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Characterization of the optical properties of a PCM glazing system

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Abstract

The optical characteristics of an advanced glazing system are presented in this paper. The investigated glazing system is based on the incorporation of a paraffin-based Phase Change Material (PCM) into a transparent component, made of two extra-clear glass panes and a cavity where the PCM layer is placed.
Due to the highly scattering property of the system (when the PCM is in solid state), the use of a large integrating sphere equipment (75 cm diameter) is necessary to obtain reliable results.
The spectral transmission, reflection and absorption coefficients of the PCM glazing system are measured between 400 and 2000 nanometers, and the integrated values are calculated according to the relevant standards. The optical properties are determined with a maximum relative error of 4% (on the sum of the transmission, reflection and absorption coefficients), when the PCM layer is either in complete solid state or liquid state. The average error for all the optical properties is 2%.
Different thicknesses of the PCM layer are used in order to assess the dependency of the optical properties on the PCM layer thickness. The angular dependency is also investigated for beam angle up to 45 deg.

Keywords: Optical properties; integrating sphere measurements; phase change material; Advanced glazing systems

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Nomenclature

α	absorptance	[-]
β	beam angle	[deg]
δ	PCM layer thickness	[mm]
Δh	latent heat of fusion	[kJ/kg]
λ	wavelength	[nm]
ρ	reflectance	[-]
τ	transmittance	[-]
Subscript		
e	solar	[-]
l	visible	[-]
nir	near infra-red	[-]

1. Introduction

The adoption of Phase Change Material (PCM) in the building industry is gaining popularity [1–3] and different applications are presently under development, or even available in the market. A particular technology, which has been investigated since the early Nineties, concerns the incorporation of a PCM layer into a transparent system. In fact, because of the ability of certain PCMs to transmit (part of) the visible spectrum of the solar radiation, it is possible to combine a PCM layer with transparent/translucent layers [4–6], in order to create a building component that exhibits a (relatively) high thermal inertia, together with transparency in the visible spectrum. Therefore, the aim of this class of technology is to transform the façade into a thermal/solar energy storage element, by increasing its thermal inertia, while still allowing the exploitation of day-lighting.

While the first experimental analyses on such a class of technology were mostly aimed at assessing the efficiency in cold-dominated climates [4,6], a more recent experimental campaign [7] was carried out in Italy, in a warmer climate (Torino: Lat. 45,07N, Long. 7,43E, - Cfa: Humid subtropical climate, according to Köppen climate classification [8]). The aim of this activity was to obtain reliable experimental data on the thermo-physical behavior of a simple PCM glazing prototype in warmer climate, where avoidance of cooling loads due to solar irradiation, especially in office buildings and both in summer and in winter, plays a crucial role in energy saving potential during building operation.

The tested prototype was a simple Double Glazed Unit (named DGU_PCM), made of two clear glass panes, which cavity (15mm) was completely filled with a PCM. The PCM incorporated into the prototype was a commercial grade paraffin wax, purchased from a German manufacturer [9]. The nominal melting temperature of the selected paraffin wax was 35 °C (with a phase change range of about 15 °C), and the nominal latent heat of fusion Δh was about 160 kJ/kg.

The experimental campaign was carried out on a test cell facility [10] during about one year. A reference DGU without PCM layer was also monitored, in order to provide a reference. Both the glazing technologies were south-exposed and the indoor air temperature of the test cell was maintained at the desired set-point (20 °C in winter, 23 °C during the mid-season, and 26°C in summer, tolerance ± 1°C) by means of a dedicated HVAC system. The measurement apparatus consisted of about 40 sensors (heat flux meters, thermocouples and pyranometers), connected to a datalogger. Incident and transmitted solar irradiance, outdoor air and indoor air temperatures, heat fluxes and surface temperatures were continuously monitored and data analysis was carried out on hourly data.

The outcomes of the experimental investigation demonstrated that, although some drawbacks are recorded (e.g. higher U-factor, risk of overheating in very hot summer day), and some improvements are necessary (e.g. integration with night ventilation strategy, need to control the charge phase on the PCM layer), the technology may represent a solution to increase the efficiency of highly glazed façades, especially in summer conditions. If compared to the reference DGU, the DGU_PCM is able to reduce of about one quarter the energy gain through the 24h in summer.

Additional benefits could also be achieved if suitable integration strategies between the DGU_PCM and the HVAC systems were used to control the night-time energy gain due to the PCM discharge phase – e.g. if the entire night-time energy gain are removed, the total energy gain through the 24h is halved. Furthermore, it was observed that DGU_PCM allows the glass surface temperature to be suitably controlled for many boundary conditions, with a positive impact on the thermal comfort conditions.

Experimental data from the campaign were also used to calibrate and then validate a numerical model [11], developed on purpose to simulate the thermo-physical behavior of PCM glazing systems configurations. During the validation process of the numerical tool, the need of reliable information about the optical properties of the PCM layer was highlighted. In fact, when in solid state, the PCM layer behaves like a diffusive medium and relevant scattering effects can be observed. On the contrary, when in liquid state, the PCM layer is no longer a scattering medium and direct transmission becomes dominant.

As result of this property, the physical-mathematical modeling of the propagation and absorption of radiation (UV-VIS-NIR range) within the solid-state PCM layer claims for a far more complex approach than the one used for conventional transparent components (e.g. a glass pane). Furthermore, the experimental characterization of the optical properties of PCM layer is not widely investigated in literature, although some very detailed studies on the optics of such materials have been carried out [12].

Therefore, laboratory measurements are necessary to obtain a reliable set of data (i.e. the optical properties of paraffin wax layers) that can be implemented into numerical tools for simulation. This paper illustrates the characterization activity carried out with a large integrating sphere to evaluate the optical properties (transmission, absorption and reflection coefficient) of a paraffin wax layer coupled with two clear glass panes.

2. Materials

In order to characterize the optical properties of paraffin wax layers, several samples are realized. All the samples have a common structure: a DGU made of two panes of extra-clear glass, 4mm thick each, and a cavity with different thickness. In total, six samples are realized, combining 3 different cavity thicknesses (i.e. $\delta = 6, 15, 27$ mm) with two different paraffin waxes – i.e. a paraffin wax with a nominal melting temperature of 21 °C and a paraffin wax with a nominal melting temperature of 35 °C. The samples used for the characterization are shown in Figure 1. Each sample has a gross frontal area of 25 cm x 25 cm, while the area that can be used to measure the optical properties is 21 cm x 21 cm.

Fig. 1. Samples of DGU_PCM systems used to carry out the optical characterization of PCM glazing systems: on the left, the PCM layer in liquid state; on the right, in solid state.

The two different melting temperatures are chosen to ensure that the PCM layer stays in the same state of aggregation (solid or liquid) for the entire duration of the measurement. Therefore, the samples containing the paraffin wax which nominal melting temperature is 21 °C are used to characterize the liquid state of the paraffin wax, while the samples that contain the paraffin wax which nominal melting temperature is 35 °C are used to characterize the solid state of the paraffin wax.

This procedure can be adopted considering that no relevant differences should occur in the optical properties of two paraffin waxes, if the two nominal melting temperatures were relatively closed. In fact, the change in the thermal properties (i.e. the phase change range and the nominal melting temperature) is due to the different length of the alkane chains - the longer the chain, the higher the nominal melting temperature.

Optical properties, and especially scattering effects, also depend on the dimensions of the molecules and of the crystallites of the paraffin wax. However, considering that the two paraffin waxes have almost identical composition and very similar chain length (the difference should be about four or five C atoms every chain), a relevant change in the macroscopic optical properties of the two paraffin layers can be excluded.

Furthermore, the aim of this activity is to experimentally characterize the optical properties of this class of PCM (i.e. paraffin waxes, with nominal melting temperature in the range of ambient temperature), rather than the optical properties of a single paraffin wax. Therefore, it is reasonable to use two (or more) paraffin waxes which are made of the same class of molecules, and to consider the optical properties constant among this class of materials – provided that the molecular structures of the paraffin waxes belong to the same class.

It is important to state that the characterized optical properties (e.g. τ, α, ρ) are those of the multilayer structure "extra-clear glass + PCM layer + extra-clear glass" (i.e. the DGU_PCM), and not those of the PCM layer alone. The optical characteristics of such a 4mm extra-clear glass pane, calculated according to EN 410:2011 [13], are: $\tau_l = 0.92$, $\rho_l = 0.08$, $\tau_e = 0.91$, $\rho_e = 0.08$, $\alpha_e = 0.01$.

3. Experimental analysis

The optical characterization of complex and bulk scattering samples cannot be carried out using commercial spectrophotomers, even if equipped with integrating spheres. Scattering phenomena occurring at several centimeters from sphere ports make impossible to collect all the energy transmitted/reflected by the material. Large integrating sphere equipment is needed to perform accurate measurements on such materials. The measurement campaign was carried out by means of an experimental facility, whose characteristics are described in detail in Maccari *et.al* [14].

The optical testing of the different PCM glazing systems described in the previous section is carried out by means of an optical bench consisting of the following parts:

- A tungsten halogen lamp with adjustable power, ranging from 250 up to 1000 W. The collimated beam diameter can be modulated through a diaphragm according to the measurement requirements. Usual diameters range from 4 to 10 cm;
- The light source is mounted on a holder, which arm can rotate in order to vary the beam angle of incidence;
- An integrating sphere with a 75 cm diameter. The external shell of the sphere is made of aluminum, while the internal surface is made of spectralon, a white material with a reflectivity greater than 95% in the whole solar range (300-2500 nm). The sphere is equipped with several ports and a central sample holder; the lay out of the facility can be adjusted in order to perform transmittance, reflectance and absorptance measurements;
- A detection system consisting of three array spectrometers and three detectors: NMOS for the 250-1000nm range (dispersion 1.4 nm/pixel); InGaAs for the 900-1700nm range (dispersion 3.125 nm/pixel); ExtInGaAs for the 1600-2500nm range (dispersion 3.52 nm/pixel).

Figure 2 shows the experimental facility in the transmittance measurement mode. Spectral transmittance, reflectance and absorptance measurements are performed on the selected samples. The procedures are described here below.

- *Transmittance mode.*
  The sample port is 20 cm in diameter and the incident beam diameter is 6 cm. The transmittance is measured as the ratio of the energy transmitted by the specimen mounted on the sample port on the energy directly entering the sphere, see Fig. 2. The measurement is corrected with the auxiliary port correction method [14]. The measurements are performed at the following incidence angles: 0, 30, 45°.
- *Reflectance mode.*
  The sample port is 20 cm in diameter and the incident beam diameter is 6 cm. The radiation enters the sphere through a port facing the sample port and hits the sample with 8° angle of incidence. The reflectance is measured as the ratio of the energy reflected by the specimen mounted on the sample port on the energy entering and hitting directly the sphere wall. Only the near normal incidence reflectance is carried out.
- *Absorptance mode.*
  The sample port is 12 cm in diameter and the incident beam diameter is 6 cm. The radiation enters the sphere through the sample port and hits the sample mounted inside the sphere with a suspended rod. The absorptance is measured as the complement to one of the ratio between the energy measured when the beam hit the sample and the energy entering and hitting directly the sphere wall. The measurements are performed at the following incidence angles: 8, 30, 45°.

Measurements are performed between 400 and 2000 nm, covering the 93% of the whole solar spectrum energy. The solar quantities are calculated starting from the spectral data using the reference solar spectrum defined in ISO 9050:2003 [15].

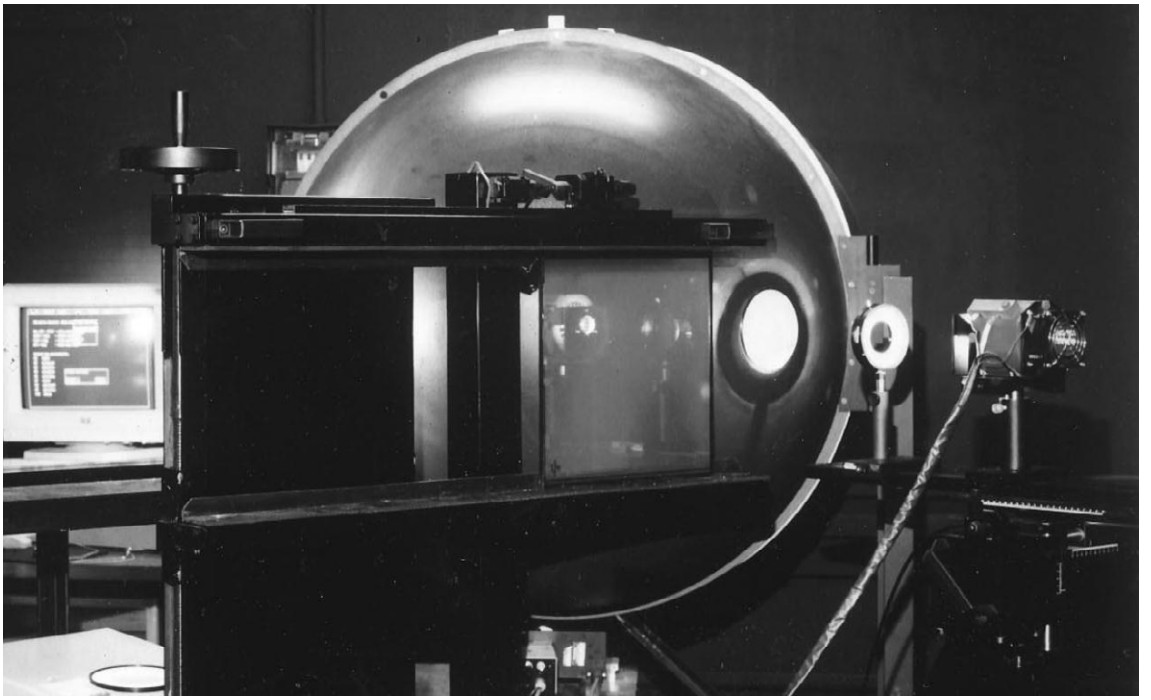

Fig. 2. View of the optical bench including: the light source, the integrating sphere, the sample holder for the transmittance mode.

4. Results

4.1. Spectral coefficients

The spectral transmittance (τ), reflectance (ρ) and absorptance (α) of the PCM glazing samples are shown in Figures 3, 4 and 5 respectively. On the left hand side of Figures 3-5, illustration (a) refers to the coefficient for the sample with a PCM layer thickness on 15 mm, in liquid state (dot line) and in solid state (solid line); illustration (b) shows the coefficient for different PCM layer thicknesses (6mm – grey solid line; 15mm – dashed black line; and 27mm – grey dot line), for the solid state of aggregation.

In Fig. 3a, the considerable difference in the transmitted energy when the PCM is in liquid state and in solid state is highlighted. It is also necessary to remind that when in solid state, paraffin-based PCMs behave like a random and diffusive medium, and relevant scattering effects take place. On the contrary, the PCM is highly transparent when in liquid state, the direct transmission is dominant, and no relevant scattering effects take place.

The transmittance for different PCM thicknesses is illustrated in Fig. 3b, and a non-linear behavior is revealed. While the transmittance for the thickest PCM layer (27mm) is always the lowest among the three samples, the transmittance of the thinnest (6mm) is very similar, and in some regions (e.g. 1400-2000 nm) even higher than the one of the 15mm thick PCM layer. The shape of the three curves is very similar, with constant selective bands (900 nm, 1200 nm and 1700-2000 nm). The highest transmittance is recorded in the visible spectrum – i.e. 400-800 nm.

The comparison between the spectrum of the reflectance of the liquid and of the solid PCM layer (Fig. 4a) reveals a considerable difference in the behavior of the system: when the PCM is in solid state, the reflectivity of the PCM glazing system greatly increases (up to 3 times) in the visible spectrum, compared

to the liquid state. The two spectra are much more similar in the range 900-1700 nm, even if the reflectivity in the solid state is always higher than the one in the liquid state, and some spectral bands are recorded (900 nm, 1200 nm, 1400 nm). In the range 1700-2000 nm the PCM glazing system shows the same behavior, regardless the state of aggregation of the paraffin wax.

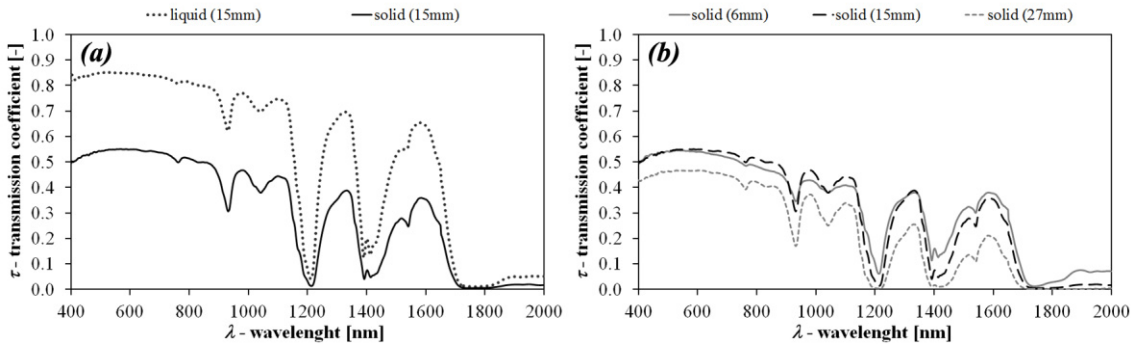

Fig. 3. a) spectral transmission coefficient for a PCM layer (DGU_PCM) of 15mm in solid and liquid state; b) spectral transmission coefficient for a PCM layer (DGU_PCM) of 6mm, 15 mm and 27mm in solid state

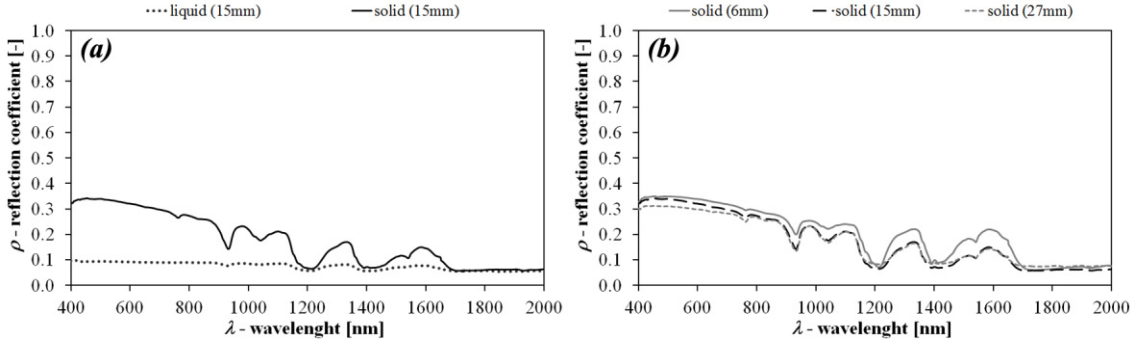

Fig. 4. a) spectral reflection coefficient for a PCM layer (DGU_PCM) of 15mm in solid and liquid state; b) spectral reflection coefficient for a PCM layer (DGU_PCM) of 6mm, 15 mm and 27mm in solid state

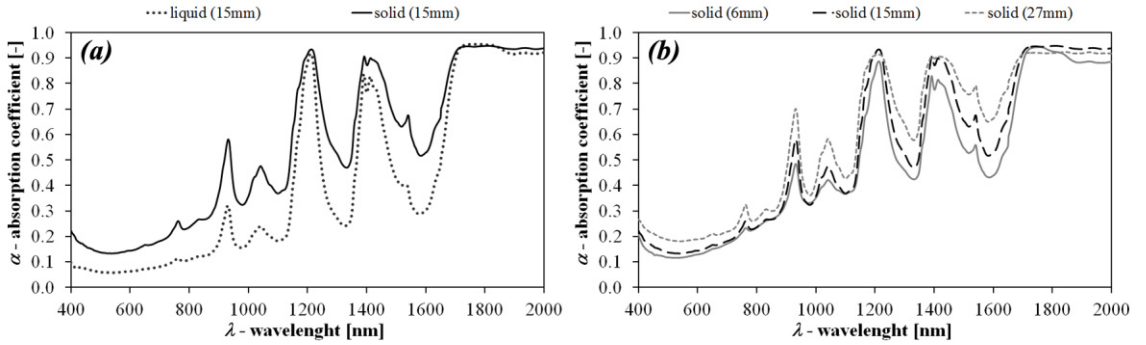

Fig. 5. a) spectral absorption coefficient for a PCM layer (DGU_PCM) of 15mm in solid and liquid state; b) spectral absorption coefficient for a PCM layer (DGU_PCM) of 6mm, 15 mm and 27mm in solid state

The dependence of the reflectivity on the PCM layer thickness is moderate, as revealed by Fig. 4b. The thinnest PCM layer presents the highest reflectivity, while the two other configurations show almost the same profile, highlighting a non-trivial, non-linear behavior with respect to the PCM thickness.

In Fig. 5a, the absorption profiles in solid and liquid state are shown. The coefficient is much higher in the case of solid PCM, but the profiles are very similar in shape, with common selective absorption bands (900nm, 1200nm and 1400nm).

The analysis of the profiles as a function of the PCM layer thickness (Fig. 5b) provides more conventional results than the previous ones: the thicker the PCM layer, the higher the absorption. The shapes of the spectra, as shown in the other cases, are not relevantly affected by the PCM thickness.

4.2. Integrated coefficients

The integral values of the transmittance, reflectance and absorptance are given In Table 1, for the visible spectrum (*l*), near-infrared (*nir*) spectrum and for the solar (*e*) spectrum, for different thicknesses of the PCM layer and for the liquid and solid state of aggregation. The incident beam angle is normal to the glass surface (8° for the reflectance and absorptance measurements). The sum of the α, ρ, τ coefficients may not be equal to 1 because of the measurement uncertainties. The average error on the sum of the α, ρ, τ coefficient is 2%, with a maximum value of 4% (visible spectrum, PCM layer 27mm).

It can be noticed that the visible transmission is always higher than the solar transmission, and that the visible/solar transmission does not decrease from the 6mm thickness to the 15mm thickness, but it slightly increases instead. The reflectance shows a decrease as the PCM thickness increases, while the absorptance increases with the PCM layer thickness.

Table 1. Integral values of the different PCM layer thicknesses on the solar, visual and nir spectra, for the liquid and solid state

State of aggregation	δ	τ_e	τ_l	τ_{nir}	ρ_e	ρ_l	ρ_{nir}	α_e	α_l	α_{nir}
[-]	[mm]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
Liquid	15	0.75	0.85	0.62	0.09	0.09	0.08	0.17	0.06	0.32
Solid	6	0.46	0.54	0.36	0.28	0.34	0.21	0.27	0.12	0.45
	15	0.46	0.55	0.35	0.26	0.33	0.18	0.30	0.14	0.49
	27	0.37	0.46	0.25	0.25	0.30	0.18	0.35	0.19	0.56

4.3. Angular characterization

The angular dependency of the coefficients is also investigated for the solid state of the 15mm PCM layer. Integral values of the coefficients for the different beam angles are given in Table 2.

Table 2. Integral values for δ= 15mm (solid state) on the solar, visual and nir spectra, for different beam angles

State of aggregation	β	τ_e	τ_l	τ_{nir}	ρ_e	ρ_l	ρ_{nir}	αe	αl	αnir
[-]	[deg]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
Solid	0 (8)	0.46	0.55	0.35	0.26	0.33	0.18	0.30	0.14	0.49
	30	0.43	0.52	0.32	0.27	0.34	0.18	0.31	0.15	0.50
	45	0.41	0.50	0.30	0.27	0.34	0.19	0.32	0.16	0.51

The PCM layer presents a conventional dependence on the beam angle – at least in the range 0-45 deg. The reflectance and the absorptance increase as the beam angle increases, and the transmittance decreases, regardless the spectrum that is investigated – i.e. solar, visible or near-infrared spectrum.

5. Discussion and conclusion

The spectral coefficients τ, ρ, α of PCM glazing samples (PCM layer of 6, 15 and 27mm) are measured by means of a large integrating sphere equipment, in the range 400-2000 nm, covering the 93% of the whole solar spectrum energy. The solar quantities are calculated starting from the spectral data using the reference solar spectrum defined in ISO 9050:2003. Both the liquid and the solid state of aggregation of the PCM are investigated.

The absorption spectrum reveals that the paraffin wax presents highly selective properties, and that the absorption in solid state is higher than in liquid state. The relevant decrease in the solar and light transmission, when the PCM is in solid state, is due to an increase in the reflection (back-scattering effect), as revealed by the integral values.

A non-linear property is revealed when a different thickness of the PCM layer is investigated. The transmission coefficient does not always decrease as the thickness of the PCM layer increases: the value obtained for $\delta = 15$mm is almost identical to the value determined for $\delta = 6$mm. Considering that the uncertainty of the measurement apparatus is lower than 2%, and that port size independency and beam size independency have been verified, it is possible to suppose that this behavior is related to the different morphologies that the solid PCM can display. In fact, during the solidification process, the PCM can either assume a homogeneous appearance, or present macro-crystals (dimension range: between about 5 mm and 1-2 cm) in a homogeneous matrix. This feature depends on the kinetic of the re-solidification process and on the boundary conditions.

The reflectance presents a non-trivial nature too, since it is higher for thinner PCM layers and it decreases when it becomes thicker. On the contrary, the absorption coefficient presents a more conventional and predictable property – i.e. it increases as the PCM layer becomes thicker.

As far as the angular dependency of the coefficients is concerned, it is possible to observe that the system presents a more conventional behaviour: the higher the beam angle, the lower the transmission coefficient and the higher both the absorption and reflection coefficients.

It is remarkable that the sum of the measured integral coefficients, regardless the spectrum that is investigated, is only 4% (maximum error) higher/lower that the theoretical value (i.e. $\tau_e + \rho_e + \alpha_e = 1$), for all the sample that are tested (i.e. $\delta = 6$, 15, 27mm); the average error is ± 2%. This demonstrates the achieved good accuracy and precision, even if the paraffin wax presents a high non-homogeneous aspect, that can determine non-trivial behaviors, and elevate scattering phenomena occur.

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