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Ray tracing method for simulating daylight transmission through tubular light pipes with anidolic concentrator

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Abstract:
Light pipes can bring both daylight from the sun and daylight from the sky into deep interior spaces of a building. However, light pipes are still considered costly. Adding an anidolic concentrator at the entry port of a light pipe will increase daylight capture and may reduce the overall cost per unit of delivered daylight flux, especially for long pipes or pipes with bends. This paper presents results of modeling, and simulation of transmission of beam daylight through tubular light pipes. Analytic method is used for tracing light rays from the sun and sources in the sky zones through the anidolic concentrator to the straight sections of a pipe through to the exit port. The vertical curvature surface of the anidolic concentrator is modelled as a parabolic section. The algorithms are coded in a MATLAB program. The results show that the concentration ratio of a concentrator is a function of its acceptance angle and the reflectance of its surface. The method can be used for analysis and design of such system.

Keywords: *daylighting; light pipe; anidolic concentrator; sky luminance; sunlight.*

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1. Introduction
Chirarattananon et al. (2010) reported that Electric lighting accounts directly for 20% of electricity consumption in an air-conditioned building while daylight is plentiful. Daylighting through windows is practical for the area within a few meters near windows. Light pipes have the potential to bring daylight into the deep interior space in a building.

Light pipes more commonly used are passive tubular pipes that comprise specularly reflective interior surfaces. Scartezzini and Courret (2002) presented that light pipes and reflector systems that can utilize direct sunlight have been shown to be more effective in bringing daylight into deeper interior spaces. Performance of light pipes can be improved by using static anidolic concentrator, which are devices that capture daylight and concentrate it to desired collimation angle, Simone et al. (2000) study anidolic concentrator connected to a roof mounted pipe by the use of a sky scanning simulator. Friedrich et al. (2010) have proven anidoic dayligthing systems to perform well under clear and cloudy skies, therefore it was considered to be a very interesting option for daylighting in tropical regions. Rabl (1985) presented the theory of non-imaging optics have been used to design for anidolic concentrator. Raytracing and flux transfer have been applied successfully to the study of a facade-mounted rectangular pipes by Hien and Chirarattananon (2009).

This paper utilizes the principle of forward ray tracing to trace transmission of light rays from sky through equal incremental areas on the aperture of an anidolic concentrator connected to a straight light pipe. The anidolic section and the pipe are modeled analytically, so the methodology used is completely analytic.

2. Ray Tracing Method for a Circular Pipe with an Anidolic Concentrator
In the method of forward raytracing, each individual ray is traced along its path of travel from a daylight source, where it is specularly reflected when it encounters a specular surface. At the point of interception with a surface, a part of radiative power in the ray is absorbed, and the other part is specularly reflected. In general, a sufficiently large number of rays are required in order to capture the transmission characteristics for a given pipe when rays enter from different positions. In the

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method used, the cross section of the anidolic concentrator is modelled mathematically as a section of parabola. The method employed in this paper is applicable for both façade mounted and roof mounted light pipes. 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 illustrates the geometrical position of a cylindrical pipe connected with an anidolic concentrator under the sky dome. In the Fig., the center of a Cartesian coordinate with the z-coordinate coincident with the zenith direction is located at the center of the exit port of the anidolic concentrator. The position of the sun is located by the solar altitude and azimuth angles. The reference angle for the azimuth is the x-axis that points towards south. The position of a sky zone is also located by its altitude and azimuth angles. Rays from the sun and from the sky enter the input aperture of the anidolic concentrator with given altitude and azimuth angles.
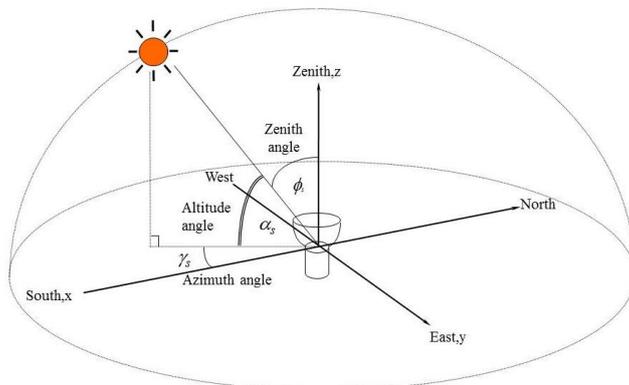

Fig. 1 The geometry of a pipe with anidolic concentrator under the sky dome.

2.1 Mathematical relationships for ray traveling through the concentrator and the pipe
Consider Fig. 2 where an imaginary surface is assumed to cover the entry port of the concentrator. A coordinate is located at the base of the concentrator
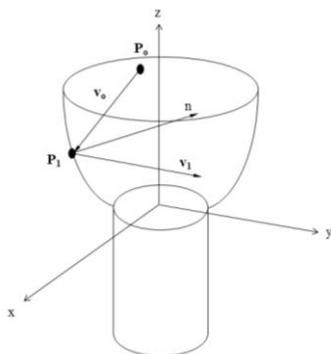

Fig. 2 The geometry of a ray entering the entry port of the anidolic concentrator.

A ray enters the port at location P_o and travels in the direction v_o. It intersects with surface of the concentrator at P_1. The normal of the surface at the point of intersection is n and the specularly reflected vector is v_1. The conjunctive point P_1 lies along the line parallel to vector v_o and can be obtained from

$$P_1 = P_o + t_o v_o \qquad (1)$$

where t_o is a scalar quantity and the point P_1 lies on the anidolic surface, so its x, y, and z coordinates follows the governing equation for the anidolic surface, where in this case is a parabolic function, given in Table 1.

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The vector $\mathbf{v_1}$ follow the law of specular reflection, the mathematical relationships for the vectors in Fig. 2 are

$$\mathbf{v_1} = \mathbf{v_0} - 2(\mathbf{v_0},\mathbf{n}) \qquad (2)$$

Once the ray is reflected from the conjunctive point, it travels along $\mathbf{v_1}$ from $\mathbf{P_1}$. Similar relationship applies when the ray travels in the cylindrical section of the pipe.

Table 1 Functional description of surfaces and normal vectors for parabolic and cylindrical surfaces

Surface Function: Parabolic
$\mathbf{S}: (x-x_o)^2+(y-y_o)^2-4a(z-z_o)$
Surface Normal
$\mathbf{n} = -\dfrac{(x-x_o)\mathbf{i}+(y-y_o)\mathbf{j}-2a\mathbf{k}}{\sqrt{(x-x_o)^2+(y-y_o)^2+4a^2}}$
Surface Function: Cylindrical
$\mathbf{S}: x^2+y^2-r^2$
Surface Normal
$\mathbf{n} = -\dfrac{x}{r}\mathbf{i}-\dfrac{y}{r}\mathbf{j}$

2.2 Mathematical model of an anidolic concentrator

The anidolic concentrator here is a compound parabolic concentrator and is based on the use of parabola curve that reflects incoming parallel rays to a focal point. Fig. 3 illustrates the two-dimensional configuration of the right hand side (RHS) of a compound parabolic concentrator (CPC). The vertex of the parabola is at (x_o,y_o), and the focus F is at (x_o,y_o+a), where 'a' is the distance between the vertex and the focus. In the Fig., both x_o and y_o are zero.

All rays parallel to y are reflected to the focal point F. The RHS of the CPC that comprises a parabolic section **b** and its base **c** is shown in Fig. 3. The height of this section is **h**, as shown in the Fig.. The LHS section comprises the mirror image of the section on the RHS. The focal point of the RHS parabola is at F while that of the LHS parabola is at F'.
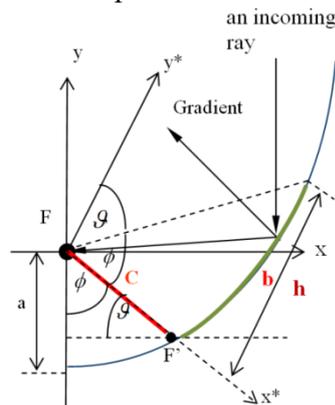

Fig. 3 The RHS of a compound parabolic concentrator.

The coordinate x* and y* form the coordinates of the RHS concentrator. The new coordinate (x*,y*) is rotated from the coordinate (x,y) clockwise by an angle ϑ, which is the acceptance half-angle and is the 90° complement of ϕ. In constructing a CPC, it is normal to first decide on the size of the diameter of the cylindrical pipe that is equal to **c**, the base of the CPC.

3. Computational procedure and results

A set of MATLAB scripts and functions has been written to compute the transmission of daylight

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rays from the sky and the sun through the concentrator and pipe system. The acceptance half-angle of the concentrator was chosen to be 40°, its base or the diameter of exit port 0.15 m, distance between the focal point and vertex 0.12 m, its height 0.2284 m, and its diameter at the entry port 0.2334 m. The 3D concentration ratio was then 2.42. The diameter of the exit port matches that of the straight pipe, here having a length of 1.00 m.

A ray with a given direction of travel is tested if it will intersect the exit or entry ports of a given section (In the concentrator, a ray can be reflected back to the entry port). If not, then it must intersect the concentrator or the pipe surface. The locations of the intersection and reflection vector are 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 the concentrator, it continues to travel into the cylindrical pipe and enter into the coordinate of the pipe. A coordinate transformation is required when the coordinates between adjacent sections are not coincident. When a ray leaves the exit port of the pipe, its position on the port and the direction of travel are recorded.

4. Results of computation for directional rays

A series of computational runs was made for *parallel rays* that were assumed to enter into the concentrator (only) at certain angles to examine some transmission characteristics. Fig. 4 shows three sample plots of ray trajectories for rays that enter at 20° and 40°. The first two on the left show ray trajectories in the concentrator. The rays at enter 20° are all transmitted through the concentrator (a) and through the straight pipe (c). Half of the rays that enter at 40° are transmitted through the concentrator and through the straight pipe.
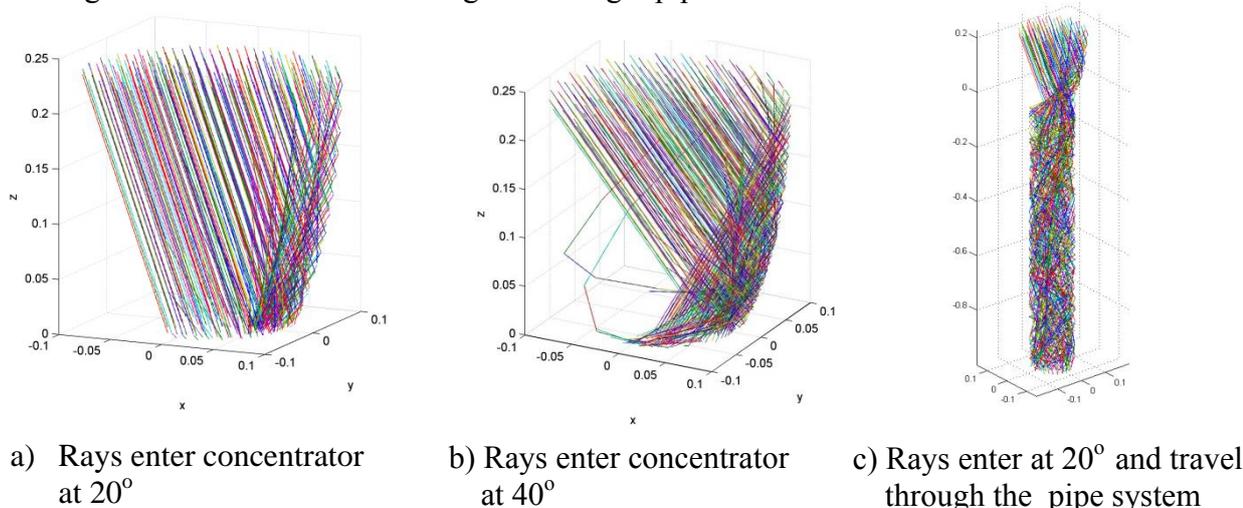

a) Rays enter concentrator at 20°   b) Rays enter concentrator at 40°   c) Rays enter at 20° and travel through the pipe system

Fig. 4 Three-dimensional plots of ray travels.

Characteristics of transmission of rays through the concentrator
Ray transmissions through a concentrator
A part of parallel light rays that enters the concentrator at an angle *smaller* than the acceptance half-angle will transmit through the exit port without intersecting the surface of the concentrator. Another part of parallel rays intersect the concentrator surface and are reflected. The closer the size of the entry angle of the parallel rays to that of the acceptance half-angle, the smaller the proportion of the rays that will transmit through the port without intersecting the concentrator surface. In this latter case, the other part of rays that intersect the concentrator surface does so at smaller angles of intersection and result in a larger number of reflections. When the entry angle of the parallel rays equals the acceptance half-angle, half of the total number of rays transmits through the concentrator, and the other half is reflected out through the entry port.

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The percentage of the number of rays transmitted from the total that enter at a given entry angle is also plotted and shown in Fig. 5.
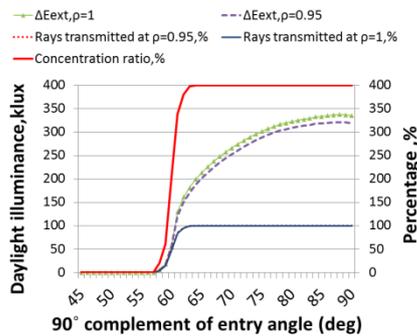

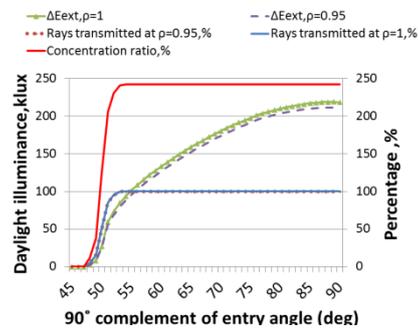Fig. 5(a) Plots for the case where the acceptance half-angle of the concentrator is 30°.

Fig. 5(b) Plots for the case where the acceptance half-angle of the concentrator is 40°.

Fig. 5 Plots for the case where the acceptance half-angle of the concentrator is 30° and 40°.

Fig. 5(a) shows, for a concentrator with an acceptance half-angle of 30°, plots of percentage of the number of rays transmitted against the 90°complement of the ray entry angle on the horizontal scale. The Fig. also shows plots of illuminace at the exit port for two cases, when the reflectance of the concentrator surface is 0.95 and when it is 1.0, for when the illuminance of the beam light is 100 klux normal to the beam. The number of rays used in the calculation is 900 for each entry angle and the increment of entry angle is 2°.

The plots of percentage of the number of rays transmitted shows rather sharp transition between the entry angle that all rays are reflected out (33° and the angle that all rays are transmitted (27°). The plots of illuminance at exit port for the case where the surface reflectance of the concentrator is 1.0 show that it rises from zero at an entry angle of 32 to 335 klux at the entry angle of 0°. For the case where the surface reflectance is 0.95, the exit illuminance only reaches 318 klux at entry angle of zero. The concentration ratio for this concentrator is 4 (or 400%). Even when the entry angle is zero, a small proportion of rays is transmitted without intersecting the concentrator surface, a larger proportion is reflected and the angles of intersection at the exit port of the rays in this portion is less than 90°.

Fig. 5(b) shows similar plots for the case where the acceptance half-angle of the concentrator is 40°, and the concentration ratio is 2.42 (or 242%). The maximum illuminance at exit port for surface reflectance of 1.0 and 0.95 are 218 and 210 klux respectively.
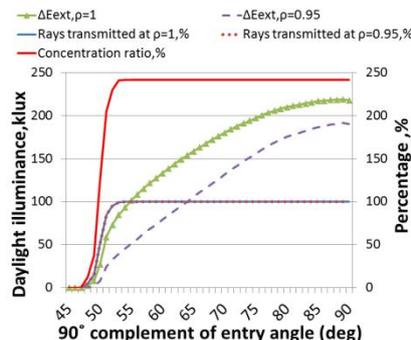

Fig. 6 Plots for the case where the acceptance half-angle of the concentrator is 40° connected to

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circular pipe is 1 m long.

Fig. 6 shows similar plots for the case where the acceptance half-angle of the concentrator is 40° connected to circular pipe is 1 m long, and the concentration ratio is 2.42 (or 242%). The maximum illuminance at exit port for surface reflectance of 1.0 and 0.95 are 218 and 190 klux respectively.

5. Conclusion

Anidolic concentrator has the potential to enhance performance of a light pipe by increasing capture of more light flux into a pipe. This paper demonstrates that analytic method can be applied to trace rays through the light pipe system. The method can be used for analysis and design of such system.

6. Acknowledgement

7. References

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