction at the point of exit with respect to the normal of the exit port is recorded. A set MATLAB scripts and functions were written using the algorithms described.

The followings exhibit results from calculation using the MATLAB program. The pipe dimensions and surface properties are:

- straight rectangular pipe, width 0.05 m, height 0.06 m, length 0.17 m, surface reflectance 0.99
- inlet and outlet pie-shape bend, radius of the bend 0.06 m (this matches the height of the pipe), width of the bend 0.05 m (this matches the width of the pipe), surface reflectance 0.99.

*Case 1*: Rays enter with altitude angle 30$^o$ and azimuth angle 0$^o$

The x-axis of the entry port coincides with the x-axis of the main coordinate. The rays with an azimuth angle of 0$^o$ would travel along the length of the pipe. If the altitude angle at entry is relatively small, some rays would travel straight through the entry pie-shape bend without intersecting any surface of the entry port. The right most three columns in Table 1 show that all four rays does not intersect any surface in the entry bend and intersect the straight pipe and the exit bend each only once. The resultant illuminance at the exit port of the light flux is 459 lux compared to the entry illuminance of 1,000 lux (normal to the rays). At the exit port the rays leave close to the edge next to the straight pipe.

**Table 1** Ray position and direction at exit port and number of reflections in each pipe section.
Entry illuminance: 1,000 lux, Exit illuminance: 459 lux

| Ray No. | Ray position at exit | | | Ray direction at exit | | | Number of reflections | | |
|---|---|---|---|---|---|---|---|---|---|
| | x | y | z | x | Y | z | Ent bend | Pipe | Exit bend |
| 1 | 0 | 0.0447 | 0.0125 | -0.9063 | 0.4227 | 0 | 0 | 1 | 1 |
| 2 | 0 | 0.447 | -0.0125 | -0.9063 | 0.4227 | 0 | 0 | 1 | 1 |
| 3 | 0 | 0.0496 | 0.0125 | -0.9763 | -0.2165 | 0 | 0 | 2 | 1 |
| 4 | 0 | 0.0496 | -0.0125 | -0.9763 | -0.2165 | 0 | 0 | 2 | 1 |

*Case 2*: Rays enter with altitude angle 30$^o$ and azimuth angle 90$^o$

The azimuth angle of the rays in this case contrasts with that in Case 1. The entering rays will intersect either the side surface or the bend surface. The number of reflections shown in the three right most columns in Table 2 confirms this point. The numbers of reflections in other sections are also large when these are compared with those in Table 1. The resulting illuminance of the exit light flux is also substantially reduced (at 125 lux).

*Case 3*: Rays enter with altitude angle 90$^o$ and azimuth angle 0$^o$

The altitude angle of the rays in this case contrasts with that in Case 1. The entering rays will intersect the bend surface once. The number of reflections shown in the three right most columns in Table 2 confirms this point. The number of reflections in other sections is relatively large when these are compared with those in Table 1. The exit vectors points in the downward direction so the resulting illuminance of the exit light flux at 579 lux is reduced largely due to larger number of reflections compared to that in Case 1.

**Table 2** Ray position and direction at exit port and number of reflections in each pipe section
Entry illuminance: 1,000 lux, Exit illuminance: 125 lux

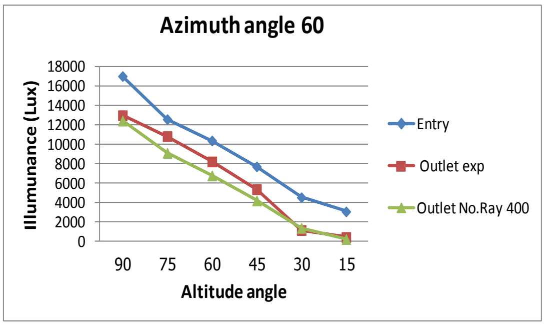
| | Ray position at exit | | | Ray direction at exit | | | Number of reflections | | |
|---|---|---|---|---|---|---|---|---|---|
| Ray No. | x | y | z | x | Y | z | Ent bend | Pipe | Exit bend |
| 1 | 0 | 0.0131 | 0.0030 | -0.4375 | 0.2421 | -0.8660 | 4 | 17 | 1 |
| 2 | 0 | 0.0131 | -0.0220 | -0.4375 | 0.2421 | -0.8660 | 4 | 18 | 0 |
| 3 | 0 | 0.0196 | -0.0047 | -0.1714 | -0.4697 | -0.8660 | 4 | 7 | 4 |
| 4 | 0 | 0.0196 | -0.0203 | -0.1714 | -0.4697 | 0.8660 | 4 | 7 | 5 |

**Table 3** Ray position and direction at exit port and number of reflections in each pipe section.
Entry illuminance: 1,000 lux, Exit illuminance: 579 lux

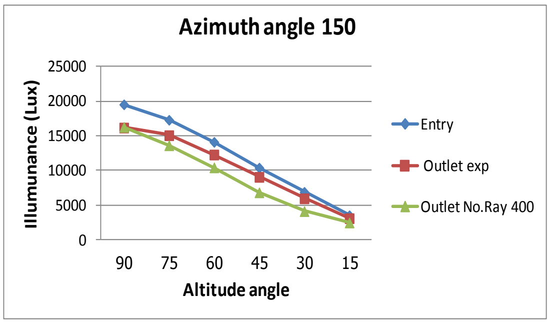
| | Ray position at exit | | | Ray direction at exit | | | Number of reflections | | |
|---|---|---|---|---|---|---|---|---|---|
| Ray No. | x | y | z | x | Y | z | Ent bend | Pipe | Exit bend |
| 1 | 0 | 0.0131 | 0.0125 | -0.8750 | 0.4841 | 0 | 1 | 5 | 0 |
| 2 | 0 | 0.0131 | -0.0125 | -0.8750 | 0.4841 | 0 | 1 | 5 | 0 |
| 3 | 0 | 0.0196 | 0.0125 | -0.3427 | -0.9394 | 0 | 1 | 1 | 1 |
| 4 | 0 | 0.0196 | -0.0125 | -0.3427 | -0.9394 | 0 | 1 | 1 | 1 |

## 3.2 Experimental and calculation results

Fig. 3 shows sample experimental and calculation results, Fig. 3(a) for the case when the azimuth angle is 60$^o$ and Fig. 3(b) for when it is 150$^o$. Both Figs. show that the calculation results agree reasonably well with those from experiments.




(a) For azimuth angle 60$^o$




(b) For azimuth angle 150$^o$

**Fig. 3** Two graphs of illuminance of entry and exit light fluxes.

## 4. Conclusion

The results from experiments agree well with those from experiments. This shows that the analytic method of raytracing and algorithms used not only give accurate results, but also lead to insight on the mechanisms of light transmission through each section of the pipe with bends.

## 5. Acknowledgement

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