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Investigation of the Efficacy of Horizontal Hollow Light Tubes for Energy Conservation in Illuminating Buildings

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Abstract: This study investigates the properties of light transmission and distribution, examining how incident light angles impact illuminance distribution and daylight factor. Light tubes are acknowledged as promising tools to enhance lighting conditions and reduce energy consumption in building design. The study involved installing horizontal hollow light tubes, each measuring 0.5 m in length and 0.30 m in diameter, on a wooden test model. A 20-watt LED lamp was employed as the light source, and an illuminance meter recorded the values at various horizontal and elevation angles. The study's assessment included calculating the average illuminance and daylight factor to obtain light transmission efficiency and energy-saving potential. The findings revealed that both aluminum alloy and zinc alloy tubes experienced a decrease in illuminance as incident elevation angles increased, with the most effective light transmission occurring at a horizontal angle of 90°. Notably, the aluminum alloy tube outperformed the zinc alloy tube, demonstrating more than a 15% increase in light transmission efficiency. Furthermore, the daylight factor values from both types of tubes aligned with established standards for residential and office activities, underscoring their potential as energy-efficient lighting solutions for spaces lacking natural light or with limited illumination.

Keywords: light hollow tube; light reflection performance; illuminance; energy consumption saving; horizontal light pipe

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1. Introduction

In Thailand, the majority of the geographic location is subjected to high levels of solar radiation throughout the year. Solar radiation reaches its highest levels between April and May, with peak levels of 20 to 24 MJ/m^2-day observed during this period. Over the course of a full year, the daily average of solar radiation is approximately 18.2 MJ/m^2-day. [1–3]. As a result of these conditions, significant thermal gain is appearing in buildings, which leads to an increase in energy demands in both the air-conditioning system and lighting for improving the life quality of inhabitants. Electrical lighting energy use in buildings ranges from one-tenth to two-fifths of the total electrical energy consumed. Recently, there has been a growing emphasis on designing and advancing buildings that offer improved environmental conditions for occupants while minimizing energy consumption [4,5]. The integration of daylight into building design has been recognized as a promising approach to enhance lighting conditions and mitigate energy consumption linked to lighting in buildings [6–8]. Significant energy savings can also be achieved when sensors turn off electrical lights in unoccupied building zones that would otherwise be on, which is also the most successful control strategy used to reduce energy from electric lighting [9]. By promoting the adoption of energy-saving technologies, this investigation aims to support the global efforts towards a greener and more sustainable built environment.

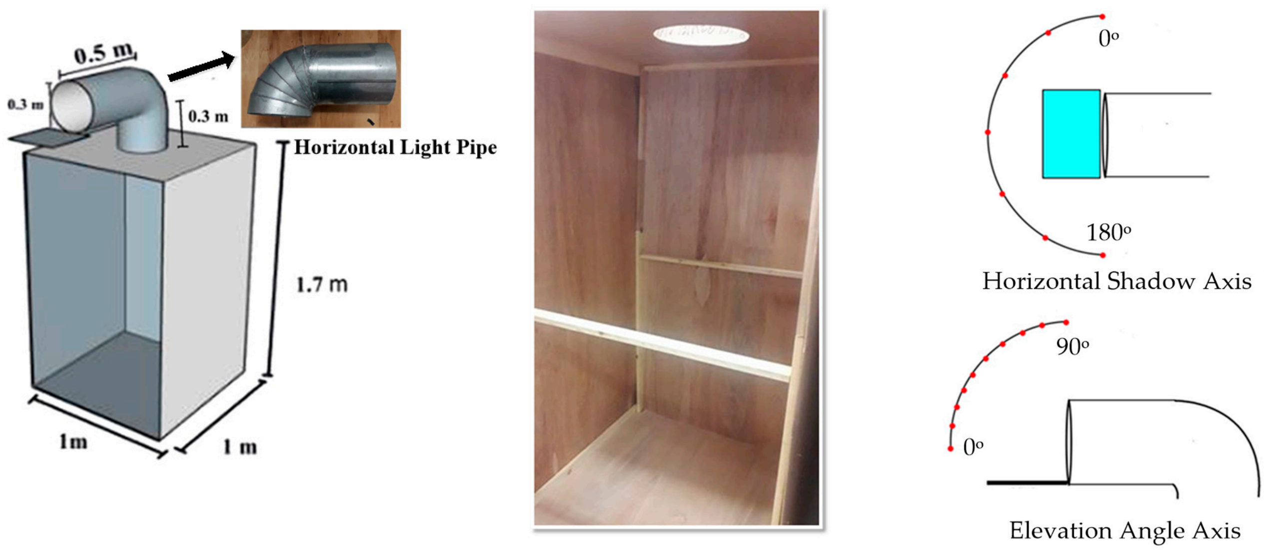
Light tubes offer a practical solution to introduce natural daylight into the interior spaces of buildings [10,11]. These commercially available light pipes have been employed to provide illumination in areas lacking windows, for example, interior offices and workspaces, basements, storage rooms, manufacturing facilities, libraries, and other spaces within buildings where there is limited access to natural light [5]. A standard light tube system generally consists of three components: a dome, a light tube, and a diffuser. The initial component of the system is a dome crafted from transparent polycarbonate material, engineered to reduce ultraviolet light while permitting both diffuse and direct light to enter the light pipe [12]. The second component is a light tube that connects from the dome and reflects the collected daylight into a diffuser that is installed on the room's ceiling. Finally, the diffuser is made from white polycarbonate material and diffuses the collected daylight into the room [13].

Numerous studies have been conducted to explore different facets of light pipe systems with the objective of enhancing their performance, including the integration of supplementary functions such as ventilation. In colder regions, top lighting systems that are incorporated into skylights, roof monitors, and clerestory roof windows have the potential to reduce heating, ventilation, and lighting costs and thus save energy [14,15]. Canziani et al. [16] designed a horizontal light pipe featuring a trapezoidal shape and a dynamic reflector, which effectively tracks solar rays to enhance lighting in deeper areas and achieve improved homogeneity. Rosemann et al. [17] focused on using cost-effective materials and components to demonstrate the additional energy-saving benefits. In addition to that, the daylight penetration factor (DPF) of light pipes serves as a quantitative evaluation metric to assess the efficiency and performance of the daylight system. It quantifies the extent to which the light pipes effectively transmit natural daylight into the interior spaces of the building, thus indicating the overall effectiveness of the daylighting strategy. The DPF measures the relationship between the minimum cell and the average room illuminance. It assesses the uniformity of daylight distribution in a room, with higher values signifying a more uniform spread of light [18–20]. As per the guidelines outlined by the European Standard EN 17037 for assessing daylight in buildings during overcast conditions, an effective lighting system is characterized by a daylight factor (DF) as follows: DF $\leq$ 0.2%: insufficient daylight, 0.2% $<$ DF $\leq$ 0.6%: low daylight, 0.6% $<$ DF $\leq$ 2.0%: moderate daylight, 2.0% $<$ DF $\leq$ 5.0%: good daylight, and DF $>$ 5.0%: excellent daylight [21]. These DF values indicate the target level of natural daylight entering the indoor spaces. Aligning the daylight factor and daylight penetration factor is significant for meeting the precise lighting requirements of a space and its intended purpose. Designers and architects use these metrics to ensure adequate daylight levels in indoor designs and to rely less on electric lighting.

Given their lighter weight and greater chemical resistance in comparison to steel sheets, aluminum alloy and zinc alloy sheets are commonly used as roofing and siding materials in Thailand [22–25]. As a result, these materials were examined as potential alternatives for constructing the horizontal hollow light tubes that transmit external light into the interior spaces of buildings. The focus of the design for the aluminum and zinc alloy sheets was centered around the creation of horizontal light hollows, which were 0.50 m in length and 0.30 m in diameter. The purpose of these hollows was to evaluate the illumination distribution, light reflection properties, and daylight factor at different horizontal and elevation angles. Moreover, the innovative method employed in this research to incorporate daylighting strategies through the utilization of light tubes, its revelations regarding material effectiveness, and its focus on energy-conserving lighting systems collectively represent a significant asset to the domains of architecture, architectural design, and sustainable practices. These discoveries can serve as guiding principles for professionals and policymakers, aiding them in informed choices aimed at establishing more sustainable and energy-efficient built environments.

2. Materials and Methods

The main goal of this research was to extensively examine the light transmission and distribution properties of horizontal hollow light pipes made from commercially accessible aluminum alloy and zinc alloy materials. The pipes were carefully built with specific dimensions, having a length of 0.5 m and a diameter of 0.30 m. These light pipes were then mounted on the upper surface of a wooden testing model (the thermal conductivity of plywood is approximately 0.169 W/m·K), which itself measured 1 m in width, 1 m in length, and 1.75 m in height, as depicted in Figure 1a. Taking the concept of the "working plane" into account within office and residential contexts, this wooden test model was fabricated. This term refers to the horizontal surface used for activities such as work, writing, and computer usage. Its height is a common standard, representing the vertical distance from the floor to this surface, usually ranging between 0.7 and 0.8 m for non-adjustable desktops. This surface can extend workstations and circulation spaces. In office and residential settings, the standard height of this horizontal surface-to-ceiling distance typically falls between 2.4 and 3 m [26–28]. Therefore, a test model dimension of 1 m wide × 1 m long × 1.75 m high was selected, considering both the principles of the working plane and working area. In the experiment, a 20-watt LED lamp was employed as the light source to simulate overcast conditions. The elevation angle was methodically adjusted, varying from 0° to 90°, with increments of 10°. The horizontal angle was tested at 0°, 30°, 60°, 90°, 120°, 150°, and 180°, as illustrated in Figure 1b. For assessing illumination levels, a DIGICON LX-70 illuminance meter was utilized, known for its high precision. This device offers an accuracy of +/−2% rdg + 2 dgt. The measurements were conducted at three different levels: 200 lx, 2000 lx, and 10,000 lx. This instrument was used to measure the illumination at nine specific points located at both the upper and lower regions of each horizontal hollow light tube. This illuminance meter was positioned on the radius plane of the light hollow at both the top and bottom ends, as illustrated in Figure 1c. In order to find the average amount of illuminance in the horizontal aluminum and zinc alloy pipes, all the recorded values from the top and bottom sides were aggregated and analyzed. Subsequently, this calculated average illuminance served as the basis for evaluating the light transmission efficiency of the light tubes. Furthermore, the illuminance levels at the upper and lower termini positions were taken into account to further compute the light transmission performance. To illustrate the light distribution, an illuminance meter recorded the internal illuminance on the floor at 25 distinct positions within the testing model and 1 distinct position outside the testing model, as shown in Figure 1d. Each study procedure is exhibited in Figure 1e. The daylight factor was calculated by comparing the average indoor illuminance on the floor with the ambient illuminance in horizontal and unshaded regions. The experimental setup was conducted in a testing model located in an area with a Tropical Savanna climate, featuring marked dry and wet seasons, and a Tropical Monsoon climate, known for its distinct wet and dry periods, all with consistently high temperatures [29,30].



(a) (b)

Figure 1. *Cont.*

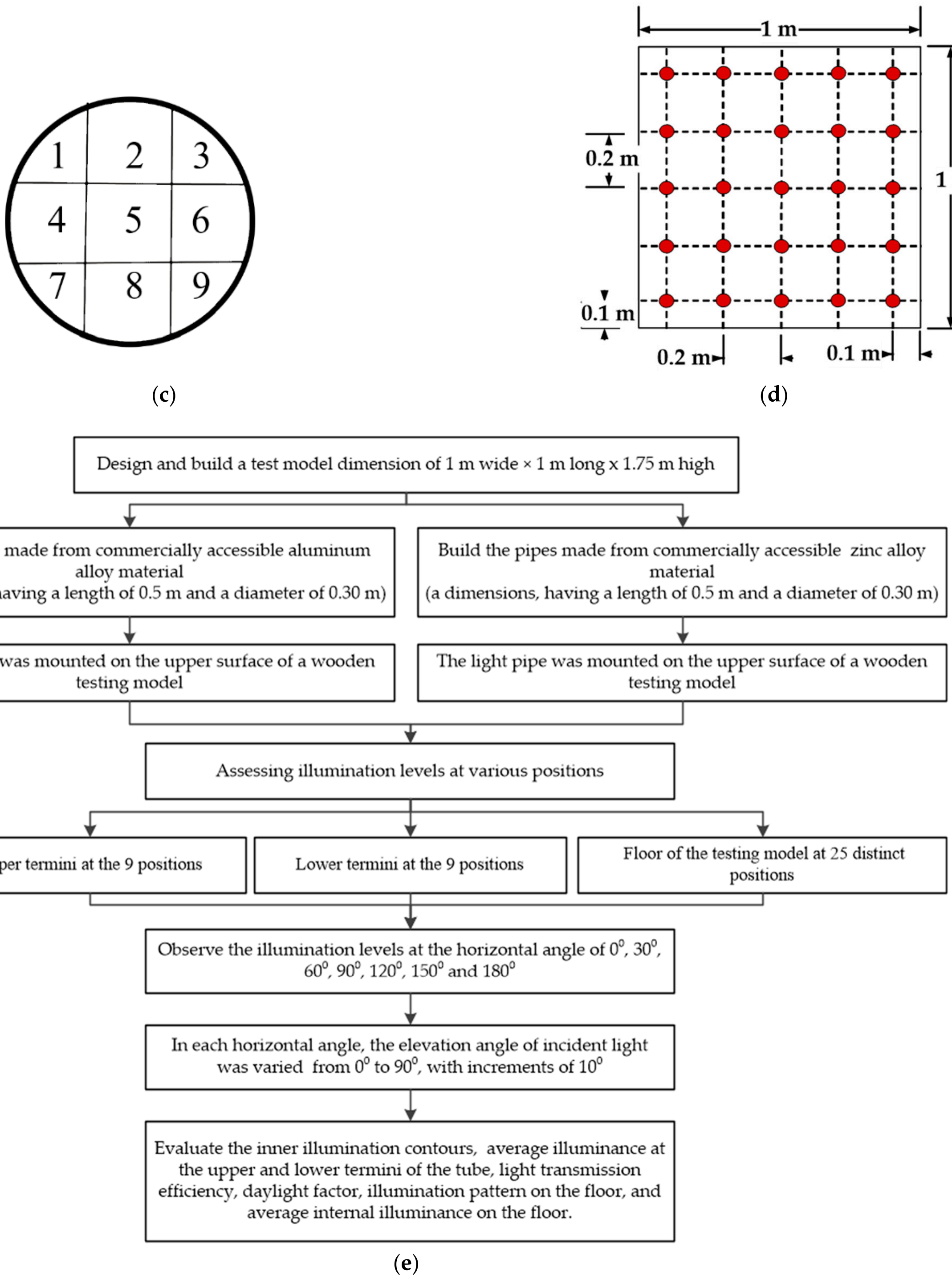


Figure 1. (**a**) View of the experimental testing area; (**b**) light source positions onto the light hollow; (**c**) illuminance measurement at the upper and lower termini of the horizontal hollow light tubes; (**d**) the internal illuminance locations on the floor; and (**e**) methodological flow diagram.

3. Results

Figure 2 illustrates the inner illumination contours at nine distinct positions located at both the upper and lower termini of the aluminum alloy light tube. The tube's dimensions include a diameter of 0.30 m and a length of 0.50 m. The inner illumination contours were measured at various incident light angles. To illustrate the illuminance distribution in the two-dimensional horizontal plane at the upper and lower termini positions of the hollow, a color intensity representation was employed. The internal illumination of the top hollow end positions ranged from 3486 lx to 4263 lx, and that of the bottom hollow end positions ranged from 687 lx to 1075 lx at an incident light angle of 0°, indicating a non-uniform distribution for both top and bottom side ends, as depicted in Figure 2. The incident light angle increases from 0° to 90°, and there is a noticeable change in the internal illumination at all positions located at the upper and lower ends of the light tube. At each position, the internal illuminance values gradually decreased as the angle of the incoming light increased from 0° to 90°.

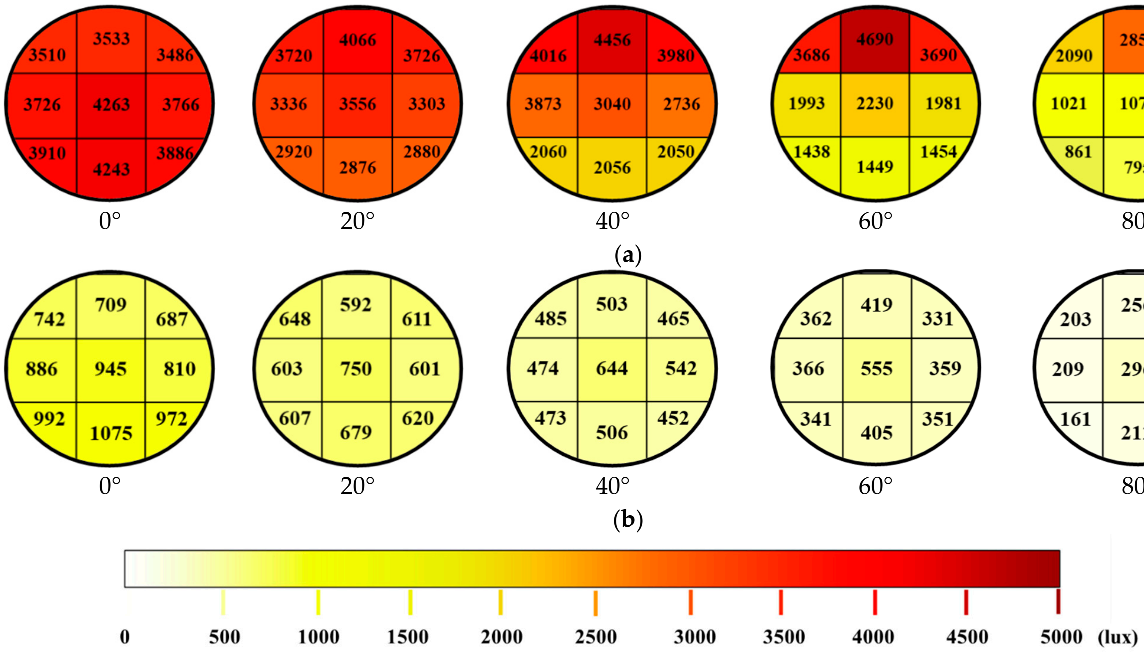


Figure 2. Internal illumination contours of aluminum alloy hollow at (**a**) the top and (**b**) bottom end positions at the horizontal angle of 90°.

The uniformity of illuminance distribution at the bottom end positions of the aluminum alloy hollow light pipe was assessed using two key ratios: "min to max" and "min to average" illuminances [31]. The "min to max" ratio, which is close to 1, signifies minimal variation in lighting levels, with the lowest illuminance nearly equal to the highest illuminance, ensuring uniform lighting distribution. Similarly, the "min to average" ratio, also close to 1, indicates uniformity, with the minimum illuminance being nearly the same as the average illuminance. Most of both "min to max" and "min to average" illuminances, exceeding 0.70 at different horizontal and elevation angles, demonstrate relatively uniform lighting distribution, contributing to comfortable and functional lighting in diverse settings. These findings are exhibited in Table 1.

Figure 3 presents logarithmically transformed results, showing the average illuminance at various incident angles for the nine measured positions on both the upper and lower sides of the horizontal aluminum alloy and zinc alloy hollows. The dimensions of these hollows were 0.30 m in diameter and 0.5 m in height. When examining the aluminum alloy hollow light pipe, Figure 3a,b exhibit the logarithmically transformed average illuminance at the upper and lower termini for each incident angle. The illuminance at the upper and lower termini positions of the tube varied as the incident light elevation and horizontal angles were varied. For instance, with a horizontal shadow angle of 30°, the logarithmically transformed illuminance at the top termini location of the tube decreased from 3.51 lx to 2.83 lx as the elevation angle of incident light increased from 0° to 90°. Similarly, as depicted in Figure 3a,b, the logarithmically transformed illuminance at the lower termini positions decreases from 2.69 lx to 1.77 lx as the elevation angle of the incident light increases from 0° to 90°. The trend of logarithmically transformed illuminance at the upper and lower termini positions for horizontal angles of 60°, 90°, 120°, and 150° closely mirrored that of the horizontal angle of 30°. Conversely, for horizontal angles of 0° and

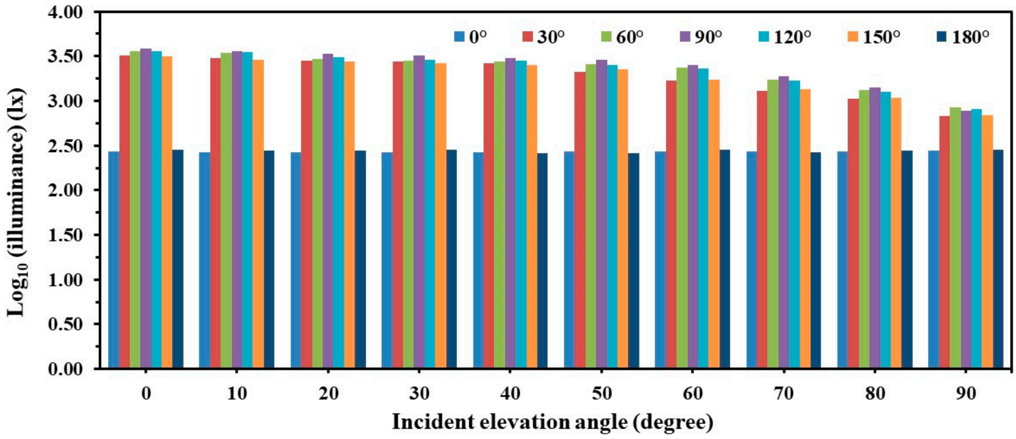
180°, the logarithmically transformed illuminance at the upper and lower termini positions remained constant, as shown in Figure 3a,b.

Table 1. Summary of internal illumination uniformity at bottom end positions for aluminum alloy hollow at different horizontal and elevation angles describing illuminance distributions.

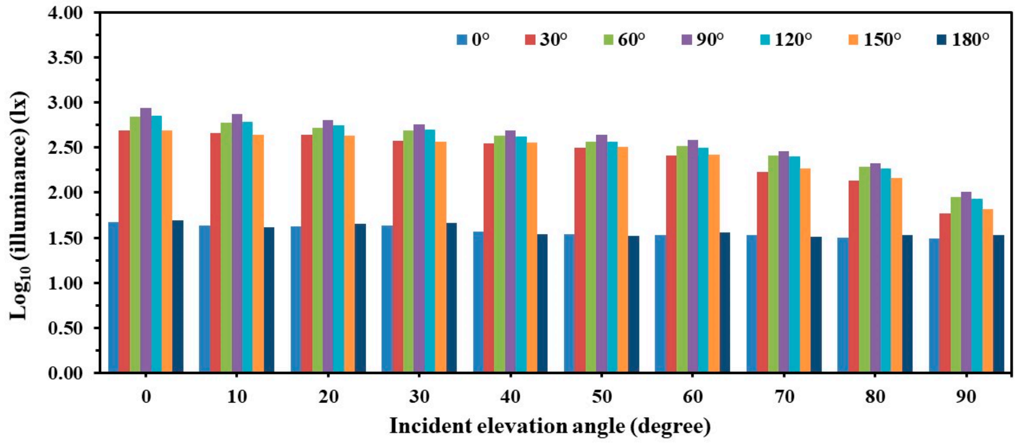
Horizontal Angle (Degree)	Elevation Angle (Degree)	Minimum Illuminance (lx)	Maximum Illuminance (lx)	Average Illuminance (lx)	Minimum to Maximum Ratio	Minimum to Average Ratio
0	0	40.7	55.7	47.6	0.73	0.85
	10	35.7	50.7	43.4	0.70	0.82
	20	35.7	49.3	42.8	0.72	0.83
	30	36.7	48.7	43.2	0.75	0.85
	40	32.0	42.7	37.2	0.75	0.86
	50	30.3	38.7	34.8	0.78	0.87
	60	29.3	37.7	33.9	0.78	0.87
	70	28.0	40.0	33.7	0.70	0.83
	80	27.3	36.3	31.8	0.75	0.86
	90	27.0	35.3	30.8	0.76	0.88
30	0	425.3	556.7	494.3	0.76	0.86
	10	401.3	520.7	454.8	0.77	0.88
	20	378.7	482.3	423.2	0.79	0.89
	30	355.7	446.7	391.1	0.80	0.91
	40	316.3	403.7	355.0	0.78	0.89
	50	254.7	366.7	313.9	0.69	0.81
	60	206.7	297.3	255.7	0.70	0.81
	70	141.3	208.3	171.0	0.68	0.83
	80	125.0	149.3	136.6	0.84	0.92
	90	51.7	71.0	59.5	0.73	0.87
60	0	601.7	776.0	701.1	0.78	0.86
	10	517.0	651.7	597.5	0.79	0.87
	20	480.3	588.7	538.7	0.82	0.89
	30	391.3	556.7	486.0	0.70	0.81
	40	352.0	561.3	424.8	0.63	0.83
	50	325.7	499.3	367.0	0.65	0.89
	60	286.7	428.3	330.6	0.67	0.87
	70	204.3	305.0	258.9	0.67	0.79
	80	144.7	244.3	195.9	0.59	0.74
	90	74.7	103.3	88.9	0.72	0.84
90	0	687.3	1075.3	868.9	0.64	0.79
	10	662.0	858.7	750.5	0.77	0.88
	20	592.0	750.7	634.9	0.79	0.93
	30	542.3	644.7	575.1	0.84	0.94
	40	452.7	644.0	494.3	0.70	0.92
	50	391.7	598.0	438.6	0.65	0.89
	60	331.3	555.0	384.7	0.60	0.86
	70	232.7	437.0	287.1	0.53	0.81
	80	161.3	296.3	210.5	0.54	0.77
	90	74.7	136.3	102.1	0.55	0.73
120	0	616.0	783.3	714.8	0.79	0.86
	10	532.3	665.0	611.7	0.80	0.87
	20	447.0	621.3	557.9	0.72	0.80
	30	401.3	570.0	497.7	0.70	0.81
	40	343.0	549.7	414.8	0.62	0.83
	50	325.3	499.3	367.3	0.65	0.89
	60	265.7	409.7	311.6	0.65	0.85
	70	197.3	296.7	252.1	0.67	0.78
	80	133.7	231.3	187.2	0.58	0.71
	90	72.0	99.3	85.2	0.72	0.84

Table 1. *Cont.*

Horizontal Angle (Degree)	Elevation Angle (Degree)	Minimum Illuminance (lx)	Maximum Illuminance (lx)	Average Illuminance (lx)	Minimum to Maximum Ratio	Minimum to Average Ratio
150	0	419.7	551.3	488.3	0.76	0.86
	10	382.7	501.7	435.9	0.76	0.88
	20	363.7	480.6	410.3	0.76	0.89
	30	333.0	432.7	373.0	0.77	0.89
	40	322.7	410.0	361.3	0.79	0.89
	50	265.7	377.7	325.1	0.70	0.82
	60	213.7	304.3	264.8	0.70	0.81
	70	155.3	222.0	185.3	0.70	0.84
	80	134.0	158.7	145.6	0.84	0.92
	90	57.7	76.0	65.2	0.76	0.88
180	0	42.7	58.0	50.19	0.74	0.85
	10	34.7	50.0	42.33	0.69	0.82
	20	37.7	51.0	44.89	0.74	0.84
	30	39.7	51.7	45.96	0.77	0.86
	40	29.0	39.7	34.33	0.73	0.84
	50	28.3	37.0	33.15	0.77	0.85
	60	31.3	40.3	36.19	0.78	0.87
	70	26.7	39.0	33.07	0.68	0.81
	80	29.3	39.0	34.04	0.75	0.86
	90	30.3	37.7	33.93	0.81	0.89

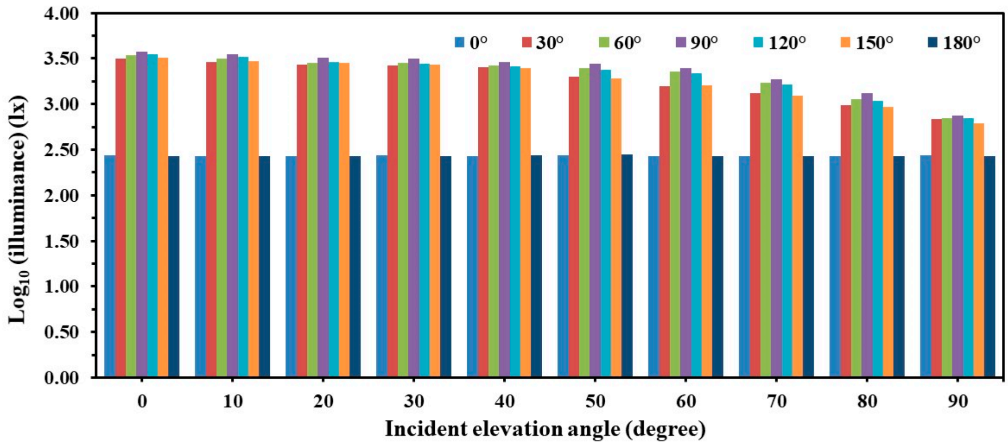


(**a**)

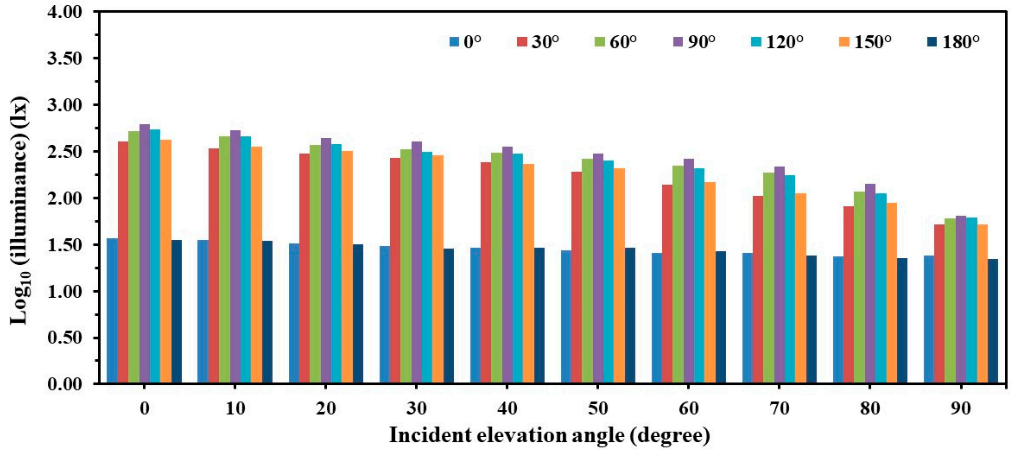


(**b**)

Figure 3. *Cont.*



(**c**)



(**d**)

Figure 3. Logarithmically transformed average illuminance at the (**a**) upper and (**b**) lower termini positions of aluminum alloy tube; and the (**c**) top and (**d**) bottom termini positions of zinc alloy tube.

Upon evaluating the zinc alloy tube under various elevation and horizontal angles, the logarithmically transformed illuminance trend at the upper and lower termini locations demonstrated similarities with that of the aluminum alloy tube. At a horizontal angle of 30°, the logarithmically transformed illuminance at the upper termini location of the tube decreased from 3.50 lx to 2.84 lx, and at the lower termini location, it decreased from 2.60 lx to 1.72 lx as the elevation angle of the incident light increased from 0° to 90°, as illustrated in Figure 3c,d. This pattern of logarithmically transformed illuminance at the upper and lower ends of the horizontal light tube persisted consistently for shadow angles of 60°, 90°, 120°, and 150°, mirroring the trend observed at the 30° shadow angle. Moreover, the logarithmically transformed illuminance at the upper and lower termini of the tube remained constant for horizontal angles of 0° and 180°, as depicted in Figure 3c,d. It was observed that the logarithmically transformed maximum illuminance at the upper and lower termini location of both the aluminum alloy tube and the zinc alloy tube was at the horizontal angle of 90° in all horizontal angles in each elevation angle. This preferred angle of incidence is generally perpendicular to the upper termini surfaces of both tube variants, maximizing light capture. This phenomenon arises from light reflecting off the surface and being directed downwards within the tube. Any departure from perpendicularity reduces the effective collection area, leading to decreased light intake and potential losses, as light may escape the system. This consideration becomes particularly important when factoring in the varying position of the light source [29–36]. These findings indicate a common decrease in illuminance at the upper and lower termini of both types of tubes in response to an increase in the incident elevation angle of the light source. At lower incident angles of the light source into the light pipe, the light pipe exhibited higher illuminance due to the combination of light reflection from certain parts and the predominant direct transmission of light through the tube. On the other hand, when the light source was positioned at higher elevation angles inside the light tube, the illuminance of the tube was mainly influenced by the intensity of light reflection within the tube.

Figure 4 displays the computed average illuminance at the upper and lower positions of both the aluminum alloy tube and the zinc alloy tube. This assessment aimed for examining their light transmission capabilities under various horizontal and elevation angles. This investigation builds upon prior research outlined in [37]. When the horizontal angle was set at 0°, the light transmission efficiency of both types of tubes decreased from 17% to 11% and from 13% to 9%, respectively, as the elevation angle was increased from 0° to 90°. Figure 4 illustrates that the light transmission efficiency of both types of tube remained comparable at horizontal angles of 30°, 60°, 120°, 150°, and 180°, as observed at the 0° horizontal angle. The light transmission efficiency of both tube types exhibited peak performance at a horizontal angle of 90° across all elevation angles. This phenomenon arises due to total internal reflection, occurring when light strikes the inner surface of the reflective tube at an angle surpassing the critical angle. At this point, the light is entirely reflected within the tube, preventing its escape. The achievement of total internal reflection is essential to minimize light loss during tube transmission [29–34]. Furthermore, it was evident that the aluminum alloy tube exhibited over 15% superior light transmission performance compared to the zinc alloy tube at all incident light horizontal and elevation angles. The fact that the aluminum alloy tube showed significantly higher reflective efficiency than the zinc alloy tube implies that it can serve as a suitable alternative daylight system in areas of a room that are deep inside or in windowless areas such as corridors, halls, vestibules, stores, or public spaces where there is a need for natural lighting but not for visual tasks. This could result in an energy saving of approximately 30% when the light tube is utilized in buildings [38].

During the experiment for the interior illumination distribution on the floor, a completely darkened environment was necessary to examine illuminance distribution. Factors such as the reflectance and transmittance properties of room materials, as well as the illuminant environment requirements for the room, were disregarded. Figure 5 presents the interior illumination distribution of the aluminum alloy light tube, as measured at 25 distinct floor locations under varying incident light angles. The distribution of illuminance in a two-dimensional horizontal plane is visually depicted using a color intensity representation. At a fixed horizontal shadow angle of 90°, the illuminance on the floor of the test room varied between 17.7 lx and 43.7 lx as the elevation angle of the incident light was set at 0°, displaying a non-uniform distribution, as illustrated in Figure 5a. Subsequently, as the angle of the incident light increased from 0° to 90°, the illuminance at each floor position within the test room exhibited alterations. The illuminance on the floor of the testing model exhibited a decrease as the elevation angle of the incident light increased from 0° to 80°, as depicted in Figure 5b–d. Conversely, at other horizontal and elevation angles, the interior illumination contours on the floor from the aluminum alloy light tube closely resembled that of the 90° horizontal angle. Upon examination of the interior illumination contours on the floor in the testing room with the zinc alloy hollow, it was observed to be similar to that of the aluminum alloy hollow when considering various incident light horizontal and elevation angles.

The study assessed the uniformity of illuminance distribution on the test room floor using "min to max" and "min to average" illuminance ratios. However, it is worth mentioning that these metrics were initially developed for evaluating electric lighting and may not be directly applicable to daylight performance, as indicated by Kent et al. [31]. These ratios are calculated by comparing the lowest recorded illuminance (minimum) to the highest recorded illuminance (maximum) and the minimum to the average illuminance on the floor. A ratio close to one signifies minimal variation in lighting levels, indicating uniform distribution. The results from the horizontal aluminum alloy and zinc alloy hollows showed ratios close to one, suggesting uniform lighting distribution, as shown in Table 2. Variations in these ratios help assess the uniformity of illuminance distribution, which is essential for achieving comfortable and functional lighting in different settings. The values are illustrated in Table 2.

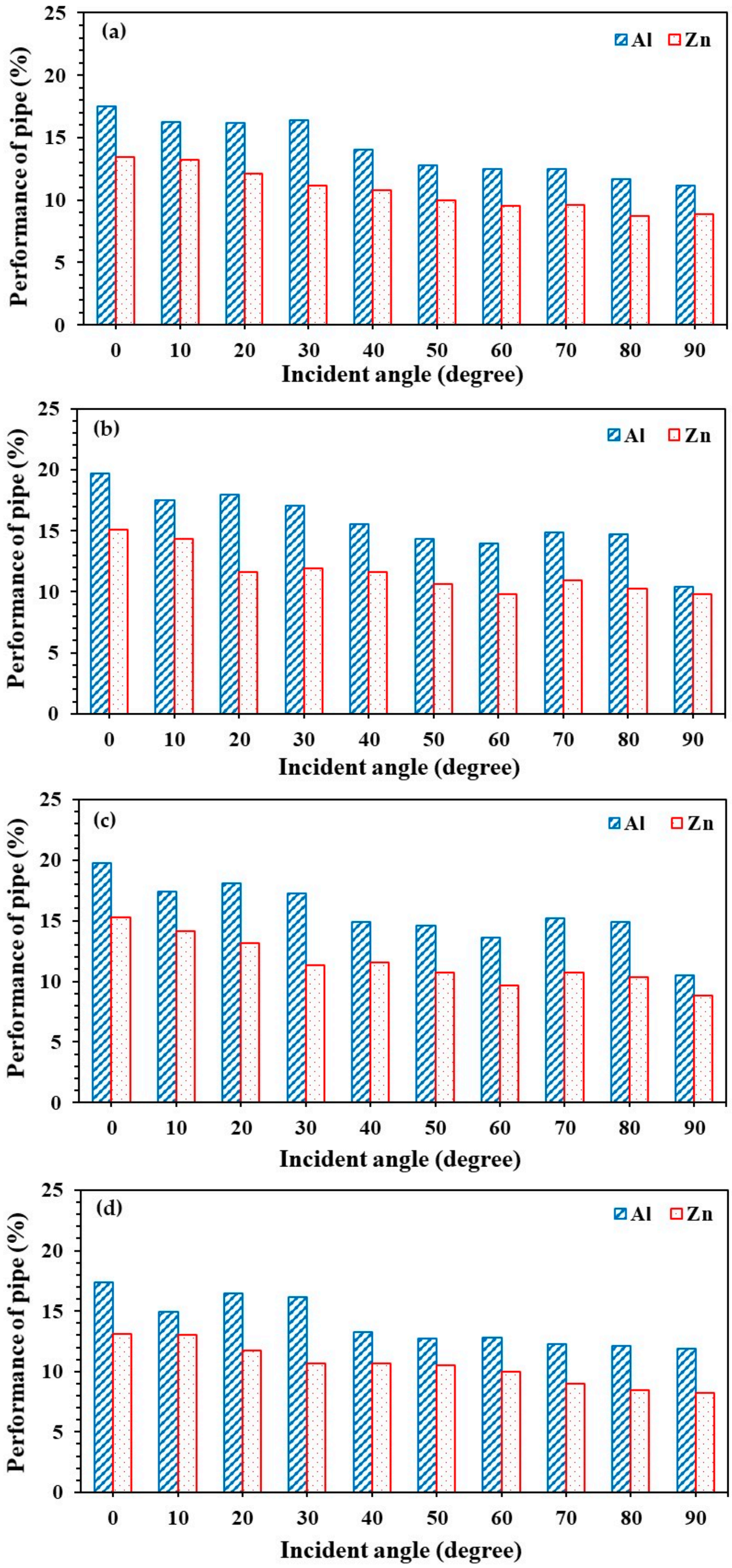


Figure 4. Light transmission characteristics of both the aluminum alloy hollow and the zinc alloy hollow at different horizontal angles: (**a**) 0°; (**b**) 60°; (**c**) 120°; and (**d**) 180°.

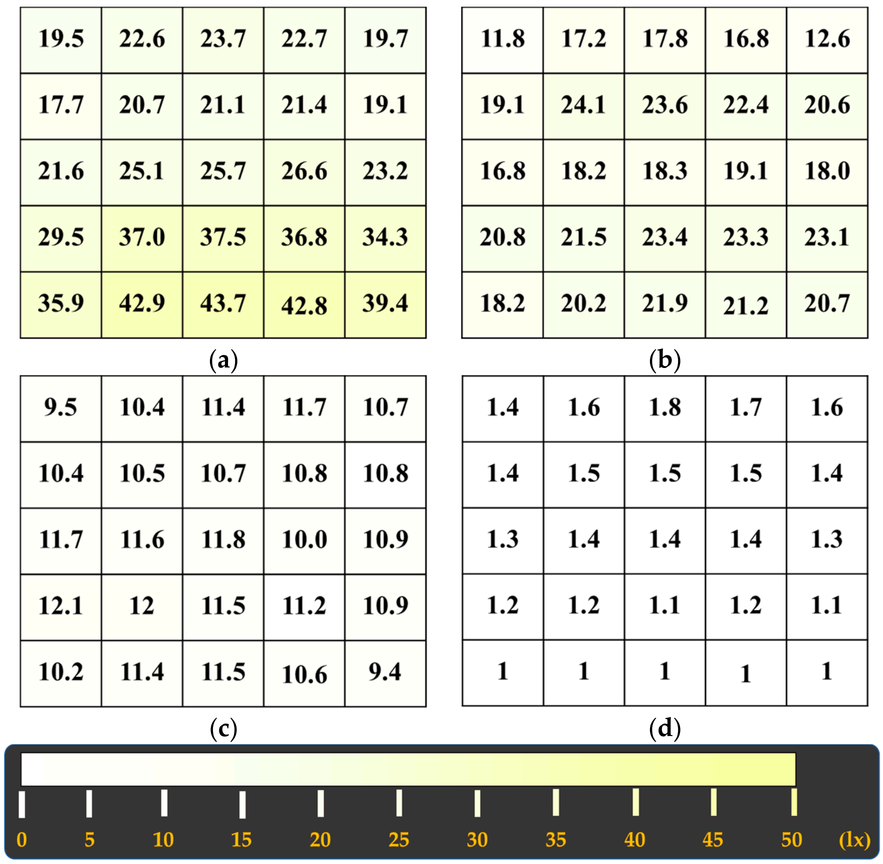


Figure 5. Illumination pattern on the floor from the aluminum alloy at the horizontal angle of 90° and various elevation angles of (**a**) 0°; (**b**) 20°; (**c**) 40°; and (**d**) 90°.

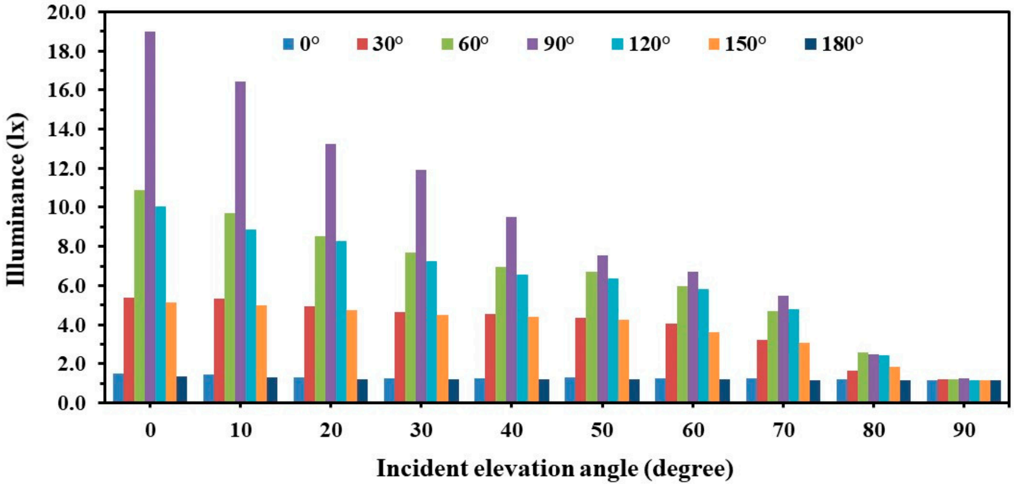
Table 2. Summary of illuminance distribution uniformity on the test room floor for aluminum alloy hollow and zinc alloy hollow at various horizontal and elevation angles.

Horizontal Angle (Degree)	Elevation Angle (Degree)	Minimum Illuminance (lx)		Maximum Illuminance (lx)		Average Illuminance (lx)		Minimum to Maximum Ratio		Minimum to Average Ratio	
		Al	Zn	Al	Zn	Al	Zn	Al	Zn	Al	Zn
0	0	1.3	0.8	1.9	1.3	1.6	1.1	0.67	0.62	0.81	0.71
	10	1.2	0.8	1.8	1.3	1.5	1.1	0.66	0.62	0.79	0.73
	20	1.1	0.8	1.7	1.3	1.4	1.1	0.67	0.62	0.81	0.70
	30	1.1	0.8	1.7	1.3	1.3	1.1	0.67	0.59	0.85	0.70
	40	1.1	0.8	1.5	1.3	1.3	1.1	0.73	0.62	0.86	0.70
	50	1.2	0.8	1.6	1.3	1.4	1.1	0.74	0.62	0.88	0.74
	60	1.1	0.8	1.6	1.3	1.3	1.1	0.70	0.62	0.84	0.74
	70	1.1	0.8	1.5	1.3	1.3	1.1	0.73	0.62	0.85	0.73
	80	1.1	0.8	1.4	1.3	1.3	1.1	0.80	0.62	0.87	0.73
	90	1.1	0.8	1.4	1.3	1.2	1.1	0.80	0.62	0.91	0.72
30	0	4.5	3.2	6.9	5.8	5.6	4.4	0.65	0.56	0.81	0.73
	10	4.6	3.2	6.8	5.3	5.6	4.1	0.68	0.60	0.83	0.77
	20	4.2	2.9	6.3	4.7	5.2	3.6	0.66	0.62	0.81	0.79
	30	3.9	2.8	6.1	3.9	4.9	3.3	0.64	0.70	0.80	0.83
	40	3.7	2.6	5.5	3.6	4.8	3.0	0.68	0.71	0.78	0.85
	50	3.7	2.5	5.1	3.2	4.6	2.8	0.73	0.78	0.81	0.90
	60	3.3	2.1	4.9	2.9	4.2	2.5	0.67	0.74	0.78	0.85
	70	2.8	2.0	4.0	2.5	3.4	2.2	0.71	0.81	0.84	0.91
	80	1.1	1.1	2.2	1.9	1.7	1.5	0.51	0.60	0.65	0.74
	90	1.1	0.8	1.4	1.3	1.2	1.1	0.80	0.59	0.90	0.71

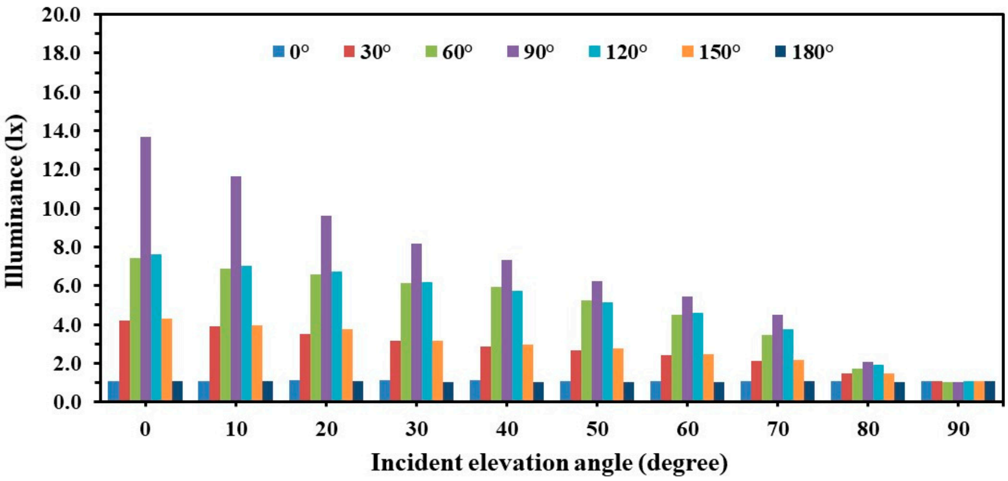
Table 2. *Cont.*

Horizontal Angle (Degree)	Elevation Angle (Degree)	Minimum Illuminance (lx)		Maximum Illuminance (lx)		Average Illuminance (lx)		Minimum to Maximum Ratio		Minimum to Average Ratio	
		Al	**Zn**	**Al**	**Zn**	**Al**	**Zn**	**Al**	**Zn**	**Al**	**Zn**
60	0	7.3	4.6	18.6	13.1	11.4	7.7	0.39	0.35	0.64	0.59
	10	6.6	4.1	15.0	11.8	10.1	7.2	0.44	0.35	0.66	0.57
	20	4.7	3.9	12.1	11.6	8.9	6.9	0.39	0.34	0.52	0.57
	30	6.5	3.6	9.9	10.8	8.0	6.4	0.66	0.33	0.81	0.56
	40	6.0	3.3	8.8	10.5	7.3	6.1	0.69	0.32	0.83	0.55
	50	6.0	3.2	8.0	8.5	7.0	5.5	0.74	0.37	0.85	0.58
	60	5.3	3.0	7.0	7.7	6.2	4.7	0.76	0.38	0.85	0.63
	70	4.1	2.7	5.7	4.8	4.9	3.6	0.71	0.56	0.83	0.75
	80	2.1	1.3	3.2	2.2	2.7	1.8	0.64	0.60	0.77	0.73
	90	1.1	0.8	1.5	1.3	1.3	1.1	0.73	0.59	0.89	0.72
90	0	12.5	7.5	30.3	24.0	19.8	14.3	0.41	0.31	0.63	0.52
	10	11.4	7.1	23.7	19.2	17.2	12.2	0.48	0.37	0.67	0.59
	20	8.5	6.0	16.9	15.4	13.8	10.1	0.50	0.39	0.61	0.59
	30	7.4	5.0	15.8	12.9	12.4	8.5	0.47	0.39	0.59	0.59
	40	7.0	4.7	13.1	10.9	9.9	7.7	0.53	0.43	0.70	0.61
	50	6.9	4.5	8.7	8.5	7.9	6.5	0.79	0.53	0.87	0.69
	60	6.2	3.9	8.6	6.8	7.0	5.7	0.72	0.58	0.88	0.69
	70	4.9	3.8	7.0	5.6	5.7	4.7	0.71	0.69	0.86	0.82
	80	1.9	1.5	3.3	2.8	2.6	2.2	0.59	0.52	0.75	0.67
	90	1.1	0.8	1.7	1.3	1.3	1.1	0.67	0.59	0.84	0.71
120	0	6.8	4.9	17.1	13.3	10.5	8.0	0.40	0.37	0.64	0.61
	10	6.0	4.3	14.3	11.8	9.3	7.3	0.42	0.36	0.64	0.58
	20	6.3	4.1	11.6	11.7	8.7	7.0	0.54	0.35	0.73	0.58
	30	6.0	3.7	9.2	10.7	7.6	6.5	0.65	0.35	0.79	0.57
	40	5.8	3.6	8.5	9.9	6.8	6.0	0.69	0.36	0.85	0.60
	50	4.8	3.2	7.9	7.8	6.6	5.4	0.60	0.41	0.72	0.59
	60	5.5	3.0	6.9	7.1	6.1	4.8	0.80	0.43	0.90	0.63
	70	3.8	2.9	6.5	5.8	5.0	3.9	0.59	0.50	0.77	0.74
	80	1.9	1.7	3.1	2.3	2.5	2.0	0.60	0.71	0.73	0.82
	90	1.1	0.8	1.5	1.3	1.2	1.1	0.77	0.59	0.91	0.70
150	0	4.5	3.3	6.6	5.8	5.4	4.5	0.68	0.57	0.84	0.74
	10	4.3	3.3	6.4	5.4	5.2	4.1	0.66	0.62	0.81	0.80
	20	4.0	3.0	6.4	5.2	5.0	3.9	0.63	0.58	0.80	0.77
	30	3.8	3.0	5.9	3.7	4.7	3.3	0.65	0.80	0.82	0.89
	40	3.7	2.8	5.3	3.4	4.6	3.1	0.70	0.80	0.81	0.89
	50	3.6	2.6	4.8	3.2	4.4	2.9	0.76	0.79	0.82	0.88
	60	3.4	2.3	4.7	3.1	4.2	2.6	0.74	0.76	0.82	0.89
	70	2.7	2.1	3.8	2.6	3.2	2.2	0.71	0.81	0.83	0.92
	80	1.3	1.2	2.0	1.8	1.9	1.6	0.65	0.66	0.66	0.76
	90	1.1	0.8	1.3	1.5	1.2	1.1	0.85	0.53	0.94	0.68
180	0	1.2	0.8	1.7	1.3	1.4	1.1	0.69	0.59	0.83	0.69
	10	1.1	0.8	1.6	1.3	1.3	1.1	0.70	0.62	0.83	0.70
	20	1.1	0.8	1.5	1.3	1.3	1.1	0.77	0.62	0.88	0.70
	30	1.1	0.8	1.4	1.3	1.3	1.1	0.80	0.62	0.89	0.71
	40	1.1	0.8	1.4	1.3	1.2	1.1	0.80	0.62	0.90	0.71
	50	1.1	0.8	1.5	1.3	1.3	1.1	0.77	0.62	0.88	0.72
	60	1.1	0.8	1.5	1.3	1.3	1.1	0.77	0.62	0.89	0.71
	70	1.1	0.8	1.4	1.3	1.2	1.1	0.80	0.62	0.92	0.70
	80	1.1	0.8	1.3	1.3	1.2	1.1	0.85	0.62	0.92	0.72
	90	1.1	0.8	1.3	1.3	1.2	1.1	0.85	0.62	0.93	0.73

The average illuminance was determined by assessing illuminance measurements at 25 specific locations on the floor for both types of tubes at varying incident horizontal and elevation angles of the light source, as depicted in Figure 6. With regard to the aluminum alloy light pipe, Figure 6a presents the average illuminance on the floor. The variation in average illuminance on the floor was observed as the incident light elevation and horizontal angles were changed. When the horizontal angle of 90° was taken into account, it was observed that the average illuminance value on the floor dropped from 20 lx to 1 lx as the elevation angle of the incident light increased from 0° to 90°. Similar trends of average illuminance on the floor were observed for the horizontal angles of 30°, 60°, 120°, and 150°, as compared to the horizontal angle of 90°. In contrast, the average illuminance on the floor remained steady for the horizontal angles of 0° and 180°, as depicted in Figure 6a.



(**a**)



(**b**)

Figure 6. Comparison of average internal illuminance on the floor from horizontal light tubes: (**a**) aluminum alloy light tubes; and (**b**) zinc alloy light tubes.

Similar to the aluminum alloy tube, a corresponding trend in illuminance on the floor was observed with the zinc alloy pipe across each elevation and horizontal angle. Specifically, at the horizontal angle of 90°, the average illuminance decreased from 14 lx to 1 lx as the elevation angle of the incident light increased from 0° to 90°, as demonstrated in Figure 6b. The trend of average illuminance on the floor for the horizontal angles of 30°, 60°, 120°, and 150° was similar to that of the horizontal shadow angle of 90°. However, for the horizontal shadow angles of 0° and 180°, the average illuminance on the floor remained stable, as shown in Figure 6b. Upon considering the horizontal shadow angle of both types of tubes, it was observed that the average maximum illuminance was achieved at the horizontal angle of 90°. The average illuminance on the floor decreased when there was a variation in the horizontal shadow angles from 90° to 60° and 120°, 30° and 150°, 0° and 180°, respectively.

The daylight factor was determined by dividing the average indoor illuminance by the ambient illuminance. The average daylight factor for the aluminum alloy hollow is presented in Figure 7a, exhibiting variations as a result of changes in both the incident light elevation and horizontal angles. When considering a horizontal shadow angle of 90°, the average daylight factor decreased from 18.2% to 1.2% as the incident light elevation angle increased from 0° to 90°. A similar trend in the average daylight factor was observed for horizontal angles of 30°, 60°, 120°, and 150°, mirroring that of the 90° horizontal angle. Conversely, for horizontal angles of 0° and 180°, the average daylight factor remained constant, as depicted in Figure 7a. Similarly, the trend of the average daylight factor in the zinc alloy tube paralleled that of the aluminum alloy tube for each elevation and horizontal angle. At a horizontal angle of 90°, the average daylight factor decreased from 13.1% to 1.0% with an increase in the incident light elevation angle from 0° to 90°, as illustrated in Figure 7b. The trend of the average daylight factor for the horizontal shadow angles of 30°, 60°, 120°, and 150° was comparable to that of the horizontal angle of 90°. For the horizontal angles of 0° and 180°, the average daylight factor remained constant, as shown in Figure 7b.

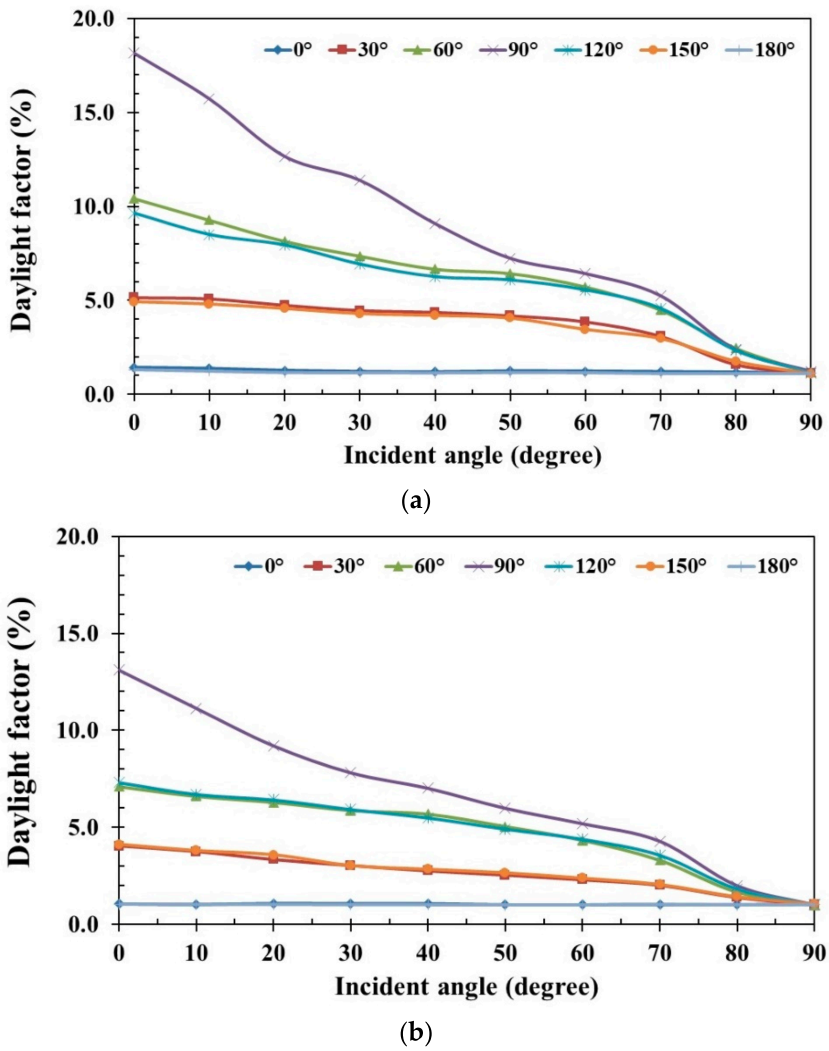


Figure 7. Floor daylight factor comparison for horizontal light tubes: (**a**) aluminum alloy light hollow; and (**b**) zinc alloy light hollow.

The investigation revealed that the average maximum daylight factor for both the aluminum alloy tube and the zinc alloy tube occurred at a horizontal angle of 90° when comparing their respective horizontal angles. Subsequently, the average daylight factor showed a decrease when the horizontal angles deviated from 90° to 60°, 120°, 30°, 150°, 0°, and 180°, respectively. The obtained daylight factor values from both types of tubes in this study align with previous research, indicating that spaces with $\leq$0.2% daylight factor have very low daylight levels, requiring significant artificial lighting. Spaces with 0.2% < DF $\leq$ 0.6% have better but potentially insufficient lighting for detailed tasks. Those with 0.6% < DF $\leq$ 2.0% receive a reasonable amount of daylight for general activities, and spaces with 2.0% < DF $\leq$ 5.0% have substantial natural light, suitable for most tasks and creating a comfortable environment. Spaces with DF > 5.0% enjoy abundant natural light, perfect for high-quality lighting and a pleasant indoor atmosphere, consistent with prior findings. Furthermore, the alignment of minimum illuminance values with the EN 17037-recommended target illuminances of 300 lx, 500 lx, and 750 lx for half of the working surface ensures that the indoor environment meets the visual requirements of occupants [17,21,39,40]. These findings suggest that the implementation of horizontal tubes made of aluminum alloy and zinc alloy could serve as a feasible option for providing daylight in areas within buildings that have limited access to windows or are entirely windowless. Generally, hollow light tubes encompass a collector, reflective tube, and diffuser to capture and distribute natural sunlight indoors. The theory involves continuous sunlight capture, minimal light loss through reflective tube channels, and uniform diffusion within the room. Natural sunlight enhances aesthetics, reduces electric lighting demands, and aligns with sustainable practices. These tubes optimize daylighting strategies and relate to sustainable building principles. The angle theory explores factors like incidence, reflection, total internal reflection, tube length, diffuser design, and building orientation, influencing system efficiency. Understanding the angles of light during design is crucial, as it leads to optimal performance, promoting energy conservation and improved indoor environments [31–36].

To achieve energy efficiency in interior building lighting systems, one must determine the appropriate lighting power density (LPD). This metric is derived by dividing the electric lighting power required per unit area to achieve a specified indoor illumination level [41–45]. It is important to note exceptions, such as showcase lighting or non-permanent building installations, which are not included in LPD calculations. Furthermore, LPD calculations exclude parking lot areas. The building code refrains from specifying illuminance on the working plane, given separate standards exist for minimum illuminance requirements based on usage types [46,47]. Type 1 buildings, for instance, have flexibility in LPD based on their design, allowing for tailored lighting solutions, like dividing residential areas or meeting high illuminance requirements in hospitals.

Efficient energy performance in interior building lighting systems involves creating effective and cost-efficient lighting setups that deliver sufficient illumination while minimizing energy consumption. This assessment evaluates both electric lighting and daylight strategies, examining their energy usage, environmental impact, and effectiveness in providing appropriate lighting. Key concepts, such as lighting power density (LPD) and normalized power density (NPD), are pivotal in quantifying and optimizing energy use in indoor lighting. NPD, an extension of LPD, accounts for available daylight to reduce dependence on artificial lighting. It is calculated by dividing total electric lighting power density by the available daylight factor (the ratio of indoor daylight illuminance to outdoor illuminance). In this study, daylight factor values obtained from both types of tubes align with previous research, emphasizing daylight's contribution in areas with 1–2% daylight factor for residential activities and 2–4% daylight factor for office building activities [17,39,40]. NPD represents the combined lighting power required to achieve desired illuminance levels while factoring in natural daylight. This concept encourages energy efficiency by promoting the integration of daylighting strategies into lighting design, aligning with CIE standards to create well-lit, energy-efficient, and environmentally responsible spaces [41–45]. The study's outcomes can inform architects, building designers, and policymakers in making informed choices about sustainable lighting solutions and advancing energy conservation goals in the built environment, including reducing energy-related greenhouse gas emissions. Ultimately, this research contributes to the broader objective of creating more energy-efficient and environmentally responsible buildings for a sustainable future.

4. Discussion

The research described focuses on the light transmission and distribution properties of horizontal hollow light pipes made from aluminum and zinc alloys. Inner illumination contours at various positions on the aluminum alloy light tube ranged from 3486 lx to 4263 lx at the top and from 687 lx to 1075 lx at the bottom with a 0° incident light angle. Illuminance decreased consistently as the incident angle increased from 0° to 90°, peaking at 90°. The illuminance varied with changing incident light elevation and horizontal angles. For example, at a 30° horizontal angle, illuminance decreased from 3205 lx to 676 lx at the top and from 494 lx to 59 lx at the bottom with elevation angle changes. The maximum light transmission efficiency for both types of tubes occurred at a horizontal angle of 90°. This is due to total internal reflection, which minimizes light loss. At a 90° horizontal angle, illuminance ranged from 17.7 lx to 43.7 lx at a 0° elevation angle, displaying non-uniform distribution. Illuminance decreased as the elevation angle increased. The trend mirrored that of the 90° horizontal angle, showing the highest illuminance on the floor for both types of tubes at 90° and decreasing illuminance on the floor at other horizontal angles. Daylight factor decreased from 18.2% to 1.2% at a 90° horizontal angle as the elevation angle increased from 0° to 90°. A similar trend was observed for other horizontal angles.

The study evaluates these properties under different incident light angles and provides valuable insights into the potential applications of these materials in achieving energy-efficient indoor lighting. Daylighting strategies benefit from the findings, promoting energy savings and reduced reliance on artificial lighting during daylight hours [6–9]. This aligns with sustainable building practices by minimizing energy consumption, enhancing aesthetics, and supporting sustainability goals. Design optimization through angle considerations contributes to better performance, energy conservation, and improved indoor environments [31–36]. Related concepts include lighting power density (LPD) and normalized power density (NPD), key metrics in energy-efficient building design [41–45]. The daylight factor aligns with energy-efficient building standards, and the research emphasizes broader environmental and energy conservation objectives [46,47]. This research enhances energy-efficient building design with insights on using aluminum and zinc alloy light pipes, aligning with established concepts in lighting design and sustainability, making it valuable for building design and energy conservation.

Moreover, this work has presented several limitations and considerations that should be noted: 1. Material selection: The research focused on horizontal hollow light pipes made from commercially available aluminum alloy and zinc alloy materials. The choice of these materials might not represent all the possible materials used in such applications. Other materials might exhibit different optical properties and performance characteristics. 2. Idealized test model: The experiments were conducted in a controlled test model with specific dimensions. The model had limited scale, demonstrating daylight performance within a 1 m^2 interior room. This may not offer a comprehensive perspective for larger and intricate building designs, particularly concerning daylight distribution. Actual buildings have varied architectural features, internal layouts, and different surface properties, all of which can influence daylight distribution and performance. 3. Limited variability: The study primarily considered changes in incident light elevation and horizontal angles. It did not account for variables like changing weather conditions, geographical locations, or the position of the sun throughout the day. Applied situations can experience substantial variability due to these factors. 4. Sensitivity to position and orientation: The findings indicate that the maximum illuminance occurred at specific angles, particularly when the incident light was nearly perpendicular to the tube's upper surface. Though this information is valuable, it also highlights the sensitivity of these systems to the position of the sun. The feasibility and performance of these systems might be different at other locations and times. 5. Lack of dynamic data: The study provided static measurements and illuminance values at different angles, but it did not capture the dynamic aspects of changing daylight conditions throughout the day. A more comprehensive assessment would require data on the system's performance over time and its adaptability to varying daylight intensities. 6. Assumptions in LPD and NPD: The paper discussed the concept of lighting power density (LPD) and normalized power density (NPD) but did not address all the possible factors and variations that can affect these metrics in practical applications. Applied energy efficiency calculations may need to consider additional variables and constraints. 7. Practical application: The research focused on the technical aspects of the light pipes and their illumination characteristics. It did not explore the practical challenges and costs associated with implementing these systems in actual buildings. Practical applications may require additional considerations, including maintenance, installation, and economic feasibility.

These limitations should be considered when applying the findings of this study to practical architectural and lighting design. Further research and practical experimentation are needed to address these considerations and advance the understanding of daylighting systems and their energy efficiency.

5. Conclusions

The work investigates the light transmission and distribution properties of horizontal hollow light tubes constructed from both aluminum alloy and zinc alloy, considering a range of incident light angles. The "min to max" and "min to average" illuminance ratios at various horizontal and elevation angles indicate a relatively uniform lighting distribution on the floor and at the lower end positions of the hollow. A reduction in illuminance is observed with an increase in the elevation angle of the incident light. Notably, the aluminum alloy tubes outperform their zinc alloy counterparts, boasting more than a 15% increase in light transmission efficiency. The research reveals that these horizontal tubes perform optimally at a 90° horizontal angle due to total internal reflection, which minimizes light loss during transmission. Consistently, the aluminum alloy tube surpasses the zinc alloy tube in terms of light transmission efficiency. Within the context of energy efficiency, the study introduces the concepts of lighting power density (LPD) and normalized power density (NPD). NPD accounts for available daylight to decrease reliance on artificial lighting, thereby promoting energy-efficient lighting design. This research significantly contributes to the advancement of energy-efficient and environmentally responsible building design, aligning with global endeavors to create a more sustainable built environment. It offers valuable insights for architects, building designers, and policymakers to make well-informed decisions regarding sustainable lighting solutions and energy conservation objectives.

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Nomenclature

DF	Daylight factor
DPF	Daylight penetration factor
LED	Light-emitting diode
LPD	Lighting power density
NPD	Normalized power density
CIE	International Commission on Illumination

References

1. Khedari, J.; Sangprajak, A.; Hirunlabh, J. Investigation of thermal performance by applying a solar chimney with PCM towards the natural ventilation of model house under Climate of Thailand. *Renew. Energy* **2001**, *25*, 267–280. [CrossRef]
2. Thongtha, A.; Khongthon, A.; Boonsri, T.; Chan, H.Y. Thermal effectiveness enhancement of autoclaved aerated concrete wall with PCM-contained conical holes to reduce the cooling load. *Materials* **2019**, *12*, 2170. [CrossRef]
3. Thongtha, A.; Boontham, P. Experimental investigation of natural lighting systems using cylindrical glass for energy saving in buildings. *Energies* **2020**, *13*, 2528. [CrossRef]
4. Yan, T.; Sun, Z.W.; Gao, J.J.; Xu, X.H.; Yu, J.H.; Gang, W.J. Simulation study of a pipe-encapsulated PCM wall system with self-activated heat removal by nocturnal sky radiation. *Renew. Energy* **2020**, *146*, 1451–1464. [CrossRef]
5. Kim, J.T.; Kim, G. Overview and new developments in optical daylighting systems for building a healthy indoor environment. *Build. Environ.* **2010**, *45*, 256–269. [CrossRef]
6. Chayawat, C.; Satakhun, D.; Kasemsap, P.; Sathornkich, J. Environmental controls on net CO_2 exchange over a young rubber plantation in Northeastern Thailand. *Sci. Asia* **2019**, *45*, 50–59. [CrossRef]
7. Krarti, M.; Erickson, P.M.; Hillman, T.C. A simplified method to estimate energy savings of artificial lighting use from daylighting. *Build. Environ.* **2005**, *40*, 747–754. [CrossRef]
8. Li, D.H.W.; Lam, T.N.T.; Wong, S.L.; Tsang, E.K.W. Lighting and cooling energy consumption in an open-plan office using solar film coating. *Energy* **2008**, *33*, 1288–1297. [CrossRef]
9. Kent, M.; Huynh, N.K.; Schiavon, S.; Selkowitz, S. Using support vector machine to detect desk illuminance sensor blockage for closed-loop daylight harvesting. *Energy Build.* **2022**, *274*, 112443. [CrossRef]
10. Lopin, M.K. An overview of daylighting systems. *Sol. Energy* **2002**, *73*, 77–82. [CrossRef]
11. Ekren, N.; Gorgulu, S. An investigation into the usability of straight light-pipes in Istanbul. *Energy Ed. Sci. Tech. Part A Energy Sci. Res.* **2012**, *30*, 637–644.
12. Jenkins, D.; Muneer, T.; Kubie, J. A design tool for predicting the performances of light pipes. *Energy Build.* **2005**, *37*, 485–492. [CrossRef]
13. Oakley, G.; Riffat, S.B.; Shao, L. Daylight performance of light pipes. *Sol. Energy* **2000**, *69*, 89–98. [CrossRef]
14. Garcia, H.V.; Esteves, A.; Pattini, A. Passive solar systems for heating, daylighting and ventilation for rooms without an equator-facing façade. *Renew. Energy* **2002**, *26*, 91–111. [CrossRef]
15. Wong, I.; Yang, H.X. Introducing natural lighting into the enclosed lift lobbies of high-rise buildings by remote source lighting system. *Appl. Energy* **2012**, *90*, 225–232. [CrossRef]
16. Canziani, R.; Peron, F.; Rossi, G. Daylight and energy performances of a new type of light pipe. *Energy Build.* **2004**, *36*, 1163–1176. [CrossRef]
17. Rosemann, A.; Mossman, M.; Whitehead, L. Development of a cost-effective solar illumination system to bring natural light into the building core. *Sol. Energy* **2008**, *82*, 302–310. [CrossRef]
18. Alrubaih, M.S.; Zain, M.F.M.; Alghoul, M.A.; Ibrahim, N.L.N.; Shameri, M.A.; Elayeb, O. Research and development on aspects of daylighting fundamentals. *Renew. Sustain. Energy Rev.* **2013**, *21*, 494–505. [CrossRef]
19. Smith, B.J.; Phillips, G.M.; Sweeney, M. Chapter 9—Daylighting. In *Environmental Science*; Routledge: London, UK, 2014.
20. Zhang, X.; Muneer, T. Mathematical model for the performance of light pipes. *Light Res. Technol.* **2000**, *32*, 141–146. [CrossRef]
21. *SIST EN 17037:2019*; Daylight of Buildings. Slovenian Institute for Standardization: Ljubljana, Slovenia, 2019.
22. Ozarisoy, B.; Altan, H. Bridging the energy performance gap of social housing stock in south-eastern Mediterranean Europe: Climate change and mitigation. *Energy Build.* **2022**, *258*, 111687. [CrossRef]
23. Altan, H.; Ozarisoy, B. An analysis of the development of modular building design elements to improve thermal performance of a representative high rise residential estate in the coastline city of Famagusta, Cyprus. *Sustainability* **2022**, *14*, 4065. [CrossRef]
24. Pleshkov, S.; Brakale, G.; Vedishcheva, I. A Project aimed to increase energy efficiency of the object swimming pool universitet sky by application of hollow mirrored tubular light guides under trade mark. *Mater. Sci. Eng.* **2018**, *463*, 042050.
25. Ahsan, M.D.; Ahsan, R.U.; Kim, Y.R.; Ashiri, R.; Cho, Y.J.; Jeong, C.; Park, Y.D. Cold metal transfer (CMT) MAW of zinc-coated steel. *Weld. J.* **2016**, *95*, 120–132.
26. Sharma, L.; Ali, S.F.; Rakshit, D. Performance evaluation of a top lighting light-pipe in buildings and estimating energy saving potential. *Energy Build.* **2018**, *179*, 57–72. [CrossRef]
27. Vasilakopoulou, K.; Kolokotsa, D.; Santamouris, M.; Kousis, I.; Asproulias, H.; Giannarakis, I. Analysis of the experimental performance of light pipes. *Energy Build.* **2017**, *151*, 242–249. [CrossRef]

28. Mehta, D. A Review on Challenges of Daylight-Based-Classroom-Studies and their Methodology Regarding Architectural-Design Process. *Int. J. Innov. Res. Sci. Eng. Technol.* **2020**, *9*, 15.
29. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World map of the Köppen-Geiger climate classification updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef]
30. Rubel, F.; Brugger, K.; Haslinger, K.; Auer, I. The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800–2100. *Meteorol. Z.* **2017**, *26*, 115–125. [CrossRef]
31. Kent, M.G.; Schiavon, S.; Jakubiec, J.A. A Dimensionality reduction method to select the most representative daylight illuminance distributions. *J. Build. Perform. Simul.* **2020**, *13*, 122–135. [CrossRef]
32. Freewan, A.A.Y.; Al Dalala, J.A. Assessment of daylight performance of Advanced Daylighting Strategies in Large University Classrooms; Case Study Classrooms at JUST. *Alex. Eng. J.* **2020**, *59*, 791–802. [CrossRef]
33. Obradovic, B.; Matusiak, B.S. Daylight autonomy improvement in buildings at high latitudes using horizontal light pipes and light-deflecting panels. *Sol. Energy* **2020**, *208*, 493–514. [CrossRef]
34. Šikula, O.; Mohelníková, J.; Plášek, J. Thermal CFD analysis of tubular light guides. *Energies* **2013**, *6*, 6304–6321. [CrossRef]
35. Baglivo, C.; Bonomolo, M.; Congedo, P.M. Modeling of light pipes for the optimal disposition in buildings. *Energies* **2019**, *12*, 4323. [CrossRef]
36. Kómar, L.; Kocifaj, M. An accurate prediction of daylight pipe harvesting of interior space. *Appl. Sci.* **2019**, *9*, 3552. [CrossRef]
37. Mohelnikova, J. Daylighting and energy savings with tubular light guides. *WSEAS Trans. Environ. Dev.* **2008**, *4*, 200–209.
38. Görgülü, S.; Ekrenb, N. Energy saving in lighting system with fuzzy logic controller which uses light-pipe and dimmable ballast. *Energy Build.* **2013**, *61*, 172–176. [CrossRef]
39. Yaik, W.L.; Mohd, H.A.; Dilshan, R.O. Internal shading for efficient tropical daylighting in Malaysian contemporary high-rise open plan office. *Indoor Built Environ.* **2013**, *22*, 932–951.
40. Hansen, V.G.; Edmonds, I. Methods for the illumination of multilevel buildings with vertical light pipes. *Sol. Energy* **2015**, *117*, 74–88. [CrossRef]
41. Linhart, F.; Scartezzini, J.L. Evening office lighting—Visual comfort vs. energy efficiency vs. performance? *Build. Environ.* **2011**, *46*, 981–989. [CrossRef]
42. Skarżyński, K.; Rutkowska, A. The interplay between parameters of light pollution and energy efficiency for outdoor amenity lighting. *Energies* **2023**, *16*, 3530. [CrossRef]
43. Commission Internationale de l'Eclairage. *CIE 150: Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations*; CIE: Vienna, Austria, 2017.
44. *EN 13201-5:2016-1-5*; Road Lighitng. CEN: Brussels, Belgium, 2016.
45. Pracki, P.; Dziedzicki, M.; Komorzycka, P. Ceiling and wall illumination, utilance, and power in interior lighting. *Energies* **2020**, *13*, 4744. [CrossRef]
46. *EN 12464-1:2011*; Light and Lighting—Lighting of Work Places—Part 1: Indoor Work Places. BSI: London, UK, 2011.
47. Ananwattanaporn, S.; Patcharoen, T.; Bunjongjit, S.; Ngaopitakkul, A. Retrofitted existing residential building design in energy and economic aspect according to thailand building energy code. *Appl. Sci.* **2021**, *11*, 1398. [CrossRef]