Possibilities of using light pipes to buildings

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Abstract. Daylighting has become a significant parameter in a building design nowadays to achieve more sustainable. The common method of utilization of daylight is to allow its transmission through windows. With such method, only areas a few meters close to the windows are sufficiently illuminated. This paper aims to show that light pipes can be used to bring daylight for illumination in deep interior spaces. The general problem of high-rise building is lacks daylight in a deep space. Light pipes are an example of light transporting systems with highly reflective interior surfaces that are used to transfer natural daylight from both the sun and the sky from the exterior of a building into its interior spaces. A pipe consists of a light collector at the outer end, a light transport section, and light distributor at the inner end. The light collector may be located at roof level or façade a building or located on the building façade. For a new building, roof-mounted light pipes can be designed to provide daylighting for the top floors. For existing buildings, roof-mounted light pipes where the pipes are to extend through some top floors may have limited application, but façade-mounted pipes may still be feasible to apply. The results presented in this paper show that potential of light pipes to commercial buildings is feasible and economical.

1. Introduction

In the past, the adequate standards of living in this world are food, clothing, and housing. Nowadays, people are seeking more than the basic needs but a common reason is to achieve more comfortable. Humanity’s expanding needs are increasing, but our resources are limited. The energy uses in buildings accounts for a large share of the total end use of energy. The global buildings sector consumed 30% of total final energy end-use in 2016. Building account for 28% of energy-related carbon dioxide (CO\textsubscript{2}) emissions. Around 60% of the world’s electricity is consumed in residential and commercial buildings [1]. Energy use in buildings is projected to increase by 32% and electricity use in buildings grows 2% annually between 2015 and 2040. [2]. The building sector is acknowledged to achieve the Paris agreement’s goal of limiting global warming below 2ºC [3]. Improvement of energy efficiency in building sector could limit building energy demand to ensure the ambition. The demand of energy in building varies among regions according to topology, climate, culture, lifestyle, level of economics, age, ownership and location of the building. Energy use in buildings for various purposes: heating, cooling, lighting, and others.

The difficult challenge of building designer is to make occupant comfort by maintaining low-energy use. Renewable energy is an important strategy in order to reach net-zero energy buildings (ZEB), which are addressed in the ZEB Roadmap Examination Committee, Japan [4]. Lighting is a key strategy to
reach net zero energy building by taking advantage of daylight use. In addition, daylight helps occupants to maintain a good health, [2]. Daylighting design approach is to establish more sustainable energy and environment. Study of daylight uses are widespread and various. However, most of technologies and design methods are made for specific cases, [5].

There are various methods to convey daylight through opening into a building such as window, clerestory, roof, etc, [6-8]. There is a technology system called “Core sun-lighting” [9] is used for bringing sunlight to a space is far from window. There are two innovative daylighting systems to illuminate core space of a building which are light guiding system (LGS) and light transporting system (LTS) [10]. Core sun-lighting systems are normally applicable for the buildings in big cities where land cost is expensive. For maximum return of investment, building developers must to build a building upward on a limited space land. The general problem of high-rise building is lacks daylight in a deep space. Light pipes are an example of light transporting systems with highly reflective interior surfaces that are used to transfer natural daylight from both the sun and the sky from the exterior of a building into its interior spaces. A pipe consists of a light collector at the outer end, a light transport section, and light distributor at the inner end. The light collector may be located at roof level or façade a building or located on the building facade [11].

Daylighting performance can be evaluated by using various methods. Initially, performances of light pipe are evaluated by developing theoretical calculation [12,13]. Tracing rays through light pipes with many bends based on analytical method are well validated with those experiments [14,15].

Computer-based design tools are beneficial tool in pre-design process. There are many tools or software for building developers to design and simulate lighting in a buildings such as RADIANCE, DAYSIM, PHOTOPIA, DIVA, AGI, etc., A well-known raytracing software that was developed in 1985 is RADIANCE, which is an open source code and free of charge [16]. Since then many more have appeared including Photopia [17,18]. The programs utilize 3D-creating software to create the connected mesh of polygons such as AutoCAD, SOLIDWORKS, or RHINOCEROUS. In using one of these programs for tracing the travels of rays in light pipe, the user must decide the size of mesh (or the number of polygons) and the number of rays to be used, as both affects accuracy of the results of calculations.

A limited number of studies have assessed cost and feasibility of using light pipes in Japan. This study aims to present economic analysis. There are a lot of different methods of evaluating light pipes. In order to do cost analysis, this study is using theoretical method by Zastrow and Witter [12] to compute light transmission through light pipes which is efficiently and quickly in pre-design stage. In spite of that, there are a few studies on visualization of daylight distribution in building interior through light pipes. In addition, simulation time of creating a scene is very long. These reasons lead to a solution for designing light pipes by getting the pipe designs from the theoretical method and then built in with 3D software for simulating a visualization.

This paper aims to present an example office using light pipes for application in Japan. This paper presents results of modeling and simulation of transmission of daylight through light pipes. The performances of light pipes are calculated and present in this paper. The daylight distributions in the building are illustrated by using a commercial software “DIVA for Rhino”, is a highly optimized daylighting and energy modeling plug-in for Rhinoceros [19].

2. Methodology
The first methodological step is to build model of a standard office building in Japan for representing Japan’s office building. The second step is to assess lighting requirement of the office model when using electric lighting. The next step is to assess the daylight transmission through the light pipe of given configuration from roof-mounted light pipe or facade-mounted light pipe. The last step is to determine the cost of the pipes and the cost of electricity saving by utilizing daylight through the pipes instead of electric light.
An example of building in this study is referred to a standard of office building in Japan [20] as illustrated in figure 1. The floor plan of the office building model is used to illustrate the assessment of the amount of light flux required in details as shown in figure 2.

3. Total light flux and electrical energy cost of office building.

The lumen method is used to calculate total light flux that is required to the office model, it is assumed that LED lamps or lamps with efficacy of 120 lm/W. The value of coefficient of utilization (CU), is determined from room cavity ratio of office space with ceiling and wall reflectance are 70% and 50%, is 0.8. Light loss factor is assumed of 0.7.
Table 1. Requirement illuminance and light flux.

| Zone          | Room area (m²) | Illuminance, E (lux) | Power density, P (W/m²) | Electric power (kW) | Required light flux (lm/m²) | Annual lighting energy (kWh/m²/Y) | Total annual lighting electricity + included cooling load (kWh/m²/Y) |
|---------------|----------------|----------------------|-------------------------|---------------------|-----------------------------|----------------------------------|---------------------------------------------------------------|
| Office        | 7,233.80       | 500.00               | 7.44                    | 53.82               | 892.86                      | 13.59                            | 16.99                                                       |
| Monitoring room | 39.00         | 750.00               | 11.16                   | 0.44                | 1,339.29                    | 20.39                            | 25.49                                                       |
| Circulation area | 3,288.45   | 150.00               | 2.23                    | 7.34                | 267.86                      | 4.08                             | 5.10                                                        |

Note: klm is kilo lumen.

The total area of the office building model of 10,561.25 m², the required light flux of office zone, monitoring zone, and Circulation zones are rounded to 900, 1340, and 270 lm/m², respectively. Assuming the building is operated for 1827 hours. The total lighting energy of the model office building is approximately 38.06 kWh/m²/Y. The efficacy of daylight is at least twice those of artificial light source, so its contribution to cooling load is less than half. Electric light contributes 20% of cooling load. Use of daylight reduces total cooling load by 10%. Electricity from cooling contributes 50% to building total, so daylighting reduces 5% of electrical energy on cooling and thus reduces a total electricity of 25%. Using a cost of 17.22 Yen/kWh for peak load in summer, the net lighting energy cost saving is approximately 2,400 Thousand Yen/Y.

4. Daylight through light pipes for office building

Light pipes can be used to provide spaces far from window or deep zone while daylight through window can provide only perimeter zone as show in figure 3. The visualization is simulated by DIVA to assess the daylight penetration through the window. The target illuminance is set as 500 lux with occupant hour from 9 am to 5 pm during weekday. The total annual hours of occupancy at the work place are 1827.

![Figure 3](image_url)  
Figure 3. Climate-based simulation of the office model by DIVA.

The mean daylight autonomy (500 lux) is 26% for active occupant behavior. The percentage of the space with a daylight autonomy larger than 50% is 29% for active occupant behavior. For this building model, light pipe can be used to provide the area in orange frame, where lack of daylight and far from the perimeter zone as shown in the figure 4.
In order to compute light transmission through the pipes, Zastrow and Witter [12], presented a simple relationship for transmission function of light through a pipe in equation (1). This study is using the relationship to determine possibilities of applying the pipes into the building before designing suitable configuration of pipes for each space utilization.

$$T = \frac{R l \tan \theta}{d_{\text{eff}}} \quad (1)$$

At present, the pipe surfaces are fabricated with aluminium and attached with specular film which have reflectance (R) of 99%. The effective diameter of the pipe ($d_{\text{eff}}$) and the pipe length ($l$) are shown in table 2. The area where required daylight flux in figure 4 which is computed following by the required light flux for each functional room are also shown in table 2.

Daylight availability in this study is used weather data of Tokyo, Japan. Figure 5 illustrates isoclines of hourly global illuminance. The reference global illuminance in the calculation will be taken as 100 klux for roof-mounted pipes. The reference value for façade-mounted pipes when daylight of half sky in front of the façade to be used is 50 klux. The reference angle ($\theta$) of daylight rays enter to the pipe entry is taken as 45˚.

Figure 4. Space lack daylight.

Figure 5. Contour plot of global illuminance.
Table 2. Table: Configuration of light pipes

| Room       | Floor | Type  | Pipe height(m) | Pipe width(m) | Pipe length(m) | \(D_{\text{eff}}\) | Utilized area (m²) | Required Flux(klm) |
|------------|-------|-------|----------------|---------------|----------------|---------------------|---------------------|---------------------|
| Office1    | 7-2   | Roof  | 4              | 4             | 20             | 2.37                | 256.5               | 230.85              |
| Office1    | 1     | Façade| 1              | 4             | 18             | 2.09                | 172.8               | 155.52              |
| Office2    | 7-1   | Roof  | 3              | 3             | 24             | 2.37                | 116                 | 104.40              |
| Hallway    | 7-1   | Roof  | 1.6            | 1.65          | 24             | 1.28                | 213.75              | 57.71               |
| Fac1       | 1     | Façade| 0.5            | 0.25          | 10             | 0.68                | 65.1                | 17.58               |
| Lobby      | 1     | Façade| 0.5            | 0.75          | 12             | 0.28                | 40                  | 10.80               |
| Common     | 1     | Façade| 0.5            | 0.75          | 10             | 0.48                | 52                  | 14.04               |

The light pipes are rectangular which are commonly fabrication as the duct system. A roof-mounted pipes are applicable to employ at the office spaces as illustrated in figure 6. Dimension of the roof-mounted pipes for the office zones are assumed as 4 m wide and 4 m long. The amount of light flux can deliver from the top floor down to the second floor. Daylight available flux, flux used, and the remaining flux through a pipe for the office 1 are shown in table 3. The roof mounted-pipes for office 1, office 2, and hallway are set at the middle of space where lack of daylight as shown in figure 4. Table 3 show remaining flux can provide until the second floor of office 1.

Table 3. Daylight flux available from roof-mounted pipe of office 1.

| Floor number | Distance from roof (m) | Dimension of pipe | Entry Area (m²) | \(D_{\text{eff}}\) | Available flux (klm) | Flux utilized (klm) | Remaining flux (klm) |
|--------------|------------------------|-------------------|-----------------|-----------------|---------------------|---------------------|---------------------|
| 7            | 1                      | 4m x 4m           | 16              | 3.16            | 1594.92             | 230.85              | 1364.07             |
| 6            | 5                      | 4m x 4m           | 16              | 3.16            | 1342.55             | 230.85              | 1111.70             |
| 5            | 9                      | 4m x 4m           | 16              | 3.16            | 1080.33             | 230.85              | 849.48              |
| 4            | 13                     | 4m x 4m           | 16              | 3.16            | 815.07              | 230.85              | 584.22              |
| 3            | 17                     | 4m x 4m           | 16              | 3.16            | 553.47              | 230.85              | 322.62              |
| 2            | 21                     | 4m x 4m           | 16              | 3.16            | 301.78              | 230.85              | 70.93               |
Figure 6. Example of light pipes for office 1.

For façade-mounted pipes, daylight from the sun may not enter for some duration because it can capture daylight from half-hemisphere sky. For this building, office 1 at 1st floor is applicable to apply the pipe which has one-side opening. The dimension of the pipe is shown in table 2 and figure 6. The areas near window are illuminated by daylight through window until 7m. The exit port of the pipe is opened at the center of utilized space, at 18 m from the entry which is the same as length of the pipe. The daylight from the exit port is efficient to provide whole space where lack of daylight from window. The light flux remains to provide the farthest space at 26.2 m. The total of available light flux is approximately 200 klm which is sufficed to provide the space required 155 klm. The example of daylight transmission through façade-mounted pipe for office 1 at 1st floor is shown in table 4.

Table 4. Daylight flux available from façade-mounted pipe for office 1 at 1st floor.

| Distance (m) | Flux entry at facade faced to the sun (klm) | Used light flux (klm) | Remaining flux (klm) |
|-------------|------------------------------------------|----------------------|---------------------|
| 0           | 200.00                                   | 200.00               |                     |
| 7           | 191.29                                   | 0                    | 191.29              |
| 8           | 190.08                                   | 8.1                  | 181.98              |
| 9           | 188.87                                   | 16.2                 | 172.67              |
| 10          | 187.67                                   | 24.3                 | 163.37              |
| 11          | 186.48                                   | 32.4                 | 154.08              |
| 12          | 185.30                                   | 40.5                 | 144.80              |
| 13          | 184.13                                   | 48.6                 | 135.53              |
| 14          | 182.96                                   | 56.7                 | 126.26              |
| 15          | 181.80                                   | 64.8                 | 117.00              |
| 16          | 180.65                                   | 72.9                 | 107.75              |
| 17          | 179.50                                   | 81                   | 98.50               |
| 18          | 178.36                                   | 89.1                 | 89.26               |
5. Assess the cost of pipes and electricity saving in substituting electric by daylight through light pipes

The light pipes are assumed to be fabricated by aluminium sheet (with thickness of 8 mm) with reflective film (reflectance of 99%). The total cost shown in table 5 included material and labour cost [21].

The payback period and net present value (NPV) are determined for cost-effectiveness of the pipe. The parameters of economic analysis are assumed to be used in the evaluation. The lifetime of the project is assumed as 30 years. The projected discount rate is approximately about 1.3%. The escalation rate of electricity according to the time is 8%. The cost of electricity is shown in section 3.

| Material          | Total cost (Yen/m²) |
|-------------------|---------------------|
| Aluminium sheet   | 9,400               |
| Reflective film   | 4,000               |
| **Sum total**     | **13,400**          |

The payback period of installing pipes is about 13 years. Net present value is positive; this means that this project has profitability for investment. For façade-mounted pipes the surface area of pipes is computed along the utilized space however it is possible to reduce material and labor cost. For example, reflectors or concentrators can be added at the entrance to reflect daylight into deeper zone, this solution can reduce the material cost instead of fabrication the long pipes. Although the overall net present value (NPV) of this project result in low positive at the present, because the labor cost of installing pipes is very expensive compare to the current electricity cost. The benefits of the project should not be focused only the money. The advantage of conveying daylight through the light pipes is significantly beneficial to occupant health. This reason is should be included in investment analysis and need to find the greatest NPV solution in the future. And the energy crisis is the most significantly consideration, therefore, a new building should reach zero or less energy consumption by employing more natural resources.
6. An example of simulation of daylight through light pipe by DIVA
The material properties of building and light pipes are assumed to be used in this simulation. Reflectance of wall and ceiling is assumed as 50% and 70%. Reflectance of light pipe is 99%. Glazing transmittance is assumed as 88%. DIVA is used RADIANCE as its engine which provide a forward ray tracing mode to render image for evaluating light transmitted through the pipes. This study presents some visualization examples of light distribution in the office space as shown in figure 7 and 8.

Figure 7. Visualization of light through a roof-mounted pipe for office 1 at 7th floor.
The visualizations in figure 7 and 8 show that the area far from window when the room has no a light pipe, the illuminance is very low. In figure 7(b) and 8(b), the illuminance in the room with a light pipe are higher. The visualizations are useful to view daylight distribution in the room interior, lighting designers can use as a primary tool in the design process.

7. Conclusion
Daylight is necessary for occupant health and beneficial to motivate occupant performance. The result presented in this paper show the possibility of applying light pipes to a standard office building in japan is potential. In economic aspect, light pipes for Japan’s commercial buildings is feasible and worth, as payback period was examined about 13 years. The method of determining daylight transmittance through the pipe is simply to primary examine the possibility and not yet present the actual design. However, this method is able to show the potential of using roof-mounted and façade-mounted pipes. For the future study, the careful design of the pipes is very important to deliver the daylight and aware to cause glare interior. The simulation tool is helpful to visualize daylight environment in design and evaluating process.

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Acknowledgement
This study was supported by the Institute of Science and Technology, Meiji University.