Utilization of Light Pipes for Industrial Lighting as a means of Saving Energy

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Abstract: In most of the industries windows are rarely used for daylighting because it requires windows with large dimensions. Huge windows can cause non-uniform illumination on a task plane. Every industry requires different levels of illumination for manufacturing and assembly work. The required illumination level can be achieved by using artificial lighting which will consume more energy. The use of artificial light may also create glare at some point which can be uncomfortable while performing a task. This can be avoided if daylight can be harnessed by using light pipes. This not only reduces energy consumption which will bring down the bills but will also give comfort with less probability of glare. The geometry of the pipe, the internal reflectance factor, and the location of the light pipe with respect to the ambiance help in determining the illumination in a specific area. The main focus of this paper is to study the effect of illuminance in a room by varying the height over the working plane by a light pipe. For this an industrial shop floor of 10m x 10m is taken as sample and simulated using the software HOLIGLIM 4.4. The results can be replicated for a larger dimension of an industrial shop floor.

Keywords: *Light Pipes, Illuminance, Daylighting, Threshold Illuminance, Energy saving.*

1. Introduction

The daylight limit in buildings that are illuminated through the windows at the perimeter are up to 15 feet from the perimeter. Here there are chances that the illuminance is not uniform with higher intensity near the glazing and lower concentration at the deep cores of the building especially at the ducts and corridors. So these areas depend upon electrical lighting to obtain the required illumination. This causes increase in energy consumption and cost as mentioned by Nadal, 2005 in her MS thesis [1]. The light pipe is a concept used to direct the sunlight and skylight through a hollow tube into areas that are inaccessible to daylight. The light pipe consists of a dome at the rooftop to collect sunlight and skylight, a hollow tube having high reflectance to transmit the collected light, and a diffuser at the bottom to spread the light uniformly on the indoor surface. The performance of a light pipe is affected by various factors including the solar altitude, sky condition, geometry of the pipe, and materials used to construct the pipe as concluded by Zhang and Munner, 2000 [2]. As suggested by Alejandro P. D. in his Master's thesis, it is preferable to use simple light pipes in mid and low latitudes with ubiquitous clear skies, whereas in higher latitudes optical redirecting systems (ORS) could be used for better results. Critical design parameters for light pipes include aspect ratio and specular reflectance of the pipe [3]. Thanyalak S., Kyosuke H., 2019 showed that light pipes can be used to bring daylight for illumination in deep interior spaces [4].

Ayodeji Omishoren et al., 2019 observed that mobile concentrator heads with roof heliostats are efficient in temperate climates. They also observed that roofs sloping towards the south are better [5]. Light pipes possessing laser-cut panels can provide sufficient lighting in deep plan buildings during daytime as experimented by Hansen and Edmonds, 2003 [6]. Stanislav Darula et al., 2010 developed the "software HOLIGLIM 4.4- The Hollow Light Guide Interior Illumination Method which can calculate indoor illuminance distribution considering standard daylight situations and real light propagation through hollow tube" [7]. This software also helps to study the light illumination in various climatic zones [8]. The aspect ratio of the light pipe is a crucial parameter in the daylight autonomy (DA) and continuous daylight autonomy (DAc) for evaluating daylight. The length of the light pipe is a decisive factor when it comes to reduction of glare and solar irradiation during summer. Since the sky conditions are not the same throughout the year, the light pipes have to be integrated with artificial lighting sources to ensure sufficient visual comfort during the daytime [9]. S. Ahmed, A. Zain-Ahmed et al., 2006 found that "the transmitted illuminance and the distance from the light pipe could be linear or non-linear, depending on the minimum distance from the light pipe". [10, 11]. Hanlin Li, Dan Wu, Jinzhi Zhou, 2021 concluded that in a moderate climate zone, an increase in the opening size of the tube in a tubular daylight guidance system (TDGS) enhanced the daylighting performance but the heating/cooling load increased in the hot and cold regions. The TDGS system works more efficiently for clear skies as compared to the overcast sky [12]. Aluminum alloy pipe has a better reflective and light transmission performance as compared to zinc alloy [13].

There are different levels of illumination recommended for different industrial applications. For performing specific task, minimum required illuminations in standard values of LUX are well known [14]. The paper describes how the illuminance obtained by light pipes can be categorized based on the Indian standard code of practice for industrial lighting IS: 6665-1972 for different industries [15]. These levels are categorized as highly critical, moderate and below average based on the illumination lux level standards for different industries. In this experimentation those tasks are selected which requires moderate illumination in the range of 300-500 lux [16]. These include illumination levels at assembly shop, aircraft factory, canning and preserving factories, carpet factory, and motor vehicle factory and so on. Accordingly desired illuminance specifications can be obtained by varying different parameters of the light pipe and observing the area of illuminance. The scope of the paper is: (a) the illuminance obtained by a single pipe for different diameters and to extend it for two and three light pipes (b) vary the height of the pipe from the working plane to optimize it. This method is desired to cover maximum usable area of the shop floor with appropriate illumination, deficit if any can be filled with artificial lighting (which would be consuming electrical energy). The attempt in this paper is to maximize the illuminated area with light pipe usage and save energy to maximum extent.

2. Research Methodology

The main aim of this experiment is to study the room illumination using different light pipe dimensions and varying the height over the working plane for a single light pipe using the simulation set-up [7] as shown in figure 1. The software HOLIGLIM 4.4 is used to study the illumination pattern for a room having dimensions 10m x 10m and calculation resolution of 0.15m x 0.15m. The model selected is Sky model CIE Overcast 1:3 (I.1. ISO 15469:2004) with an altitude of 73.4º (90 degrees = sun is in zenith), Azimuth of 180º (180 degrees=sun is in south) and the latitude of the room is 40º on 30/11 at 10 AM (Sun's position from date and time). The cupole or dome's transparency

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is taken as 0.95. The internal reflectance of the tube is taken as 0.800 which is closer to that of aluminum sheet and the length of the tube is 2m. The optical interface has the transparency of Lambertian (whole optical interface is diffuse) part of 0.750 and outer diameter as 1m. The grid density for diffuser illuminance is medium resolution and low resolution for luminous intensity solid.

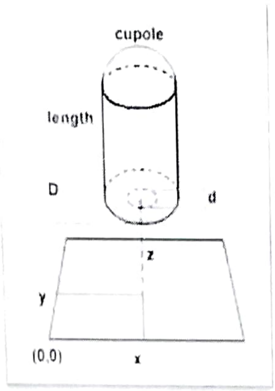

Figure 1. Light tube Set-up in HOLIGLIM 4.4 (7)

The illuminance is calculated with the room co-ordinate system at x position and y position as 5m x 5m and the z position as 2m which is the height over the working plane. The area of illuminance is calculated for the isolines obtained especially for the area below the light pipe and the illuminance in lux is noted down for the same in the light pipe for a length of 2m and outer diameter varying between 0.50m to 2m.

The simulation is extended by keeping the length of the tube and outer diameter of the optical interface constant at 2m and 1m respectively and varying the height over the working plane i.e., the z position between 0.1m to 8m. The area of illuminance formed just below the light pipe is calculated from the isolines obtained and the lux range noted down for the same. The required threshold illuminance for the given area of illuminance is tabulated and height of the working plane is optimized for illuminance range comfortable for human interactions. The experiment is extended to two pipes and three pipes under similar conditions. The same observations are taken by varying the distance between the pipes.

3. Results and discussion

The light pipe is placed in the center of the room at 5m in a 10m x 10m closed room. The length of the tube is kept constant at 2m and the diameter of the optical interface is varied between 0.5m to 2m. It is observed that the area of illuminance increases with the diameter of the light pipe. The area of illuminance just below the light pipe is less but the illuminance in lux is more. As the distance is increased from the center of the room toward the corners, the area of illuminance increases but the intensity of illumination decreases. The required threshold of illuminance is calculated by interpolation of the illuminance obtained for the different areas illuminated by the light pipe as shown in table 1.

Table 1. Required Threshold Illuminance for Light Pipes of Different Diameters with Area of Illuminance

Required Threshold	Area (m^2) D=0.5m	Area (m^2) D=0.75m	Area (m^2) D=1m	Area (m^2) D=1.25m	Area (m^2) D=1.50m	Area (m^2) D=1.75m	Area (m^2) D=2m
300	0.7	1.5	5.9	4.3	7.06	11.57	16.05
250	0.8	1.7	6.5771 384	5.11	8.4	13.33	17.9
200	0.99	2.13	7.52	6.3	10.4	15.85	20.4
150	1.26	2.76	8.9	8.15	13.63	19.82	24.2
100	1.79	3.97	11.39	11.79	20.02	27.16	30.78
50	3.26	7.40	17.25	22.21	38.66	46.54	46.43

When the height of the working plane is varied from minimum of 0.1m to maximum of 8m, the illuminance range decreases as shown in table 2 i.e., the height of the working plane is inversely proportional to the illuminance obtained. The largest area has lesser illuminance covered. The length of the tube can be determined by changing the height of the working plane if the area to be illuminated for a particular application is known. When the height of the working plane is 2m, lesser area is illuminated but with comfortable illuminance for human interaction. The height of the working plane required for a better illumination in the z position is 2m.

Table 2. Height of the working Plane and Illuminance with Energy Saved

Height of the working plane (m)	Area of the first inner isoline ((m^2)	Lux Range	Energy Saved (W)
1	11.34115	1500-2500	11.34%
2	12.56637	250-500	12.57%
3	52.81017	100-250	52.8%
4	32.16991	60-140	32.16%
5	50.26548	40-90	50.26%
6	105.6832	30-60	100%
7	28.27433	25-45	28.27%
8	18.09557	20-35	18.09%

This result was extended by applying these conditions to two light pipes with length 2m and diameter of 1m. In the first case the pipes are placed 2m apart at (x, y) position 4m x 5m and 6m x 5m and in the second case the pipes are placed 1m apart at (x, y) position 4.5m x 5m and 5.5m x 5m respectively. The work plane illumination for the same is as shown in figure 2. It can be seen that when the light tubes are placed far apart larger area will be illuminated with lesser illuminance. It is observed that when the light pipes are placed close to each other the area of illuminance decreases but total illuminance increases.

The same concept was repeated with three light pipes. In the first case the light pipes are placed 1.5m apart at (x, y) position 3.5m x 5m, 5m x 5m and 6.5m x 5m and in the second case it is placed 1m apart at (x, y) position 4m x 5m, 5m x 5m and 6m x 6m respectively [17]. The work plane illumination for the same is as shown in figure 3. The area of illuminance is more when the number of light pipes are increased. Uniformity is better when the light pipes are placed close to each other.

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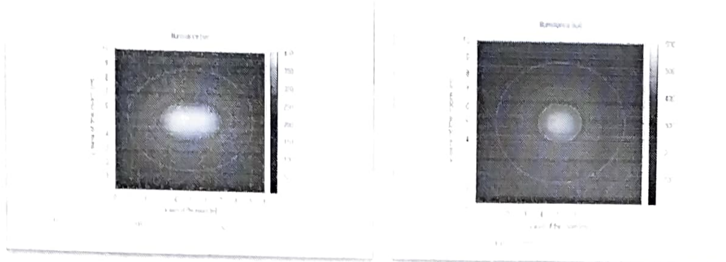
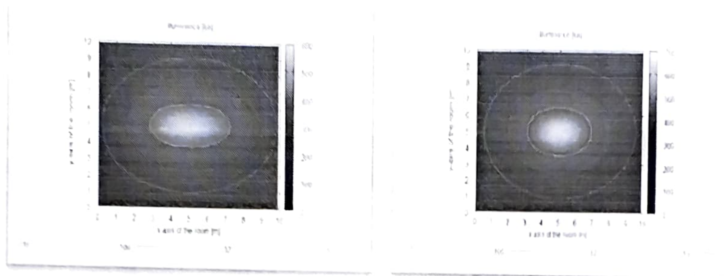


(a) (b)

Figure 2. Illumination by two Light Pipes: (a) 2m apart (b) 1m apart



(a) (b)

Figure 3. Illumination by Three Light Pipes: (a) 1.5m apart (b) 1m apart

The threshold of illuminance for industrial buildings and processes can be categorized into three parts: 1) for highly critical applications illuminance greater than 300 lux (2) moderate applications between 100 to 300 lux and (3) below average applications less than 50 lux. From the IS: 6665-1972 standards as shown in table 3, it can be seen that illuminance greater than 300 lux is required in Jewelry and Watchmaking industry, Clothing and Textile industry, Boot and Shoe factories, Assembly shops etc.

In most of the industries illuminance between 100 to 300 lux is sufficient. Illuminance less than 50 lux is mostly applicable in farming industry, Electricity Generating Stations: Outdoor locations etc. If we consider the general factory areas then an average illumination of 100-150 lux is sufficient for lighting. For this purpose a light pipe of length 2m and diameter 1m placed at a height of 3m from the working plane can illuminate around 52.8% (for the first inner isoline) of the total area as shown in table 2. This can save that much amount of energy as artificial lighting will not be required in that area. So depending on the application length, diameter and height of the working plane can be decided.

The results show that a light pipe of a suitable length and diameter placed at the correct height and coordinate can provide required illumination thereby bringing down the energy consumption to a greater extent. The readings are consistent with the results noted by Jiraphorn M., Atthakorn T., 2021 while comparing the performance of aluminum and zinc hollow light pipes by varying the incident angle and diameter of the light pipes [13]. The illuminance obtained in a particular area is the function of the diameter of the light pipe [18].If the task of room illumination is not fulfilled by a single light pipe then the number of light pipes can be increased and placed at appropriate positions to sufficiently light the room. So number of light pipes depend on the room dimensions and the architectural design [18].

TABLE 3: Required illumination in industrial applications (IS: 6665-1972 standards)

HIGHLY CRITICAL	AVERAGE ILLUMINATION IN (LUX)	MODERATE	AVERAGE ILLUMINATION IN (LUX)	BELOW AVERAGE	AVERAGE ILLUMINATION IN (LUX)
Aircraft factory and Maintenance hangers	300-450	General factory areas	100-150	Factory outdoor areas	20
Fine work, for example, radio and telephone equipment, typewriter and office machinery assembly	700	Bakeries	100-200	Boiler houses-Boiler rooms and outdoor plants	20-50
Very fine work, for example, assembly of very small precision mechanisms, instruments , Jewelry & Watch making	1500	Electricity Generating Stations : Indoor Locations	150-300	Electricity Generating Stations : Outdoor Locations	20-50
Boot and shoe factories	700-1000	Breweries & Distilleries	150-200	Farm buildings-boiler houses and stables	50
Clothing factories	300-1500	Chemical Work	100-300	Gas Works	20-50
Dye sinking & dye works	300-2000	Collieries	100-300	Iron & Steel works-Marshalling and outdoor stockyards	10-20
Glove making	300-1500	Book binding	200-300	Garages-Parking area (interior)	70

It can be seen from the results that the position and dimensions of the light pipe and the area of illumination help to decide the nature of task that can be performed in an Industry. High precision operations require more illumination especially at the shop floors as compared to the medium illumination required at the administrative office. The number of light pipes and their positions at the workstation can be modified according to the illumination required. Therefore the number of light pipes required in a particular area depends on the type of utility that is to be executed.

4. Conclusion

The research work reported in this paper points to the application of light pipes in efficient lighting as an energy saving alternative by using daylight in industries. From the simulations performed on HOLIGLIM 4.4 it can be concluded that if requirement (threshold) of illumination lux level is reduced the area of illumination gets increased. To improve the illumination range more light pipes can be added at appropriate positions depending upon the visual tasks to be performed. But care must be taken not to cause discomfort due to excessive illumination. By selecting the correct light pipe dimensions and positions on the roof any industrial shop floor can be illuminated with the required light intensity. From the results it can be seen that in a 10m x 10m industrial shop floor, a light pipe can sufficiently light the room with minimum use of artificial lighting thus saving 52% of energy. In this way energy can be saved effectively by using daylight for 8 to 10 hours and can be augmented with artificial lights if required depending upon the sky conditions. This arrangement works efficiently in industries where windows are not recommended for daylighting.

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