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A new affordable and quick experimental device for measuring the thermo-optical properties of translucent construction materials

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Abstract

The knowledge of thermo-optical properties of building materials is an essential factor for studying human comfort inside the building. Experiments are generally used to determine these properties. Each thermo-optical coefficients (i.e. the thermal conductivity, optical reflectance, transmittance and absorbance of the materials) can be measured separately by various devices. However, considering the new and complex materials that are emerging, for example, the translucent materials, the existing measuring instruments are finding it challenging to characterize these coefficients correctly. In this article, a new experimental device based on a spherical environment is proposed. The proposed system is capable of measuring the optical reflectance, transmittance, absorbance, and the thermal conductivity of homogeneous and innovative construction materials over a short experimental duration. The measurement protocol, the physical laws associated with the new experimental device, and the calibration tests of the measuring sensors are described. Furthermore, an application test based on a known reference, a polycarbonate construction material, is described in detail to prove the ability of the device to correctly measure these thermo-optical property coefficients. The results obtained show a relative error around of +/- 5%. Comparisons of the absolute error with the test results from the experimental device proposed by ASTM International (formerly the American Society for Testing and Materials) show that the maximum errors contributed by the new system described in this work to perform these measurements are generally acceptable. For the polycarbonate material, we obtained the following relative errors: 4.5% for the thermal conductivity, 4.7% for the optical reflectance, 0.56% for the optical transmittance and 1.78% for the optical absorbance.

Keywords:

Optical reflectance, Optical transmittance, Optical absorbance, Thermal conductivity, Low-cost device, Experimentation, Heat transfer, Polycarbonate

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¹ **1. Introduction**

² Human beings have always researched to live in comfort whatever the environment that sur-
³ rounds them. Even when it comes to shelter inside a building, this comfort pursuit has always
⁴ been the top priority. That is why interior comfort indicators have been defined by civil engineers.
⁵ Majority of these indicators are based on the knowledge of the thermo-optical properties of con-
⁶ struction materials. In fact, understanding some properties of construction materials (i.e. thermal,
⁷ acoustic, visual or even pollution-related phenomenon) is an essential factor for studying human
⁸ comfort inside the building. These properties either make life inside a building comfortable or not.
⁹ Visual comfort particularly needs quantitative indicators to judge whether a home is adequately
¹⁰ lit to avoid either darkness or visual glare. Three coefficients are directly responsible for indoor
¹¹ visual comfort: optical reflectance, optical transmittance and optical absorbance of the material.
¹² It is also necessary to have physical variables to characterize the thermal insulation in a building
¹³ to prevent the person inside from feeling too hot or cold (thermal comfort). One coefficient is
¹⁴ particularly important: the thermal conductivity of the material. These indicators are related to
¹⁵ the structure of the building materials used. Experiments on the construction materials generally
¹⁶ determine the comfort indicators. Each thermo-optical coefficient can be measured separately us-
¹⁷ ing various devices. However, considering the new and complex materials that are emerging, like
¹⁸ translucent materials among others, the existing measuring instruments find it challenging to char-
¹⁹ acterize them correctly. Moreover, the specific and high cost sensors are incapable of measuring
²⁰ the thermo-optical coefficients simultaneously.

²¹ With the discovery of new and much more sophisticated building materials (i.e., phase change
²² materials, translucent materials, thin reflective products, etc.), the measurement of thermo-optical
²³ properties, such as the optical absorbance, reflectance, transmittance, and thermal conductivity of
²⁴ such materials, is becoming increasingly complicated. Existing devices do not take into account
²⁵ certain complex phenomena related to the nature of the material. Additionally, the high costs
²⁶ associated with designing these measuring devices considerably slow the progress needed to stan-
²⁷ dardize new experimental methods capable of truly considering the heat transfer phenomena of
²⁸ such innovative materials. Accordingly, a technique that can achieve the simultaneous measurement
²⁹ of these four coefficients on a single machine must be developed. This article responds to the three
³⁰ abovementioned problems. An inexpensive experimental device has been designed to measure all
³¹ four thermophysical coefficients (i.e., transmittance, reflectance, absorptance, and thermal con-
³² ductivity) of complex construction materials. The following steps have been taken to achieve this
³³ objective:

- ³⁴ • The first step was to design the system from less expensive materials, imagine the principal
³⁵ light source (i.e., monochromatic) and choose the measurement sensors and their positions
³⁶ in the measurement system;

- 37 ● The second step was to define the laws associated with the thermal phenomena of the system,
 38 the source, and the measurement sensors used;
- 39 ● The third step was to establish a measurement protocol and then test the reliability of the
 40 system to measure the four thermo-optical coefficients of a complex construction material
 41 based on measurement standards [? ?].

42 **2. State-of-the-art measurement methods**

43 The techniques employed to measure radiative fluxes by thermal heat transfer and optical
 44 phenomena (photometric energy transfer, also known as luminous fluxes) for a given wavelength
 45 are similar. The main aspect that differentiates these techniques is the type of measurement sensor
 46 used: on one hand, a fluxmeter (generally called a radiometer) is used to measure radiative fluxes
 47 in Wm^{-2} ; and on the other hand, a luxmeter (generally called a photometer) is used to measure
 48 artificial lighting or daylighting fluxes in Cdm^{-2} (or in lux). A summary of the existing techniques
 49 capable of measuring thermal radiation in the visible and IR environment (i.e., the case of interest
 50 herein) is presented below.

51 *2.1. Measurement of reflectance (ρ)*

52 Reflection of heat is the process by which a fraction of the radiant flux incident on a surface
 53 is returned into the same hemisphere whose base forms the surface that contains the incident
 54 radiation. The general definition of reflectance (ρ) is the ratio of the reflected radiant flux (ϕ_ρ) to
 55 the incident radiant flux (ϕ_i) given by (??).

$$\rho = \frac{\phi_\rho}{\phi_i} \quad (1)$$

56 Several forms of reflectance can be measured separately: total, diffuse, specular, or coherent
 57 [?]. Some reflectances are simple to measure [? ? ? ? ?], whereas others are relatively
 58 difficult to measure [?]. The first reflectometer dates back to 1938 [? ?]. Some of the existing
 59 reflectometers are specifically dedicated to the measurement of normal incident radiation [? ?].
 60 The corresponding measurement and acquisition techniques are described in [? ? ? ?]. Many
 61 studies have been performed on angle resolved measurements based on hemispherical systems [? ?
 62 ? ? ? ? ? ? ?]. Most of these devices are designed on the basis of integrating spheres (see the
 63 state-of-the-art methods for measuring transmittance in section ?? for more details). Numerous
 64 studies on the general theory of integrating spheres have thus been conducted to enable these
 65 measurements [?]. Integrating spheres are most commonly used when taking specular and diffuse
 66 flux measurements of a material (specimen) in the visible or near-infrared spectral range [? ? ? ? ?
 67 ? ?]. Many articles have been published to thoroughly explain the instrumentation, method, and
 68 procedure related to the measurement of the reflectance of a material installed in an integrating

69 sphere [? ? ? ? ?]. The use of integrating sphere methods to measure the optical properties of
 70 solar energy materials and solar cells is illustrated in the works of A. Parretta et al. [? ? ? ? ?
 71 ? ? ?]. Thanks to these experimental devices, it is possible to measure the diffuse and specular
 72 reflectance separately, and the sum of these two reflectances constitutes the total reflectance of the
 73 material. Several sample positions in integrating spheres have been proposed in previous studies [? ?
 74 ? ? ?]. Alternatively, other forms of measurement systems have been proposed as substitutes in
 75 the literature when the configuration of the integrating sphere does not allow the reflectance to be
 76 measured; these alternatives take specular hemispherical, paraboloidal, and ellipsoidal forms [? ?
 77 ?]. The energy source used in these experiments is generally monochromatic and coherent, such as
 78 a laser (see the literature for more information on the subject [? ? ?]). Other laboratories prefer
 79 to use a goniometer to measure the BRDF (i.e. Bidirectional Reflecting Distribution Function)
 80 [?]. The methods for measuring the reflectance are described in [? ? ?]. Several shape
 81 configurations, as well as the ideal color of an integrating sphere, have been discussed in the
 82 literature [? ?]. The mixture of barium (BaSO_4) additive with the product that will be used for
 83 painting inside the sphere makes it suitable to produce a high reflectance inside the sphere. Barium
 84 is generally a white powder and can be used in optical applications because of its relatively constant
 85 spectral reflectance ranging from ultraviolet to infrared wavelength. Barium sulfate exhibits a
 86 diffuse reflectance characteristic and is resistant to high-intensity optical radiation. We obtain a
 87 solution in the form of paint by mixing barium sulphate and water. This paint can be used as a
 88 coating to diffuse reflectance plates and integrating spheres. The typical high reflectance value of
 89 barium sulphate solution is 99% in the visible spectrum between 380 nm and 780 nm. The best
 90 material used for reflectance standards is the Spectralon®, produced by Labsphere. A detailed
 91 description of the characterisation of these standards can be found in [?]. Many documents on
 92 the manufacturing, calibration, and characterization of the reflectance of a specimen are available
 93 in [? ? ?].

94 2.2. Measurement of transmittance (τ)

95 The transmission flux is used to describe the process by which incident radiant flux leaves a
 96 surface from a side other than the incident side, usually the opposite side. The transmittance (τ)
 97 is the ratio of the transmitted flux (ϕ_τ) to the incident flux (ϕ_i) given by (??).

$$\tau = \frac{\phi_\tau}{\phi_i} \quad (2)$$

98 Researchers generally employ a spectrometer to measure the transmittance coefficient [? ?].
 99 The source used in most experiments is a monochromatic light (e.g., a laser). Since 1972, many
 100 measuring devices based on this technique have been developed [? ? ? ? ?], most of which utilized
 101 an integrating sphere system ([? ? ? ?]). The reliability and robustness of these experimental
 102 devices and the measurement methods used are detailed in the literature [? ? ? ? ? ?]. For
 103 more information about the spectrometer system, see [?].

104 Currently, many laboratories are conducting joint studies to compare the different transmittance
105 measurement methods proposed in many countries.

106 *2.3. Measurement of absorptance (α)*

107 The definition of absorption is the process by which incident radiant flux is converted into
108 another form of energy, usually heat. The absorptance is the fraction of incident flux that is
109 absorbed. The absorptance (α) of an element is defined by (??):

$$\alpha = \frac{\phi_\alpha}{\phi_i} \quad (3)$$

110 The absorption of a construction material is generally not measured because the errors gener-
111 ated by the experimental devices utilized to characterize the absorptance are very high. Several
112 laboratories prefer to apply indirect measurements to obtain this physical property (i.e., to deduce
113 the value of the absorptance from measurements of other measurable thermo-optico-physical vari-
114 ables). In fact, it is easier to derive the absorptance from the law of energy conservation given by
115 equation (??).

116 *2.4. Measurement of thermal conductivity (k)*

117 The thermal conductivity (k) characterizes the amount of heat required per m^2 for 1 m of
118 a homogeneous material to obtain a temperature difference of 1° between two sides over a unit
119 of time. The thermal conductivity is an intrinsic property of a material that varies according to
120 the temperature at which the measurement is carried out. Measurements are usually conducted
121 at 300 K to facilitate the comparison of some elements with others. When the specimen is not
122 homogeneous (i.e., when it is heterogeneous but uniformly distributed), a useful value of the thermal
123 conductivity is obtained in the laboratory as a weighted average of the coefficients of each material.

124 Ref. [?] emphasized the use of only one physical parameter, the thermal conductivity, in
125 design, construction and evaluation based on the ASTM E1225 standard [?]. The methods for
126 measuring thermal properties are divided into two groups [?]: steady methods and dynamic meth-
127 ods. Dynamic methods do not need to reach a steady state and are therefore faster than steady
128 methods; however, dynamic methods are more difficult to apply. In our work, we use the steady
129 method based on a Peltier plate heat source. The ASTM E1225 standard describes a technique
130 for determining the thermal conductivity of homogeneous isotropic solids using a comparative heat
131 flux meter. This technique can determine the thermal conductivity in the approximate range from
132 0.2 to $200 \text{ Wm}^{-1}\text{K}^{-1}$ over a temperature range between 90 and 1300 K (or from -183° to 1026°)
133 but the precision of this method is not sufficient. Other methods and processes exist for measuring
134 thermophysical properties. For example, Ref. [?] described a quantitative thermography tech-
135 nique that is currently accepted as a reliable method for measuring the thermal transmittance and
136 thermal conductivity of opaque elements.

137 It has been more than fifty years since Parker et al. [?] released their original paper intro-
 138 ducing the flash technique. Since then, this photothermal experimental method has been extended
 139 worldwide and has become the most popular approach for measuring the thermal diffusivity and
 140 thermal conductivity of solids. The simplicity and efficiency of the measurement process, the accu-
 141 racy and reliability of the results, and the possible applications under a wide range of experimental
 142 conditions and materials are the main advantages of this method. The flash method has become
 143 the standard in many countries, which is evidence of its universality [?].

144 **3. Materials and method**

145 *3.1. Description of the new double integrating sphere device*

146 The initial configuration of the prototype is based on the one developed by Parretta in 2007 [?
 147] denoted as double-cavity radiometer (DCR) (see Figure ?? and ??).

148 Parretta et al. [?] developed a radiometric method suitable for measuring both the total
 149 power and the flux density profile of concentrated solar radiation. The high-flux density radiation
 150 is initially collected by the first optical cavity where it is integrated, after which it is driven
 151 and attenuated into the second optical cavity, where it is measured by a conventional radiometer
 152 operating under a stationary irradiation regime. The attenuation factor is regulated by properly
 153 selecting the aperture areas between the two spherical cavities.

154 Parretta device has been designated to characterise a concentrated solar beam. In this article,
 155 the newly developed design for measuring the optical and thermal properties of materials has taken
 156 inspiration from Parretta's device.

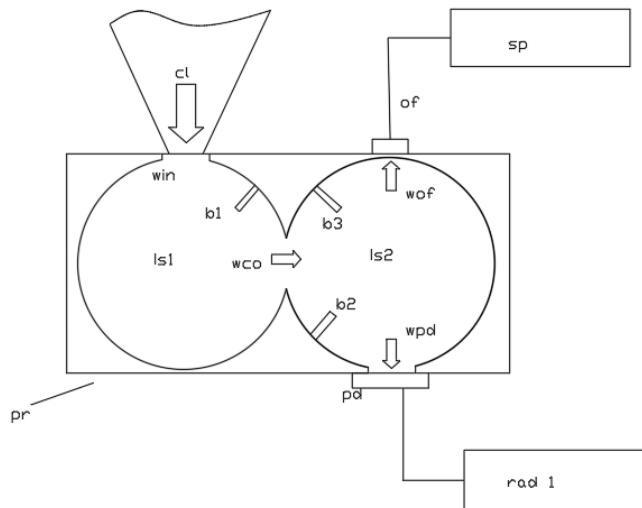


Figure 1: Schematic of the DCR (double-cavity radiometer) [?] for kind permission of A. Parretta

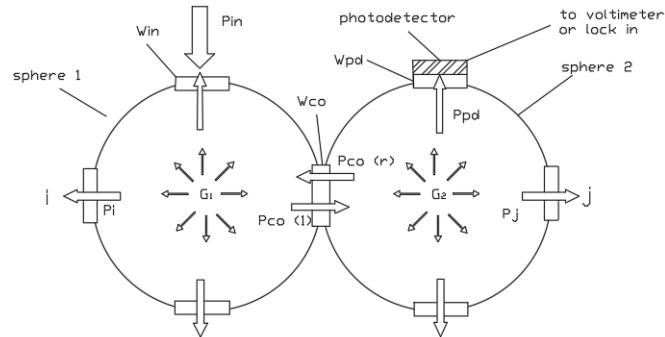


Figure 2: General radiation transfer schematic of the radiometer with two coupled integrating spheres [?] for kind permission of A. Parretta

¹⁵⁷ Taking advantage of this two-sphere configuration to transmit fluxes, other authors began to
¹⁵⁸ improve upon this idea to develop instrumentation.

¹⁵⁹ In this work, the article of Chong [?] is of special importance. An optical scanner capable
¹⁶⁰ of acquiring the flux distribution pattern of a light source on a 2D flat surface was designed and
¹⁶¹ built; for this purpose, 25 single-row photodiodes with fixed distances that can scan and acquire
¹⁶² flux distribution data in a 2D measuring plane were used. The research of Morales [?] was also
¹⁶³ of special relevance, as the locations of the detectors were reduced to 3 optimal places.

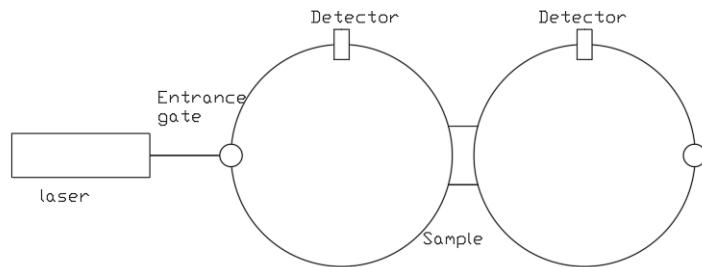


Figure 3: Integrating spheres [?]

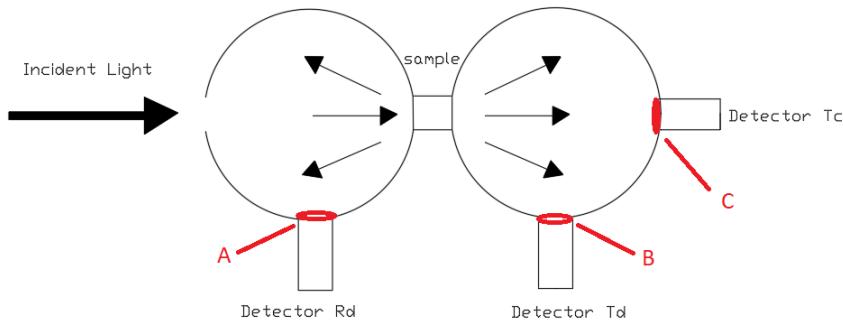


Figure 4: Double integrating sphere arrangement for the simultaneous measurement of the reflectance (one sensor in position A) and the transmittance (two sensors in position B and C) for a given specimen material (see [?])

164 An integrating sphere with a diameter of 5.08 cm and 1.27 cm ports (i.e. openings) was used
 165 in Salas Master degree in research (see [?]). This integrating sphere is made of a material
 166 commercially known as Spectralon®, which as previously discussed, is famous for having the
 167 highest diffuse reflectance of all known materials (it is capable of reflecting 99% of incident light
 168 in the range of 200-1100 nm); in addition, this material is highly Lambertian. Salas [?] also
 169 used a He-Ne laser with a power of 12 mW, but to adapt it to more materials, the power must
 170 be increased. The material should be larger to measure its thermal conductivity. Upon examining
 171 the results obtained in the above-mentioned thesis, spheres with a diameter of 30 cm and a laser
 172 with a power reaching up to 200 mW were used.

173 Having described the design of the device, the particular design of this study will be introduced
 174 as well as the dimensions and materials used.

175 3.1.1. Integrating spheres

176 To construct the integrating spheres, two spheres of 30 cm in diameter obtained from the lamp-
 177 shades of the luminaries were used. A detailed description on how to build a low cost integrating
 178 sphere from garden lamps can be found in the chapter 13 of ref. [?].

179 The problem with these spheres is that they are made of a translucent plastic material. This
 180 is evident, as they were designed to transmit fluxes (light and thermal heat) from the interior to
 181 the exterior.

182 It is therefore important to limit the exchange of heat flow between the interior of the spheres
 183 and the external environment. It is also essential that the flows conveyed inside the spheres should
 184 not be able to propagate towards the outside.

185 To solve this problem, the outer surface was painted Matt black and the inner surface Matt white
 186 so that the sphere resembles an inner Lambertian surface as much as possible. In this condition,
 187 the opacity of the sphere could also be obtained. Concerning heat transfer, a protocol for excluding
 188 radiation fluxes (i.e., exterior fluxes penetrating inside the sphere during the experiment) will be
 189 presented. For further details about this protocol, see section ??.

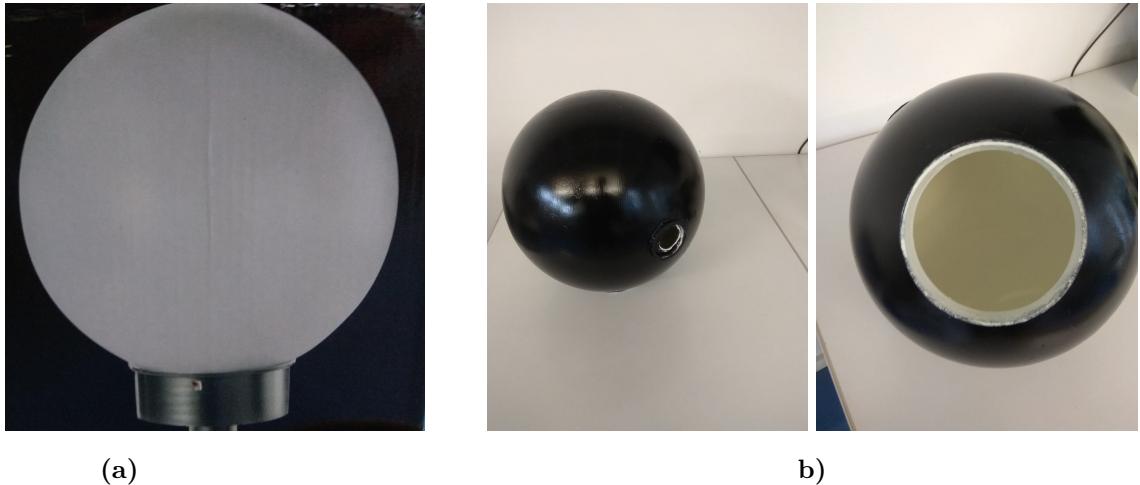


Figure 5: Sphere using in the experimentation: (a) Unpainted sphere ; (b) Painted integration spheres: white inside and black outside

190 *3.1.2. Light source*

191 For the thermal flux emission source, we selected a red monochromatic laser ($\lambda = 650\text{nm}$).The
192 output power is approximately 200 mW (Class 3B). The laser source adopts a common USB
193 interface, a polymer battery and an imported metal module (see [Figure ??,a.](#) for the form).

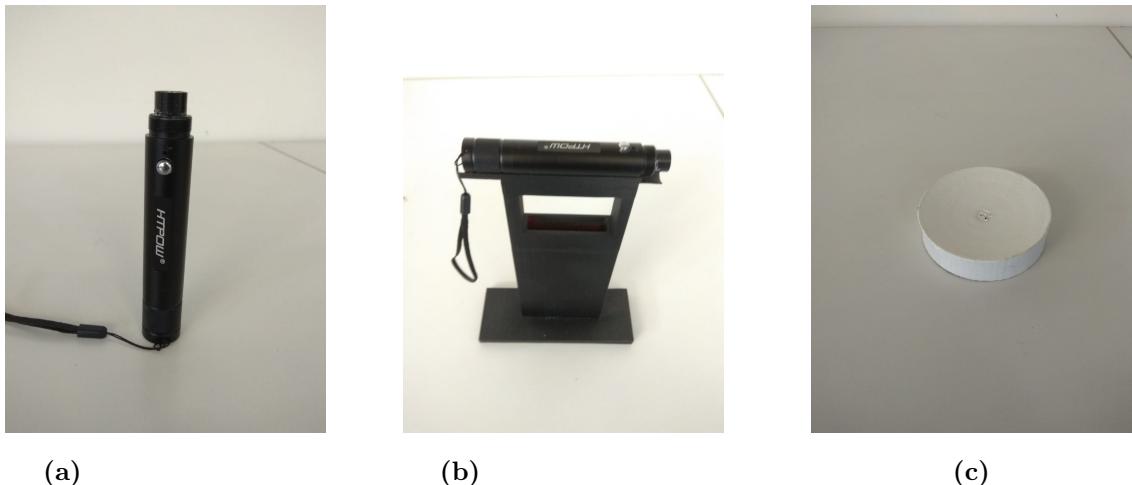


Figure 6: Supports: (a) Laser form; (b) Laser support and (c) Sphere support

194 For more information about the technical details of the laser, see appendix A.

195 *3.1.3. Supporting and finishing parts*

196 As we can see in [Figure ??,a.](#), by removing the lower part of the sphere (where the lamp is
197 originally housed), we have an opening 11.5 cm in diameter. A piece with a regular internal surface
198 has been reproduced by a 3D printer that can be inserted where the lamp used to be (see [Figure ??,c.](#)). These pieces have been painted Matt white on one side and Matt black on the other to
199 avoid transmittance fluxes.
200

201 To achieve mechanical stability, cylinders of 5.5 cm height and 11 cm diameter were reproduced
202 by means of a 3D printer and attached to the lower part of the sphere. These cylinders are
203 characterized by having a small ring with a height of 0.5 cm in their lower parts that will later be
204 used to create rails to move the spheres (see the rail in Figure ??,a.).

205 To move the laser to the correct position, a support was built (see Figure ??,b.) using a 3D
206 printer.

207 *3.1.4. Specimen support*

208 By means of the abovementioned 3D printer, five cylinders with an outer diameter of 5.5 cm
209 and an inner diameter of 4.5 cm have been manufactured with different heights depending on the
210 samples to be studied: 1 cm, 0.8 cm, 0.6 cm, 0.5 cm and 0.2 cm (see Figure ??). These cylinders
211 are white to reflect any flux that could be produced inside. The cylinders are placed to connect
212 the two spheres, allowing the beam from the laser to directly impact the specimen.



Figure 7: Specimen support

213 The diameters of the cylinders were calculated to facilitate the measurement of the thermal
214 conductivity, as we will see in section ???. The specimens used in the experiment have identical
215 diameters (i.e., approximately 3.5 cm). The diameter of the cylinder sample holder is larger
216 than that of the specimen (i.e., interior diameter equal at 3.49 cm and exterior 4.5 cm, for 0.5 cm
217 thickness). The contact position of the two spheres with the cylinder sample holder were established
218 by means of two others fixed cylinders in the exterior surfaces of the spheres (see Figure ??). The
219 height of the cylinder sample holder varies as function of the thickness of the studied sample. First,
220 the sample is joined to the cylinder sample holder, then the cylinder sample holder is tightened to
221 the fixed cylinder on the two spheres.



Figure 8: Contact between sample, cylinder sample holder, fix cylinder and opening spheres

3.1.5. Source of hot and cold radiation fluxes

To measure the thermal conductivity of a material, it is necessary to have a source of both hot and cold radiation fluxes to generate a thermal flux between the surfaces. Two Peltier plates (model TEC1-12706, see appendix B for more information) are available for this purpose. Figure ?? shows the location of the thermal conductivity k value measurements. When these plates are connected to a power supply, one of their surfaces cools down, whereas the other heats up. The dimensions of the Peltier plates are 4 cm x 4 cm, so the specimens must be smaller than this area to obtain a uniform flow; the specimen support is calculated accordingly. To dissipate heat from the plates, a heat sink is deployed (see Figure ??).

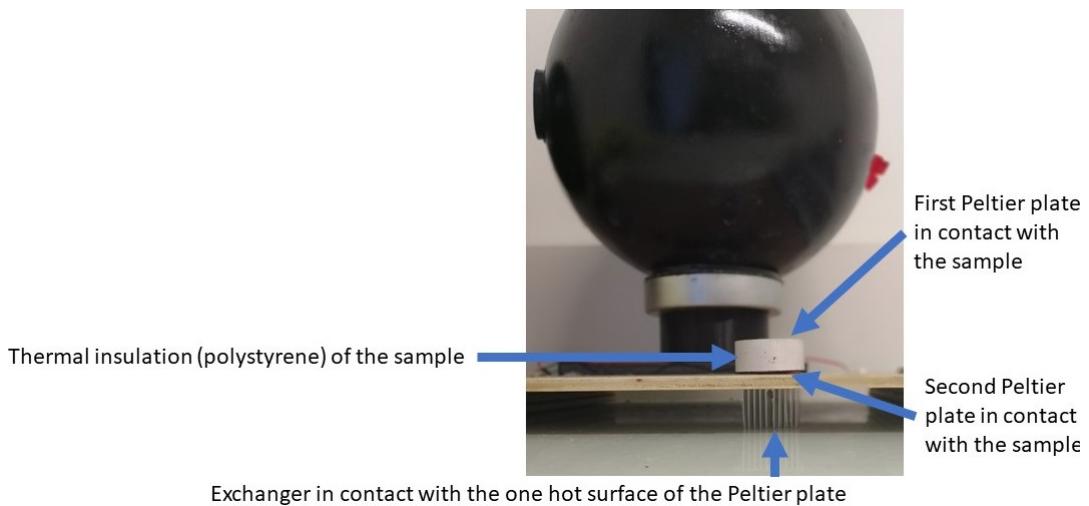


Figure 9: Thermal Conductivity measurements k location



Figure 10: Heat sink

231 3.2. Measurement of optical reflectance (ρ), transmittance (τ), and absorbance (α)

232 The integrating sphere devices have been built with materials that generate Lambertian surfaces
 233 [?], that is, surfaces that reflect radiation fluxes in a diffuse manner (see Figure ??,b.) and whose
 234 intensity distribution of the reflected flux obeys Lambert's cosine law, given by the following
 235 relationship:

$$I_r(\theta) = I_0 \cos\theta \quad (4)$$

236 where I_r is the reflected radiant intensity expressed in W/sr, I_0 is the radiant intensity of the
 237 radiation reflected at $\theta_0 = 0^\circ$ and θ is the angle measured from the normal. Figure ??,a. shows
 238 the radiant intensity distribution generated by a Lambertian surface. Another way of defining a
 239 Lambertian surface is to say that its radiance L in $Wsr^{-1}m^{-2}$ is constant, that is independent on
 240 the observation angle θ .

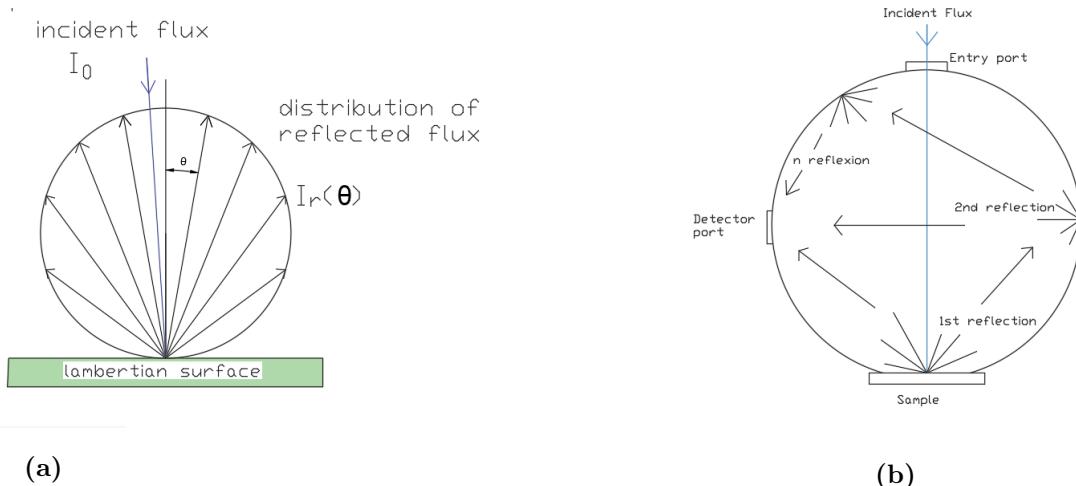


Figure 11: Reflection phenomena within the sphere: (a) Model of reflected flux from a Lambertian surface / (b) Multiple reflections in an integrating sphere

241 The standards of diffuse reflectance, like those realised by BaSO₄ coating or by Spectralon®
 242 (Labsphere) do not behave as perfect Lambertian diffusers. To better understand how they differ

243 from an ideal Lambertian diffuser, see the work of Parretta [?].

244 Assuming that the integrating sphere has Lambertian walls, the incident flux to the sphere
 245 is reflected several times such that the incident flux is homogeneously distributed over the entire
 246 surface of the sphere (an ideal integrating sphere reflects the incident flux entirely; spheres of higher
 247 quality reflect approximately 99% of the flux in relation to the design wavelength range). Energy
 248 irradiance is defined as the radiant flux per unit of irradiated area (see Equation (??)).

$$E = \frac{\Phi}{A} \quad (5)$$

249 where ϕ is the radiant flux whose unit is the Watt (W) and A is the surface irradiated by the
 250 radiant flux in square meters (m^2). Therefore, the irradiance has power units on the surface units.

251 The total flux incident on the surface of the integrating sphere can be calculated in a very
 252 simple way because the irradiance is homogeneous. The irradiance on a detector placed in one of
 253 the openings of the sphere will be equal to the irradiance on the whole integrating sphere:

$$E_{sphere} = E_{detector} = \frac{\phi_{detector}}{A_{detector}} \quad (6)$$

254 and thus:

$$\phi_{sphere} = \phi_{detector} \frac{A_{sphere}}{A_{detector}} \quad (7)$$

255 where ϕ_{sphere} is the flux contained within the sphere, $\phi_{detector}$ is the flux in the detector, A_{sphere}
 256 and $A_{detector}$ are the areas of the sphere and the detector, respectively, where $A_{sphere} = 2\pi R^2$.

257 The flux contained in the sphere will be greater than the incident flux. The radiant flux
 258 contained within the sphere is higher than the incident flux because the incident flux undergoes
 259 multiple reflections within the sphere, which is more obvious if the contributions from each reflection
 260 are summed up. This fact is made explicit by the introduction of the concept of "sphere multiplier"
 261 [?].

262 For the first reflection, the reflected flux is:

$$\phi_1 = \phi_i \rho \quad (8)$$

263 Where ϕ_i is the incident radiant flux and ρ is the reflectance of the sample. The quantity f as
 264 the fraction of ports area is expressed as:

$$f = \frac{A_{doorSphere} + A_{doorDetector}}{A_{sphere}} \quad (9)$$

265 Here, $A_{doorSphere}$ is the entry port area, $A_{doorDetector}$ is the detector port area, and A_{sphere} is
 266 the surface of the integrating sphere. In the second reflection, the reflected flux is:

$$\phi_2 = \phi_i \rho \rho_w (1 - f) \quad (10)$$

267 Where ρ_w is the reflectance of the internal wall of the sphere. The reflectance of the detector
 268 was assumed negligible, whereas the reflectance of the entry port is naturally zero. The sample
 269 area was also neglected. The third reflection presents:

$$\phi_3 = \phi_i \rho \rho_w^2 (1 - f)^2 \quad (11)$$

270 and so on until the n-th reflection, whose contribution is:

$$\phi_n = \phi_i \rho \rho_w^{n-1} (1 - f)^{n-1} \quad (12)$$

By adding all these contributions, the flux integrated by the sphere after n reflections becomes:

$$\phi_{sphere}^n = \phi_i \rho + \phi_i \rho \rho_w (1 - f) + \phi_i \rho \rho_w^2 (1 - f)^2 + \dots + \phi_i \rho \rho_w^{n-1} (1 - f)^{n-1} = \phi_i \rho \sum_{k=0}^{n-1} \rho_w^k (1 - f)^k \quad (13)$$

271 By stretching n to infinity, we finally have:

$$\phi_{sphere} = \phi_i \frac{\rho}{1 - \rho_w (1 - f)} \quad (14)$$

Now, by erasing the reflectance in terms of the flux, the following can be obtained:

$$\rho = \frac{\phi_{sphere}}{\phi_i} [1 - \rho_w (1 - f)] \quad (15)$$

For the flux passing through the sample to the second integrating sphere (see Figure ??), we have:

$$\phi_{sphere2} = \phi_\tau \frac{\rho}{1 - \rho_w (1 - f)} \quad (16)$$

272 Where $\phi_{sphere2}$ is the radiant flux contained within the second integrating sphere and ϕ_τ is the
 273 flux transmitted by the sample. From Eq.?? we obtain from the transmitted flux:

$$\phi_\tau = \phi_{sphere2} \frac{1 - \rho_w (1 - f)}{\rho} \quad (17)$$

274 Assuming again that the irradiance is homogenous at any point of the second integrating sphere,
 275 the total flux rate contained in the sphere can be written as a function of the flux rate on the detector
 276 mounted therein:

$$\phi_{sphere2} = \phi_{detector2} \frac{A_{sphere2}}{A_{detector2}} \quad (18)$$

277 By matching the two previous equations, the following is obtained:

$$\phi_\tau = \phi_{detector2} \frac{A_{sphere2}}{A_{detector2}} \frac{1 - \rho_w (1 - f)}{\rho} \quad (19)$$

278 When some of the photons incident on the sample are not absorbed or reflected by the material,
 279 they will pass through the sample and follow the same direction of propagation as the incident

beam if allowed to propagate freely. The radiant flux composed of these photons is called the coherent flux, and we represent it with $\phi_{\tau coherent}$.

With incident fluxes, it is simple to obtain the diffuse and coherent transmittances. Finding these transmittances is achieved by the following equations:

$$\tau_{diffuse} = \frac{\phi_{\tau}}{\phi_i} \quad (20)$$

$$\tau_{coherent} = \frac{\phi_{\tau coherent}}{\phi_i} \quad (21)$$

where $\tau_{diffuse}$ is the diffuse transmission and $\tau_{coherent}$ is the coherent transmission.

Knowing the reflectance and transmittance, it is possible, thanks to the energy conservation argument, to know the absorptance of the medium. Thus, the sum of the transmitted, reflected and absorbed fluxes must be equal to the incident flux and is given by:

$$\phi_i = \phi_{reflected} + \phi_{\tau} + \phi_{\tau coherent} + \phi_{\alpha} \quad (22)$$

By dividing everything by ϕ_i , we have:

$$1 = \rho + \tau_{diffuse} + \tau_{coherent} + \alpha \quad (23)$$

where α is the absorbtance of the medium. From this equation, it is possible to determine the absorption coefficient and the extinction coefficient of the material studied. Another technique for measuring the extinction coefficient of a material is ellipsometry. This technique allows the use of a model to determine the complex refractive index of a material as a function of its reflection coefficients and the phase change of the flux reflected from the surface of the material.

294

295 3.3. Fourier's law under steady-state conditions to determine k

The techniques for measuring the thermal conductivity of a material differ depending on the method employed to measure the surface temperature of the material and the type of contact (fluid-solid or solid-solid) selected for the surface measurement. Heat transfer is defined as the energy interaction caused solely by a temperature difference. Heat fluxes are a function of temperature differences, thermophysical properties, dimensions and geometries, time, and fluid flow. Heat transfer processes are classified into conduction, convection and radiation. Conduction is the transfer of energy from the most energetic particles to less energetic particles within a substance (solid, liquid or gas). In the presence of a temperature gradient, heat will flow from a high-temperature region to a low-temperature region. The heat flux transferred by conduction q_c (Wm^{-2}) is given by Fourier's law in Equation ??.

$$q_c = -k.gradT = -k \frac{T_2 - T_1}{L} \quad (24)$$

306 where the temperatures T_2 and T_1 are measured at a distance L. The k parameter, expressed in
307 $Wm^{-1}K^{-1}$, is a constant and represents a heat transport property known as thermal conductivity.
308 Thermal conductivity is an inherent characteristic of a material and indicates its heat conduction
309 capacity. A high thermal conductivity indicates that the material is a good conductor of heat,
310 while a low thermal conductivity indicates that the material is a thermal insulator, i.e., a poor
311 heat conductor.

312 *3.4. Experimentation and Metrology*

313 *3.4.1. Flux sensors used in the experimentation and calibration tests*

314 Measuring heat flow from conventional sensors on a curved surface (inside an integrating sphere)
315 is very complicated. Therefore, an original solution is proposed: to install microscopic photodiodes
316 capable of assuming the same role as a conventional fluxmeter. For this reason, 3 silicon PIN
317 photodiodes (see Figure ??) have been used as thermal flux detectors. To use these sensors, they
318 first had to be calibrated with a reference fluxmeter; additionally, by means of the laser employed
319 in the experiment, it is possible to convert mV to Wm^{-2} .

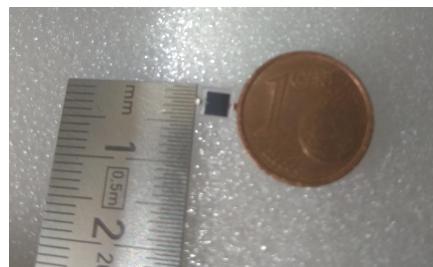


Figure 12: Silicon PIN photodiode

320 To calibrate the silicone PINs, a fluxmeter (calibrated using the same reference sensor) is used.
321 The fluxmeter and two PINs were first placed inside a box measuring 30 cm high. The inside was
322 lined with a white paper to make it somewhat similar to our model. The laser was placed in the
323 upper part, and the box was closed. The laser was left on, and in the last two and a half minutes,
324 the intensity of the laser dropped from 200 mW to 0 mW; we used this range for our calibration
325 (see Figure ??).

326 A calibration factor of 2.671 was obtained between the reference fluxmeter and the PIN for
327 the range between 0 and 127 mW (see Figure ??). The maximum value of the photodiode cor-
328 responded to 360 mV (approximately 127 mW in the fluxmeter), and the minimum value was 60
329 mV (corresponding to the offset of the sensor).

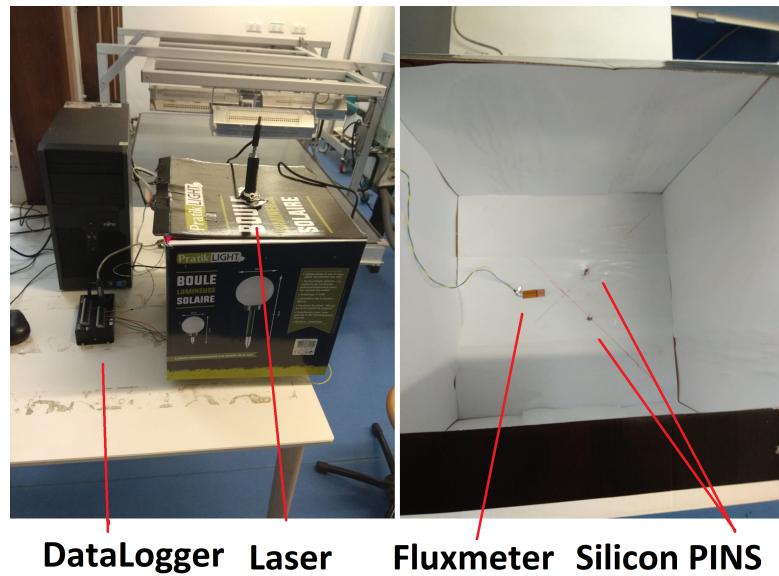


Figure 13: Calibration test of a silicon PIN

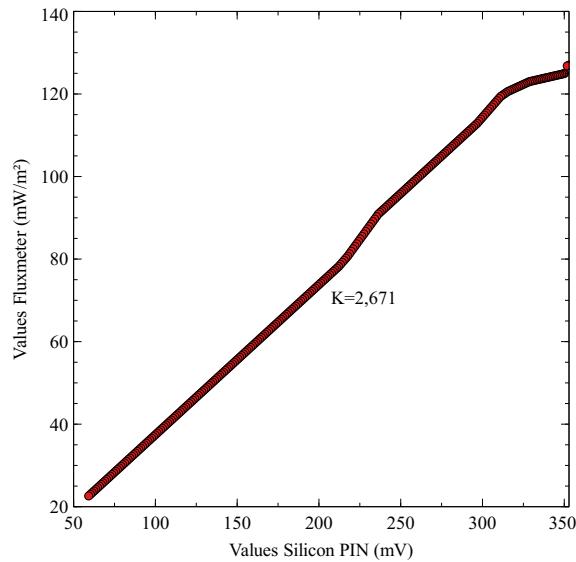


Figure 14: Comparison of the values between the fluxmeter (in mW/m^2) and the photodiode PIN (in mV)

330 A value of 0 is not reached in this calibration because the photodiode is very sensitive, and
 331 when the laser is turned off, the PIN is able to sense the external radiation flux and the internal
 332 temperature.

333 *3.4.2. Temperature sensors : calibrating the type K thermocouples*

334 To calibrate the thermocouples, a EUROLEC thermostat (model CECS3) (see Appendix C for
 335 more information) was used; the thermocouples were calibrated before being used to measure the
 336 temperature (See Figure ?? for the data acquisition environment and Figure ?? for the results of

337 calibrations tests).



Figure 15: Data acquisition for the calibration tests

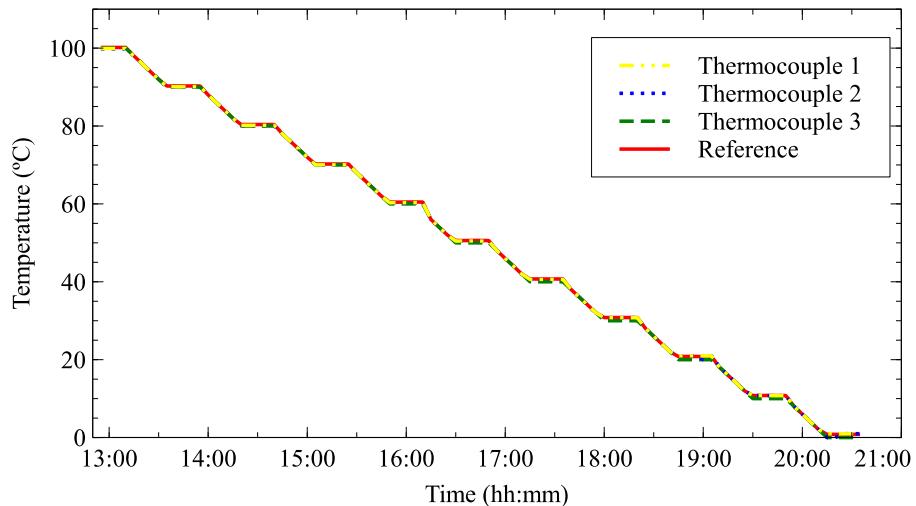


Figure 16: Calibration of the thermocouples

338 The two thermocouples used to conduct the thermal conductivity experiments have relative
339 errors lower than 0.9%.

340 3.4.3. Heat flux source: Peltier plate material

341 The next step is to position the specimen on top of one of the Peltier plates without taking it
342 out of the support (attaching a type K thermocouple on both plates) and coating the specimen
343 with a polystyrene ring to achieve greater insulation. Figure ??,a. and Figure ??,b.,c.,d. show the
344 positions of the type K thermocouples and the two Peltier plates used in the experiments and the
345 thermal insulation around the specimen composed of the construction material.

346 The other Peltier plate is placed on top to generate a heat flux, and both plates are connected
347 to generators with different voltages and intensities depending on the specimen (see Figure ??).

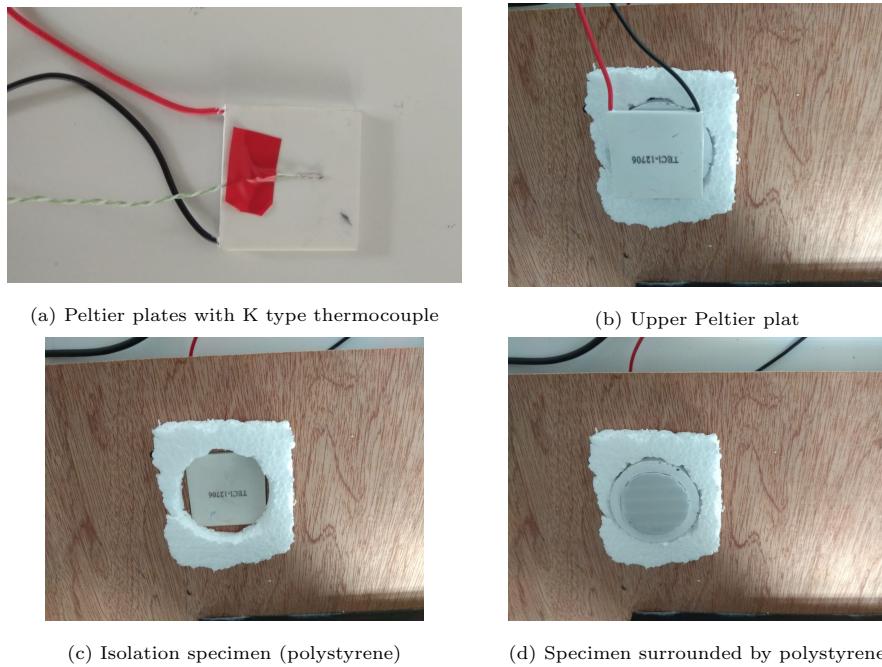


Figure 17: Thermal conductivity measurements

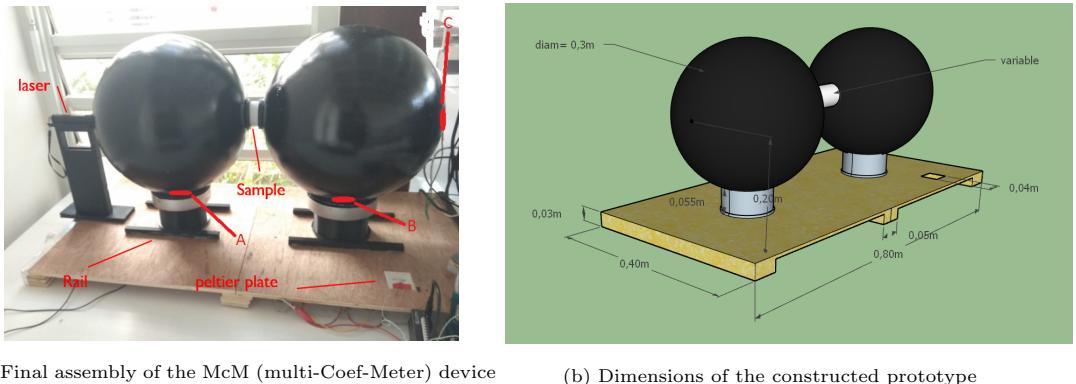


Figure 18: The Multi-Coef-meter (i.e., McM device)

348 3.5. Description of the new measuring device: Multi-Coef-Meter (i.e. McM)

349 Finally, Figure ?? shows the prototype McM proposed in this work for measuring the 4 ther-
 350 mophysical properties of building materials. In this image, the sensors (i.e., photodiode PINs)
 351 positioned at points A, B and C (See Figure ?? for the sensors positions) measure the reflected flux
 352 ($\phi_{reflected}$), the diffuse transmittance flux (ϕ_T), and the coherent transmittance flux ($\phi_{Tcoherent}$)
 353 of the studied specimen, respectively. The positions of the photodiode PIN sensors (i.e., A, B and
 354 C) are shown in Figure ??,a. The dimension of the McM device are reported in Figure ??,b.

355 The techniques for measuring the thermal conductivity of material are different depending on
 356 the method of measuring the surface temperature of the material and the type of contact selected
 357 for the surface measurement (fluid-solid or solid-solid). In this article, the technique followed is
 358 the transient plane source (TPS). See the work of ASTM organisation [?] and Manetti [?] for

359 more information's about the technique for the measurements.

360 Let D and F (see Figure ??) be two Peltier plates with known properties (see Appendix B).
361 Let E be a specimen for which we are trying to determine the thermal conductivity k_x knowing its
362 surface A_x and its thickness d_x . The measurement technique consists of sandwiching the sample
363 E to be studied (see Figure ??) using the other two Peltier plates D (hot source with temperature
364 T_1 for example) and F (constant cold source with temperature T_2 for example) with constant flux.
365 To maintain the constant flux at the surfaces of each Peltier plates in contact with the sample,
366 constant temperature is needed, therefore, constant power. This constant flux passes through the
367 specimen (see Figure ??). The constant flux is used to deduce the value of the thermal conductivity
368 of specimen E from the following relationship (conservation of the flux by the Fourier law in the
369 steady state with the conduction heat exchange):

$$\phi = k_x A_x \frac{T_2 - T_1}{d_x} \quad (25)$$

370 The relation (??) is used to determine the thermal conductivity value k .

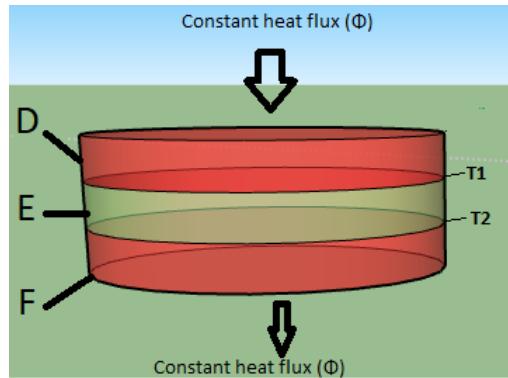


Figure 19: TPS (Transient Plane Source) method illustration

371 The specimen is insulated by polystyrene to neglect the influence of the cross-flow (i.e. horizontal-
372 flux) in regards to the downward flux (vertical or descendant flux) of the measurement.

373 **4. Applications to polycarbonate and other construction materials (validation of the
374 new device)**

375 *4.1. Specimen tests*

376 To confirm the reliability and functionality of the proposed McM device, we compared three
377 different types of homogeneous samples, as shown in Figure ??, whose thermal properties we already
378 know: iron (solid grey color), wood (red color) and polycarbonate (white color). This comparison
379 was also intended to classify polycarbonate from among two types of building materials: one has
380 intermediate conductive properties (wood) and another that efficiently conducts heat (iron).

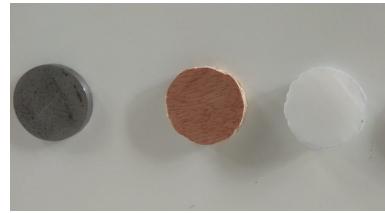


Figure 20: Specimen tests: iron, wood, polycarbonate

381 The exact dimensions and thermo-optico-physical properties of each specimen test are given in
 382 Tables ??, ?? and ???. The only fixed dimension to respect during the experiment in the McM
 383 (i.e. Multi-Coef-Meter device) is the diameter of the sample (i.e. 0.04 m). As far as thickness is
 384 concerned, it is possible to vary from 0 to 0.20 m (i.e., by moving the two spheres of the device
 385 apart).

386 *4.2. Conditions of the experiments*

387 Each sample was placed in the specimen support with the sizes described in ?? and then placed
 388 between the two spheres and in the path of the laser; then, measurements of the silicon PIN (which
 389 we placed in the position shown in Figure ?? before and after actuating the laser) were taken to
 390 determine how much radiant flux of the laser was transmitted, absorbed and reflected. For the
 391 different samples, the values reported in Table ?? - ?? were obtained and compared with those
 392 of the same material from the literature to calculate the relative error. At least three repeatable
 393 measurements were performed for each sample, and the measurement values were averaged.

394 Due to the small dimensions of the specimens used in the experiments, steady-state condi-
 395 tions are observed for two minutes. The measurement conditions are applied in two steps. First
 396 measurement is taken prior to switching on the laser (to take into account thermal effects due to
 397 the environment outside the two spheres influencing the sensors). Then, a second measurement is
 398 made (a few minutes later) when the laser is running. This measurement represents the value of
 399 the global flux inside and outside the spheres that the sensors can identify. The difference between
 400 these two values gives us the radiant flux from the laser alone (i.e., a measurement without any
 401 thermal influence from the environment outside the two spheres). The radiant flux measurement
 402 conditions of each specimen are given in Tables ??, ?? and ??.

Material : Wood	Sensor positions (see Figure ??,a.)		
Measurements (in mWm^{-2})	A	B	C
Without laser (i)	1,87	2,99	0
With laser (ii)	117,93	3,02	0
Real fluxes = (ii)-(i)	116,06	0,02	0

Table 1: Values obtained by silicon PINn (sensors) for the wood specimen

Material : Iron	Sensor positions (see Figure ??,a.)		
Measurements (in mWm^{-2})	A	B	C
Without laser (i)	0	2,99	0
With laser (ii)	112,32	4,49	0
Real fluxes = (ii)-(i)	112,32	1,49	0

Table 2: Values obtained by silicon PINs (sensors) for the iron specimen

Material : Polycarbonate	Sensor positions (see Figure ??,a.)		
Measurements (in mWm^{-2})	A	B	C
Without laser (i)	4,07	4,08	0,75
With laser (ii)	86,86	72,63	11,23
Real fluxes = (ii)-(i)	82,78	68,51	10,48

Table 3: Values obtained by silicon PINs (sensors) for the polycarbonate specimen

403 For measurements of the thermal conductivity of the specimen, the initial conditions needed to
 404 obtain the thermal steady-state condition depend strongly on the material to be studied. Tables ??
 405 through ?? summarize the measurement values obtained for each sample material when this steady
 406 state is reached. The heat flux created by the Peltier plates that makes it possible to determine this
 407 constant varies according to the specimen studied. The wood (Table ??) does not easily allow the
 408 flux to pass through the specimen (i.e., the wood provides good thermal insulation) unlike the iron
 409 specimen (see Table ??), which is an excellent thermal conductor and therefore allows the heat flux
 410 to pass through the specimen quickly. Concerning the translucent material (i.e., the polycarbonate
 411 specimen), the heat flux through the material is similar to that through the wood specimen (see
 412 Tables ?? and ??). The Polycarbonate can therefore be used for isolated construction building.

Polycarbonate					
Voltage (V)	Intensity (A)	Thickness (m)	Area (m^2)	ΔT	Flux (W)
7	0,565	0,006	0,00125664	85,5	3,955

Table 4: Polycarbonate flux and measurement data

wood					
Voltage (V)	Intensity (A)	Thickness (m)	Area (m^2)	ΔT	Flux (W)
6,7	0,565	0,005	0,00125664	94	3,7855

Table 5: Wood flux and measurement data

Iron					
Voltage (V)	Intensity (A)	Thickness (m)	Area (m^2)	ΔT	Flux (W)
12	1,8	0,007	0,00125664	1,55	21,6

Table 6: Iron flux and measurement data

413 *4.3. Comparisons between the reference values and measurements*

414 The total error due to the experimental device does not exceed 2%, which comprises 1% relative
 415 error contributed by all the measuring sensors and 1% relative error due to the concept of the system
 416 (i.e., the constructed McM system: the colors used, the position of the laser, the form of the system
 417 and the characteristics of the material used). For this reason, +/- 2% error is introduced for all the
 418 relative errors between the reference values and the experimental values during the comparison.
 419 Table ?? reviews these comparisons.

		K ($W m^{-1} K^{-1}$)	ρ (-)	τ (-)	α (-)
Iron	Reference	79,5	0,65	0	0,35
	Experimental (McM)	77,63	0,63	0	0,37
	Relative error (in %)	2,35	3,07	-	5,71
Wood	Reference	0,17	0,15	0	0,85
	Experimental (MCM)	0,16	0,16	0	0,84
	Relative error (in %)	5,88	1,42	-	1,23
Polycarbonate	Reference	0,22	0,12	0,82	0,06
	Experimental (McM)	0,23	0,11	0,82	0,061
	Relative error (in %)	4,54	4,75	0,56	-1,78

Table 7: Table of comparisons between the test measurements and reference values

420 The properties of the iron sample used as a reference have been simulated on the basis of
 421 the knowledge of the materials provided by the manufacturer: see https://refractiveindex.info/?shelf=other&book=Ni-Fe&page=Tikuisis_bare150nm concerning reflectance and transmittance, then <https://thermttest.com/materials-database#iron> concerning thermal conduc-

424 tivity (selection iron grey Cast Pearlitic (4.12C)).

425

426 The properties characterizing the wood sample used as a reference sample are given by the man-
427 ufacturer Polytec (choose the reference Notaio Walnut in the list to have the value of the reflectance.
428 The wood being opaque, does not allow light to pass through, so its transmittance is zero. We then
429 analytically deduced the value of its optical absorbance from the formula $\alpha = 1 - \rho$. Regarding the
430 value of the thermal conductivity, a reference is given by the manufacturers on the following site
431 (take teak wood (across grain:): <https://thermttest.com/materials-database#wood>.

432

433 The properties used to characterize the reference polycarbonate are those defined in the tech-
434 nical document (with the conformity test) of the following manufacturer (see page 6 for thermal
435 conductivity and page 7 for the values of reflectance and transmittance for a 6 mm panel of
436 model 2RS/1.3): https://www.sunclear.fr/sites/default/files/Termoclear_Plus_AT_6_14_2192_v1_07_2020.pdf. The value of the reference optical absorbance is deduced analytically
437 from the knowledge of reflectance and transmittance by $\alpha = 1 - \rho - \tau$.

439

440 Our first remark is that ASTM E1225 [?] stipulates that a device measuring the thermal
441 conductivity of a building material and contributing a relative error around 5% can be considered
442 reliable. Concerning the reflectance, transmittance and absorptance, ASTM E903 [?] affirms that
443 measurements of these coefficients having relative errors of less than 4% are acceptable. The McM
444 device contributes relative errors around the ASTM values (i.e. around 5%) recommendations.
445 Nevertheless, the CIE [?] illustrates the difficulty of measuring these thermal properties, and
446 thus, the proposed devices sometimes contributes a relative measurement error of more than 5%.

447 Our second remark is that the experimental device is able to not only simultaneously character-
448 ize the thermo-optic-physical coefficients (i.e., absorbance, reflectance, and transmittance) of highly
449 variable homogeneous materials and, more particularly, translucent materials (i.e., polycarbonate)
450 but also instantly measure the value of the thermal conductivity of the same material.

451 Our third remark is that overall, the measurement errors of the proposed instrument are higher
452 for the translucent material (polycarbonate) and lower for other more insulating materials (i.e. for
453 example the wood). In general, the errors for polycarbonate are higher than the opaque materials
454 (i.e. wood and iron).

455 Figure ?? illustrates the evolution of the thermal properties of each specimen.

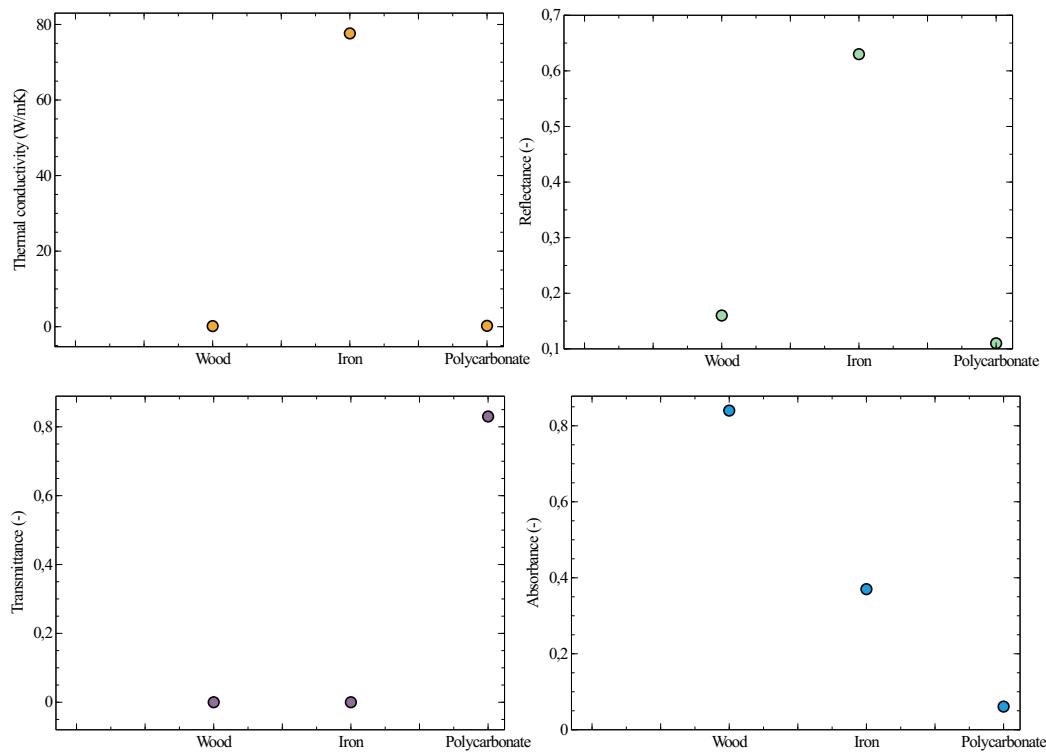


Figure 21: Thermophysical properties of the specimens studied: wood, iron and polycarbonate

Concerning the study of translucent materials, it is clear that polycarbonate can be used as thermal insulation in buildings because it has a similar thermal conductivity coefficient to that of wood (see Figure ??). Therefore, polycarbonate has an insufficient capacity to transmit the heat that passes through it due to its low thermal conductivity (see Figure ??). This behavior is not likely to create condensation problems in the rooms of such buildings because it has a very low absorption coefficient (see Figure ??). The polycarbonate used in this experiment reflects very little heat (see Figure ??) due to its light grey color. If necessary, a manufacturer could use polycarbonate with a much darker color to reflect greater amounts of heat flux and thus further reduce the heat flowing through it. This type of material is ideal for buildings in humid tropical weather zones. Polycarbonate could be used, for example, to heat a closed veranda in winter. This material can also considerably reduce the excessive moisture content on walls and ceilings.

5. Conclusions and perspectives

Scientific progress in the field of civil engineering has led to the emergence of new, peculiar thermal and optical characteristics in building materials. Currently, this is mainly the case for translucent materials. This complexity leads us to reflect on new measurement procedures that respect standard norms and perfectly satisfy the characterization of these innovated materials. This paper presents a new measuring device to simultaneously determine the values of optical and thermal coefficients (i.e., the thermal conductivity, reflectance, transmittance and absorptance

474 coefficients) of complex materials. The proposed device is relatively simple and economical; it is
475 based on the theory of wave propagation in a spherical environment called an integrating sphere
476 (a closed system). The energy source used to avoid Lambertian phenomena of flux diffusion is a
477 monochromatic laser pointer of approximately 650 nm. The idea of a thermal flux measurement
478 sensor based on a microphotovoltaic cell is also discussed to meet the constraints related to the
479 positions of the measurement sensors inside the hollow sphere constituting of our experimental
480 device. These sensors have been specially calibrated through comparison with a reference fluxmeter
481 exposed to the same monochromatic source (laser). In this research, we propose a new protocol
482 adapted to this measurement system. The experimental measurement results obtained show that
483 the innovative device has an overall error of around 5% (which is acceptable for a machine that
484 measures heat fluxes according to the ASTM standard recommendation) and has a maximum
485 energy source power reaching up to 200 mW.

486 Since the beginning of the 20th century, research has been carried out to develop an instrument
487 capable of simultaneously measuring the transmittance, absorptivity and reflectance of a material
488 regardless of whether it is opaque, transparent or translucent. This process, in addition to being
489 very challenging mathematically, has been very expensive because when it has been implemented
490 experimentally, two integrating spheres and high-precision detectors were used, but they were
491 excessively expensive; besides, the spheres and detectors were very laborious to manufacture.

492 Another disadvantage that arose was that the instrumentation allowed the measurement of the
493 thermophysical properties of materials with certain dimensions only.

494 In the present study, these disadvantages are alleviated through the use of low-cost materials
495 as well as a novel method of measuring the properties of materials with different dimensions.

496 Another advantage that we achieve with this configuration is the possibility of measuring the
497 conductivity and diffusivity by simply making a few small adjustments.

498 In the future, it would be interesting to modify the experimental setup to study the thermal
499 diffusivity of complex materials.

500 Similarly, a study should be conducted to propose a low-cost and straightforward experimental
501 system capable of measuring all the thermophysical properties of a liquid or gaseous substance
502 simultaneously.

503 **Acknowledgement**

504 The authors would like to thank Professor Antonio Parretta (University of Ferrara in Italy) for his
505 valuable advice on this work as well as the European project ERASMUS+ for the financial support
506 of this research project through internship grants.

Appendix A

Laser features	
Wavelength	650 nm
Output power	200 mW
Useful life	5000-8000 hours
Point size	<18 mm of 10 m
USB interface	Andrews 2.0
Housing material	aeronautical aluminum
Surface treatment	oxidation treatment, rubber painting
Electronic protection	PCB protection, reverse polarity protection
Waterproofing standard	IPX4
Operating current	<320 mA
Operating voltage	DC=3.7 V
Operating temperature	5°C - 50°
Net weight	80 g
Dimensions	20 x 140 mm

Table A. Laser features

Appendix B

Performance specifications TEC1-12706		
Hot-side temperature (°C)	25°C	50°C
Qmax (Watts)	50	57
Delta Tmax (°C)	66	75
I _{max} (Amps)	6.4	6.4
V _{max} (Volts)	14.4	16.4
Module resistance (Ohms)	1.98	2.30
Dimensions	40 mm X 40 mm X 3.8 mm	

Table B. Performance specifications TEC1-12706

509 **Appendix C**

510 **Properties CSEC3**

511 The CSEC Series encompasses an economic range of temperature calibration sources and is available
512 in three versions, each of which provides a highly accurate, very stable temperature output that is
513 ideal for the calibration of probe thermometers as well as general-purpose temperature measuring
514 instruments.

- 515 • To use with probe thermometers
- 516 • Standard front 7-hole probe insert
- 517 • PID controller with platinum film sensor
- 518 • High accuracy and stable temperature source
- 519 • User-adjustable temperature
- 520 • User-adjustable °C or °F display

521 The CSEC3 Series covers a temperature range from -30.0°C below the ambient temperature
522 (min -10°C) to +105.0°C.