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Daylighting through Light Pipe for Deep Interior Space of Buildings with Consideration of Heat Gain

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Abstract: Daylighting has been perceived to possess high potential for application in tropical climate. Traditional method of daylighting utilizes daylight from sky (skylight) through window on the side of a building (sidelighting). Such application requires extensive shading to prevent direct light from the sun (sunlight) from entering since it will introduce excessive radiation into the interior, which is now extensively air-conditioned. Another drawback of sidelighting is that the level of resulting illuminance falls exponentially with distance from the window into the interior. Use of light shelves might help overcome this limitation to some extent but its applicability and effectiveness are limited to certain time of a day and to certain months of the year in tropical region. Study on the use of tiltable mirror for reflecting sunlight through light pipe to illuminate the deep interior space of a building is reported in this paper. A ray tracing technique was used to calculate sunlight reflected from a tiltable mirror into the light pipe and its reflection at the end of the light pipe into the deep interior space in the building. mathematical model has been developed for calculating the resulting illumination. The model also accounts for the heat gain across the wall of the light pipe into the ceiling plenum, into the room below and that reaches the illuminated space. Physical experiments conducted confirmed the expected accuracy of the model. The model can be used to trade off between heat gain and its effect on air-conditioning load and light gain for various configurations of light pipe.

Keywords: Daylighting, Light Pipe, Sunlighting, Ray Tracing, Sun Tracking.

Introduction

The use of day lighting for illumination in building offers great potential for both energy conservation and increased human comfort. Considerable researches have been conducted on using natural daylight for illumination of interior room space of both domestic and commercial buildings. Daylight through window can provide sufficient illumination only within 5 m from window. Moreover daylight level falls exponentially with distance from the window into the interior. However, the use of larger windows to provide sufficient illumination in deep interior space has proven to be ineffective. Light pipe and mirror system is one of the configurations that can provide higher work plane illuminance levels deeper into a space. Some studies focused on vertical light pipes. Oakley presented daylight performances of six vertical light pipes (top day lighting), located in three different areas: a workshop, a residential landing, and a small office [1]. Jenkins (2003) proposed a model that can predict the light levels resulting from a pipe of given dimensions and also proposed methods of calculating for overcast skies [2]. Jenkins (2004) summarized operational uses of several methods including comparative calculations of similar models in its reflection at the end of the light pipe [3]. Vertical light pipe provides very high illumination on the workplane but it can only illuminate the room in top floor of a multi-storied building. The horizontal light pipe and mirror system can be installed in a room in any floor of a building and can provide workplane illuminance over substantial daytime operating hours of a year. Scartezzini designed, installed and experiment with three different anidolic systems (anidolic ceiling, integrated anidolic system, and anidolic solar blinds) under clear and overcast sky condition [4]. Beltran conducted experiment for four different types of horizontal light pipes in office room (with depth 9.1m) to provide higher workplane illuminance levels deep into the space [5]. Canziani described in very detail the installation and demonstration of the light pipe in a test simulating room. Daylighting performances were simulated in different conditions of external illuminance and an assessment of the lighting energy savings was included [6].Chirarattananon developed a model of light delivery and heat transfer based on a general configuration of a plenum in a test room [7]. In his experiment, the whole plenum here was used as a light pipe. The calculation results were compared with results from physical measurements.

Study on the use of movable mirror for reflecting sunlight through light pipe to illuminate the deep interior space of a building is reported in this paper. To investigate the effectiveness of light pipe and mirrors system, a mathematical model for calculation of illumination on surfaces of the room is developed. A ray tracing technique was used to calculate sunlight reflected from tiltable mirror into the light pipe and its reflection at the end of the light pipe into the deep interior space in the building. The model also accounts for the heat gain across the wall of the light pipe into the ceiling plenum, and into the room below. Modeling of the process of daylight delivery and mechanisms of heat transfer will enable trading off between light gain and increased air-conditioning load.

In this study, a number of experiments have been conducted using an experimental room, an outdoor laboratory area in Energy Park of the Asian Institute of Technology (AIT) to validate various algorithms used by comparing calculation results with results from physical measurements. Lux meters, heat flux meters, thermocouples and pyranometer were installed in a test room, in light pipe and attic to measure illuminance, temperature, heat flux and solar radiation. The values of weather parameters used were record as 15-minute data. These parameters include ambient temperature and relative humidity, direct and diffuse daylight, direct and diffuse solar radiation, infrared radiation from sky, temperatures on surface of ground and wind speed. Experimental values were compared with results from output of simulation program. The comparison shows that the mathematical model is reasonably accurate. The outputs of the computer program are illuminance on surfaces of the room, temperatures, heat flux of all sections and cooling coil load for the test room. The model would be useful to identify the most effective configuration of light pipe and mirror system.

Design of Light Pipe System in Experimental room

Experimental room

A measurement was conducted using an experimental room 6m width x 6m depth x 2.65m ceiling height (exterior dimension) in Energy Park in AIT (Fig. 1). A window (6m width x 1.5m height) is located on the East wall of the room. In this experiment, the window was covered by opaque PVC sheet to obstruct the daylight coming into room. Tilted roof is used, with the roof ridge aligns along East-West direction. The room is supported by a steel frame. The walls consist of light construction material: Cellocrate, microfibre glass wool as an insulation and gypsum. The room is divided into two identical parts by one internal wall aligns East-West direction: South and North parts. Horizontal light pipe and mirror system was installed in the south part of the room for conducting the measurements and verifying the developed model. Vertical light pipe was installed in the other part of the room for studying of top lighting (other study).

Design of light pipe

The design of light pipe and mirror system is presented in Fig. 2. The light pipe is designed to fit within the ceiling plenum (attic). It needs to be small enough to fit with other building subsystems (air-conditioning system, lighting, water pipes, etc.) within the ceiling plenum. The square (0.55m x 0.55m) aperture was covered by 3mm clear glazing with 87% transmittance. The length of light pipe was set at 5.75m (interior depth of the test room) and the cross section width and height was 0.55m. Interior surface of light pipe was covered by two different types of material. A specular reflective aluminum sheet (with 78% specular reflectance) was used on the 4.6m long from aperture of light pipe. A diffuse white polyethylene foam (with 89% diffuse reflectance) was used on the 1.15m at the back end of light pipe. The distribution opening (0.55m x 1.15m) was formed by 6mm clear glazing with 84% transmittance at the back end of the light pipe and located on the ceiling. Three mirrors were designed to increase the illuminance in the room space. The horizontal mirror was located horizontal and touched to the lower edge of aperture. The vertical mirror was located vertical and touched to the side edge of aperture; this mirror may attach on the right or left of light pipe depending on the position of the sun in the sky. The tiltable mirror was stood at front of aperture with distance 4.2m from it; and the height of this mirror (2.925m) was at the same level of light pipe. The tiltable mirror can turn manually so that the reflected sun ray always comes along the light pipe and touches the back surface of light pipe. Parameters and materials of experimental room, light pipe and mirror system are summarized in the Table 1

Fig. 1 Experimental room and mirrors.

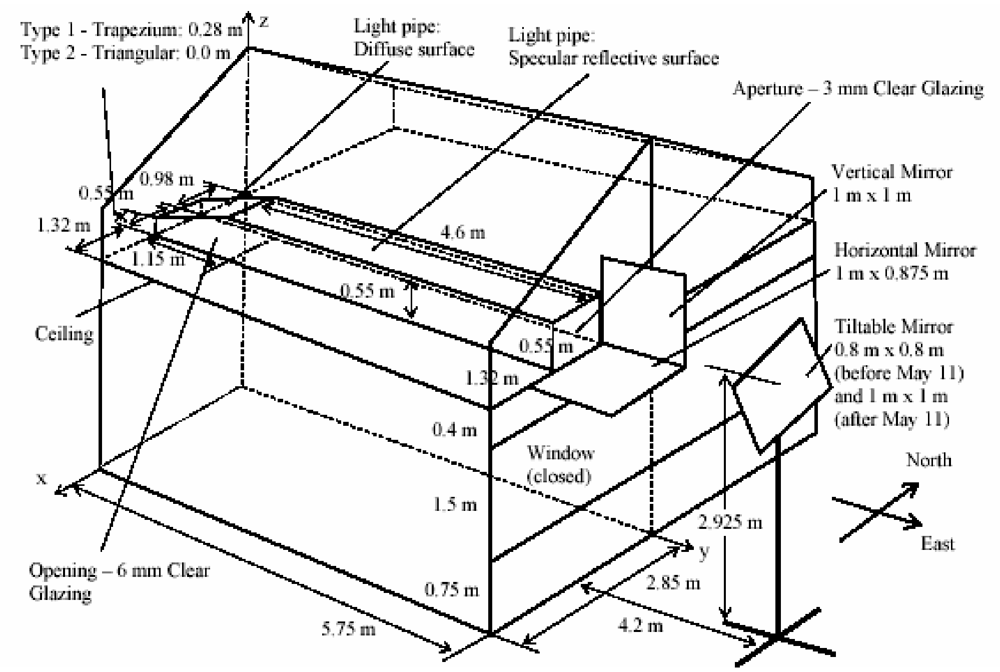

Fig. 2 Design of Light Pipe in experimental room (all value is the interior dimension)

Table 1 Parameters and materials of experimental room, of light pipe and mirror system

Item of experimental room	Dimension (m)	Area (m^2)	Surface property		Material
			Property	Value	
Room					
Wall	5.75 x 2.85 x 2.65	45.58	Diffuse reflective	0.7	Gypsum; Glass wool; Cellocrate;
Ceiling	5.75 x 2.85	16.3875	Diffuse reflective	0.7	Gypsum
Floor	5.75 x 2.85	16.3875	Diffuse reflective	0.42	PVC
Aperture	0.55 x 0.55	0.3025	Transmittance	0.87	3mm clear glazing
1st part of light pipe	0.55 x 0.55 x 4.6	10.12	Specular reflective	0.78	Aluminum sheet; wood
2nd part of light pipe					
Light pipe type 1	-	1.7582	Diffuse reflective	0.89	White polyethylene foam; wood
Light pipe type 2	-	1.3336	Diffuse reflective	0.89	White polyethylene foam; wood
Opening	0.55 x 1.15	0.6325	Transmittance	0.84	6mm clear glazing
Horizontal mirror	1 x 0.875	0.875	Specular reflective	0.78	Aluminum sheet; metallic frame
Vertical mirror	1 x 1	1	Specular reflective	0.78	Aluminum sheet; metallic frame
Tiltable mirror*					
Before 11 May 04	0.8 x 0.8	0.64	Specular reflective	0.65	Aluminum sheet; metallic frame
After 11 May 04	1 x 1	1	Specular reflective	0.65	Aluminum sheet; metallic frame

*Note * - The 1st tiltable mirror was fall and break downs, then it was replaced by the 2nd one.*

To increase overall efficiency of the light pipe, the section above opening (at the end of light pipe) was designed with an inclined angle. This study considers two types of light pipe corresponding to two different inclined angles of this section (see Fig. 2). Two types were called trapezium light pipe and triangular light pipe

Sensors and data measurement

Illuminance on the floor and walls of the test room due to sunlight entering into room through light pipe was measured by a lux meters. Five points on the floor: “point 90%”, “point 70%”, “point 50%”, “point 30%”, “point 10%”; two points on the walls (west and south) (Fig. 3) and one point under opening were measured.

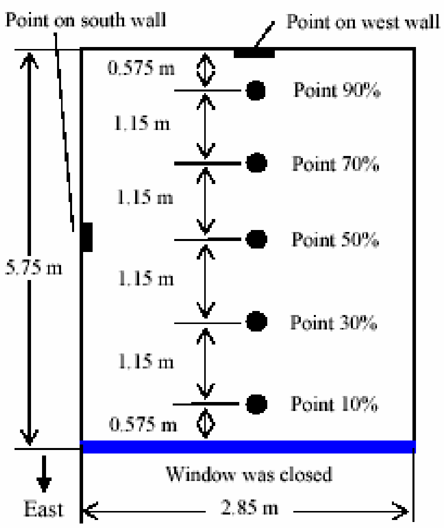

Fig. 3 Points on the floor and walls for illuminance measurement

Temperatures on surfaces of roof, ceiling, light pipe, wall and temperatures of air in the room, light pipe and attic were measured using thermocouples. Heat fluxes through roof, ceiling, wall of light pipe and wall of the room were measured using a heat flux meters. The pyranometer was used to Tiltable measure solar radiation on the point under opening. The dataloger was recorded and stored as 15-minute interval data during 7:00-17:00.Ambient temperature and relative humidity, direct and diffuse daylight, direct and diffuse solar radiation, infrared radiation from sky, temperatures on surface of ground and wind speed are routinely measured and recorded in the station in Energy Park, AIT

Experimental schedule

The study was conducted experiment for two types of light pipe: 1) The trapezium light pipe (at the end); and 2) The triangular light pipe. Experiments combines each type of light pipe with four different cases of mirrors: a) Light pipe with horizontal mirror, b) Light pipe with horizontal and vertical mirrors, c) Light pipe with horizontal, vertical and tiltable mirrors and d) Light pipe with horizontal and tiltable mirrors. The measurements were conducted for 17 days in year 2004. They are 17, 18 Mar; 17, 30 April; 19, 25, 30 May; 3, 4, 26, 30 June; 5 July; 17, 24, 25, 26 August and 23 September. Table 2 represents the experimental schedule

Table 2 Experimental schedule

	Type of light pipe	Type of mirrors	Experimental date
1	Trapezium	a) Horizontal	17 Apr, 19 May
		b) Horizontal + Vertical	25 May, 3 Jun
		c) Horizontal + Vertical + Tiltable	17, 18 Mar *, 30 May, 4 Jun
		d) Horizontal + Tiltable	30 Apr
2	Triangular	a) Horizontal	17, 24, 26 Aug
		b) Horizontal + Vertical	26 Jun, 5 Jul
		c) Horizontal + Vertical + Tiltable	30 Jun
		d) Horizontal + Tiltable	25 Aug, 23 Sep

*Note: * - No air-conditioning in test room on these days.*

Model Development

Daylight calculation

Beam sunlight and diffuse skylight enters the light pipe through transparent aperture. The ray tracing technique [7] is used for analytical treatment of sunlight, while the flux transfer method [8] is used for analysis of the diffuse light component. A rectangular coordinate is set up as shown in Fig. 2. Each section (plane surface) of the room, light pipe, mirrors is represented by its corner point. ***For beam sunlight,*** a sunlight incident on a surface of aperture of light pipe is assumed to produce five components as shown in Fig. 4. Specular reflection component is in the same plane formed by the incident and the plane normal. Its reflection angle is equal to the incident angle. Diffuse

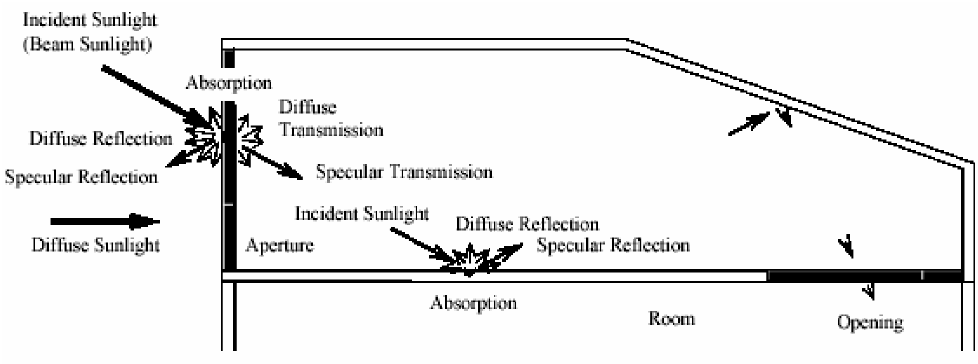

Fig. 4 Trajectory of beam radiation in light pipe.

The position of the sun relative to the coordinate in Fig. 2 is calculated by geometrical relationships given in [9] for a given time. A number of sun rays are assumed to be distributed evenly across the aperture of the light pipe. Total light flux from these rays equals the sunlight falls on the aperture of the light pipe. Each ray is traced individually. The incident point of a ray on a plane and the reflective ray are calculated by geometrical relationships given in [9]. Tracing ends when the magnitude of a ray is smaller than a given value or when the ray reaches the diffuse section. The absorbed flux on each surface section will be summed with the corresponding value calculated from diffuse skylight. This value is used in the subsequent heat transfer ***For diffuse skylight***, the flux transmitted across the aperture is treated as the direct exitance of the interior surface of aperture in the flux transfer calculation. To improve accuracy of calculation of the diffuse light flux, each surface in the room and light pipe should be divided into small section since the exitance is assumed uniform in each section. The flux balance principle is used to calculate the exitance from each surface section E_i, i = 1, . . . , n via the following flux transfer equation:

$$E_i = E_{id} + \rho_i (F_{i\rightarrow 1}E_1 + \ldots + F_{i\rightarrow i}E_i + \ldots + F_{i\rightarrow n}E_n),$$
$$i = 1, \ldots, n$$

Where n is the total number of surface sections in the room or light pipe; E_i is the exitance of surface i; E_{id} is the direct exitance from section i, ρi is the reflectance coefficient of section i, $F_{i\rightarrow j}$ is the form factor from section i to section j. Reflection and diffuse transmission components are the Lambertian component which produces equal luminance for the surface when viewed from any direction. Diffuse reflection is reflected from the aperture while diffuse transmission is transmitted through the aperture and came into light pipe. Specular transmission component is a part of sunlight continues travel into light pipe. Another part of the sunlight is absorbed by material and is called absorption. All five components sum to a quantity equal to the incident sunlight. The specular transmission ray continues traveling and is considered as incident ray to another plane. At incident point on surface of light pipe, the incident ray produces three components (see Fig. 4). Depending on material, portions of components are difference and may equal zero. For each surface section, the sum of the diffuse component of all reflected rays originating from sunlight is treated as direct exitance of the given section. The form factors between sections are calculated by analytical expression for simple geometries and by numerical methods for complex cases.

Heat gain calculation

The modeling heat gain used in this study is based on algorithms developed in [10]. The equations accounts for all driving forces of heat gain at the external surfaces and internal surfaces of the envelope of a building zone, each in a dynamic energy balance equation. Fig. 5 is illustrated of heat gain on an external wall.

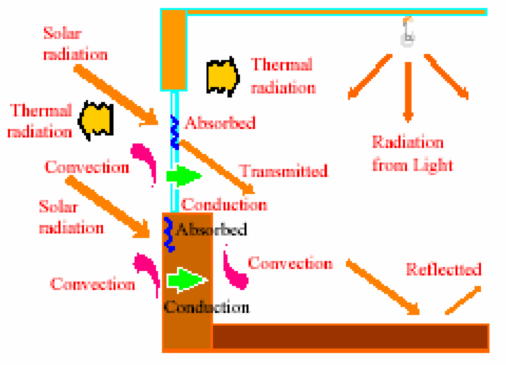

Fig. 5 Illustration of heat gain on an external wall

Energy Balance at the Surfaces of an External Wall: An energy balance equation can be written on the *exterior surface* considering absorbed solar radiation by direct and diffuse components, heat convected from air, net absorbed thermal radiation from sky, ground and other external surfaces and heat gain into the wall mass. The situation at the *interior surface* is similar to that at the exterior surface, and a similar energy balance equation is written for each surface. *Conduction Heat Gain in Wall:* Finite difference method is used for the solution of heat diffusion equations through finite walls, [11].

Heat Transfer through Glazing: The mechanism of heat transfer at the glazing is complex, especially if there is more than one layer of glazing present. In an analysis, the optical mechanism should be considered separately from the thermal mechanism. Eventually, heat transfer across the glazing comprises a term representing direct solar transmission, a term related to absorbed solar radiation on each layer of glazing, and another term related to conduction heat transfer.

Dynamic Energy Balance of Air: The air in a zone in the building interior is assumed well-mixed (as is usually assumed for an air-conditioned zone). It is in dynamic heat balance. The air in the zone receives heat convected to it from walls and other surfaces. It also receives moisture from human occupants and other sources. Ventilation air and infiltration air contribute heat and moisture to zone air directly. This zone air is circulated through the cooling coil of the air-conditioning system, where its heat is transferred to the cooling coil and part of its moisture is condensed and removed. Dynamic equation is written for the transfer of heat and moisture to air in each interior zone.

The set of dynamic, nonlinear, simultaneous equations written in accordance with energy balance consideration comprise unknown temperature variables and variables of moist air properties. These equations, over six hundred in number, are simultaneous and must be solved at each time step. A computer program written in C++ language is used. The size of time step used 15 minutes interval.

Results and Discussion

Daylight illumination

The experiments were conducted on 17 days during March-September of year 2004 (Table 2). The study selects two days for each type of light pipe to analyze and present in this report. On 3 and 26 June, horizontal and vertical (static) mirrors were operated, and on 30 May and 30 June all three mirrors were in the places. The root mean square error (RMSE) and efficiency index (EI) are used to analyze. The indexes use data from 7:00 to 17:00.

Fig. 6 shows the picture of interior space of the experimental room at 9:00am on 7 July 2004 without electric lighting. The picture shows that illuminance in space under opening is sufficient for sedentary activity. The light pipe was triangular shape and all three mirrors were operated.

Fig. 7 shows the results in comparison of illuminance on the "point 90%" of floor from both measurement and model simulation for four selected days. For the days used only static mirrors, the illuminance on floor is increased from low level at 7:00am to about 250 lux at 8:00-8:30am then reduced to very low level at 11:00-12:00am. Meanwhile for the days used tiltable mirror, the illuminance is increased to about 500-600 lux at 9:00-10:00am and is maintained at the same level until 16:00 before reducing. The figures show acceptable agreement between calculated values and measured values. The RMSE of illuminance between calculation and measurement are 19.5 lux (15.6% of average value) for 3 June; 108.9 lux (25.9%) for 30 May; 28.4 lux (38.9%) for 26 June and 113.5 lux (25%) for 30 June. The EI are 0.91, 0.75, 0.82 and 0.87 for 3 June; 30 May; 26 June and 30 June separately.

Fig. 6 Picture of interior space of the experimental room at 9.00am on 7 July 2004

For 3 and 26 June in early morning (7:00-8:15am), illuminance on the "point 90%" is about 0.5-0.7% of beam normal illuminance; it is reduced to 0.02-0.12% at 10:00am for both measured values and calculated values. For 30 May and 30 June, illuminance on the "point 90%" is maintained about 0.4-1% of beam normal illuminance for measurement and 0.5-1% for calculation for whole day

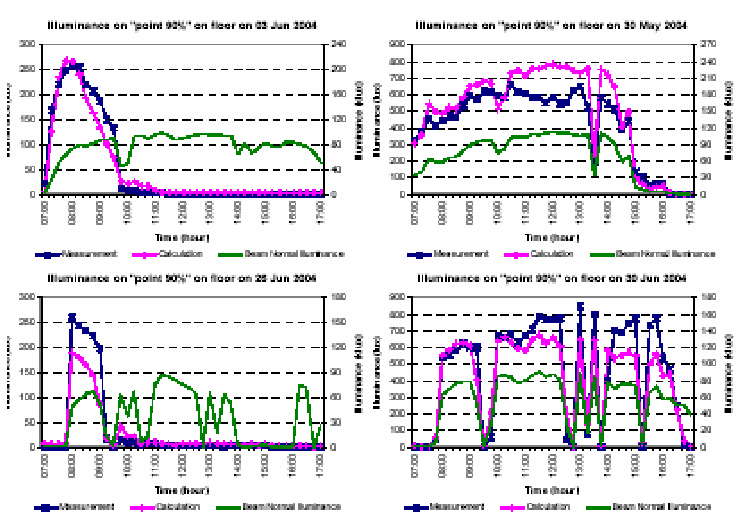

Fig. 7 Illuminance on "point 90%" of floor

For 3 and 26 June, daylight level on the "point 90%" is possible used in only three hours in morning (from 7:00am to 10:00am), with average illuminance (for 3 hours) is about 90-230 lux (about 0.26-0.32% of beam normal) for measurement and is about 60-200 lux (about 0.21-0.28% of beam normal) for calculation. Meanwhile for 30 May and 30 June, the daylight level is high for whole day (from 7:00am to17:00pm), with average Illuminance (for 10 hours) is about 190-450 lux (about 0.51-0.81% of beam normal) for measurement and is about 210-450 lux (about 0.56-0.68%) for calculation. Illuminance on the floor first depends on value of beam normal sunlight and then depends on position of the sun (date and time). It almost not depends on value of horizontal diffuse skylight. Sunlight can come into room through the light pipe much more than skylight.

The shape of the curves of illuminance on the "point 70%", "point 50%", "point 30%" and "point 10%", are similar as "point 90%" but the values are in descending order. The illuminance on the "point 70%", "point 50%" "point 30%",and "point 10%" are around 74-84%, 44-65%, 26-40% and 19-30% of the "point 90%" for measurement value and are around 83-88%, 52-57%, 32-37% and 23-28% for calculation values. Fig. 8 shows the results on the "point 10%" for four selected days.

The shape of the curves of illuminance on the point under opening is similar as "point 90%" but the value is very high. For the day used only static mirror, illuminance on this point can reach 7000-10000 lux; average illuminance for 3 hours in morning is about 2000-7000 lux. Meanwhile for the day used tiltable mirror, illuminance can reach 10000-16000 lux; average illuminance for whole daytime is about 4500-10000 lux. Daily average daylight at this point can obtain 12-18% of beam normal.

The EI between measured and calculated values for illuminance at all measurement points in experimental room for all days was calculated. The average value of EI is 0.86. It says that there are acceptable agreement between measurement and model simulation. The EIs for the west wall and the point under opening are lower than that for other points. The reason is that at certain time, the beam sunlight can reach to the lux meter (on west wall and on the point under opening), so the measurement values from these lux meters at this time are not represented for the whole section on that illuminance is assumed uniformly.

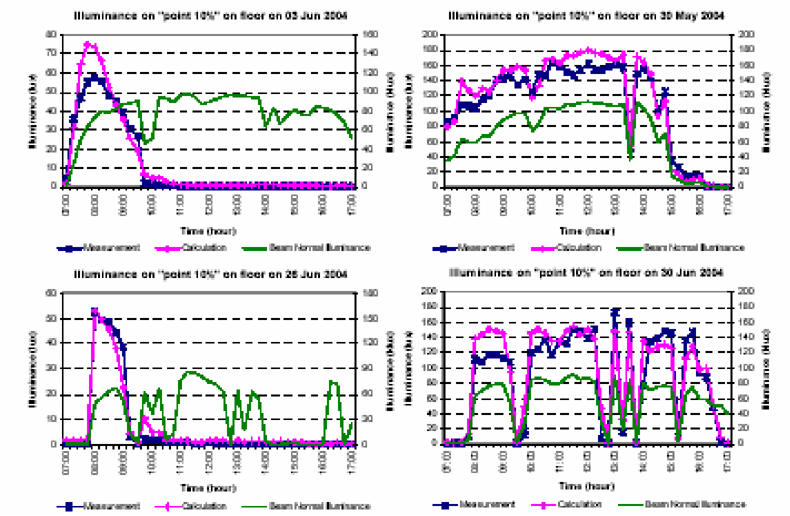

Fig. 8 Illuminance on "point 10%" of floor

Fig. 9 represents the illuminance on the floor from both measurement and calculation for 30 June. Illuminance at the "point 90%" is highest, then "point 70%", "point 50%", "point30%" and then "point 10%". For measurement, "point 90%", and illuminance on "point 50%", "point 30%", "point 10%" are around 44.2%, 26.2%, 19.2% of that on "point 90%" separately. For calculation, illuminance on "point 70%", "point 50%", "point 30%" and "point 10%" are around 83.5%, 52.2%, 32.6% and 23.8% of that on "point 90%" separately.

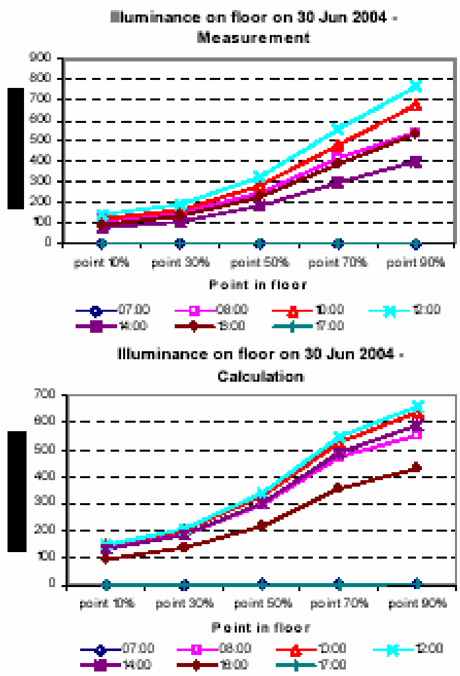

Fig. 9 Illuminance on floor on 30 June 2004

The ratios of illuminance on "point 90%" to beam normal sunlight for 8 days using tiltable mirror are shows in Table 3. The table says clearly that the triangular light pipe is better than trapezium light pipe.

Heat gain consideration

Fig. 10 presents irradiation on the point under opening for 30 Jun 2004 from both measurement and model simulation. The figure shows that solar radiation coming into room through the opening was maintained around 140 W/m2 for most of daytime (8:00-16:00). So, together with reducing electric lighting is the increasing air-conditioning load due to heat goes accompany with daylight through opening. The calculation results agree well with the experimental results.

The figures and values of heat flux transfer through wall of light pipe is not much difference among all these experimental days. Heat flux through wall of light pipe for 30 June is presented in Fig. 11. Heat flux is increased from about 0-5 W/m^2 at 7:00am to about 10-12 W/m^2 at 8:00-9:00am, then reduced to zero at 10:00-11:00am and then heat flux comes back to light pipe from attic space with the same shape but opposite sign until 17:00pm. The figure shows acceptable agreement between measured and calculated values.

Fig. 12 presents the heat flux through roof on 30 June for measurement and calculation. The heat flux is increased fast from -10-0 W/m^2 at 7:00am to 50 W/m^2 at 12:00-13:00pm and then reduced until 10-20 W/m^2 at 17:00pm.

Table 3 Ratios of illuminance on "point 90%" to beam normal sunlight

Light pipe	Mirrors	Date	Measu-rement	Calcu-lation
Trapezium	Hor.+Ver.+ Tilt.	17/Mar	0.00644	0.00674
		18/Mar	0.00822	0.00696
		30/May	0.00613	0.00717
		4/Jun	0.00636	0.00708
	Hor.+Tilt.	30/Apr	0.00523	0.00613
Triangular	Hor.+Ver. +Tilt.	30/Jun	0.00811	0.00727
	Hor.+Tilt.	25/Aug	0.00815	0.00726
		23/Sep	0.00813	0.00731

Figs. 11 and **12** show that heat comes to attic space from light pipe is much smaller than that from roof. It says that the installation of light pipe is almost not effect to the heat gain, which comes into room through ceiling.

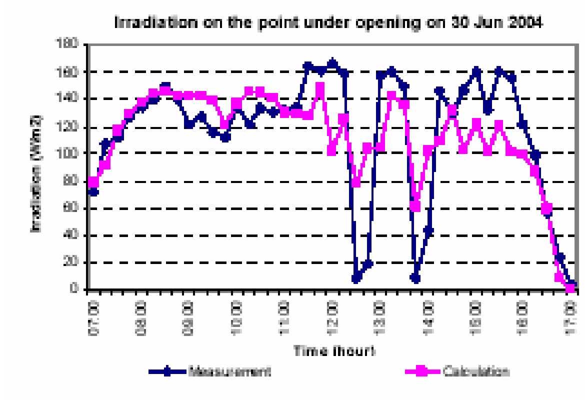

Fig. 10 Irradiation on the point under opening on 30 June.

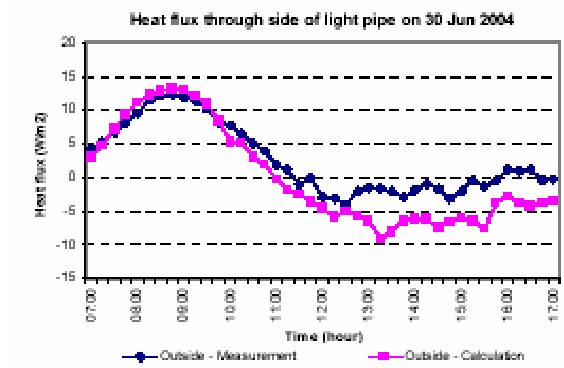

Fig. 11 Heat flux through side of light pipe

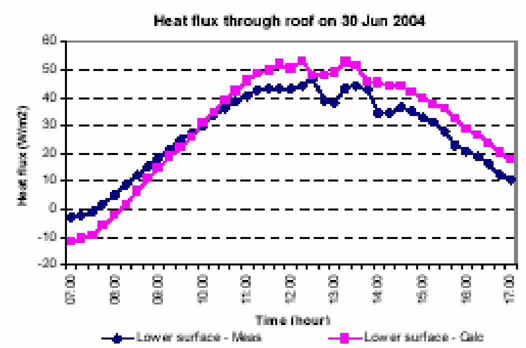

Fig. 12 Heat flux through roof on 30 June 2004.

Conclusion

The comparison between measured and calculated values shows clearly that the model developed is acceptable and sufficiently accurate. The model and computer program were developed for general case, i.e. for any configuration of room, light pipe and mirror system in any floor of the multistoried building. Although the window in the experimental room was closed, but the program can calculate in case the window is opened. The model is useful in case where trading off between daylight, heat gain and the cost of light pipe to find the optimum configuration of light pipe and mirror system. The model developed and the computer program are hoped to be used to contribute to the promotion of daylighting. In addition, here are some conclusions for this experiment: For the light pipe system without tiltable mirror, the illuminance on floor was high in morning and very low in afternoon, while for the light pipe system with tiltable mirror the illuminance on the floor is maintain at higher level during most of daytime; the illuminance on the floor under opening is around 0.51-0.82% of beam normal illuminance for the whole day and is around 100-450 lux from 8:00 to 16:00. The tiltable mirror is much more effective than two static mirrors.

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