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Application of light pipes to office buildings in Thailand

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Abstract

Daylighting in buildings is aesthetic and energy conserving. 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 and that in certain configurations it is economic to do so in Thailand. For a new building, roof-mounted light pipes can be designed to provide daylighting for the top floors. If the width of a building is not excessive, façade-mounted light pipes that have daylight entry ports on opposite east and west facades could be used. 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 application of light pipes to commercial buildings is feasible and economical.

Keywords: light pipe, daylighting, core daylighting.

1. Introduction

Commercial and residential buildings consume energy at 40% of total and electricity at up to 70% of total in a country [1]. In Thailand, the building sector consumes electricity at 57% of total [2].

Once constructed, a building will use energy at a level corresponding to its design until its major systems require replacement or parts of the building require retrofitting, which may occur every 30-40 years while basic energy performance of the system may not change during the period. Such period is much longer than the lives of industrial machines and equipment in industry and in other economic sectors.

The benefits of building energy efficiency do not accrue only to building owners and proprietors, energy efficient buildings lead to reduction in the costs expended in sourcing, producing and transporting energy in an expanding energy system in a developing economy. Therefore, the benefits also accrue to the society as a whole.

Electric lighting in a building is energy intensive and is second only to the air-conditioning. In Thailand, electric lighting contributes 20% of electricity consumption in large buildings, [3]. Fluorescent lamps and other lamps generally used are able to convert 25% of electricity supplied to light. At present, efficacy or energy efficiency of electric lamps is less than 150 lm/W. Efficacy of daylight transmitted through spectrally selective glass (such as low-E glass), where the infrared radiation is attenuated, is close to 300 lm/W, [4]. In this case, Watt here is radiative power (thermal), not electric.

Daylight is abundant during daytime in all locations in Thailand. Thai sky is luminous and day length extends to almost half of a day for every day of the year. Air-conditioning in buildings creates a situation where heat gain from windows due to exterior driving forces that include solar radiation is undesirable and must be minimized.

There are various methods to convey daylight through openings into a building such as window, clerestory, roof, etc. For maximum return of investment, building developers build a building upward on a limited plot of land. The general problem of high-rise building is the lack of daylight in deep spaces. Mirrored light pipes have high potential to be used for daylighting [5]. A CIE report examines tubular daylight guidance systems and distinguishes roof-mounted systems from façade-mounted systems [6]. For a roof-mounted system, diffuse skylight from the whole hemisphere as well as direct sunlight can enter into the system, while a simple façade-mounted system receives daylight from the half of hemisphere in front of it.

Light pipes have been individually designed and installed in buildings [7-10], but small roof-mounted light pipes comprising passive input domes and discrete output ports are increasingly commercially marketed. Rectangular light pipes fit well horizontally in the rectangular plenum above the ceiling of a building and are thus mostly façade-mounted. A document [11] reports results of a survey of light pipes installed in Thailand. Most respondents in the survey were unaware that the spaces were illuminated by daylight transmitted through light pipes. The spaces were illuminated to 300-500 lux which is comparable to spaces illuminated by electric lighting.

This paper aims to illustrate through examples that daylighting using light pipes possesses economic potential for application in Thailand. For illustration, a detailed description of application of light pipes to a new office building is presented here.

2. Methodology

The methodological step to be used here is first to adopt reference available daylight levels and daylight attribute where daylight is assumed to enter into roof-mounted light pipes and facade-mounted pipes for lighting of building core spaces. The next step comprises utilizing an office model for detailed assessment of its lighting requirement when electric lighting is used. This includes assessing the requirement on the amount of light flux required at each floor of the building and the corresponding electric power requirement. The following step is to assess the amount of daylight available from a light pipe of given size and configuration and at a given distance from top (for roof-mounted pipes) or from the façade (for facade-mounted pipes) of a building and the size of floor area the given pipe can serve.

The last step is to assess the costs of pipes and the cost of electricity saved in substituting electric lighting by daylighting through light pipes. The economic criteria to be used for determining cost-effectiveness the pipes include payback period and net present value.

3. Daylight Availability

Daylight availability refers to the extent of daylight from the sun and daylight from the sky that can be utilized at a location [12-15]. Figure 1 shows graphs of isoclines of hourly average global (horizontal), beam (normal), and diffuse (horizontal) illuminance for each month of a year, [16]. From the graphs, it can be surmised that by 8.00 and before 17.00 hourly global illuminance exceeds 30 klux, beam and diffuse illuminance exceed 10 klux. For the time near noon, global illuminance exceeds 70 klux and beam and diffuse illuminance exceed 40 klux.
From the summary information above, the reference global illuminance to be used in the investigation here will be taken as 50 klux, an approximate average between the minimum and maximum for the daytime working hours. This will be used as the reference illuminance for roof-mounted pipes. For façade-mounted pipes, only daylight from the half sky in front of the façade is available, so the reference value to be used is 25 klux. As it will become clear later, there is a need to adopt a reference angle of entry of daylight into the pipes. This reference angle is taken as 4

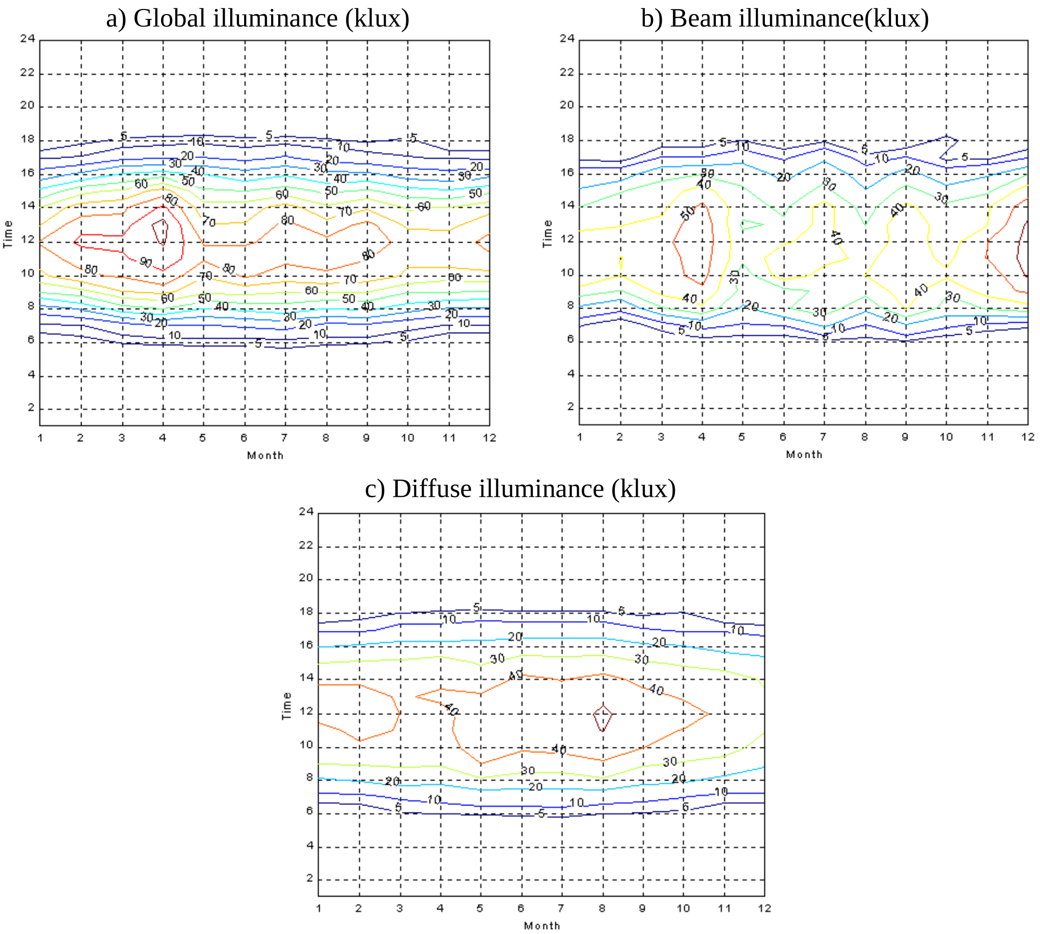

Figure 1 Contour plots of daylight illuminance.
Note: klux = kilo lux.

4. The amount of light flux (Luminous flux) required and energy cost in office buildings

An office building model is used to illustrate the assessment of the amount of light flux required in details. Figure 2 shows a perspective view of the model and Figure 3 shows floor plans of the model. The building comprises a food court on the ground (1st) floor and the 2nd to 12th floor of office. On each floor, the core service area takes up 18x18 = 324 m^2 while the main utilization area takes up 700 m^2. The height of each floor is 4 m, but the floor to ceiling height is 3 m. The operating time of the building is assumed to be between 8.00 to 17.00 hour, from Monday to Friday. This model is similar to that used in the development of the building energy code for Thailand [3].

In order to calculate total light flux required to be supplied to this building model, the lumen method of lighting calculation is used and it is assumed that T5 fluorescent lamps or lamps with efficacy of 80 lm/W (total electric power of lamp and ballast or total power supply for a set) are to be used.

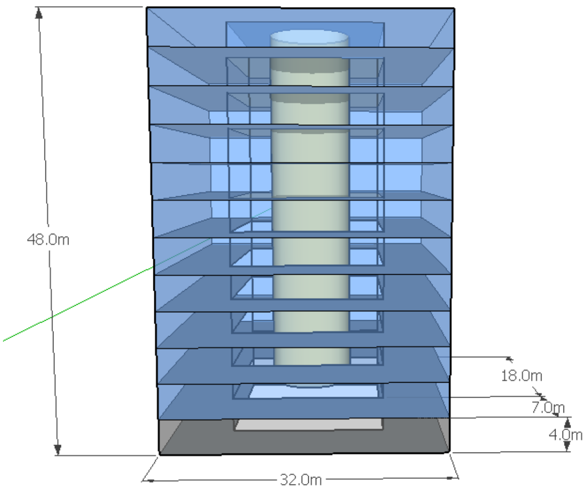

Figure 2 A perspective view of the office building model with a circular light pipe.

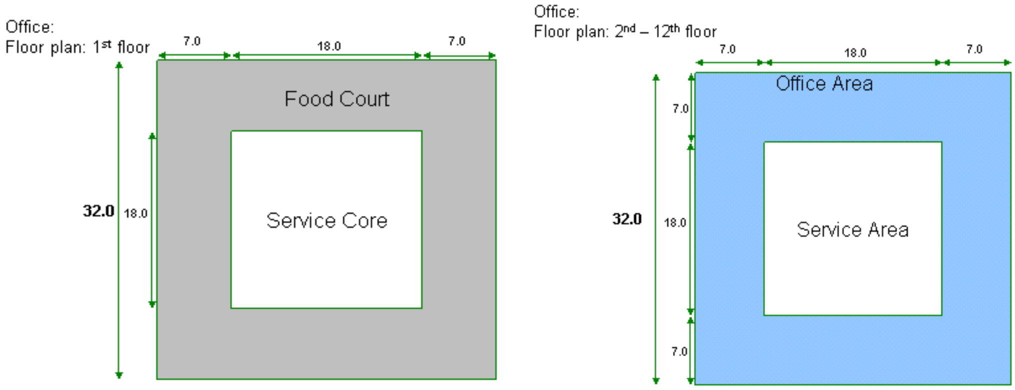

Figure 3 Floor plans of the building model.

For the lumen method, the illuminance E is calculated from the relationship

$$E = (CU)(LLF)(E_f)\left(\frac{P}{A}\right)$$

where CU = coefficient of utilization, its value is obtainable from tables produced by luminaire manufacturer,
LLF = light loss factor,
E_f = efficacy of the lamp set (lamps and ballasts),
P/A = electric power per unit area taken by the lamp set.

For the office area, partitions are assumed used in some areas. The food court area is assumed a larger continuous space. The service area comprises smaller contiguous spaces than the area of the food court. The base area in each type of space assumed for determining the value of the coefficient of utilization (CU) in the application of the lumen method is given in the second column in Table 1. Based on the assumption of the use of common parabolic reflector fixtures, the values of coefficients of utilization for each space are determined and shown in the third column. The illuminance levels assumed for each type of spaces are shown in the fourth column. The levels are compatible with those adopted by the Thailand Illuminating Engineering Association (TIEA). Assume a value of LLF of 0.7, given the efficacy of 80 lm/W and the required illuminance in the fourth columns in the table, the values power density P/A is then calculated from the relationship [1] and shown in the fifth column. With the total area of each type of space given, the total required electric power and light flux of each type of space are calculated as shown in the sixth and seventh columns.

Table 1 Data on required illuminance and calculated total electric power and light fluxes.

Area	Base area	CU	Illiminance, E (lux)	Power density (W/m^2)	Electric power (kW)	Light flux (klm)
Food court	20mx20m	0.8	300	6.7	4.7	375
Office Space	5mx5m	0.55	500	16.23	125.0	10,000
Circulation	10mx20m	0.74	150	3.62	14.1	1,126
Building total					143.8	11,501

*Note klm = kilo lumen

4.1 Total light flux and electrical energy cost of office building

Given the total area of the office building model of 12,288 m^2, the average required light flux is 936 lm/m^2. For simplicity the figure is rounded to 1,000 lm/m^2.

Assuming the building is used six days per week for a total of 2,808 hours, the total lighting energy of the model office building is then calculated as 403,681 kWh or 32.85 $kWh/m^2/Y$. 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% of lighting elctricity or 41.06 $kWh/m^2/Y$. Using a cost of 4.4 Bahts/kWh, the net lighting energy cost saving is 2,229,246 B or approximately 180 $B/m^2/Y$.

5. Application of light pipes to office buildings

Light pipes can be used to provide ‘core daylighting’ where transmitted daylight through them is used to light up the core or inner spaces of a building while daylight transmitted through windows could provide light to the peripheral spaces of a building. For the building model exhibited in Figure 2 and 3, it is assumed that daylight through windows penetrates up to 6 meters from the windows of each façade. Light pipes are used to provide daylight in the inner core of size 20 m x 20 m or 400 m^2 of the core area. In the followings, the light flux requirement of the office building is taken as 1,000 lumens per square meter of the space as summarized in the last section, without distinction on the particular type of space.

Roof-mounted light pipes are assumed to be used to receive daylight from the roof of the building model. The vertical pipes can be designed to extend through the top floors of the building up to the extent that available daylight through them is utilized. As will be shown, roof-mounted pipes are more economic and should be used for new buildings. Façade-mounted light pipes can be used on the lower floors where daylight from vertical roof-mounted pipes cannot reach. Façade-mounted pipes are less economical but can be designed to be used at lower floors of new buildings or retrofitted to the floor plenums of existing buildings.

5.1. Attenuation of light as it transmits through a pipe

When light transmits through a pipe, its radiative power is partly absorbed when it strikes the surface of the pipe. Zastrow and Wittwer, [5], consider transmission of light beam across light pipes and offer a simple relationship for the transmission of light through a cylindrical pipe as a function of the length of the pipe, the diameter of the pipe, and the angle between the light beam and the pipe.

The transmission function, T, of a pipe can then be obtained as:

$$T = R^{l \tan\theta / d_{eff}}$$

where R is the reflectance of the pipe surface,
l is the pipe length, and
θ is the angle of incidence of the light rays with the pipe, and
d_{eff} is the effective diameter of the pipe.
For a cylindrical straight light pipe with a diameter of D:

$$d_{eff} = \frac{\pi D}{4}$$

Zastrow and Wittwer also observes that d_{eff} can be expressed as a function of the cross-sectional area of a pipe. For cylindrical pipe, $d_{eff} = 0.89A^{0.5}$, and for symmetrical triangular pipe, $d_{eff} = 0.69A^{0.5}$. Daylight entering the aperture of a pipe comprises daylight from the sun and daylight from the sky. The entry angle of light from the sun changes with time and location and daylight from the sky enters from all directions in the sky hemisphere. For simplicity, both components are treated as one and as if it enters at 45° as stipulated in Section 3 on daylight availability. At present, light pipes fabricated with aluminized surfaces have specular reflectance of up to 95% and is economical, so this is assumed used in this paper.

5.2 Application of roof-mounted cylindrical pipes to office buildings

Anidolic or non-imaging concentrator can be used to concentrate or increase light flux into a light pipe [16-18]. However, highly concentrated daylight poses danger of damage to the eyes or other sensitive receivers. So, in this paper, only a concentration ratio of 2 will be used for roof-mounted pipes. Also, light pipes with larger diameter offers more advantage as its cross-sectional area is proportional to the square of its diameter. Very large pipes may pose problems in the construction and installation, so pipes of diameter of 5m only are assumed used. If one pipe delivers inadequate daylight flux, more pipes could be employed.

For the light pipe with diameter of 5 m, the cross-sectional area of the pipe is 19.63 m^2. Given reference light flux of 50 klux and concentration ratio of 2, the total light flux at entry to the pipe is 1,963.5 klm. For this pipe d_{eff} = 3.93. Using the transmission function of Zastrow and Wittwer, the expression for light flux along the pipe is $\Phi = 1,963.5(0.95)^{\frac{d \tan 45^{\circ}}{3.93}}$, where d is the distance from roof or the entry aperture of the pipe. The ceiling of the 12th floor is at 1m from the roof, so the amount of light flux available 1,938 klm. From the office building model used, the flux from the pipe will be used to illuminate the core area of 400 m^2. The required amount of light flux is 1,000 lm/m^2, so the total flux required per floor is 400 klm. The figures in the first row of Table 2 show the available flux, the flux used, and the remaining flux that travels 4m down to the ceiling of the 11th floor, where the available flux becomes 1,460 klm. The figures in Table 2 illustrates that the given light pipe can illuminate 4 floors from the roof, down to the 9th floor. Total light flux supplied by the pipe and utilized to illuminate the floors is 1,600 klm.

Table 2 Daylight flux available and utilized at each floor.

Floor number	Distance from roof, m	Available flux, klm	Flux utilized, klm	Remaining flux, klm
12	1	1,938	400	1,538
11	5	1,460	400	1,060
10	9	1,006	400	606
9	13	575	400	175

If another light pipe of the same dimension and same concentrator is employed to provide daylight flux to the 8th floor and the lower floors, the figures in Table 3 illustrate the situation. Even daylight flux is not released between the 12th floor and the 9th floor, the available flux at the 8th floor is 1,593 klm. The second pipe can illuminate 3 floors and supplies 1,200 klm.

Table 3 Daylight flux available and utilized starting from the 8th floor.

Floor number	Available flux, klm	Flux utilized, klm	Remaining flux, klm
12	1,938	-	-
11	1,839	-	-
10	1,746	-	-
9	1,657	-	-
8	1,573	400	1,173
7	1,113	400	713
6	677	400	277

Similarly, a third pipe can be used to supply floor 5, 4, and 3, and a fourth pipe for floor 2 and 1. Table 4 shows the situation of light flux utilization.

Table 4 Daylight flux available and utilized starting from the 5th floor.

Pipe number	Floor number	Available flux, klm	Flux utilized, klm	Remaining flux, klm
3	5	1,938	400	944
	4	1,839	400	496
	3	1,746	400	71
4	2	1,149	400	749
	1	711	400	311

5.3 Application of façade-mounted rectangular pipe to office buildings

For very tall buildings, daylight from roof-mounted pipes cannot reach the lower floors, and façade-mounted pipes can be employed instead. Also, for existing buildings, it is impractical to extend a light pipe through floors, but the plenum between the ceiling and the upper floor in some cases can be utilized to accommodate a façade-mounted rectangular pipe.

The span between two columns in most tall buildings exceeds 5 meters. The plenum space between the columns usually accommodates electrical cables and air supply duct. This type of space is assumed available in some existing buildings or provided for in new buildings for installation of façade-mounted light pipes.

The cross-sectional area of a façade-mounted light pipe to be used with the office building model here is assumed to have a width of 5m and a depth of 0.9 m, and a cross-sectional area of 4.5 m^2. One important disadvantage of the use of a façade-mounted pipe in tropical location is that daylight from the sun may not enter for some duration. For example, if the entry port of a pipe faces east, it will receive both sunlight and daylight from sky in the morning, and receives only daylight from the sky in the afternoon. To overcome this problem, the light pipe should extend over the width of the building, so that sunlight in the morning could penetrate to and be shared at the west end. This is vice and versa for the afternoon period. Figure 4 illustrates the configuration of such pipe. Similar configurations should be used for light pipes oriented north-south. The reference illuminance is 25 klux (when sunlight and skylight are present) at the entry of a façade-mounted pipe. In order to raise this level to the level comparable to that of the roof-mounted pipes, a concentration ratio of 4 is used.

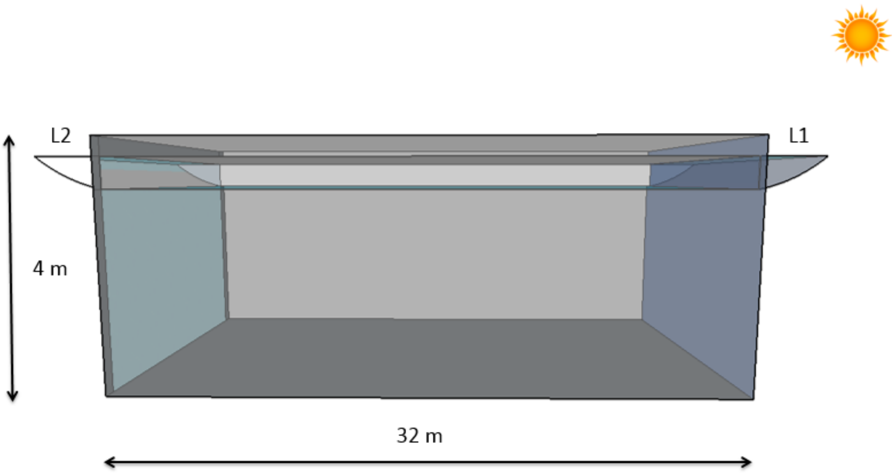

Figure 4 Side view of a façade-mounted pipe.

The amount of light flux at entry port of the pipe is 450 klm. In order to utilize the transmission function of Zastrow and Wittwer, the value of d_{eff} *for* this pipe must be evaluated. The square root of the cross-sectional area of this pipe is 4.5^0.5 = 2.12. The value of d_{eff} should be between 0.69x2.12 and 0.89x2.12. For convenience d_{eff} is taken to be 1.6. Suppose the pipe in Figure 4 is oriented east-west. In the morning, the reference daylight flux on the east, here assumed on the right hand side in Figure 4, is 100 klux. The daylight at the entry port on the west comprises only daylight from the sky. It is further assumed here that the reference daylight at entry on the west is 50 klux (with the concentration ratio of the anidolic concentrator of 4), giving a total flux of 225 klm.

Using the transmission function of Zastrow and Wittwer, available light flux contributed by daylight that enters from the east and daylight that enters from the west and the sum total along the length of the pipe are shown in Table 5. Note that light flux from the light pipe is used only in the core area at a distance 6m from the peripheral zones. So at distance between 0 and 6, and at between 26 and 32, the area will be illuminated by daylight through windows.

Table 5 Available light flux along the length of the pipe.

Distance from east, m	Light flux from east port, klm	Light flux from west port, klm	Total light flux, klm
0	450	81	531
6	371	98	469
7	360	101	460
14	287	126	414
18	253	144	396
25	202	180	382
26	196	186	381
32	161	225	386

Between distance 7m and 25m, the sum total of available light flux varies between 460 and 382 klm. The requirement of light flux for the office building is 1000 $lm.m^{-2}$ as summarized in Section 4. If the average value of this available flux, 413 klm, is used to meet the requirement over the distance of 20 m of the core area, the width of this area that the flux can be utilized is more than 20m This means that only one light pipe of width 5m are needed to provide total light flux to meet the requirement of illuminating the core office space of 400 m^2.

6. Economics of applications of the light pipes

The light pipes are expected to be fabricated from aluminium sheet and reflective aluminized film. Table 6 shows costs of both materials and labor. The labor cost is taken as half of the material costs.

Table 6 Costs of materials and labor for pipes.

Material	Cost (B/m^2)	Labor cost, B	Total cost(B/m^2)
Aluminum sheet	180	90	270
Reflective film	1,089	544	1,633
Sum total			1,903

The cost of a pipe system should include auxiliary pipes to carry light flux from the main pipe to the space below. It is assumed that the cost electricity will escalate with time. The following economic parameters in Table 7 are to be used in the evaluation.

Table 7 Values of parameters to be used.

Discount rate, %	Escalation rate, %	Number of years of life	Worth of saved electricity, $B.m^{-2}$	SPWFE
6	4	30	180	22.64

Note SPWFE = series present worth factor with escalation. The value of the electricity saved is concluded in Section 4.

6.1 Economics of applications of roof-mounted pipes

The diameter of the cylindrical pipe for each roof-mounted pipe is 5 m, the width of its circumference is then 15.71 m. Four pipes are used for the office building model. One shorter pipe will serve floor 12 down to floor 9. The second longer pipe will serve floor 8 to floor 6. The third pipe will serve floor 5 to floor 3, and the fourth pipe will serve floor 2 and 1. Table 8 shows the cost and economic figures

Table 8 Length, cost and economic figures of the roof-mounted pipes.

Length, m	Area, m^2	Cost of main pipe, B	Cost of auxiliary pipe, B	Total cost, B	Worth of electricity saved, B/Y	Payback period, Y	Net present value, B
13	204.2	388,599	388,599	777,199	288,000	2.70	5,741,729
25	392.7	747,306	388,599	1,135,906	216,000	5.26	3,753,290
37	581.2	1,106,013	388,599	1,494,613	216,000	6.92	3,394,583
45	706.9	1,345,151	388,599	1,733,751	144,000	12.04	1,525,713

It is assumed that the cost of auxiliary pipe is identical to the cost of the first main pipe. Although the subsequent pipes are longer, the auxiliary pipes should have the same configuration as those of the first pipe. All four pipes have positive NPV, but the pipe that serves the top four floors is most economical.

6.2 Economics of applications of facade-mounted pipes

The width of the rectangular pipe is 5m, depth is 0.9m, and length is 32m. Table 9 shows the cost and economic figures of this pipe.

Table 9 Length, cost and economic figures of the facade-mounted pipes

Length, m	Area, m^2	Cost of main pipe, B	Cost of auxiliary pipe, B	Total cost, B	Worth of electricity saved, B	Payback period, Y	Net present value, B
32	377.6	718,573	359,286	1,077,859	72,000	14.97	551,873

The cost of auxiliary pipe is assumed half of the cost of the main pipe since the main pipe runs along the length of the building and the length of the auxiliary pipe would not need to be as long as that for the roof-mounted pipe. However, the light flux from the façade-mounted pipe serves only the core area of one floor. The worth of electricity saved is smaller than those of roof-mounted pipes. However, the NPV of the façade-mounted pipe is positive.

7. Enhancing economics of application of light pipes

The foregoing economic figures from the applications of light pipes illustrate that the costs of light pipes, the configuration of the pipes, and the way the light flux delivered by the pipes is utilized are relevant to the economic attractiveness.

The costs of the pipes here may be under or over estimated. At present, there is no industry that can supply large pipes on a large scale. With the economy of scale and if there is a proliferation of the use of light pipes, the costs may be reduced. One example is the assumption of the use of reflective film on the interior surface of the pipes of 1,089 B/m^2. With industrial scale production, the surface could be coated directly during fabrication of the pipe instead of preparing the film and affixing it on the pipe surface.

The main dimension, the diameter, the width and depth, of the pipes presented are limited to 5 m. Pipes with larger cross-sectional dimensions can transmitted more light flux and have less attenuation (d_{eff} being larger).

Light flux is assumed utilized in the core area of the building only. The benefits of daylighting from application of light pipes in the economic analyses account only the core area. In practice, when daylighting is planned, daylight would be used to illuminate all areas that include the peripheral areas. If the benefits of daylighting of all areas are accounted, the economic figures (the payback period and NPV) will become much more favorable (The total area of one floor is 1024 m^2, where only the core area of 400 m^2 is accounted).

8. Conclusion

Daylighting using light pipe offers an effective means of bringing daylight into building interior. The results presented in this paper show that application of light pipes to commercial buildings is feasible and economical. Basically, cylindrical light pipes of 5 m in diameters are shown to apply economically to buildings of up to 12 stories and 48 m high. For taller buildings, rectangular façade-mounted pipes of width 5m are also shown be applicable for the lower floors with reduced benefit, but are still economical.

The methodology used employ building models and simplified analysis such that the requirement for supplementary electric lighting is not dealt with, since the aim of this paper is to examine the potential application of light pipes and not to present actual design. However, the methodology used is able to illustrate the potential and constraints of both roof-mounted and façade-mounted pipes. Even the paper does not illustrate how non-imaging concentrator could be constructed and employed, there are literatures that deal with the issue directly. The methodology assumes a modest value of concentration ratio in the belief that it will be more credible.

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