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Thermal and spectral impact of building integrated Mirrored Light Pipe to human circadian rhythms and thermal environment

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Highlights

- A short review on experimental and numerical thermal results on Mirrored Light Pipe (MLP)
- New experimental observations for the thermal aspect of MLP in high solar potential climate
- Evaluation of the MLP efficiency on human circadian rhythms

Abstract

Light holds an important place in the way of life of humans. The first type of lighting which could be exploited was daylight. Tubular Daylight Guidance Systems (TDGS) transport and distribute this daylight inside a building. This article focuses on one of the best known: the Mirrored Light Pipe. MLPs are multiple specular reflectance transporters.

This paper presents (i) state of the art on thermal and spectral studies on light pipes from 1998 to 2021 and (ii) proposes an experimental analysis on MLP in the climatic environment with a high solar resource for different spectral bands of the daylight spectrum. The results show that the thermal impact of the light pipe is limited. Moreover, it is demonstrated that this device promotes natural circadian rhythms. A comparison with artificial lighting highlights this device as an ideal solution for bioclimatic building design.

Keywords: Building applications ; building design ; daylight performance ; daylight ; circadian rhythm ; thermal conditions ; spectral characterization

32 **Nomenclature**

τ_{TDGS}	Transmission coefficient of the light pipe	[<i>-</i>]
ρ_{LP}	Internal reflectivity coefficient	[<i>-</i>]
A_p	Aspect ratio $A_p = \text{Length}_{LP} / \text{Diameter}_{LP}$	[<i>-</i>]
$I_{G,out,h}$	Outdoor global irradiance	[W/m ²]
$I_{d,out,h}$	Outdoor diffuse irradiance	[W/m ²]
$I_{G,in,h}$	Indoor diffuse irradiance	[W/m ²]
$L_{D,out}$	Outdoor downward longwave radiation	[W/m ²]
$L_{D,in}$	Indoor downward longwave radiation	[W/m ²]
$L_{net,out}$	Outdoor net radiation	[W/m ²]
$L_{net,in}$	Indoor net radiation	[W/m ²]
SR	Sky Ratio	[<i>-</i>]
λ	Wavelength	[nm]
ϕ_v	Luminous flux	[lm]
ϕ_e	Radiant flux	[W]
η	Luminous efficacy	[lm.W ⁻¹]
LP	Light pipe	[<i>-</i>]
LW	Long-wavelength	[<i>-</i>]

33 **Introduction**

34 Today, humans spend nearly 90% of their time in indoor environments [1]. This environment,
35 particularly in the thermal and luminous domains, is far from how the human species developed and set up its
36 mechanisms of adaptation and physiological regulation. To create interior spaces adapted to human health,
37 daylighting technologies must be exemplary: limited heat input and conservation of the properties of
38 transmitted light. Although less and less energy-consuming, artificial lighting is often at the origin of
39 chronobiological regulations modulated by a hormone: melatonin. The color temperature of light sources,
40 whether natural or artificial, affects user performance. The higher the color temperature (towards white), the
41 higher the performance [2]. This is related to the increase in vigilance caused by the inhibition of the nocturnal
42 secretion of melatonin. Recent studies show that they are linked to the direct activation of brain structures
43 involved in cognition, wakefulness and sleep regulation, and circadian rhythms [3]. Concretely, insufficient or
44 inappropriate exposure to light can disrupt traditional human rhythms, with adverse consequences on cognitive
45 performance, comfort, and health [4–6].

46 The many existing international Tubular Daylight Guidance Systems [7] are among those devices that
47 meet both energy and health criteria. They allow the transport and distribution of daylight into dark rooms,
48 away from traditional openings. Previous work [8,9] has shown the photometric performance of the light pipe

49 in extreme sunlight situations (maximum global illuminance of about 200 Klux). Moreover, they seem to offer
50 the advantage of minimizing light loss and heat gain while guaranteeing that the light retains all its health-
51 related properties. However, although mirrored light pipe seems to transmit less solar infrared (heat) than
52 visible light, few experimental studies have confirmed this.

53 This paper presents observations from experiments conducted over 2018-2019 on Mirrored Light-Pipe
54 (MLP) in Reunion Island, France. The climate in which the investigation was undertaken is presented with a
55 focus on solar irradiance. In 2021, this study is the only one to analyze the thermal impact of this type of device
56 in a tropical climate with extreme sunlight conditions. The experimental results, differentiated by the sky
57 typology, allow to qualitatively analyze the impact of the light pipe on (i) the infrared transmission, (ii) the
58 energy flux effectively transmitted, and (iii) measure the profile of the electromagnetic spectrum at the device
59 exit. This last study allowed (i) to evaluate the shape of the solar spectrum and its impact on human perception
60 and (ii) to compare the wavelength of the light pipe to that of the main artificial lighting.

61 **1. A short review on thermal and spectral light pipe investigations**

62 **1.1. Light spectrum transmitted by the light pipe**

63 The luminous intensity of a source and the color of the transmitted light has an important impact on
64 the perception of ambiance. It is generally assumed that spectral variations generated by reflective light pipes
65 do not affect the color of the transmitted daylight. In 2014, Nilsson et al. [10] confirmed this assumption. To
66 do so, they use a numerical approach and spectrophotometric measurements (controlled environment) to
67 qualify the illuminances (direct/diffuse) entering inside the pipe, neglecting the presence of the collection and
68 diffusion device. The MLP appears to have achromatic properties. The author also states that the spectroscopic
69 behavior may depend on the aspect ratio of the light pipe. It is also noted that the angle of incidence of the
70 incoming beam affects the spectral transmittance of the tube. Low angles of incidence (less than 50°) allow rays
71 of length between 400 and 800 nm (visible) to penetrate. The angles of incidence up to 50 ° extend the spectrum
72 of rays: from 400 to 1000 nm (visible + near IR).

73 In 2000, Shao and Riffat conducted an experimental study in England (real environment, northern
74 hemisphere, max illumination: 20 Klux) on a system combining light pipe and passive thermal ventilation [11].
75 Part of their study showed that this system transmitted (slightly) less IR than visible light. Under cloudy skies,
76 IR radiation is about three times less and more uniform than under clear skies.

77 In 2003, Callow [12] studied mirrored light pipes and another type of light pipe (light rods) for two
78 different real-world climatic environments: England (temperate oceanic climate, max illuminance: 80 Klux)
79 and Singapore (equatorial climate, max illuminance: 120 Klux). He showed that the light rods (based on fiber
80 optics) could provide more significant amounts of light without compromising the thermal performance of the
81 building. The transmission properties of the PMMA material that constitutes the light rods (but also the
82 collector of the MLP) favor the transmission of visible and near-infrared wavelengths but effectively limit the
83 mid-infrared and beyond, which was confirmed by the study of Nilson [10].

84 In 2019, Omishore [13] experimented with a light pipe prototype associated with an active collection
85 device (parabolic collector with concentrating mirror). The device is subjected to an artificial IR light source
86 (controlled environment). The author then records the temperature profiles and takes thermographic pictures.
87 The temperature measurement data show a significant increase in the temperature at the surface of the light
88 pipe in response to the IR radiation. The author indicates that the light pipe could be supplemented with an
89 additional vented pipe to prevent any overheating problems, which has been confirmed by other authors [14-
90 18].

91 **1.2. Impact on indoor thermal conditions and study of solar heat gain**

92 The thermal behavior of a light pipe in a real-world environment has been little studied, and even less
93 in tropical climatic conditions. The literature referenced only one author, Williams [19] in 2014. Through an
94 experimental study in a real environment, the author investigated the photometric and thermal behaviors of
95 the device for two types of the day (clear and overcast) for a seminar room located in Kingston, Jamaica
96 (northern hemisphere). The results show a significant temperature gradient during the day, increasing the
97 energy consumption of an active cooling system to maintain a comfortable temperature of 25°C. Indeed, on a
98 clear day, the diffuser was 6.68°C warmer than the ambient temperature, and the collector was nearly 4.45°C
99 warmer than the diffuser. At night, the author shows that the light pipe behaves as a thermal bridge because
100 the temperature of the dome is always lower than the temperature of the diffuser and the room.

101 In another climatic context (measurement in a real Canadian environment), Harrison [20], in 1998,
102 conducted a thermal study of a commercial light pipe measuring 0.33 m in diameter by 1.83 m in length. A
103 winter period was chosen. His experiment reported an average effective thermal resistance of 0.279 m².K.W⁻¹.
104 However, this value reflects a measurement of the outside air temperature to the inside air temperature.

105 Other authors [12,21-27] have also attempted to understand the thermal impact of the type of light
106 pipe and its geometric characteristics, the modes of heat transfer, and the influence of climate. Overall,
107 although the device has a limited impact on thermal conditions, the ratio of light input to heat input is still
108 attractive. The heat input generated by the light pipes has a lower impact than the artificial lighting.

109 **1.3. Stack ventilation with light pipe and CFD Study**

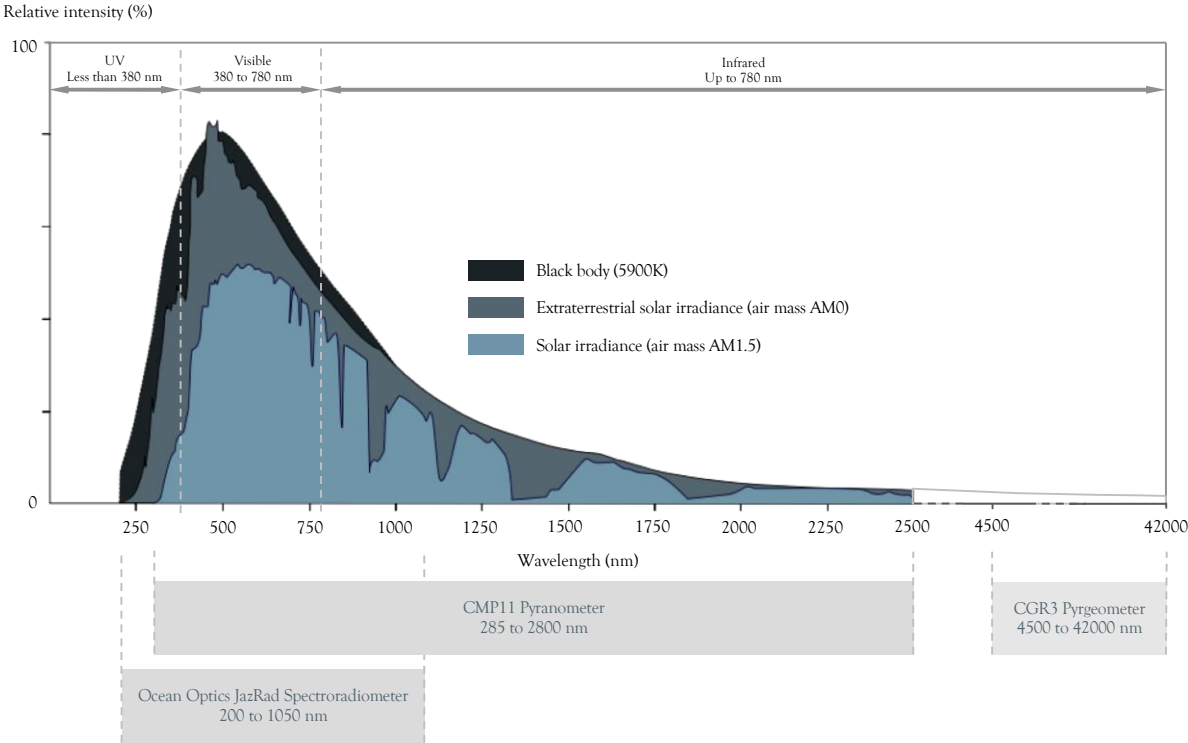
110 Several authors have been interested in studying the light pipe associated with a thermal draft [14-18].
111 In single or double tubes, the light pipe is tested to quantify the impact it could have on natural ventilation. In
112 double tubes, the temperature rise of the inner tube walls is limited by the convective phenomena occurring in
113 the outer tube. The authors have demonstrated a definite potential to couple these two phenomena through
114 numerical simulations in fluid dynamics or experimental measurements (temperature profiles).

115

116 **1.4. The originality of the paper**

117 The studies reviewed in the literature from 1998 to 2021 report thermal and spectrometric findings
 118 summarized and classified by theme in **Table 1**. These different observations were conducted in a real
 119 environment (temperate, equatorial, or tropical climates) or controlled (laboratory measurements) and
 120 exclusively in the northern hemisphere. For tropical countries, the use of daylighting technologies is a
 121 significant concern because of the heat associated with sunlight, which can increase the cost of cooling, thus
 122 reducing the energy savings resulting from the reduction of the lighting load. This paper presents the only
 123 experimental data in the southern hemisphere (different solar path) and for extreme sunlight conditions.
 124 Under these climatic conditions, we come to refute, confirm or bring a new perspective on the impact of the
 125 Mirrored Light Pipe on thermal and spectral conditions, its impact on natural human biological rhythms.

126 After an annual analysis of the solar irradiation of the study site (St-Pierre, LA REUNION, southern
 127 hemisphere) to identify the extreme climatic conditions, we oriented our approach by proposing measurements
 128 on several spectral bands of daylight (see **Figure 1**). We sought to confirm that, despite the intense solar
 129 radiation, the light pipe brings little IR GLO (pyrgeometer measurements), that the thermal effect of the
 130 transmitted energy remains low compared to the visible part (pyranometer measurements), and that the
 131 wavelength spectrum of the penetrating radiation (i) is close to the spectrum of the sunlight, to the benefit of
 132 the suppression of UV (responsible for the aging of the materials) (ii) and of better quality than any artificial
 133 lighting. We associate our spectroscopic analysis to the quality of the transmitted light about its adequacy with
 134 the natural biological (circadian) human rhythms.



135
136

Figure 1: Measurements made in the course of this work

137 All these results represent a further advance in understanding the behavior of tubular mirrored daylight
 138 guidance systems and contribute to the continuous improvement of this technology.

139 *Table 1: synthesis of numerical and experimental studies from 1998 to 2020*

Reference	Findings
<i>Light spectrum transmitted by the light pipe MLP</i>	
Nilsson et al. [10]	Achromatic properties
	Spectroscopic behavior depends on the aspect ratio
	The angle of incidence affects the spectral transmittance: (i) less than 50°: wavelengths between 400 and 800 nm (visible); more significant than 50°: from 400 to 1000 nm (visible + near IR)
Shao and Riffat [11]	Under cloudy skies, the number of IR rays is about three times lower and more uniform than under clear skies
Callow [12] Nilson et al. [10]	PMMA (collector material) favors the transmission of visible and near IR wavelengths while effectively limiting the medium and far IR
Omishore [13]	Significant increase in the surface temperature of the light pipe in response to IR radiation
<i>Impact on indoor thermal conditions and study of solar heat gain</i>	
Williams [19]	An only experimental study in tropical climatic conditions (northern hemisphere)
	Large temperature gradient during the day
	Thermal bridge at night
Harrison [20]	The average effective thermal resistance of 0.279 m ² .K.W ⁻¹ for a light pipe with Ap = 5.55
Callow [12], Callow [21], Laouadi [22], McCluney [23], Bencs [24], Perčić [25], Hien [26], Wu [27]	The heat contribution of a light pipe is lower than artificial lighting
<i>Stack ventilation with light pipe and CFD study</i>	
Varga [14], Oakley [15], Šikula [16], Šikula [17], Ait-taleb [18]	Interesting coupling of thermal draft + light contribution
	Double ducting limits the temperature rise of the reflective surface

140 2. Materials and methods

141 Reunion Island is very particular because of its high solar irradiation. As we have seen in a previous
 142 study [8] and confirmed by the literature, it is necessary to study the environment of the light pipes to
 143 understand their behavior. For this reason, we have chosen to set up an experiment to verify and validate the
 144 literature observations. Three experimental objectives have been identified:

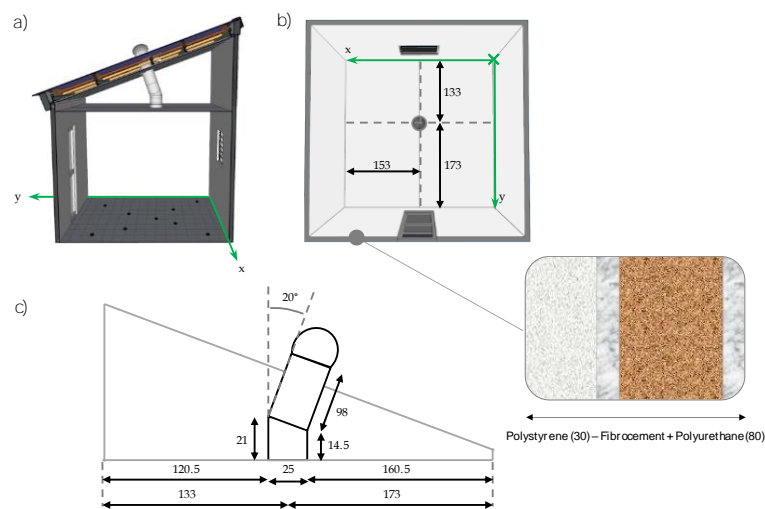
- 145 - Objective 1: Analyze the annual solar irradiation profile of the experimental site to understand
 146 the profile of the available solar resource,
- 147 - Objective 2: Measure the profile of the wavelength of the light effectively transmitted by the light
 148 pipe by highlighting the filtering effect of the device for two types of day,
- 149 - Objective 3: Evaluate the device's potential for the human circadian cycle compared to traditional
 150 artificial lighting sources.

151 Thanks to the results of the experiments set up, we will understand the impact of the light pipe on the
 152 interior ambient conditions and the comfort of the individual.

153

154 2.1. Experiment set-up

155 The study support is an experimental cell of 9m^2 located in Saint-Pierre (Reunion Island). This cell is
 156 oriented North/North-West (9°N) and positioned on a platform without any distant mask impacting the cell.
 157 The dimensions of the test cell are described in Figure 2. The vertical walls are made of composite panels
 158 (fibrocement/polyurethane/ fibrocement), and the horizontal ceiling is made of wood. Each interior face is
 159 covered with 5 cm of white polystyrene to reduce the radiative effect. The sloping roof (20°) is made of midnight
 160 blue corrugated sheet metal. A mirrored light pipe ($\rho_{\text{LP}} = 99.7\%$; $A_p = 4.6$) of the brand SOLATUBE® was
 161 installed in the roof plane. It is curved to ensure the horizontal of the diffuser.



162
 163 Figure 2: a) Cross-section view of the LGI cell b) Bottom view of the LGI c) Dimensions of the light pipe

164 2.2. Measurement & data acquisition

165 To meet each of the established objectives, we wished to set up different studies.

166 2.2.1. Measurements of short wavelength from pyranometer sensor

167 Two CMP11 pyranometers are used to measure most solar radiation (285 to 2800 nm) and mainly short
 168 wavelengths. These measurements offer elements of response to objectives 1 and 2. To answer the objective
 169 N°1, it was necessary to obtain a complete year of measurement to put forward the seasonal profile of the place
 170 of study by using two pyranometers (global and diffuse radiation). Then, to answer partly to the objective N°2,
 171 wishing to identify the filtering effect of the light pipe, we used two pyranometers. One is placed directly under
 172 the diffuser with a black plastic cap, and the other is placed outside in the plane of the sensor (Figure 3). Since
 173 this instrument is intended for outdoor measurements, its sensitivity is relatively high for indoor measurements
 174 (7 W/m^2). However, we wish to use the same instruments to have the same sensitivity wavelengths (285 to
 175 2800 nm). In this case, failing to quantify rigorously, we adopt a qualitative approach "binary." If the transmitted
 176 energy is close to the sensitivity, the measurement will show that the light pipe transmits (1) or does not transmit
 177 (0) energy. If the measured data are low (close to the sensitivity), the experiment will demonstrate that the
 178 device transmits little energy in the spectral range of the pyranometer.



Figure 3: Outdoor pyranometer CMP11 for global irradiance in the plan of the light pipe

179
180

181 The devices are connected to a CAMPBELL SCIE® brand data acquisition system and are synchronized
182 with each other. They record in one-minute time steps, like the scanning.

183 The pyranometer specifications are given respectively in Table 2.

184 Table 2: Pyranometer specifications

		Accuracy
Spectral range λ	285 to 2800 nm	
Non-linearity	100 to 1000 W/m ²	<0.2%
Temperature dependence	-40 °C to +40 °C +40 °C to +80 °C	< 5 % < 10 %
Zero offset	< 7 W/m ²	
Non-stability (change/year)		< 0.5 %
Sensitivity	7 to 14 μ V/W/m ²	
Operating temperature	-40°C to 80°C	
Maximum irradiance	4000 W/m ²	

185 2.2.2. Measurements of long-wavelength from pyrgeometer sensor

186 To pursue objective N°2, two CGR3 pyranometers (Campbell Scientific®) were used to evaluate the
187 global irradiation for the spectral band 4500 nm - 42000 nm (thermal effect). The installation methodology is
188 the same as with the pyranometers. The first is placed under the diffuser with a black plastic cap and polystyrene
189 insulation to reduce the radiative effect of the cell walls, which are themselves insulated (Figure 4.a). The second
190 is placed on the roof in the plane of the device collector (Figure 4.b).

191 As with the pyranometers, the pyrgeometers are devices for measuring in an outdoor environment, with
192 a sensitivity of about 5 W/m². To perform the most rigorous study possible on the effect of the light pipe, the
193 outdoor and indoor sensors must have the same spectral bands (4500 nm - 42000 nm). The sensitivity of this
194 sensor may be close to the values recorded indoors; the measurement must be qualitative, like the study with
195 pyranometers. In this case, failing to quantify rigorously, the qualitative binarized approach will show that the
196 light pipe transmits (1) or does not transmit (0) energy on the spectral interval 4500 nm - 42000 nm. If the
197 measured indoor data are low, the study will show that the light pipe transmits little long wavelengths.

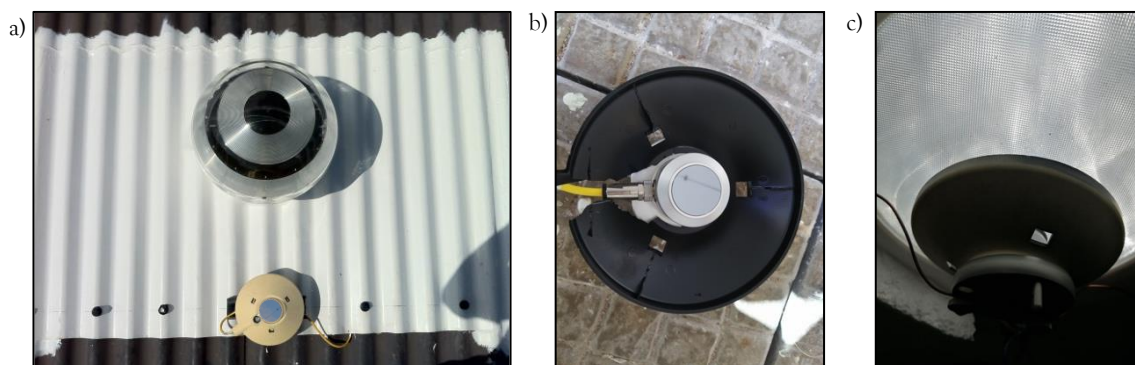


Figure 4: a) outdoor pyrometer CGR3 for global irradiance in the plan of the light pipe
 b) indoor pyrometer CGR3 with black protection and insulation provided by polystyrene
 c) sensor positioned on the light pipe diffuser

As for the pyranometers, the pyrometers are connected to a CAMPBELL SCIE® data acquisition system and synchronized. The time step and the scanning are also of the order of one minute.

The pyrometer specifications are given respectively in Table 3.

Table 3: Pyrometer specifications

		Accuracy
Spectral range λ	4500 to 42000 nm	
Non-linearity	-250 to 250 W/m ²	< 1%
Temperature dependence	-40 °C to +40 °C +40 °C to +80 °C	< 5 % < 10 %
Zero offset	dT = 5 K/h	< 5 W/m ²
Non-stability (change/year)		< 1 %

2.2.3. Spectrophotometer utility in the experiment

This study aims to bring elements of the answer to the objective N°3, seeking to establish the electromagnetic spectrum profile transmitted by the light pipe. In addition, it is a question of understanding the role that the light pipe can play on the visual comfort of the occupant and its circadian efficiency. A spectrophotometer was used to measure the electromagnetic spectrum profile at the entrance and exit of the light pipe. The spectrometric measurements are performed by an Ocean Optics® spectrophotometer, model JAZ (Figure 5).

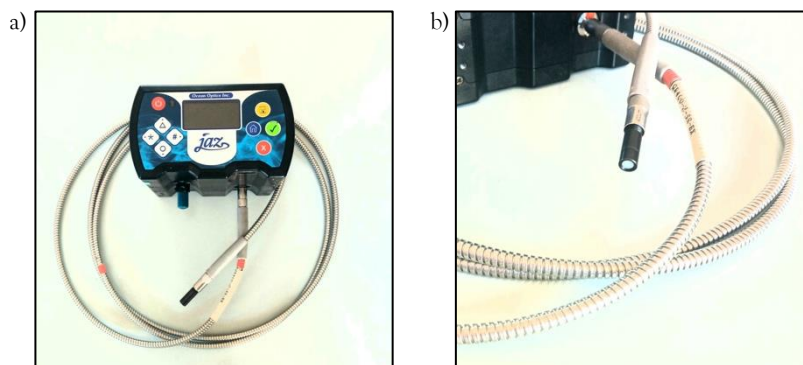


Figure 5: a) Ocean Optics® spectrophotometer, model JAZ for spectrometric measurements in the plan of the light pipe b) Photosensor cell of the spectrophotometer

216 This apparatus allows measuring the UV/Visible part of an electromagnetic source. The measurement
 217 was performed in 2 quasi-synchronous phases: first, the spectrophotometer cell was placed orthogonally under
 218 the diffuser. The cell device was placed outside in the plane of the collector. The recording was instantaneous.
 219 The specifications of the spectrophotometer are given in Table 4.

220 Table 4: Spectrophotometer specifications

Description	Jaz UV/Visible Spectrophotometer with Remote Probe
Grating options	14 different gratings, UV through short-wave NIR
Detector	2048-element linear silicon CCD array; L2 collection lens
Spectral range λ	200 to 1100 nm
Signal-to-noise ratio	250:1
Integration time	870 μ S to 65 seconds

221 2.2.4. Summary of the experiments conducted

222 All experimental scenarios were synthesized in Table 5.

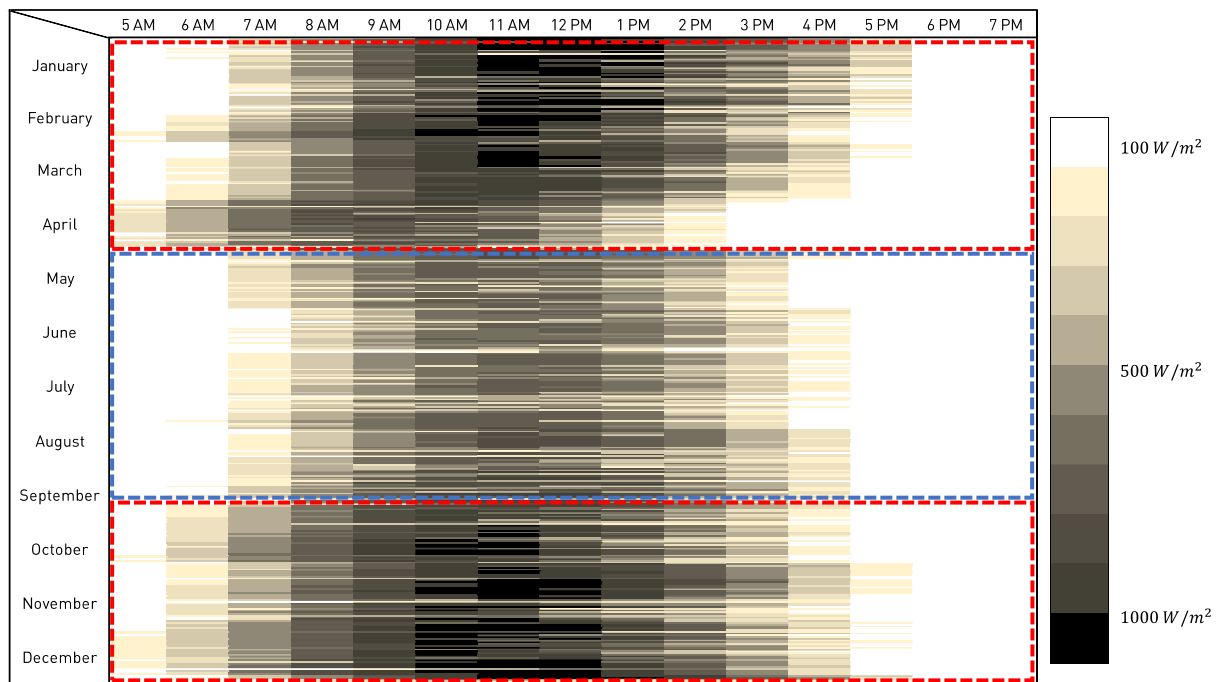
223 Table 5: Experimental scenarios

N°	Period used	Measurement	Sensors	Objectif
1	1 year (2019)	$I_{G,out,h}$ $I_{d,out,h}$ $I_{G,in,h}$	3 x CMP11 pyranometers	Quantitative approach : Annually solar resource for brief climate study
	3 days (April 2018)			Qualitative approach : Evaluate the ability of the light pipe to transmit radiation in the spectral band (285 to 2800 nm) for 3 types of the sky (clear, overcast, and intermediate)
2	3 days (June 2019)	$L_{net,out}$ $L_{net,int}$ $L_{D,out}$ $L_{D,int}$	2 x CGR3 pyrgeometers	Qualitative approach : Evaluate the ability of the light pipe to transmit IR (4500 nm to 42000 nm) for 3 types of the sky (clear, overcast, and intermediate)
3	2 days (October 2019)	Outdoor and indoor spectral irradiance ($W/m^2/nm$)	1 x JazRad spectrophotometer	Quantitative approach : Quantified the outdoor light spectrum in the plan of the collector and the indoor light spectrum under the diffuser for two types of the sky (clear and overcast) for the spectral band (200 to 1100 nm)

224 3. Results and discussion

225 3.1. Annually solar resource for brief climate study

226 We carry out a brief climatic analysis of the environment in which the light pipe is positioned. The
 227 objective is to understand the solar potential of the city of Saint-Pierre, Reunion Island (France). We seek to
 228 discern the annual evolution of the global outdoor irradiance measured with an external pyranometer
 229 (CMP11).



230

231

Figure 6: Hourly distribution of $I_{G,out,h}$ for Saint-Pierre (La Reunion, France) during the year 2019

232

233

Figure 6 highlights a significant seasonality in global irradiance corresponding substantially to the seasons present in Reunion Island. The southern summer extends from October to April. This is the period when the solar resource is most abundant. The days reach a maximum irradiance frequently between 700 W/m^2 and 900 W/m^2 , and, sometimes, up to 1000 W/m^2 (in a clear sky), and the beginning and end of the day close to 200 to 500 W/m^2 .

237

From May to September, the southern winter is the period when the maximum irradiance is around 100 to 800 W/m^2 . The days are shorter. Mornings and ends of the days provide less than 200 W/m^2 . The trend changes as early as September when the days recover from hours of sunshine.

240

Indeed, the length of the days also changes according to the season: in the first summer period, the light pipe can benefit from an irradiance of almost 11 hours. In the second period (southern winter), the length of the days is shortened to an average of 9 hours. In the third period (close to the summer solstice), the days are the longest, with more than 12 hours of sunshine.

244

Seasonality does not seem to be adequately related to the lighting needs. Indeed, a system using daylight within a building will offer significant efficiency from October to April and less for the rest of the year.

245

246 **3.2. Characterization of day types**

247 Many approaches have been made to characterize the type of sky [28], but few have been made to define
 248 typical days. We note in the literature the models of Kittler [29], Perez [30], Perraudau [31], and a simplified
 249 model [32]. The latter is based on the ratio of diffuse to global irradiance. Fakra [33] evaluated the
 250 characterization given by these indices over three types of the day (clear, intermediate, and overcast skies). He
 251 concludes that the simplified model seems to be more suitable. Apart from sunrise and sunset for each day,
 252 the SR index characterizes the day type well overall. We will use this indicator for further experimentation.

253 The Sky Ratio can be evaluated from the following ratio :

$$SR = \frac{I_{d,out,h}}{I_{G,out,h}} \tag{1}$$

254 The proposed characteristic values are listed in **Table 6**.

255 *Table 6: Characteristic values of SR*

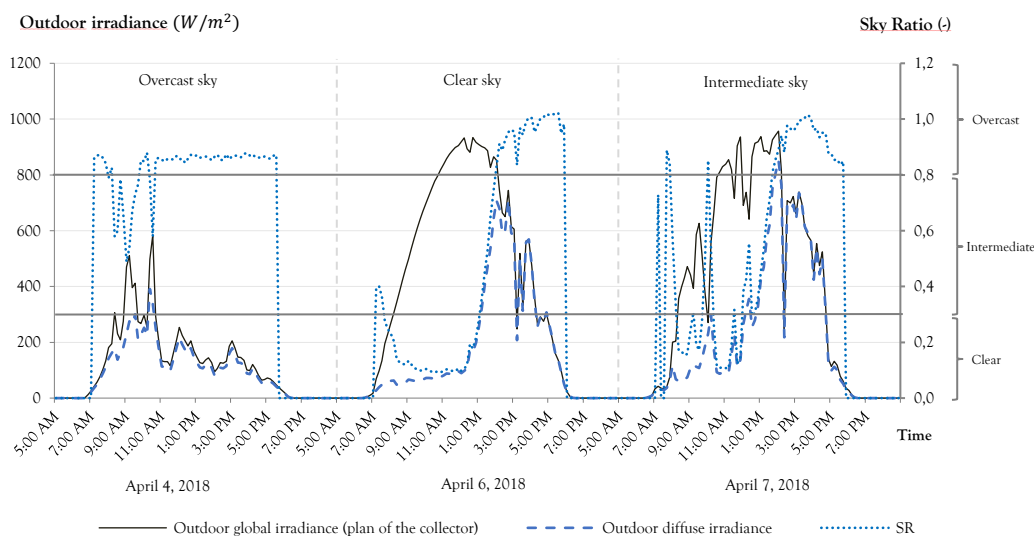
Type of sky	SR
Clear	$SR \leq 0.3$
Intermediate	$0.3 < SR < 0.8$
Overcast	$SR \geq 0.8$

256 This characterization will be used to analyze our results according to the different types of days.

257 **3.3. Irradiance through the light pipe (285 to 2800 nm)**

258 The objective of this measurement was to qualitatively assess the magnitude of energy transmitted
 259 through the light pipe inside the experimental cell for three typical days (clear, intermediate, and overcast).

260 Using the SR, we select three typical days: April 3, 6, and 7. The graphs (**Figures 7 and 8**) that follow are
 261 drawn at the 10-minute time step to reduce the impact of climatic contingencies.



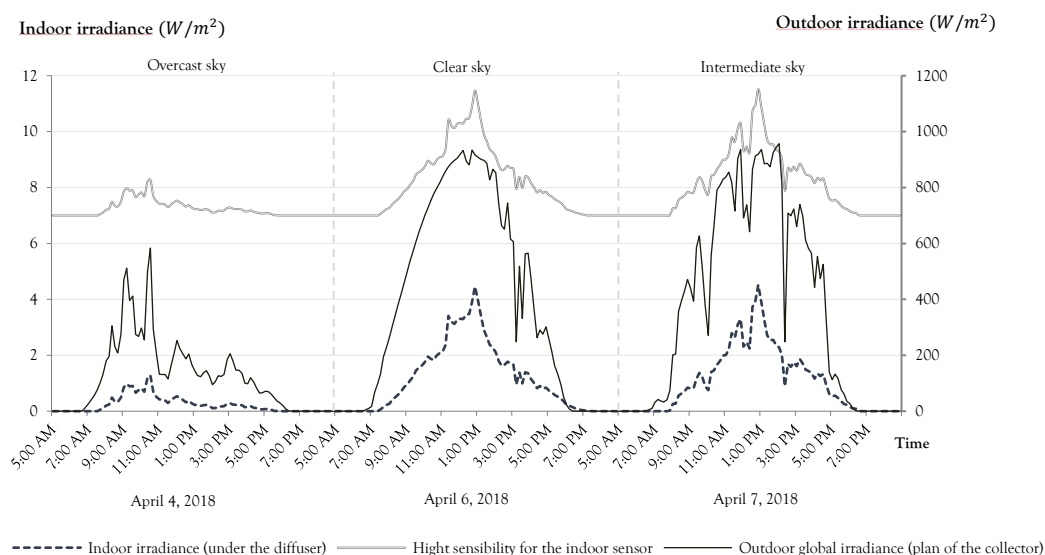
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263 *Figure 7: Global ($I_{G,out,h}$) and diffuse ($I_{d,out,h}$) outdoor irradiance for three types of days (4, 6, and 7 April)*

264 April 4 is an overcast day (Figure 7). The global irradiance profile is almost similar to diffuse irradiance,
 265 which is typical of a cloudy sky. This classification is confirmed by the SR, which reaches an average value of
 266 0.9. Events appear around 9 AM and 11 AM. They should probably be associated with a partially and
 267 momentarily clear sky.

268 April 6 is considered a clear day, with an average SR of about 0.3. The morning is clear of any clouds
 269 (the diffuse irradiance is very low), and scattered cloudy episodes may appear from 3 PM. Like those of April
 270 6, clear sky days are relatively frequent at this time of the year in Reunion Island, where the thermal breeze
 271 regime pushes the clouds in the island's heights, which allows clearing the sky for the coastal areas where the
 272 tests take place.

273 April 7 is an intermediate day, confirmed by the average SR reaching 0.4. The global irradiance can
 274 reach 900 W/m^2 with drops in irradiation caused by the presence of clouds.



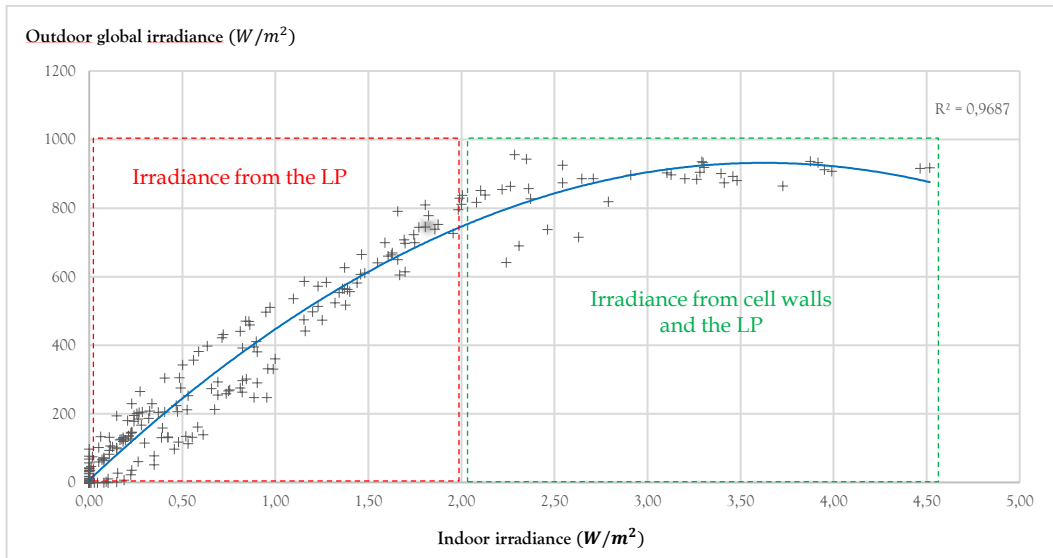
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276 *Figure 8: Indoor ($I_{d,in,h}$) and outdoor ($I_{G,out,h}$) irradiance for three types of days (4, 6, and 7 April), and the high sensibility of*
 277 *the indoor sensor*

278 We also plot the indoor and outdoor solar irradiance evolution on the same graph (Figure 8). The
 279 indoor irradiance level is low for each day and close to the sensor's sensitivity ($\pm 7 \text{ W/m}^2$, for more information
 280 about this value, see Table 2). These values do not allow us to give a precise quantity of transmitted irradiance.
 281 However, the data collected shows that low intensity is transmitted through the light pipe.

282 For the overcast day of April 4, the maximum indoor irradiance integrating the sensor's sensitivity is
 283 approximately $4.8 \pm 7 \text{ W/m}^2$ at 11 AM against 580 W/m^2 outside at the same time or more than 120 times less.
 284 For April 6 (clear sky), at 12:50 PM, the nominal global outdoor irradiance is 920 W/m^2 against $7.5 \pm 7 \text{ W/m}^2$
 285 indoors, or more than 123 times the transmitted energy. The trend is verified for April 7 (intermediate sky),
 286 where the maximum indoor irradiance is close to $8 \pm 7 \text{ W/m}^2$ at 12:50 PM against nearly 918 W/m^2 outside.
 287 The shape of the interior irradiance curve seems to be different from that of the exterior irradiance. The

288 specular reflection inside the light pipe must significantly impact the amount of energy transmitted, just as it
 289 was noticed for the illuminance in later works [8].



290

291 *Figure 9: Correlation between outdoor ($I_{G,out,h}$) and indoor ($I_{d,in,h}$) irradiance*

292 When we study the relationship between outdoor and indoor irradiance (Figure 9), we notice a strong
 293 positive linear correlation between the two parameters with an R^2 coefficient of 96.9% (see the red frame of
 294 Figure 9). The polynomial form of this correlation allows us to understand that the energy contribution by the
 295 light pipe is linear up to 780 W/m^2 but grows less quickly beyond. Moreover, the fact that the internal
 296 irradiance continues to expand beyond this level indicates the energy transmitted not by the light pipe but
 297 most probably by the diffuse thermal interreflection in the inner surface of the cell walls (see the green frame
 298 of Figure 9).

299 These findings allow us to conclude that the energy transmitted by a light pipe in the wavelength range
 300 between 285 and 2800 nm is very low, even negligible. This wavelength includes most of the electromagnetic
 301 spectrum of light: the visible range and much of the infrared (IR-near). These measurements reveal that the
 302 thermal effect, even if it is not finely expressed (related to the sensitivity of sensors), is minimal with the light
 303 pipe, compared to a window.

304 **3.4. Estimation of the luminous efficacy of the light pipe**

305 Considering the results obtained in previous work evaluating the nominal luminous fluxes transmitted
 306 by the same light pipe for the same climate [9], we can deduce the luminous efficiency of the mirrored light
 307 pipe based on the measurements performed in the previous section.

308 For this, we use the most unfavorable values of the radiant flux (the largest, because of the high sensitivity
 309 of the sensor: $+7W/m^2$), we obtain :

$$\eta_{clear_{min}} = \frac{\phi_v}{\phi_{e_{MAX}}} = \frac{\phi_v}{\phi_{e_{measure,MAX}} + Sensibility_{sensor}} = \frac{6800}{8 + 7} = \frac{6800}{15} = 453 \text{ lm.W}^{-1} \quad (2)$$

$$\eta_{\text{overcast}_{\min}} = \frac{\phi_v}{\phi_{e_{\text{MAX}}}} = \frac{\phi_v}{\phi_{e_{\text{measure,MAX}}} + \text{Sensibility}_{\text{sensor}}} = \frac{710}{4.8 + 7} = \frac{710}{11,8} = 60 \text{ lm.W}^{-1} \quad (3)$$

310 Compared with the types of artificial lighting and their characteristics presented in [9], we obtain [Table 7](#).

311 *Table 7: Comparison of the luminous efficacy of several artificial lighting solutions with those of the light pipe*

Light source	Maximum radiant flux $\phi_{e_{\text{MAX}}}$ [W]	Luminous flux ϕ_v [lm]	Minimum Luminous efficacy η_{\min} [lm.W ⁻¹]
Global outdoor irradiance According to [34]			121.5
Mirrored Light pipe curved with $\rho_{\text{LP}} =$ 99.7% and $A_p = 4.6$	Clear sky	15	453
	Overcast sky	11.8	60
Incandescent bulb	60	710	11.8
Halogen bulb	70	1200	17.1
Compact fluorescent lamp	23	1500	65,2
Traditional fluorescent tube	56	3400	60.7
LED	3	150	50

312 We note that the luminous efficacy of the light pipe in a clear sky is much better than the other current
313 artificial lighting devices and equivalent to the luminous efficacy of a traditional fluorescent tube in an overcast
314 sky. In the clear sky, despite an estimated radiant flux at the highest (15 W), the light pipe offers a luminous
315 efficiency of about 453 lm.W⁻¹, which is next to 7 times more than the compact fluorescent lamp. Compared
316 with the outdoor luminous efficacy, according to [34], we can see that the low share of thermal energy
317 transmitted in favor of a highly luminous flux allows the light pipe to improve the luminous efficacy of the
318 transmitted daylight.

319 3.5. Infrared through the light pipe (4500 nm to 42000 nm)

320 The measurement of this radiation is carried out with a Kipp & Zonen CG4 pyrgeometer sensitive to a
321 spectral range between 4500 nm and 42 000 nm (99% of the energy of the total infrared spectrum).

322 The pyrgeometer allows measuring the long wavelengths (LW). Its silicon optical window is designed to
323 allow infrared radiation to pass through. An internal thin-film coating prevents short-wave solar radiation from
324 reaching the LW thermopile (cutting off the shortest wavelengths of the solar spectrum). The infrared radiation
325 received at the Earth's surface is emitted by the entire atmospheric column (CO₂, water vapor, clouds, and
326 other particles).

327 The measurement method is possible (compare outside and inside) because the light pipe has highly
328 reflective walls ($\rho_{\text{LP}} = 99.7\%$). Measurement at the diffuser level is thus sustainable because the IR-rays coming
329 from the light pipe will be preponderant compared to the IR-rays coming from the walls of the experimental
330 cell. The latter contribute little to the overall measurement of IR. Indeed, the IR-rays passing through the tube
331 are mainly reflected and therefore reach the sensor cell. In addition, the absorbed and transmitted parts of the
332 radiation are minimized primarily to the thinness of the tube.

333 L_D is the downward radiation in LW received by the pyrgeometer from the measured object (i.e., in our
 334 case, two situations are presented: outdoor, for the sky and, indoor, for the light pipe diffuser). It is the fraction
 335 of infrared radiation (infrared irradiance) emitted by the target object. L_{net} (net radiation) represents the
 336 radiative exchange between the sensor surface ($\epsilon \cdot \sigma T^4$ with $\epsilon = 1$ if we considered black body case, given by
 337 the manufacturer) and the observed object L_D (sky or light pipe).

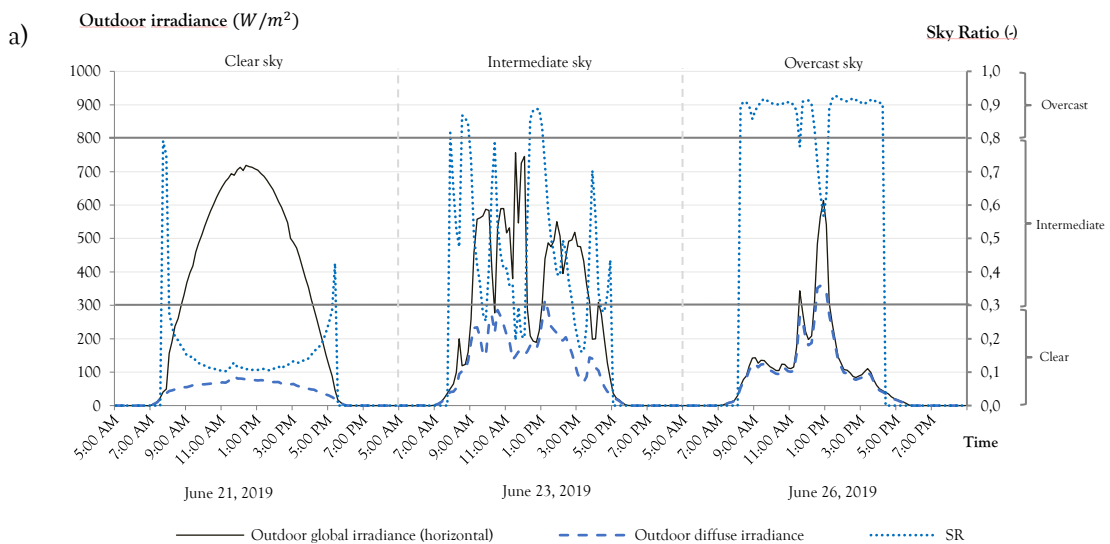
$$L_{net} = I_{object} - I_{sensor} \tag{4}$$

$$L_{net} = L_D - \sigma \cdot T^4 \tag{5}$$

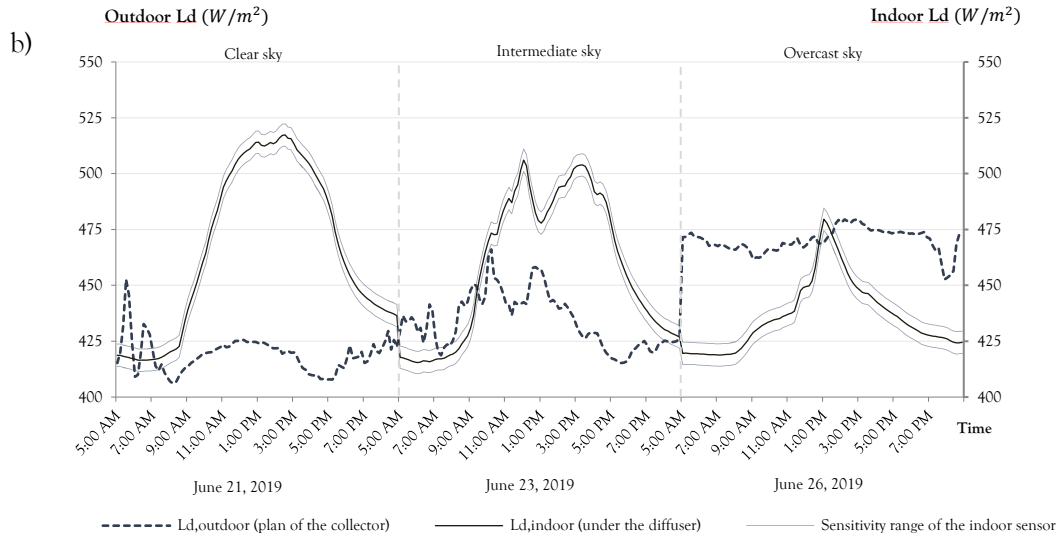
338 The sensor interprets L_{net} as the ratio between the voltage delivered by the pyrgeometer and its sensitivity.

339 L_D being always positive (the flow being always descending), the sign of L_{net} allows giving the direction
 340 of the radiative flow, and thus the direction of the exchange. Thus, in theory: when the diffuser is warmer than
 341 the collector (scenario of an overcast sky, or a beginning/end of the day), the radiative flux is rising, so the
 342 radiation L_{net} is negative (the sensor measuring positive downward). In the clear sky (or at the peak of solar
 343 radiation), the diffuser is colder than the collector, the radiative flux is downward, so the radiation L_{net} is
 344 positive. In this approach, L_{net} is zero when there is no exchange between the collector and the diffuser.

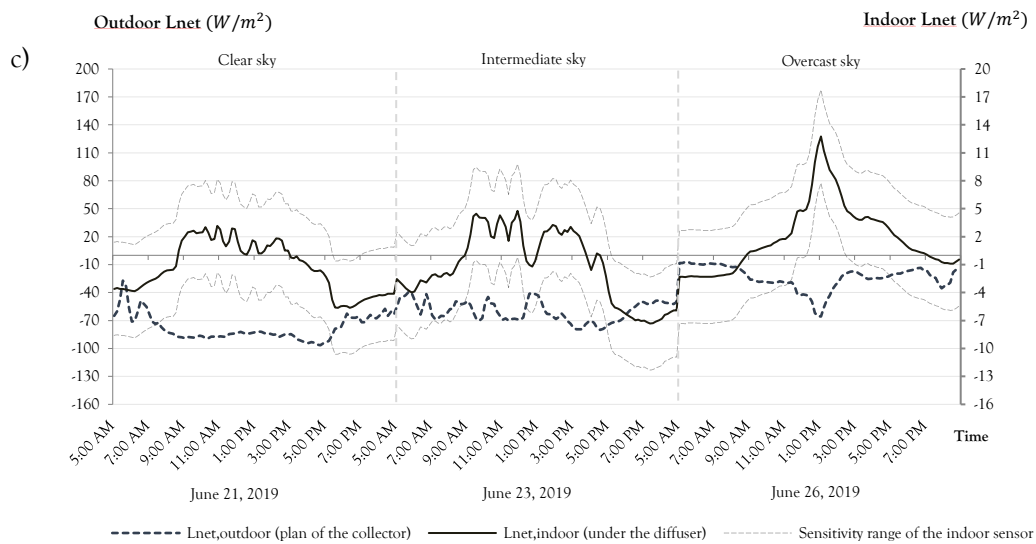
345 The curves are presented with a time step of 10mn on 15 hours per day (from 5 AM to 8 PM) for more
 346 readability.



347



348



349

350 Figure 10: a) Global and diffuse outdoor irradiance for three types of days (21, 23, and 26 June) b) Outdoor and indoor
 351 downward longwave radiation, L_D c) Outdoor and indoor net radiation L_{net}

352 June 21 (Figure 10.a) is equated with a clear sky day ($SR_{moy} < 0.3$). The high values at the beginning and
 353 end of the day are related to this index [33]. The nominal global irradiance measured by an outdoor
 354 pyranometer reaches 715 W/m^2 at 12:30 PM. We can see that the downward $L_{D,out}$ radiation at 5:30 AM
 355 reaches nearly 450 W/m^2 and then decreases to 407 W/m^2 at 8 AM (Figure 10.b). A parabolic shape is then
 356 observed between 8 AM and 5 PM, with a maximum value of 425 W/m^2 reached noon (solar noon, because
 357 of the winter solstice in Reunion Island). This observation seems coherent: at the beginning and at the end of
 358 the day (when the Sun is not yet visible), there is no radiative exchange between the ground and the sky (i.e.,
 359 $L_D = \sigma \cdot T^4$). When the Sun rises and sets, the radiative flux is rising (towards the sky) because the ground
 360 temperature increases. The net radiation $L_{net,out}$ is then negative and increases when the ground temperature
 361 rises more than that of the sky. Inside the cell and under the light pipe diffuser, the LW $L_{D,in}$ is very high, with
 362 a nominal value of more than 520 W/m^2 in the early afternoon (2:30 PM). This can be justified by the fact
 363 that the sensor measures radiation from the light pipe elements rather than the sky. As these elements rise in

364 temperature, the infra-reds recorded are those coming from the diffuser and collector. We also note that at the
365 beginning and end of the day, when the diffuser is warmer than the collector, $L_{\text{net,in}}$ is negative because the
366 radiative exchange is from the cell to the outside and reverses during the day (Figure 10.c). The values vary
367 between $\pm 3 \text{ W/m}^2$, which is very low, marking the low infrared exchange between the diffuser and the collector.

368 June 23 is an intermediate day (Figure 10.a), confirmed by the SR_{moy} reaching 0.4. The global irradiance
369 can reach 900 W/m^2 with drops in radiation up to 170 W/m^2 at 12:30 PM caused by the presence of clouds.
370 $L_{\text{D,out}}$ increases in the presence of cloud masses (Figure 10.b).

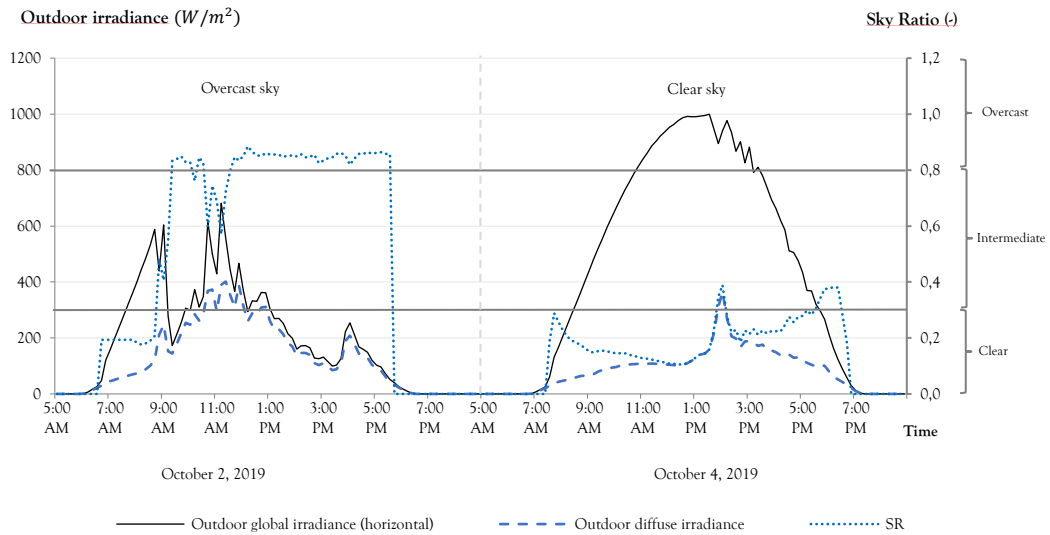
371 Finally, on June 26 (Figure 10.a), the profile of the global irradiance is almost similar to that of the
372 diffuse irradiance, which is typical of the evolution of the irradiance during an overcast sky. This classification
373 is confirmed by the SR_{moy} , which reaches an average value of 0.9. $L_{\text{D,out}}$ is close to 475 W/m^2 , which is consistent
374 with the type of sky. Instead of measuring the radiative exchanges with the sky (colder), the latter measures the
375 radiation of water droplets at air temperature (Figure 10.b). The net radiation $L_{\text{net,out}}$ is thus close to zero due
376 to the overcast condition (Figure 10.c). For the net fraction, the difference for long wavelengths is negative and
377 increases during the day. Inside the cell and under the light pipe diffuser, the downward radiation in LW $L_{\text{D,in}}$
378 is low, with a nominal value of more than 474 W/m^2 in the early afternoon (1:20 PM). This can be explained
379 by the fact that the angle of incidence is higher. Thus the radiation arrives directly on the sensor, with fewer
380 inter-reflections within the tube. This finding had been noted in the literature for a controlled environment
381 [10].

382 We also note that when the diffuser is warmer than the collector at the beginning and end of the day,
383 L_{net} is negative because the radiative exchange is from the cell to the outside. However, the value reached by
384 L_{net} is wider under cloudy skies than under clear skies, which can be explained by the low-temperature rise of
385 the light pipe components. Moreover, the measured radiation probably corresponds to radiative exchanges
386 with the water droplets trapped in the tube. However, this observation must be modulated because the values
387 reached for $L_{\text{net,out}}$ have a reduction factor of nearly ten compared to the outside, with a maximum value of
388 $L_{\text{net,in}}$ an overcast sky of about 12 W/m^2 , which confirms the weak contribution of IR by the light pipe.

389 Moreover, $L_{\text{D,in}}$ presents higher values in the clear sky than in the overcast sky, which translates to an
390 inverse behavior than the one observed in an outdoor environment when the presence of clouds strongly
391 modulates the infrared radiation (emission in the infrared of water drops or ice crystals).

392 3.6. Spectral irradiance transmitted by a light pipe (200 to 1100 nm)

393 The objective is to establish the profile of the electromagnetic wave passing through the light pipe for
394 the only two more extreme types of the day (clear sky and overcast sky). With this, we can answer the objective
395 N°2 (to establish the profile of the wavelength transmitted).



396

397

Figure 11: Global and diffuse outdoor irradiance for two types of days (2 and 4 October)

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To verify the sky type, we use daily global and diffuse outdoor irradiance (measurements with a CMP11 pyranometer), shown in Figure 11. The first day was October 2, 2019. The sky was overcast ($SR > 0.8$). At solar noon, irradiance peaked at 300 W/m^2 . The second (October 4) was a clear sky with an SR below 0.3. Its irradiance was around 1000 W/m^2 .

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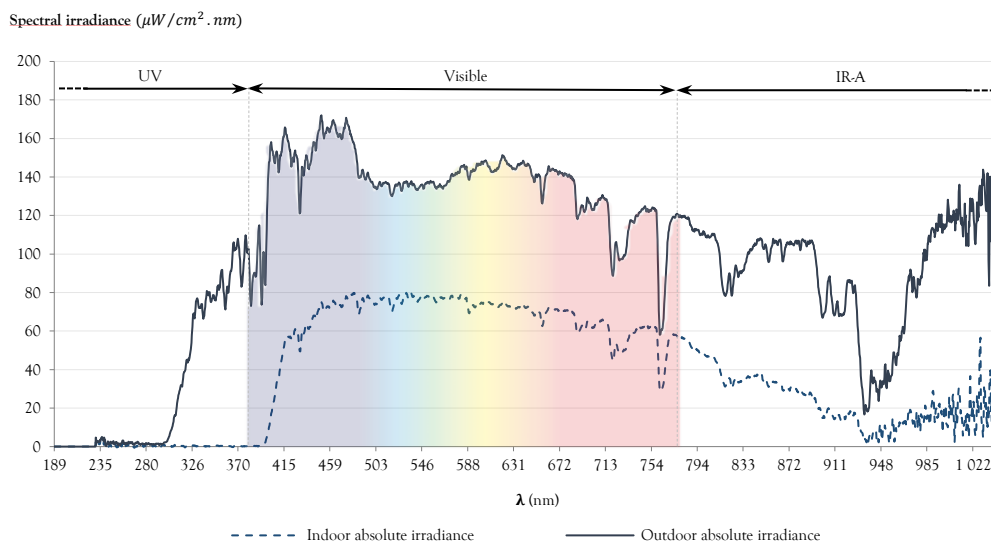
The measurements with the spectrophotometer were carried out on these two days at solar noon (i) indoors by placing the sensor in the center of the light pipe diffuser and (ii) outdoors, in the plane of the collector, by pointing at the Sun.

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The graphs below represent the solar irradiance spectrum at sea level (called AM1.5). We find the atmosphere's absorption bands in the ultraviolet (notably by ozone) and the infrared (notably by water vapor and carbon dioxide).



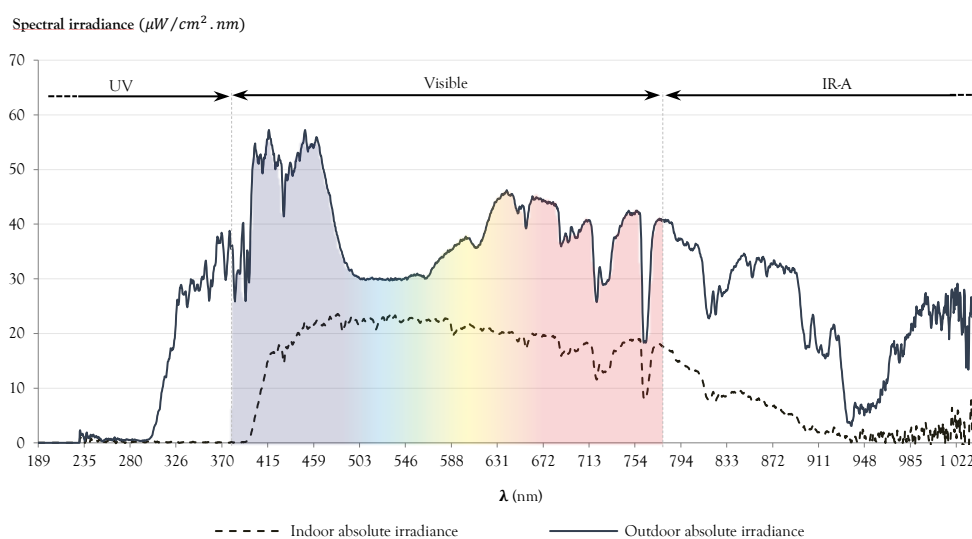
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409

Figure 12: Amount of energy transmitted by wavelength for a day of clear sky (October 4)

410 In the clear sky (Figure 12) and outside, the profile of the daylight spectrum shows us a relatively
 411 continuous spectral irradiance in the visible range. At the exit of the light pipe, no UV is detected. This is
 412 probably due to the polymethylmethacrylate (PMMA) properties, which compose the dome of the light pipe
 413 collector. This thermoplastic has the advantage of maintaining its transparency, lightness, resistance to UV
 414 (responsible for the aging of materials), and corrosion. These properties make it ideal for a collector for a dome
 415 subjected to intense mechanical or solar constraints. This same material also seems to act on the near IR, as
 416 indicated by Nilson [10] and Callow [12] in their studies.

417 Regarding the heat input, represented on the graph by the amount of A-IR, we note that the light pipe
 418 transmits only a relatively small part of near-infrared (on average, three times less than the external resource)
 419 with a substantial decrease beyond 950 nm. This analysis allows us to confirm the results of the literature [11]
 420 and the measurements made with the pyrgeometer: the light pipe is only responsible for a small part of the
 421 daily heat input. The internal spectral curve also shows that the device smoothes the spectrum of the external
 422 electromagnetic wave. The spectral irradiance at the outlet of the device is balanced on each of the visible
 423 wavelengths. Our experiment in real weather conditions (i.e., in situ) confirms the results of Nilsson et al. [10]
 424 in a controlled environment that the MLP has achromatic properties.



425

426 *Figure 13: Amount of energy transmitted by wavelength for an overcast day (October 2, 2019)*

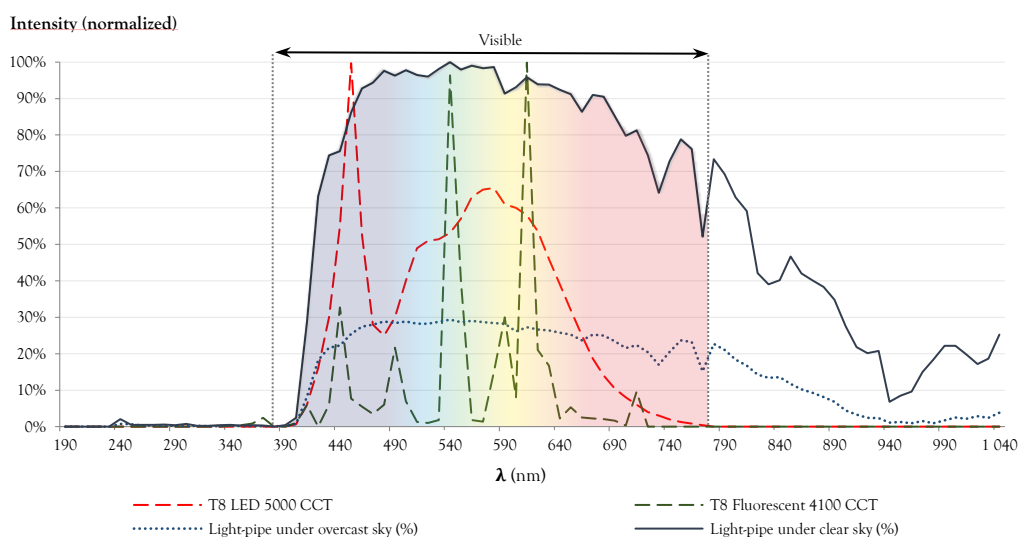
427 In overcast conditions (Figure 13), the spectral irradiance values drop by 2 to 4 times compared to the
 428 clear sky condition. Outdoors, for UV and IR-A, the electromagnetic waveform remains unchanged. The
 429 changes occur mainly for the spectral range 460-630 nm, where the sky absorbs a significant part of the visible
 430 spectrum. The profile of the spectrum transmitted by the light pipe remains unchanged compared to the clear
 431 sky condition, with a reduction of the amplitude of the spectral irradiance by a factor of 4. This value in a
 432 tropical climate is higher but close to the factor of 3 found in temperate climate by Shao and Riffat [11] in their
 433 work in a real environment (northern hemisphere, max illumination: 20 Klux).

434 Based on these findings, it is interesting to compare the spectrum of the electromagnetic wave
 435 transmitted by the light pipe with that of artificial lighting devices.

436 3.7. The efficiency of light pipe on human circadian rhythm compared by artificial lighting

437 The objective is to compare the spectrum of radiation from the light pipe for two types of the day (clear
 438 sky and overcast sky) and from two artificial lighting devices the most used and which we can easily find on the
 439 market: LED (T8) and fluorescent lamp (T8). Moreover, this artificial lighting is the most efficient, conforms
 440 to Table 7. With this comparative analysis, we can answer objective N°3, namely, to evaluate the concordance
 441 of the transmitted light with natural biological rhythms.

442 Figure 14 is based on the two days explained in the previous section: October 2, 2019 (overcast) and
 443 October 4, 2019 (clear). To provide a viable comparison, we normalize the spectral irradiance and smooth the
 444 wavelength spectra at scanning of 10 nm.



445

446 Figure 14: Normalized spectral intensity of the wave: at the exit of the light pipe for two types of the sky; under a LED
 447 luminaire (T8 LED 5000 CCT); under a Fluocompact luminaire (T8 Fluorescent 4100 CCT)

448 The visual system is composed of different biological sensors, photopic (retinal cells: cones and rods),
 449 and melanopic (ipRGCs), which ensure, respectively, biological synchronism (chronobiology) and the
 450 perception of the environment. The excitation peak of ipRGCs is not the same as that of retinal cells for image
 451 formation. It is located between 446 and 480 nm [35] [36] (towards the blue), whereas the nominal efficiency
 452 of photopic vision is found at yellow-green wavelengths, close to 555 nm [37]. Thus, the quality of illumination,
 453 and more precisely, the wavelength spectrum transmitted, will influence circadian rhythms and cognitive
 454 performance. The higher the color temperature (towards white), the higher the performance [2].

455 Moreover, Cajochen [38] showed that prolonged exposure in the late evening to monochromatic light
 456 of 460 nm (blue color) essentially reduced the secretion of melatonin compared to the exact duration of
 457 exposure to monochromatic light of 550 nm (green color). The literature [39–45] agrees that circadian rhythms
 458 influence cognitive performance: people are more focused and show a progressive improvement during the

459 biological day, whereas during the biological night, they perform poorly due to temporary attention losses.
460 Therefore, daylight, the most effective stimulus of the master clock, influences the cognitive abilities of human
461 beings.

462 Our study compares daylight (from the light pipe) and artificial lighting (Figure 14). Whatever the type
463 of sky, the spectrum of the wave coming from the light pipe dominates the blue-green colors while remaining
464 relatively balanced. As we have seen previously, the light from the device is achromatic. The LED has two peaks
465 of intensity: a maximum at 450 nm (blue color) and one at 580 nm (yellow color). This technology has a direct
466 effect on the production of melatonin. Used during the day allows inhibiting the hormone and accentuates
467 vigilance. However, the light issued is monochromatic with bluish dominance, creating discomfort on the color
468 rendering index inside. The spectrum is not complete, so the health benefit is limited. The LED studied should
469 be used in dark spaces, not used at night (scotopic vision). On the other hand, the compact fluorescent lamp
470 emits an irregular and rich spectrum in the green and yellow colors (540 nm and 610 nm), with a value of its
471 spectral intensity low in the blue wavelengths (440 nm). This type of lighting is thus to be proscribed for
472 photopic lighting (daily).

473 Overall, the experimental results show that the light pipe emits a full spectrum of light in clear and
474 overcast skies. This light favors chronobiological balance and promotes cognitive performance. The
475 intermittence of its luminous flux also allows the occupant to be connected to the climatic variation outside,
476 an important point in the study of visual comfort in the building.

477 4. Conclusion and perspective

478 A literature review allowed us to understand that the mirrored light pipe allowed the transmission of
479 achromatic light. Some works have also noted that the transmitted wavelength depended on the angle of
480 incidence of the rays and the aspect ratio. Another finding is that the proportion of IR radiation transmitted
481 is influenced by the type of sky and the kind of material used for the collector. Other studies have revealed that
482 the light pipe, during the night, could work on the thermal environment conditions by acting as a thermal
483 bridge. During the day, the literature notes that this device has only a small heat input, lower than artificial
484 lighting. All the studies reviewed were conducted in temperate, continental climatic conditions and only one
485 in tropical conditions. They are all located in the northern hemisphere.

486 This paper presents the only experimental data in the southern hemisphere (different solar trajectories)
487 and extreme sunlight conditions. We have aimed to address three distinct objectives: (1) to analyze the annual
488 solar irradiation profile of the experimental location, (2) to measure the spectral profile of the light wavelength
489 effectively transmitted by the light pipe for different spectral bands, and (3) to evaluate the potential of the
490 device on the respect of the human circadian cycle compared to conventional artificial lighting sources.

491 Several measurements were conducted on different spectral bands to meet these initial objectives, with
492 quantitative and qualitative approaches. The studies are called "qualitative" because of the low values measured
493 indoors, very close to the sensitivity of the sensors. The instruments are thus used to detect flux without

494 targeting the exact value of the transmitted flux. This approach was applied to measurements in the spectral
495 bands 285 to 2800 nm and 4500 nm to 42000 nm. We have still quantified, with sensitivity, the value of the
496 energy transmitted by the light pipe. For example, in the clear sky, we noted a radiant flux (285 to 2800 nm)
497 of nearly $7.5 \pm 3.5 \text{ W/m}^2$ inside, or less than 123 times the outdoor solar irradiance. This value allowed us to
498 estimate the minimum luminous efficacy of the light pipe (taking into account the highest radiant flux) in a
499 clear sky (591 lm.W^{-1}) and overcast sky (85.5 lm.W^{-1}), and then to compare them to the luminous efficacy of
500 various sources. The latter shows a result nine times higher in the clear sky than a compact fluorescent lamp.
501 The results for the 4500 nm to 42000 nm range (LW, IR) also show that the thermal impact of the mirrored
502 light pipe is limited. The "quantitative" studies concern the measurements associated with the
503 spectrophotometer covering the electromagnetic wave spectrum from 200 to 1100 nm. At the exit of the light
504 pipe, no UV is detected, and the spectral profile of the transmitted light shows us a relatively continuous
505 spectral irradiance in the visible range. This confirms the literature findings: the light pipe, in the clear sky as
506 overcast, diffuses an achromatic light, unlike the artificial lighting source studied.

507 We show that this system is well suited to promote visual comfort thanks to its non-visual effects
508 (intermittence of the luminous flux, chronobiology, and cognitive performance). It can provide full-spectrum
509 light in spaces that have few or no openings in the front. These rooms typically use artificial lighting that does
510 not regulate circadian rhythms. Our experimental work has shown that the light pipe brings little heat and
511 does not modify the visible light spectrum, thus providing beneficial light for humans.

512 Our experimental study was conducted on a single type of mirrored light pipe (curve, with an aspect
513 ratio of 4.6). These results allow us to understand the thermal and spectral behavior of the light pipe. The
514 evolution of geometric parameters (different aspect ratios, straight rather than a curved light pipe) or
515 photometric parameters (different reflection coefficient) will modify the number of light rays transmitted. The
516 level of interior illuminance will also change. However, this should not affect the spectroscopic profile of the
517 light passing through it. As found in the literature, the dominant parameter to act on the spectrum profile is
518 the angle of incidence of the incoming rays. Further studies may confirm these hypotheses.

519 The light pipe is the most successful daylighting device to meet the growing need for bioclimatic design
520 in a device focused on human well-being. The study of multimodal comfort would allow orienting technical
521 innovations so that the building can adapt to the human being, and not the opposite.

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