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Review

Integrated Systems of Light Pipes in Buildings: A State-of-the-Art Review

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Abstract: Artificial lighting comprises nearly one-third of the total electrical load of buildings, resulting in significant carbon emissions. Reducing the carbon emissions caused by artificial lighting is one of the ways to achieve low-carbon buildings. To meet the demand for high-efficiency, energy-saving, and comfortable lighting, light pipes are increasingly used in buildings. This paper reviews the research and development of light pipes and integrated technology. Sky conditions as a dynamic factor always affect the performance of light pipes. The combination of light pipes and an artificial lighting system can effectively solve this problem. A light pipe can be integrated with a ventilation stack to achieve the ventilation and cooling or heating of a building. A lighting-heating coupled light guide can improve the energy efficiency and sustainability in buildings, such as where antimony tin oxide nanofluid is introduced to absorb additional heat and then provide domestic hot water. The application of a photocatalyst to light pipes can realize air purification and self-cleaning. The use of light pipes does not consume electricity and can reduce the time spent using artificial lighting, thus allowing for power savings. From a whole life cycle perspective, the use of light pipes can be a balance of cost and benefit. In conclusion, such information could be useful for engineers, researchers, and designers to assess the suitability of applying integrated light pipes in different building types and examine the potential of energy and cost savings.

Keywords: light pipes; daylighting; lighting; integrated systems; ventilation; air purification

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1. Introduction

Buildings currently account for a third of global energy consumption and a quarter of CO_2 emissions [1]. Cooling, heating, and lighting are the main factors affecting building energy consumption. Artificial lighting accounts for about 33% of building electricity consumption [2]. Improper lighting can cause visual discomfort, reduce work efficiency, and even affect health [3–5]. In contrast, daylighting has good color rendering. It is one of the most ideal sources of biological circadian rhythm regulation, and its use can have a positive impact on indoor personnel and reduce building energy consumption [6–11].

Regarding the mechanism of collecting daylight, there are two types of light pipes, named active type and passive type. The active systems collect daylight by sun-tracking concentrators, such as the Himawari system in Japan, the HSL system in the USA, the Arthelio system in Europe, and the Heliobus system in Switzerland [12]. This type can collect daylight efficiently, but it is rarely used in construction because of the high cost. In contrast, passive light pipes are simpler and the production cost is lower. It is more and more widely used. This article is an overview of passive light pipes.

The light pipe is one of the lighting devices that introduce daylight into a space. It is generally composed of three parts: light collector, hollow tube, and diffuser (see Figure 1). The collector is produced from a transparent polycarbonate material, designed to collect lights from the sky. The light is reflected multiple times in the hollow tube with highly reflective material on the inner wall. A diffuser is generally produced from opal or prismatic material placed on the ceiling of a room. The light pipe lighting system gathers natural outdoor light through the light harvesting device (light collector) and channels it into the system. After strengthening and efficiently transmitting the light, the diffuser at the bottom of the system will evenly channel the light to any indoor places where light is needed. The propagation of the optical path within the light pipe is achieved by total reflection. When light enters from the side of the light pipe, it will undergo multiple total reflections on the walls inside the light pipe, which allows the light to be directed along the length of the light pipe. During propagation, the light is constantly reflected on the walls of the light pipe until it reaches the other end of the light pipe or is output to the place which needs to be illuminated. This all-reflective propagation allows the light pipe to transmit light efficiently, so that the light can be evenly distributed on the surface of the light pipe, thus achieving the illumination effect. Compared with traditional side windows and skylights, light pipes have better heat insulation performance and flexibility [13]. The influence of the light pipe on indoor temperature fields is not obvious, and the temperature rise at a similar illumination level is far less than that of artificial lighting [14]. It can avoid glare to ensure sufficient light comfort [15,16]. The light pipe is gradually being recognized for its levels of energy-saving and comfort.

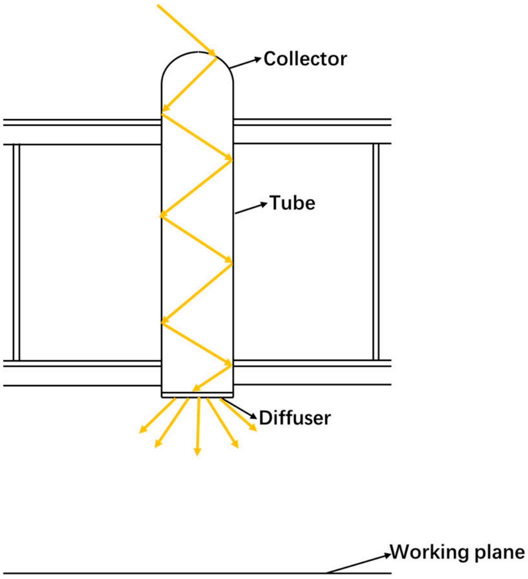


Figure 1. Components of a light pipe.

Based on the evaluation theory of tubular light guides, relevant studies provide a detailed description of a tubular light guide model with a flat glass cover under clear sky conditions with direct solar radiation [17]. Various physical aspects have been considered, including the elevation angle of incident light rays, the number of incident levels, the length and diameter of the light pipe, and the optical properties of the light pipe components. This theoretical framework allows for an in-depth exploration of how light penetrates the surface from a physics perspective and which incidence angles may be more suitable. Simultaneously, the study visually presents the propagation of light rays within the tubular light guide, including vertical plane projection, horizontal plane projection, and an axonometric scheme.

The chemical structures of light pipes encompass the arrangement and composition of materials utilized in the fabrication of these optical devices. The chemical structures play a pivotal role in dictating the optical properties and overall performance of light pipes. Organic polymers, such as polymethyl methacrylate (PMMA), are frequently employed in the construction of light pipes, offering a balance of transparency, flexibility, and ease of fabrication. The chemical structure of these polymers influences their refractive indices and, consequently, the guiding and transmission of light within the pipe. In the case of glass light pipes, the chemical composition of borosilicate glass or other specialized glass types is crucial. The unique arrangement of silicon, oxygen, and other elements in the glass matrix influences its optical transparency, thermal stability, and resistance to environmental factors. The continuous advancements in nanotechnology have introduced nanostructured materials into the realm of light pipe design. Nanoengineered surfaces, coatings, or additives contribute to tailoring the optical properties of light pipes, enabling precise control over light propagation and enhancing their performance [13,18].

The stability of light pipes refers to their ability to maintain consistent and reliable performance over time. Their stability is crucial in ensuring that they can withstand various environmental conditions and usage scenarios without significant degradation in their optical properties. Several factors affect the stability of light pipes: (1) Material durability: materials with high durability and resistance to environmental factors, such as temperature changes or humidity, contribute to the long-term stability of the light pipe [19]. (2) Mechanical integrity: a robust design and construction ensure that the light pipe can withstand physical stresses and maintain its performance under normal usage conditions. (3) Chemical resistance: chemical resistance of the materials used ensures that the light pipe remains stable even when subjected to potentially corrosive substances.

The preparation methods of light pipes involve specific techniques and processes employed in the fabrication of these optical devices designed for efficient light transmission. Several key methods are utilized: (1) Molding and extrusion: one prevalent technique involves molding or extruding materials, such as polymers, into the desired shape of the light pipe. This method is suitable for producing light pipes with straightforward geometries and is often employed for cost-effective mass production. (2) Glass forming: for light pipes requiring higher optical precision, glass forming techniques are utilized. This involves shaping glass through processes like blowing, drawing, or precision machining to achieve the desired optical properties [20]. (3) Coating and cladding: thin layers of materials with specific refractive indices may be applied to modify light transmission properties or improve efficiency [18]. (4) Fiber optic manufacturing: in the case of fiber optic light pipes, a complex process known as drawing is employed. This involves stretching a preformed rod of glass or other materials to create long, thin fibers. These fibers can transmit light over long distances with minimal loss.

The authors of this article carried out a state-of-the-art review on light pipes in buildings. The light pipe is an effective system to provide daylighting for remote and windowless spaces within buildings. Solar altitude, cloud volume, external illuminance, and aerosols in the atmosphere all affect daylighting performance. These factors can be uniformly referred to as sky conditions. Sky conditions are constantly changing over time. In addition to these dynamic factors, the components of the light pipe and the orientation of the light pipe also have an impact on daylighting performance. To enhance daylighting performance, the traditional light pipe has been modified. With the above factors, it is difficult to accurately predict the daylighting performance. Prediction methods have been continuously improved. Existing prediction methods tend to consider the transmission efficiency of the three main components of the light pipe separately, and then combine them to calculate the total efficiency. Based on meeting the requirements of lighting, light pipes can be combined with ventilation systems, artificial lighting, and air purification. Since buildings generate significant energy consumption, the change in electricity consumption and the economic benefits of using light pipes for lighting are also being considered.

In Section 2, light pipes combined with artificial lighting are presented. Light pipes combined with the ventilation system are described in Section 3. Light pipes combined with ATO (Antimony Tin Oxide) nanofluids and photocatalysis are described in Section 4. The energy consumption and the economic efficiency of light pipes are described in Section 5. Prediction methods for integrated systems and influence of orientation on the integrated system are discussed in Section 6. The major findings of the article are summarized in Section 7. Finally, Section 8 discusses further improvements of this study.

2. Light Pipes Combined with Artificial Lighting

Generally, solar altitude, cloud volume, and external illuminance are considered to be weather factors that affect the lighting performance of the light pipe. In a day, the luminous flux introduced by the light pipe increases with the increase of solar altitude and decreases with the increase of cloud cover [21]. In addition, the light distribution on the working plane is more uniform when the solar altitude is low [22]. The efficiency of the light pipe under overcast conditions is slightly higher than that under clear sky conditions [23]. With the change of seasons, the luminous flux output by the light pipe in summer is better than that in winter, but there will be obvious light and dark changes on the working plane in summer [24]. However, among solar altitude, cloud cover, and external illuminance, external illuminance has the greatest impact on internal illuminance. The influence of solar altitude and cloud cover on internal illuminance may be affected by changes in external illuminance [25]. The research by Vasilakopoulou [26] further pointed out that the average internal illuminance and the maximum internal illuminance have an exponential relationship with the external illuminance, respectively. In addition to the above factors that affect the daylighting performance of the light pipe, Kocifaj [27] has shown that aerosols in the atmosphere are also one of the factors. Different types of aerosols will have different effects on illuminance patterns and efficiency.

Light pipes cannot meet the indoor illuminance requirements in some situations, and artificial lighting equipment is needed for auxiliary lighting. A study on light pipe systems stated that these devices, when paired with electric lighting controls, could achieve 20% energy savings [28]. Thus, the combination of passive light pipes and artificial lighting equipment systems has come into being. In this integrated system, in most cases, luminaires are installed over individual workstations or defined visual task areas and equipped with, variously, integrated network controls, occupancy sensors, personal dimming, or daylight dimming. The two systems are not physically connected. This system can maximize the use of available daylight. However, the color rendering of the two light sources is significantly different, which may bring an uncomfortable visual experience. Unstable daylight makes the artificial lighting system open and close frequently or adds more complicated control systems, which may reduce the service life of the system or increase the cost. Görgülü and Ekren [29] illuminated a windowless room via a light pipe and dimmable electronic ballasts. During the operation of the system, the required 350 lux illumination level on the work plane was measured and retained by the controller throughout the day.

3. Light Pipes Combined with the Ventilation System

Integration of the passive stack ventilation system and light pipes would make both technologies more attractive. The basic idea is to guide daylight into the building and air out of the building using an integrated structure (see Figure 2). The integration of these technologies proved to be feasible [30]. The light pipe-natural ventilation system experimental apparatus is shown in Figure 3. To enhance the natural stack ventilation and prevent reverse flow, a winding terminal is installed on the top of the light-vent pipe [31–34]. Common forms of wind terminals are shown in Figure 4. To enhance the driving force of natural ventilation, Elmualim et al. [35] used dichroic materials to construct light pipes, which increased the flow of natural ventilation by 14%. L. Shao and Riffat [36] combined light-vent pipe with heat pipes and used the principle of thermosyphon, which can not only enhance ventilation but also be used for building heating. This system can be realized without relying on a mechanical driving force. Taengchum et al. [37] designed a light pipe integrated with a solar-heated ventilation stack that can be used for night ventilation and designed a method that can be used to design a system to achieve the required ventilation rate, transmit a given luminous flux, and evaluate the cost-effectiveness of the configuration. This system needs to use a hot water pump as the circulating power.

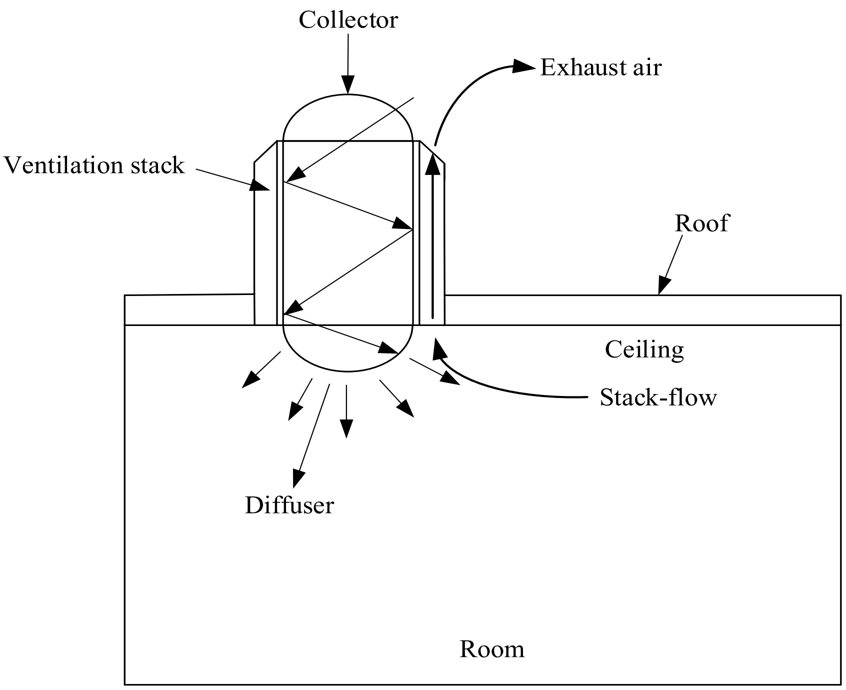


Figure 2. Combined the light pipe and passive stack ventilation system.

Figure 3. Light pipe-natural ventilation system experimental apparatus.

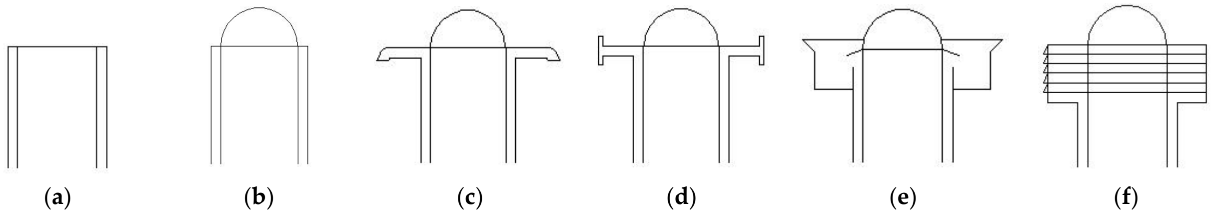


Figure 4. Different ventilation terminals: (**a**) open channel, flat top; (**b**) open channel, hemispherical dome; (**c**) umbrella type; (**d**) H-pot type 1; (**e**) H-pot type 2; (**f**) shutter type.

4. Light Pipes Combined with ATO Nanofluids and Photocatalysis

The physical properties of the three components (light collector, hollow tube, and diffuser) of the light pipe affect the optical properties. The research on the three components is summarized in Table 1. Mohelnikova et al. [17] and Robertson et al. [38] proved that the daylighting performance of the hemispherical dome is better than that of the flat glass cover. Collectors of the light pipes are installed outdoors. The surface of the collector is inevitably exposed to the sun and debris, which affects the lighting effect [39] and reduces the service life of the collector. Applying a super-hydrophobic layer to the collector can realize self-cleaning, which plays an important role in improving the lighting performance [40]. The major constraints to the development of superhydrophobic coatings are expensive superhydrophobic materials, nano-feature durability, coating stability, precipitation/condensation problems, impact problems, and emulsifier/oil wetting problems [41,42].

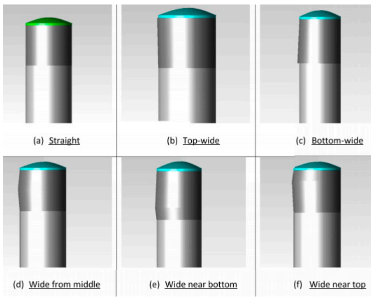
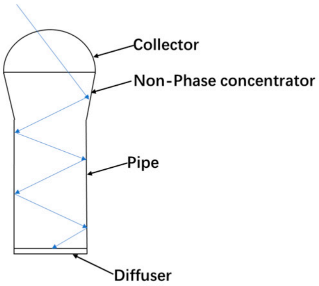
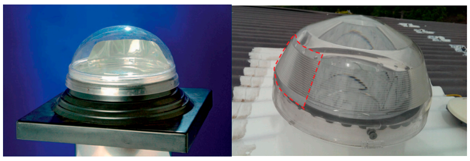
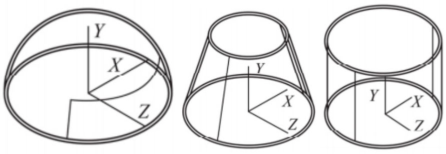
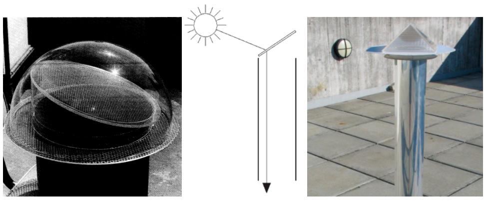
The length, diameter, and inner wall material of the hollow tubes have an impact on the light reflectivity of light pipes. The ratio of the diameter to the length of the reflecting tube is defined as the aspect ratio of the light pipe. Only the length and diameter of light pipes are changed to obtain different specifications of light pipe. Different specifications of light pipes with the same aspect ratio have the same Transmission Tube Efficiency (TTE) under a CIE (International Commission on Illumination) standard overcast sky [43]. Transmission Tube Efficiency (TTE) is defined as the ratio of the output light flux to the input light flux of the light pipe. The efficiency is a decreasing function of aspect ratio independent of whether overcast sky or clear sky conditions are taken into consideration [44]. Wu et al.'s [45] study showed that higher reflectance of the inner surface will lead to a higher efficiency of the straight pipe. For a light pipe with an elbow, under the same bending angle and light reflection ratio, the TTE of elbows with different pipe diameters is basically the same. The reflective material on the inner wall of the light pipe determines the color rendering properties of transmitted light [46,47]. With an increase of the number of reflections and the change of the angle of incident ray, the color characteristics of the optical tube will change. Furthermore, Nilsson et al. [47] used spectrophotometer measurement and ray-tracing simulation methods to quantitatively verify that highly reflective films with spectral variations of a few percent do not markedly affect the color of the transmitted light. Different geometrical shapes, thicknesses, and fabrication materials lead to different optical properties of the diffuser. We found that light pipes with "snow type" diffusers had better performance compared with the "diamond type" ones [48]. Swift et al. [49] experimentally studied 1 mm thick diffuser (the diffusing material used is Plexiglas), finding that it performed better when the uniformity of illumination was improved and the loss of luminous flux was small. Robertson et al. [38] compared three different diffuser types. From the perspective of luminous flux, flat Fresnel performed the best, followed by flat frosted, and curved frosted performed the worst. However, there is a modest disbenefit to the Fresnel when there is diffuse light only. Two-component glazing can solve this problem [50]. The inner parts of circular glazing work like Lambertian diffusers while the edges of the glazing are built of clear glass. This diffuser can reduce light loss and enhance the use of direct light. Ikuzwe and Sebitosi [51] designed a light collimator made of frosted aluminum, which improved the illuminance of the working surface under sunny conditions compared with commercial diffusers. When rough re-used aluminum cooking foil is used as the interior lining of the collimator, uniform spatial light distribution can also be obtained. Kocifaj and Petržala [52] proposed a new method of designing the diffuser. Under the premise of reducing light loss, the diffuser is designed according to the illuminance distribution required. It has been proven that such a slab can mimic the illuminance distribution required, while the particle sizes and refractive indices have been determined from optimization routines.

The incident angle of light affects the performance of the light pipe, and the number of reflections in the tube for light with different incident angles is different. The number of reflections of low-angle incident light is more than that of high-angle incident light. At the same time, the reflection coefficient of the reflective material on the inner wall of the tube will also affect the reflection of light. The larger the reflection coefficient, the smaller the light loss. Therefore, reducing the number of reflections of light in the tube is one of the ways to enhance the performance of light pipes. Optimization methods are described in Table 2. Sharma et al. [53] compared the performance of modified light pipes which have a slight difference in their designs in the upper 20 cm length of the pipe compared to a conventional light pipe. Wang et al. [54] added a non-phase concentrator inside the light pipe to improve the lighting performance of the light pipe system. Kim and Kim [13] developed a new type of light pipe. The south-facing optical device is placed in the dome. The inside of the tube is coated with thin prismatic material. The diffuser is made of acrylic. The efficiency of this new light pipe is 99%, and it is suitable for sunny and cloudy days. Robertson et al. [38] experimentally showed that a deflector can provide up to a 22% increase in illuminance when there is significant direct light present and reduce the illuminances by approximately 5% under lower, diffuse light conditions. Malet-Damour et al. [55] showed that the orientation of the deflector device placed in the dome needs to be adjusted according to sky conditions, otherwise the light transmittance will be affected. Similar experiments were also conducted. We simulated the effects of different structures of domes and deflectors on the performance of the light pipe, and the results showed that the structure of the lighting hood, the size of the reflector, and sky conditions all affect the lighting performance [56]. Edmonds et al. [57] enhanced the performance under clear skies in winter by adding LCP (Laser-Cut Light-Deflecting Panels) to light pipe domes. However, this system fails to redirect light down the pipe for greater azimuth angles. Venturi et al. [58] got a similar conclusion. Garcia Hansen et al. [59] studied the influence of a pyramid LCP, which provides panel area exposed to the incident light, though it has a reduced area of light collection at any one time. The system can increase the performance of light pipes for low elevation angles.

Table 1. Papers devoted to studying the influence of the three main components of light pipes on daylighting.

Authors	Collector		Tube				Diffuser		
	Geometrical Shape	Light Transmittance	Length	Diameter	Inner Wall Material	Bend	Geometrical Shape	Thicknesses	Fabrication Material
Swift and Smith [46]			√	√	√				
Swift et al. [49]			√	√				√	
Mohelnikova et al. [17]	√	√	√	√	√				
Wu et al. [48]							√		
Kocifaj [50]									√
Robertson et al. [38]	√		√	√	√	√			
Darula et al. [23]			√	√	√				
Nilsson et al. [47]					√				
Ikuzwe and Sebitosi [51]					√				
Gao et al. [43]			√	√					
Kocifaj and Petržala [52]									√
Wu et al. [45]			√	√	√	√			

Table 2. Methods of reducing the number of reflections of light.

Type	Illustration	Authors
Differences in the upper 20 cm length of the pipe with a conventional light pipe		Sharma et al. [53]
Non-phase concentrator		Wang et al. [54]
A south-facing optical device in the dome and a thin prismatic material inside of the tube		Kim and Kim [13]
Deflectors used in domes		Robertson et al. [38]; Malet-Damour et al., 2019 [55]
Domes and reflectors of different structures		Wu and Wang [56]
Different types of LCP		Edmonds et al. [57]; Venturi et al. [58]; Garcia Hansen et al. [59]

It was found that the fluid mixed with metal or metal oxide nanoparticles, named nanofluids, would have unique optical and thermal properties [60,61]. A new lighting-heating coupled TDDs (LH-TTDs) system was developed based on ATO nanofluids which can absorb thermal energy from solar IR radiation to heat domestic hot water, with almost no effects on the visible solar radiation, thus having both lighting and heating functions [62]. The designed LH-TDD is composed of a receiving dome, lighting pipe, and ATO-nanofluid-contained diffuser. Results showed that the ATO nanofluids of 100 ppm can absorb 50% solar radiation coming along with more efficient visible lighting. In a case study in Beijing, the total energy-saving performance improved by 10%.

We developed a system combining a light pipe with photocatalysis which could not only introduce sunlight into the room but also serve as an air purifier [63,64]. A certain amount of photocatalyst sprayed on the outside of the diffuser of the light pipe can have a purifying effect on the air (see Figure 5). However, this still has some technical problems, such as low efficiency and film curing of the catalyst. A new efficient catalyst will be pursued.

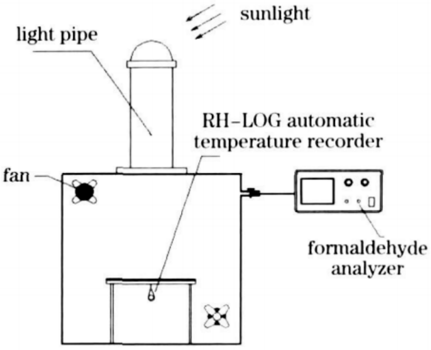


Figure 5. Experimental apparatus of the light pipe combined with photocatalysis.

5. Energy Consumption and Economic Efficiency of Light Pipes

The impact of light pipes on indoor energy consumption is mainly in three aspects: the influence of radiation and heat conduction of light pipes on indoor energy consumption, and the influence of light pipes on the energy consumption of artificial lighting. Compared to windows, the light pipe transfers less heat [65]. In the case of excessive heat loss, the heating energy required in winter may be greater than the saved lighting energy consumption. Large-diameter light pipes cause higher heat loss than small-diameter light pipes [66]. Our research showed that under the same brightness conditions, the increased indoor heat of light pipes is less than that of artificial lighting equipment in Beijing [48]. However, the increase in heat cannot be ignored in tropical regions [67,68]. Pirasaci [69] showed that the overall heat transfer coefficient of the light pipe can be decreased by using an acrylic separator plate in the light pipe. However, solar radiation was not considered. For the installation of light pipes on insulated roofs of low-energy buildings, thermal bridge effects may occur. Šikula et al. [70] indicated that additional glasses units installed in light pipes have a positive effect on solving thermal bridging and condensation problems. However, this can also result in lower overall optical transmittance.

The light distribution of the working plane is composed of two parts. A large part of the light energy is directly irradiated to the working plane through the diffuser, and the rest of the light energy is refracted to the working plane through the ceiling, walls, furniture, floor, etc. The increase in the average reflection coefficient will lead to a significant increase in the average indoor illuminance, which will reduce the time spent on artificial lighting [55]. According to Section 2, perfecting the hybrid lighting system can also effectively increase the energy-saving rate.

The investment of the light pipe system includes initial investment and operation investment. The initial investment includes the cost of the light pipe system and the artificial lighting equipment. The initial investment of the light pipe system is much higher than that of the pure power system. To reduce the cost of the product, the polymer acrylonitrile butadiene styrene (ABS), coated with aluminum by physical vapor deposition (ionization), was evaluated for some tests [71]. Although the market cost was reduced by about 50%, the reflectivity was affected. Operational investment is mainly electricity and maintenance costs. Mayhoub and Carter [72] demonstrated that the light pipe system is generally not economical using conventionally accepted measures of both cost and benefit. They used whole life cycle costing (WLCC) to analyze the costs and benefits of using the two main classes of daylight guidance to light offices as an alternative to conventional electric lighting. A more favorable balance of cost and benefit is obtained. Feng et al. [73]

took an underground garage with a combined lighting scheme of a light pipe system and LED lighting system as the research object. This project designs and installs 20 sets of spherical light pipe systems and 15 sets of flat plate light pipe systems. The simulation results showed that the scheme met the standard illuminance requirements. This project can save 16,306.5 kWh of electricity throughout the year and save about 14,000 yuan in electricity bills.

6. Discussion

6.1. Prediction Methods for Integrated Systems

For the light pipes combined with artificial lighting, a study aimed at optimizing lighting and energy saving, and an algorithm for the integrated light pipe and artificial lighting system, was proposed [74]. It should be noted that an integrated system in which light pipes and artificial sources are not physically related, but the artificial lighting is controlled by daylight sensing systems. In addition, there are few theoretical prediction methods for integrated systems. In the existing prediction methods, the performance of light pipes can be predicted by changing the spatial parameters and performance indicators (aspect ratio, inner wall reflectivity, the light transmittance of collectors and diffusers, common sky models, etc.). This type of prediction is based on the assumption of the three components of light pipes and the transmission process. To obtain more accurate, consistent, and actual performance prediction results, different geometric shapes and optical characteristics of light pipe components are also considered. More simulation and verification are needed. Various forms of light pipe components and complete climate observation data also need to be provided and referenced. For a light pipe with an elbow, the existing method of calculating light transmission efficiency is proved to be wrong [75].

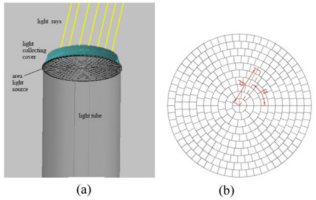
Zhang et al. [76,77] used the Daylight Penetration Factor (DPF) to predict the performance. DPF is defined as the ratio of a given point's internal illuminance to the total external illuminance. Carter [78] used commercial lighting analysis software. These methods of calculating 'static' daylight can be used for the assessment of the performance regarding the same room without solar light pipes. Jenkins et al. [79,80] in the UK developed a model that uses the cosine law of illuminance to describe the distribution of light from the solar light pipes taking into account pipe elbow pieces or bends, named luxplot. Kocifaj et al. [81] proposed a physical model to study interior daylight illuminance distribution based on ray-tracing, named HOLIGILM. The results of this study suggest that the daylight factor should be replaced by the Useful Daylight Illuminance and that more research was needed to establish appropriate criteria for acceptable luminance ratios in the case of well-daylit buildings. The above studies have taken the three main parts of the light pipe as a whole and studied their performance under specific sky conditions. These methods may not give consistent results when the form of the daylighting cover changes or when the sky conditions are constantly changing. Verso et al. [82] presented an approach to characterize the daylighting performance of solar light pipes in terms of light transmission method: the global light transmission efficiency is determined as the product of the efficiencies of the three individual components (collector, pipe, and diffuser). Based on the daylight coefficient method, Wang et al. [83,84] analyzed the transmission characteristics of light in a cylindrical light pipe and established a mathematical model of the light transmission characteristics of the light pipe. This method can calculate the efficiency of the light pipe at any time and under any sky conditions. This mathematical model filled in the blanks of daylighting analysis software. Chen et al. [85] set a new method to evaluate the optical performance according to the output luminous flux. The method uses position (α, d) and angular distribution of luminous flux (Φ, θ, φ) information to describe the optical properties of the light pipe's dome. An artificial neural network used for the predicted performance was introduced [86].

The advantages and disadvantages of some approaches proposed before 2004 have been summarized [87]. The methods proposed after 2004 are summarized in Table 3.

Table 3. Prediction methods of light pipes.

Equations	Nomenclatures	Characteristic	Advantage	Disadvantage	References
--	--	Artificial neural network is used to calculate the illumination of the light pipe.	It can avoid the complicated process of light propagation without assumptions.	Need to collect a large number of light pipe learning samples to achieve the purpose of wide application.	[86]
$E_i = 0.406\prod_{\varphi_1}^{\varphi_n} e^{-0.0052\varphi}\,\frac{E_{ex}e^{-0.111A}\pi r^2 cos^4\theta}{V^2}$	E_i: internal illuminance (lux); E_{ex}: external illuminance (lux); φ: angle of pipe elbow (°); r: pipe radius (m); V: vertical distance of pipe diffuser; to point of measurement/prediction (m); A: pipe aspect ratio;	The distribution of light from the light pipe is described by the cosine law of illuminance (a quartic cosine model).	Fewer input data requirements. The room area and the number of light pipes is not restricted. Consider bending at any angle. Model building is based on a larger range of tests.	There is a lack of descriptions of parameters such as solar dimensions and sky conditions. The types of light pipes that can be used are limited. The influence of factors such as light collector and diffuser is not considered.	[80]
Collector performance: $\eta_{b,collector(\gamma_s)} = \frac{\Phi_{b,with\ collector(\gamma_s)}}{\Phi_{b,without\ collector(\gamma_s)}}$ $\eta_{d,collector(\gamma_s)} = \frac{\Phi_{d,with\ collector(\gamma_s)}}{\Phi_{d,without\ collector(\gamma_s)}}$ $\eta_{collector(\gamma_s)} = \frac{E_{b,out}\cdot\eta_{b,collector(\gamma_s)}+E_{d,out}\cdot\eta_{d,collector(\gamma_s)}}{E_{g,out}}$ Similarly, pipe performance: $\eta_{pipe(\gamma_s)} = \frac{E_{b,out}\cdot\eta_{b,pipe(\gamma_s)}+E_{d,out}\cdot\eta_{d,pipe(\gamma_s)}}{E_{g,out}}$ Diffuser performance: $\eta_{diffuser} = \tau_{l,diffuser}$	$\Phi_{b,with\ collector}$ and $\Phi_{b,without\ collector}$, $\Phi_{d,with\ collector}$ and $\Phi_{d,without\ collector}$ the luminous flux values (lm) which are measured (or calculated) in correspondence of the output section of a pipe associated to the collector to analyze, with reference respectively to direct sunlight (beam component) and diffuse skylight (diffuse component), with and without the collector; $E_{b,out}$, $E_{d,out}$, $E_{g,out}$ are respectively the direct, diffuse and global external horizontal illuminance due to an obstructed sky (lux); $\tau_{l,diffuser}$ luminous transmittance value of the diffuser	An approach to characterizing photometric performances of the light pipe in terms of light transmission efficiency was presented.	This method can determine the overall efficiency based on external conditions.	Lack of component diversity and climate database.	[82]

Table 3. *Cont.*

Equations	Nomenclatures	Characteristic	Advantage	Disadvantage	References
$\tau_{TDD} = \frac{E(x)_{in-total} \cdot \pi \cdot R^2}{E_{exterior-total} \cdot \pi \cdot R^2} = \frac{\sum_1^n \eta DC_{a\gamma}(x) L_{a\gamma} \Delta S_{a\gamma} + DC_{sun}(\gamma_{sun}) E_{sun}(\gamma_{sun})}{E_{diffuse}(\gamma_{sun}) + E_{sun}(\gamma_{sun})}$	τ_{TDD}: the efficiency of the light pipe; $E(x)_{in-total}$: the output lumen of the light pipe at a specified situation; $E_{exterior-total}$: the illuminance entering the light pipe; R: the radius of the pipe;n: frequency of reflection; $DC_{a\gamma}(x)$: The daylight coefficient; $DC_{sun}(\gamma_{sun})$: the corresponding daylight coefficient of the sun; $L_{a\gamma}$: the luminance of the element (cd/m^2); $\Delta S_{a\gamma}$: is the angular size of the sky element (sr); $E_{diffuse}$: is the horizontal diffuse illuminance value; E_{sun}: the measured horizontal direct illuminance; γ_{sun}: the elevation angle of the sun; $\eta = 1$	A new mathematical model on the basis of the daylight coefficient method for light pipes' light transfer characteristics was presented.	Combining different sky brightness models, can calculate the transmission efficiency of light pipes under various sky conditions.	Need complete climate observation data.	[83,84]
$E_{LED} = \frac{\Phi_{LED} \cdot N \cdot UF \cdot MF}{A}$	E$_{LED}$: the necessary LED lumens; Φ_{LED}: the flux emitted by all the LED lamps included in one light pipe; N: the number of light pipes in the room; UF: is the utilization factor of the luminaire; MF: is the maintenance factor of the luminaire; A: the area of the working/reference plane	A methodology for optimizing the design of light pipes integrated with artificial lighting was presented.	This method gives a rough estimate for the energy savings that result from the use of light pipes and artificial lighting controlled to supplement the daylight systems, employing only the necessary wattage.	Currently suitable for small-sized rooms with only one light pipe.	[74]
$L = d \times \begin{cases} \sin(\alpha - \varphi)\varphi < \pi \\ \sin(\alpha - \varphi + \pi)\varphi > \pi \end{cases}$ $\Phi_{out} = \Phi_{in} \times R^n$ $R^n = f(L, \theta)$	L: the distance from the center to the incident point of light on the incident plane; φ: the horizontal angle of spherical coordinate in the testing direction in luminous intensity of a point source into a 3D surface; Φ_{out}: output flux; Φ_{in}: input flux; R: reflectivity; n: frequency of reflection 	The collector is divided into many small light-emitting pieces. Each piece can be regarded as a point source, described by an intensity distribution curve.	Collector and light pipe are calculated separately. The original data are measurable by commercially available instruments, so it can be used in actual engineering practice.	The influence of sky conditions and elbows are not considered.	[85]

6.2. The Influence of the Orientation of Light Pipes on the Integrated System

The appropriate integrated system should be selected according to the orientation of light pipes. Architectural forms affect the orientation of the light pipe. The orientation of the light pipe includes vertical direction, horizontal direction, and inclined direction. Different installation forms can be connected through elbows to meet different needs. Courret et al. [88] compared the daylighting performance of a test room equipped with a horizontal light pipe and the same test room equipped with double facade glass. Measurements have established that the daylight factor on the work plane 5 m from the window is more than doubled. Chirarattananon et al. [89] proposed that the use of a light pipe in the plenum above the ceiling in multi-storied buildings for transmission of sunlight is one such viable configuration. Further, Heng et al. [90] studied the influence of the cross-sectional shape and the number of openings of the horizontal light pipe on deep plan buildings. Some buildings with sloping roofs are more suitable for installing light pipes with inclined bends. Darula et al. [76] analyzed the illuminance distributions under the diffuser and the light distribution of the indoor working surface of bent light pipes. The maximum light efficiency of bent light pipes can be expected in the situation when sunbeams entering the tube will be quasi-parallel with the upper tube axis. Kocifaj et al. [91] proved that light pipes can transmit lighter if bent rather than being straight under a temperate climate. Baroncini et al. [92] designed a double light pipe that can lead daylight into a multi-story room. The main difficulty of using light pipes in multi-story buildings is to ensure that each layer extracts and distributes the same amount of light. Garcia-Hansen and Edmonds [93] installed transparent plastic cones with a base angle of 37.5° on the transparent part of the light pipe to extract and distribute equal amounts of light at each level. Kennedy and O'Rourke [94] achieved the purpose of multi-story building lighting by opening side apertures of the light pipe.

7. Conclusions

This paper reviewed the research and development of integrated systems for light pipes. This research classified and introduced the development of integrated systems for light pipes from the aspects of artificial lighting, the ventilation system, ATO nanofluids and photocatalysis, energy consumption, and economic efficiency.

The major survey findings are as follows:

(1) The combination of light pipes and artificial lighting can meet illuminance levels in poor daylight conditions. The combination of light pipes with other technologies is feasible. Integration of a passive stack ventilation system and light pipes allows daylight to enter the building while exhausting indoor air. The combination of light pipes and photocatalytic systems can realize lighting and air purification at the same time. The use of superhydrophobic material on the outer surface of A collector can improve the service life of a light pipe. From a whole life cycle perspective, the use of light pipes can be a balance of cost and benefit.

(2) There are few theoretical prediction methods for integrated systems. In the existing prediction methods, the performance of the light pipe can be predicted by changing the space parameters of the room and the performance index (aspect ratio, reflectivity of pipes, transmittance of collector and diffuser, common sky model, etc.) of the light pipes.

8. Future Perspectives

According to the state-of-the-art achievements, the following research directions are recommended:

(1) The establishment of overall efficiency and heat transfer model of integrated system is important for the practical application of light-vent pipe systems and light-solar water heater systems. The light-vent pipe may increase a building's occupied area, and requirements such as fire prevention should be considered.

(2) The integrated systems of light pipes need to be studied via the technical and economic analysis of the light pipes combined with ventilation systems, and light pipes combined with ATO nanofluids and photocatalysis.

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Nomenclature

ATO	Antimony Tin Oxide
TTE	Transmission Tube Efficiency
CIE	International Commission on Illumination
LCP	Laser-Cut Light-Deflecting Panels
ABS	Acrylonitrile Butadiene Styrene
WLCC	Whole Life Cycle Costing

References

1. González-Torres, M.; Pérez-Lombard, L.; Coronel, J.F.; Maestre, I.R.; Yan, D. A Review on Buildings Energy Information: Trends, End-Uses, Fuels and Drivers. *Energy Rep.* **2022**, *8*, 626–637. [CrossRef]
2. Mujan, I.; Anđelković, A.S.; Munćan, V.; Kljajić, M.; Ružić, D. Influence of Indoor Environmental Quality on Human Health and Productivity—A Review. *J. Clean. Prod.* **2019**, *217*, 646–657. [CrossRef]
3. Kwong, Q.J. Light Level, Visual Comfort and Lighting Energy Savings Potential in a Green-Certified High-Rise Building. *Build. Eng.* **2020**, *29*, 101198. [CrossRef]
4. Lamb, S.; Kwok, K.C.S. A Longitudinal Investigation of Work Environment Stressors on the Performance and Wellbeing of Office Workers. *Appl. Ergon.* **2016**, *52*, 104–111. [CrossRef] [PubMed]
5. Bellia, L.; Bisegna, F.; Spada, G. Lighting in Indoor Environments: Visual and Non-Visual Effects of Light Sources with Different Spectral Power Distributions. *Build. Environ.* **2011**, *46*, 1984–1992. [CrossRef]
6. Carter, D.J. Tubular Guidance Systems for Daylight: UK Case Studies. *Build. Res. Inf.* **2008**, *36*, 520–535. [CrossRef]
7. Bellia, L.; Pedace, A.; Barbato, G. Daylighting Offices: A First Step toward an Analysis of Photobiological Effects for Design Practice Purposes. *Build. Environ.* **2014**, *74*, 54–64. [CrossRef]
8. Hraska, J. Chronobiological Aspects of Green Buildings Daylighting. *Renew. Energy* **2015**, *73*, 109–114. [CrossRef]
9. Yu, X.; Su, Y. Daylight Availability Assessment and Its Potential Energy Saving Estimation—A Literature Review. *Renew. Sust. Energ. Rev.* **2015**, *52*, 494–503. [CrossRef]
10. Bellia, L.; Acosta, I.; Campano, M.Á.; Fragliasso, F. Impact of Daylight Saving Time on Lighting Energy Consumption and on the Biological Clock for Occupants in Office Buildings. *Sol. Energy* **2020**, *211*, 1347–1364. [CrossRef]
11. Wirz-Justice, A.; Skene, D.J.; Münch, M. The Relevance of Daylight for Humans. *Biochem. Pharmacol.* **2021**, *191*, 114304. [CrossRef]
12. Yuan, Z.; Zhang, X.; Zhan, Q. Application research overview on active tubular daylight guidance system based on light transmission technology. *China Illum. Eng. J.* **2009**, *20*, 13–19+23. [CrossRef]
13. 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]
14. 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. Sust. Energ. Rev.* **2013**, *21*, 494–505. [CrossRef]
15. Canziani, R.; Peron, F.; Rossi, G. Daylight and Energy Performances of a New Type of Light Pipe. *Energy Build.* **2004**, *36*, 1163–1176. [CrossRef]
16. Baglivo, C.; Bonomolo, M.; Beccali, M.; Congedo, P.M. Sizing Analysis of Interior Lighting Using Tubular Daylighting Devices. *Energy Procedia* **2017**, *126*, 179–186. [CrossRef]
17. Mohelnikova, J. Tubular Light Guide Evaluation. *Build. Environ.* **2009**, *44*, 2193–2200. [CrossRef]
18. Sreelakshmi, K. Daylight Performance of Collector-Diffuser Combinations in Light Pipe Systems at Different Geographical Locations. *Sol. Energy* **2024**, *267*, 112254. [CrossRef]

19. Katsumasa, I.; Hiroyuki, T.; Mitsunobu, M.; Yi-Wei, S.; Xiao-Song, Z.; Yuji, M. Transmission properties of dielectric-coated hollow optical fibers based on stainless tube. *Opt. Fibers Sens. Med. Diagn. Treat.* **2018**, *10488*, 1048804. [CrossRef]
20. Dogan, Y.; Morrison, M.; Hu, C.; Atkins, R.A.; Solmaz, M.E.; Madsen, C.K. Fabrication of Advanced Glass Light Pipes for Solar Concentrators. *Optifab* **2017**, *10448*, 104482G. [CrossRef]
21. Wang, W.; Li, S.; Ma, C. Experimental study on lighting performance of light pipe in winter. *Acta Energiae Solaris Sin.* **2008**, *29*, 1489–1493. [CrossRef]
22. Tsang, E.K.W.; Kocifaj, M.; Li, D.H.W.; Kundracik, F.; Mohelníková, J. Straight Light Pipes' Daylighting: A Case Study for Different Climatic Zones. *Sol. Energy* **2018**, *170*, 56–63. [CrossRef]
23. Darula, S.; Kocifaj, M.; Mohelníková, J. Hollow Light Guide Efficiency and Illuminance Distribution on the Light-Tube Base under Overcast and Clear Sky Conditions. *Optik* **2013**, *124*, 3165–3169. [CrossRef]
24. Li, S.; Wang, W.; Ma, C. Experimental study and analysis on lighting performance of light pipe. *Acta Energiae Solaris Sin.* **2009**, *30*, 586–590. [CrossRef]
25. Yun, G.Y.; Shin, H.Y.; Kim, J.T. Monitoring and Evaluation of a Light-Pipe System Used in Korea. *Indoor Built Environ.* **2010**, *19*, 129–136. [CrossRef]
26. 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]
27. Kocifaj, M.; Kómar, L.; Kohút, I. Modeling the Aerosol Effects on the Light Field below a Tubular-Pipe: A Case of Clear Sky Conditions. *Sol. Energy* **2014**, *107*, 122–134. [CrossRef]
28. Sharp, F.; Lindsey, D.; Dols, J.; Coker, J. The Use and Environmental Impact of Daylighting. *J. Clean. Prod.* **2014**, *85*, 462–471. [CrossRef]
29. Görgülü, S.; Ekren, N. Energy Saving in Lighting System with Fuzzy Logic Controller Which Uses Light-Pipe and Dimmable Ballast. *Energy Build.* **2013**, *61*, 172–176. [CrossRef]
30. Oakley, G.; Riffat, S.B.; Shao, L. Daylight Performance of Lightpipes. *Sol. Energy* **2000**, *69*, 89–98. [CrossRef]
31. Lu, S.; Lu, Y.; Sheng, J.; Wang, W.; Ma, C. CFD research on effects of natural ventilation in light pipe system. *J. Eng. Thermophys-Rus.* **2007**, *28*, 5–8. [CrossRef]
32. Varga, S.; Oliveira, A.C. Ventilation Terminals for Use with Light Pipes in Buildings: A CFD Study. *Appl. Therm. Eng.* **2000**, *20*, 1743–1752. [CrossRef]
33. Oliveira, A.C.; Silva, A.R.; Afonso, C.F.; Varga, S. Experimental and Numerical Analysis of Natural Ventilation with Combined Light/Vent Pipes. *Appl. Therm. Eng.* **2001**, *21*, 1925–1936. [CrossRef]
34. Sirén, K.; Helenius, T.; Shao, L.; Smith, S.; Ford, B.; Diaz, C.; Oliveira, A.; Varga, S.; Borth, J.; Zaccheddu, E. Chapter 76—Combining Light Pipe and Stack Ventilation—Some Development Aspects. In *World Renewable Energy Congress VI*; Sayigh, A.A.M., Ed.; Pergamon: Oxford, UK, 2000; pp. 395–400. [CrossRef]
35. Elmualim, A.A.; Smith, S.; Riffat, S.B.; Shao, L. Evaluation of Dichroic Material for Enhancing Light Pipe/Natural Ventilation and Daylighting in an Integrated System. *Appl. Energy* **1999**, *62*, 253–266. [CrossRef]
36. Shao, L.; Riffat, S.B. Daylighting Using Light Pipes and Its Integration with Solar Heating and Natural Ventilation. *Light. Res. Technol.* **2000**, *32*, 133–139. [CrossRef]
37. Taengchum, T.; Chirarattananon, S.; Exell, R.H.B.; Kubaha, K.; Chaiwiwatworakul, P. A Study on a Ventilation Stack Integrated with a Light Pipe. *Appl. Therm. Eng.* **2013**, *50*, 546–554. [CrossRef]
38. Robertson, A.P.; Hedges, R.C.; Rideout, N.M. Optimisation and Design of Ducted Daylight Systems. *Light. Res. Technol.* **2010**, *42*, 161–181. [CrossRef]
39. Wu, Y.P.; Wang, X.D.; Chen, Z.G.; Zhang, C.Y. Experimental Study on the Influence of Daylighting Performance of Solar Light Pipes by Dusts and Condensation. In *Sustainable Development of Urban Environment and Building Material*; Advanced Materials Research; Trans Tech Publications Ltd.: Bäch, Switzerland, 2012; Volume 374, pp. 1096–1099. [CrossRef]
40. Wu, Y.; Lei, X.; Lu, Y.; Chen, H. Research progress of superhydrophobic anti-reflection films applied on transparent surfaces of solar devices. *CIESC J.* **2021**, *72*, 21–29. [CrossRef]
41. Hooda, A.; Goyat, M.S.; Pandey, J.K.; Kumar, A.; Gupta, R. A Review on Fundamentals, Constraints and Fabrication Techniques of Superhydrophobic Coatings. *Prog. Org. Coat.* **2020**, *142*, 105557. [CrossRef]
42. Mehmood, U.; Al-Sulaiman, F.A.; Yilbas, B.S.; Salhi, B.; Ahmed, S.H.A.; Hossain, M.K. Superhydrophobic Surfaces with Antireflection Properties for Solar Applications: A Critical Review. *Sol. Energy Mat. Sol.* **2016**, *157*, 604–623. [CrossRef]
43. Gao, M.; Xu, G.; Cao, G.; Li, D.; Yu, J.; Liu, Q. Simulation analysis of efficiency and illumination distribution of light guide under CIE Overcast Sky condition in Dalian area, Liaoning. *Acta Energiae Solaris Sin.* **2017**, *38*, 2303–2308.
44. Darula, S.; Kocifaj, M.; Kittler, R.; Kundracik, F. Illumination of Interior Spaces by Bended Hollow Light Guides: Application of the Theoretical Light Propagation Method. *Sol. Energy* **2010**, *84*, 2112–2119. [CrossRef]
45. Wu, X.; Wang, C.; Ouyang, J. Analysis of transmission tube efficiency of light pipe based on TracePro. *China Illum. Eng. J.* **2020**, *31*, 145–150.
46. Swift, P.D.; Smith, G.B. Cylindrical Mirror Light Pipes. *Sol. Energy Mat. Sol.* **1995**, *36*, 159–168. [CrossRef]
47. Nilsson, A.M.; Jonsson, J.C.; Roos, A. Spectrophotometric Measurements and Ray Tracing Simulations of Mirror Light Pipes to Evaluate the Color of the Transmitted Light. *Sol. Energy Mat. Sol.* **2014**, *124*, 172–179. [CrossRef]

48. Wu, Y.; Yue, Z. Experimental Investigation on Light-Thermal Effects of Solar Light Pipes Used in USTB Gymnasium under Sunny Conditions in Beijing. In Proceedings of the 2009 International Conference on Energy and Environment Technology, Guilin, China, 16–18 October 2009; Volume 1, pp. 147–150. [CrossRef]
49. Swift, P.D.; Smith, G.B.; Franklin, J. Hotspots in Cylindrical Mirror Light Pipes: Description and Removal. *Light. Res. Technol.* **2006**, *38*, 19–28. [CrossRef]
50. Kocifaj, M. Efficient Tubular Light Guide with Two-Component Glazing with Lambertian Diffuser and Clear Glass. *Appl. Energy* **2009**, *86*, 1031–1036. [CrossRef]
51. Ikuzwe, A.; Sebitosi, A.B. A Novel Design of a Daylighting System for a Classroom in Rural South Africa. *Sol. Energy* **2015**, *114*, 349–355. [CrossRef]
52. Kocifaj, M.; Petržala, J. Designing of Light-Pipe Diffuser through Its Computed Optical Properties: A Novel Solution Technique and Some Consequences. *Sol. Energy* **2019**, *190*, 386–395. [CrossRef]
53. 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]
54. Wang, W.; Li, S.; Ma, C. Experimental study and analysis on lighting performance light pipe with a conic concentrator. *J. Beijing Univ. Technol.* **2009**, *35*, 1675–1679. [CrossRef]
55. Malet-Damour, B.; Bigot, D.; Guichard, S.; Boyer, H. Photometrical Analysis of Mirrored Light Pipe: From State-of-the-Art on Experimental Results (1990–2019) to the Proposition of New Experimental Observations in High Solar Potential Climates. *Solar Energy* **2019**, *193*, 637–653. [CrossRef]
56. Wu, Y.; Wang, Z. Simulation and experimental analysis of light pipes with reflector under direct sunlight. *J. China Coal Soc.* **2019**, *44*, 1941–1948. [CrossRef]
57. Edmonds, I.R.; Moore, G.I.; Smith, G.B.; Swift, P.D. Daylighting Enhancement with Light Pipes Coupled to Laser-Cut Light-Deflecting Panels. *Light. Res. Technol.* **1995**, *27*, 27–35. [CrossRef]
58. Venturi, L.; Wilson, M.; Jacobs, A.; Solomon, J. Light Piping Performance Enhancement Using a Deflecting Sheet. *Light. Res. Technol.* **2006**, *38*, 167–179. [CrossRef]
59. Garcia Hansen, V.; Edmonds, I.; Bell, J. Improving daylighting performance of mirrored light pipes Passive vs. active collection systems. In Proceedings of the PLEA2009—26th Conference on Passive and Low Energy Architecture, Quebec City, QC, Canada, 22–24 June 2009.
60. Taylor, R.; Coulombe, S.; Otanicar, T.; Phelan, P.; Gunawan, A.; Lv, W.; Rosengarten, G.; Prasher, R.; Tyagi, H. Small Particles, Big Impacts: A Review of the Diverse Applications of Nanofluids. *J. Appl. Phys.* **2013**, *113*, 011301. [CrossRef]
61. Qureshi, M.Z.A.; Ashraf, M. Computational Analysis of Nanofluids: A Review. *Eur. Phys. J. Plus.* **2018**, *133*, 71. [CrossRef]
62. Liu, X.; Shen, C.; Wang, J. Investigation on the Lighting/Heating Performance of Tubular Daylighting Devices (TDDs) Based on Nanofluids. *Energy Build.* **2022**, *263*, 112028. [CrossRef]
63. Wu, Y.; Ma, C. Status of studies and applications of photocatalytic technology in building environment and facility field. *Heat. Vent. Air Cond.* **2006**, *36*, 29–36. [CrossRef]
64. Wu, Y.; Wang, X.; Ma, C. Solar light pipe combined with photocatalysis to decompose formaldehyde under sunny conditions in summer in Beijing. *Acta Opt. Sin.* **2008**, *28*, 2408–2415. [CrossRef]
65. Oakley, G.; Smith, S.J.; Shao, L.; Riffat, S.B. TripleSave-the investigation and monitoring of a combined natural daylighting and stack ventilation system. In Proceedings of the World Renewable Energy Congress VII, Dublin, Germany, 29 June–5 July 2002.
66. Šikula, O.; Mohelníková, J.; Plášek, J. Thermal CFD analysis of tubular light guides. *Energies* **2013**, *6*, 6304–6321. [CrossRef]
67. Williams, D.A.; Dorville, J.M. Investigating the thermal and lighting performance of light pipes for sunny and cloudy conditions in insular tropical climate. *J. Elec. Eng.* **2014**, *2*, 221–227. [CrossRef]
68. Darula, S.; Kittler, R.; Kocifaj, M. Luminous Effectiveness of Tubular Light-Guides in Tropics. *Appl. Energy* **2010**, *87*, 3460–3466. [CrossRef]
69. Pirasaci, T. Investigation of laminar natural convection heat transfer within tubular daylighting devices for winter conditions. *J. Build. Eng.* **2015**, *4*, 52–59. [CrossRef]
70. Šikula, O.; Mohelníková, J.; Plášek, J. Thermal analysis of light pipes for insulated flat roofs. *Energy Build.* **2014**, *85*, 436–444. [CrossRef]
71. Spacek, A.D.; Neto, J.M.; Biléssimo, L.D., Jr.; Santana, M.V.F.D.; Malfatti, C.D.F. Proposal of the tubular daylight system using Acrylonitrile Butadiene Styrene (ABS) metalized with Aluminum for reflective tube structure. *Energies* **2018**, *11*, 199. [CrossRef]
72. Mayhoub, M.S.; Carter, D.J. The costs and benefits of using daylight guidance to light office buildings. *Build. Environ.* **2011**, *46*, 698–710. [CrossRef]
73. Feng, X.; Wu, X.; Xu, Y.; Zhang, L.; Qi, S. Analysis of the Composition of Optical Guide System and Multi-light Source Combined Lighting Scheme. *Jiangxi Build. Mater.* **2022**, *3*, 211–213.
74. Vasilakopoulou, K.; Synnefa, A.; Kolokotsa, D.; Karlessi, T.; Santamouris, M. Performance Prediction and Design Optimisation of an Integrated Light Pipe and Artificial Lighting System. *Intl. J. Sust. Energy* **2016**, *35*, 675–685. [CrossRef]
75. Wang, C.; Gao, Q.; Gao, W.; Ouyang, J. Discussion about Calculation Method of Light Transmission Efficiencies of Elbows in Cylindrical Light Pipes. *Sol. Energy* **2022**, *238*, 39–43. [CrossRef]
76. Zhang, X.; Muneer, T. Mathematical Model for the Performance of Light Pipes. *Light. Res. Technol.* **2000**, *32*, 141–146. [CrossRef]

77. Zhang, X.; Muneer, T.; Kubie, J. A Design Guide for Performance Assessment of Solar Light-Pipes. *Light. Res. Technol.* **2002**, *34*, 149–168. [CrossRef]
78. Carter, D.J. The Measured and Predicted Performance of Passive Solar Light Pipe Systems. *Light. Res. Technol.* **2002**, *34*, 39–51. [CrossRef]
79. Jenkins, D.; Muneer, T. Modelling Light-Pipe Performances—A Natural Daylighting Solution. *Build. Environ.* **2003**, *38*, 965–972. [CrossRef]
80. Jenkins, D.; Muneer, T.; Kubie, J. A Design Tool for Predicting the Performances of Light Pipes. *Energy Build.* **2005**, *37*, 485–492. [CrossRef]
81. Kocifaj, M.; Darula, S.; Kittler, R. HOLIGILM: Hollow Light Guide Interior Illumination Method—An Analytic Calculation Approach for Cylindrical Light-Tubes. *Sol. Energy* **2008**, *82*, 247–259. [CrossRef]
82. Verso, V.R.M.L.; Pellegrino, A.; Serra, V. Light Transmission Efficiency of Daylight Guidance Systems: An Assessment Approach Based on Simulations and Measurements in a Sun/Sky Simulator. *Sol. Energy* **2011**, *85*, 2789–2801. [CrossRef]
83. Wang, S.; Li, L.; Zhang, B. Daylight coefficient computational method-based study on calculation method of tubular daylight device efficiency. *Build. Sci.* **2013**, *29*, 12–15. [CrossRef]
84. Wang, S.; Zhao, J.; Wang, L. Research on Energy Saving Analysis of Tubular Daylight Devices. *Energy Procedia* **2015**, *78*, 1781–1786. [CrossRef]
85. Chen, B.; Wei, Y.; Li, X.; Cao, R.; Jin, P. Numerical Modeling of Tubular Daylighting Devices. *Optik* **2017**, *145*, 95–98. [CrossRef]
86. Wang, A. Artificial neural network applicable for light guide lighting calculation. *China Illum. Eng. J.* **2000**, *36*, 21–24. [CrossRef]
87. Jenkins, D.; Muneer, T. Light-Pipe Prediction Methods. *Appl. Energy* **2004**, *79*, 77–86. [CrossRef]
88. Courret, G.; Scartezzini, J.-L.; Francioli, D.; Meyer, J.-J. Design and Assessment of an Anidolic Light-Duct. *Energy Build.* **1998**, *28*, 79–99. [CrossRef]
89. Chirarattananon, S.; Chedsiri, S.; Renshen, L. Daylighting through Light Pipes in the Tropics. *Sol. Energy* **2000**, *69*, 331–341. [CrossRef]
90. Heng, C.Y.S.; Lim, Y.-W.; Ossen, D.R. Horizontal Light Pipe Transporter for Deep Plan High-Rise Office Daylighting in Tropical Climate. *Build. Environ.* **2020**, *171*, 106645. [CrossRef]
91. Kocifaj, M.; Kundracik, F.; Darula, S.; Kittler, R. Availability of Luminous Flux below a Bended Light-Pipe: Design Modelling under Optimal Daylight Conditions. *Sol. Energy* **2012**, *86*, 2753–2761. [CrossRef]
92. Baroncini, C.; Boccia, O.; Chella, F.; Zazzini, P. Experimental Analysis on a 1:2 Scale Model of the Double Light Pipe, an Innovative Technological Device for Daylight Transmission. *Sol. Energy* **2010**, *84*, 296–307. [CrossRef]
93. Garcia-Hansen, V.; Edmonds, I. Methods for the Illumination of Multilevel Buildings with Vertical Light Pipes. *Sol. Energy* **2015**, *117*, 74–88. [CrossRef]
94. Kennedy, D.M.; O’Rourke, F. Experimental Analysis of a Scaled, Multi-Aperture, Light-Pipe, Daylighting System. *Sol. Energy* **2015**, *122*, 181–190. [CrossRef]