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Research Article

An Approach Method to Evaluate Wood Emissivity

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Throughout the ages, wood has been used in constructions. Therefore, most of the built heritage is made with wooden structures. Wood is a renewable, versatile, long-lasting, and environmentally sustainable material. It is comfortable, is aesthetically very valued, and has crucial environmental importance. Thus, being a widely used long-life material, it requires techniques for monitoring its state of integrity. Inspection needs to be done in production, in the work site, and during its useful life. Infrared thermography (IRT) is a nondestructive, noninvasive, noncontact diagnostic technique. It evaluates the surface temperature of objects based on the emitted radiation. Nevertheless, the accurate measurement of temperature is strongly dependent on the emissivity value of the material. This paper presents an expedite method to measure wood emissivity values, using active infrared thermography. Wood samples of the *Pinus pinaster* species were used in the experiments. The thermal contrast of the samples was performed by applying three different heating methods: conduction, convection, and radiation. The emissivity values of the three tests were compared with each other and with data from the literature, showing satisfactory results and validating the presented methodology. The procedure can also be adopted, with some adjustments, to other materials and *in situ* analysis, contributing to emissivity measurements.

1. Introduction

Environmental awareness in the construction sector, as well as the increasing of sensitive consumers concerned on environmental issues, has led to some containment in the use of more processed materials (such as concrete, steel, and glass) and return the use of natural and sustainable materials such as wood. Building materials with mineral or metallic mineral origin contribute to the greenhouse effect. Instead, one cubic meter of tree growth consumes 1 ton of carbon dioxide and releases 0.7 tons of oxygen [1]. The sustainability of the forest depends on the valorization of the products and services that it provides. Due to its adaptability, productivity, and versatility, *Pinus pinaster* became the most representative Portuguese forest species. This wood represents 3% of the GDP of Portuguese economy, 12% of the industrial gross domestic product, and 10% of the total Portuguese exports. *Pinus pinaster* is valued because of the quality of its products, although it turns out that the wood of *Pinus pinaster* can be given more added values. Its physical, mechanical, technological, and aesthetic characteristics indicate that it is wood with the same potential as the softwoods from the northern European forests, which are widely used in the construction of houses and furniture. This is the reason why the wood samples used in this study are *Pinus pinaster* Aiton [2]. Some pathologies affect the durability and the useful life of the wood. Fungi and insects are the main organisms that degrade the wood and can lead to disastrous consequences, such as failure of structures. Low-cost evaluation of the state of conservation of wood elements without damaging them can be carried out with noninvasive techniques [3]. Visual inspection is the initial wood evaluation technique [4]. Then, it is convenient to apply an instrumental evaluation technique.

Infrared thermography (IRT) detects radiation in the infrared spectrum usually between 2 to 5.6 μm and 8 to 14 μm because these spectral windows present poor atmospheric absorption [5]. This is a nondestructive, noncontact technique that can be used to assess the wholesomeness of wood. This allows visualizing the superficial temperature of the objects; it is based on the radiation emitted by the object.

Temperature is the physical parameter to investigate because all bodies whose temperature is above 0 Kelvin emit infrared radiation [6]. Thermography is the result of a complex interaction between the heat source, the material, and its defects [6]. Active and passive heating procedures are used to enhance the properties of the materials. The potential applications of IRT are vast. Examples of IRT for the evaluation of wood structures in historic buildings are presented in [7, 8]. The distribution pattern of the surface temperature detects discontinuities and changes in the building structures [9]. This technique provides information on the location, characteristics of the materials, shape and state of deterioration of elements, and constructive systems [9]. Studies have confirmed that density, knots, biological decay, and cracking are factors that affect surface temperature [10].

For more accurate IRT evaluations, it is necessary to know the emissivity of the object of the study together with the reflected temperature [11]. These two parameters are not the only ones that affect the thermographic analysis. The angle under observation influences the measure and should be registered [12]. Determination of the emissivity from different angles of observation can be found in [13]. Radiation from a surface occurs in all directions. However, in actual scenarios, surface radiation is reflected in all directions in a heterogeneous way. That is why the preferred method is to measure the normal or near-normal radiation of the surface [13]. Actually, the radiation emitted by the surface and captured by using the thermal camera only varies significantly for angles greater than 60° related to the observation perpendicular to the sample. Thermographic cameras interpret infrared radiation from the surface. They use emissivity, reflectivity, and, occasionally, the transmissivity of infrared radiation [14]. Emissivity is used to characterize the optical properties of the materials, taking into account the amount of energy emitted compared to an ideal black body [14]. The emissivity value varies between 0 (perfect mirror reflector) and 1 (perfect emitter, black body). Surface conditions, such as roughness and the nature of the material, also affect this parameter. The reflected temperature, mainly dependent on the surrounding radiation, is another factor that affects the thermographic temperature accuracy [14, 15].

Wood, like most building materials, has high emissivity, generally above 0.8 [14]. Several emissivity values of building materials at different temperatures and different spectral windows are presented in [11, 14]. The use of an average emissivity of 0.924 for any type of wood is proposed in [16]. It is an average emissivity for samples of wood of different species that are subject to different temperature values with a spectral band of 7.5–13 μm. Emissivity is measured from the thermal gradient to induce the thermal response of the surface. It is considered that 20°C is a satisfactory difference [17, 18], while ASTM E1933-99a recommends minimum of 10°C [19]. In this research, this standard was the only reference found to define the procedure for expeditious emissivity determination of several materials using IRT. For the temperature differences used in the active thermography (10 to 20°C), the emissivity variations are minimal, the reason why its noninfluence can be considered, and therefore, the calculated emissivity is for the ambient temperature [19]. Note that the wood only changes its thermal properties to values above 80°C.

The primary aim of this study is to present a more efficient procedure, developed by the authors and based on the black tape method, namely, the ETA (emissivity by thermogram analysis) method, for wood emissivity determination in a laboratory environment, using active thermography. The second goal is to give results with three heating systems, representative of the three modes of heat transfer (conduction, convection, and radiation). Two different samples of wood with similar textures of the species *Pinus pinaster* Aiton were used. This method represents a contribution to the quantitative, as well as qualitative, inspection of wood. It can be applied to other materials and *in situ* analysis, if some procedure adjustments are introduced.

2. Materials and Methods

2.1. Wood Samples. Considering the environmental and economic relevance of the species *Pinus pinaster* Aiton, as referred above, two wood samples from species *Pinus pinaster* Aiton were used with similar texture and colouration to test with the ETA method using three heating modes. On the contrary, this also allows verifying that the same wood species can have a different emissivity value and become inappropriate to attribute an emissivity to each species as it sometimes appears in the literature. In fact, in the case of wood, the emissivity varies according to the species of wood, surface finish, water content, and density [10, 12]. The chosen pine (commonly known in Portugal as *Pinho bravo* or *Pinho marítimo*) is soft and light. Even if both samples are of the same species, they have different densities because they come from different locations: one comes from the coast region (coast pine) and the other one comes from the mountains region (inland mountains pine). The wood becomes yellow golden after treated with varnish. The variability of the texture depends on the genetics and the environmental characteristics of the place where it grows. The *Pinus pinaster* texture is generally classified as coarse because the annual growth rings are well visible to the naked eye; the contrast between spring and summer wood is evident. It is a straight fiber direction wood, and the shine shows a natural spleen aspect [1]. The samples were used without any type of finishing, such as in many wood constructions and structures. In fact, many wooden constructions present untreated wooden elements or whose treatment has deteriorated/disappeared. Figure 1 shows one of the samples, which has dimensions of 20 cm (following the fiber direction length) × 15 cm (across the fibers) and is 15 cm thick. These dimensions were defined to simulate a small section of a beam. The characteristics and water content of the samples are shown in Table1.

2.2. Equipment. An infrared camera ThermaCAM FLIR T1030sc was used, as shown in Figure 2(a), with a 28° lens and focal length $f = 36$ mm, with a field of view (FOV) of 27.18°, and a close focus, minimum focusing distance 0.4 m.

Figure 1: Example of the shape of the wood samples.

Table 1: Sample conditions.

Samples	Vol. (cm^3)	Dry weight (g)	Weight (g)	Water content (%)	Density
Coast pine	4500	2507	2694	7.45	0.599
Inland mountains pine	4500	1869	2043	9.31	0.454

(a)

(b)

Figure 2: (a) IRT camera FLIR T1030sc; (b) thermohygrometer FLIR MR 176.

The focusing distance used between the camera and the sample surface was 1.0 m. The distance between the camera lens and the sample surface presents a horizontal field of view (HFOV) of 0.48 m, a vertical field of view (VFOV) of 0.36 m, an instantaneous field of view (size of one detector element) (IFOV) of 0.47 mm, with a depth of field near limit (DOF near) of 0.97 m, and a depth of field far limit (DOF far) of 1.03 m. The thermal camera works in the spectral band of 7.5–14 μm, with thermal sensitivity of 0.02°C at 30°C, and it has an accuracy of ±1°C and ±1% at 25°C and a resolution of 1024×768 pixels. The type of detector is an uncooled microbolometer (FPA). The focusing is manual or automatic [18]. The software used was FLIR Tools+. For measuring the emissivity, the black tape method was applied, having used electrical nsulating black adhesive tape *Iso Tape Tesa*. For determining the environmental conditions, a thermohygrometer FLIR MR 176 was used, Figure 2(b), and it has an accuracy of ±0.6°C and ±2.5% RH. This instrument also allows the determination of water content of the samples to a depth of 2 cm without penetration probes. Weighing of the samples was performed with an electronic scale of 5 kg capacity and accuracy of ±1 g. A tripod was used to fix the thermal camera.

2.3. Method and Laboratory Tests. A series of experiments were performed with the two samples. Thermal contrast is required between surface temperature and room temperature. The emissivity value is determined from the surface temperature of the study object. FLIR's camera and software were used for the experimental work. The methodology suggested in the FLIR's manuals [18, 20] and also mentioned in [19, 21] was followed. Adaptations were made for the determination of the apparent reflected temperature through the reflector method and the determination of emissivity (Figure 3). A thermal differential of approx. 20°C was adopted, as suggested in the FLIR T1030sc thermal camera manual [18].

The determination of the emissivity was performed according to the ETA method, developed by the authors, based on the black tape methodology, using an *Iso Tape Tesa* adhesive tape (material with a known emissivity value of 0.97 at 35°C) [22, 23]. Several strips of black adhesive tape were placed juxtaposed perpendicular to the wood fibers to cover half the face of the sample to be observed. The face that presented minor irregularities and defects was chosen. Figure 4 shows the samples after application of the black tape on half of the face to be observed. If the emissivity is known, black paint can be used. However, the painting generally requires a coat of pore sealant or surface polishing, representing, therefore, an invasive technique which is not intended.

The ETA method is based on the black tape method. In the black tape methodology, the principle is to correct the emissivity value until the temperature reading in the camera is the same as indicated by the auxiliary thermometry system (e.g., a thermocouple). However, for relatively large objects and in the case of active thermography (transient events), where the spatial and temporal variations in the surface temperature of the subject are significant, this technique could be very ineffective. Thus, the help of analysis software and image processing is used to obtain thermal surface pictures at successive times. The average of the surface temperature was obtained, and this led to getting its emissivity. The experimental steps of the ETA method are as follows:

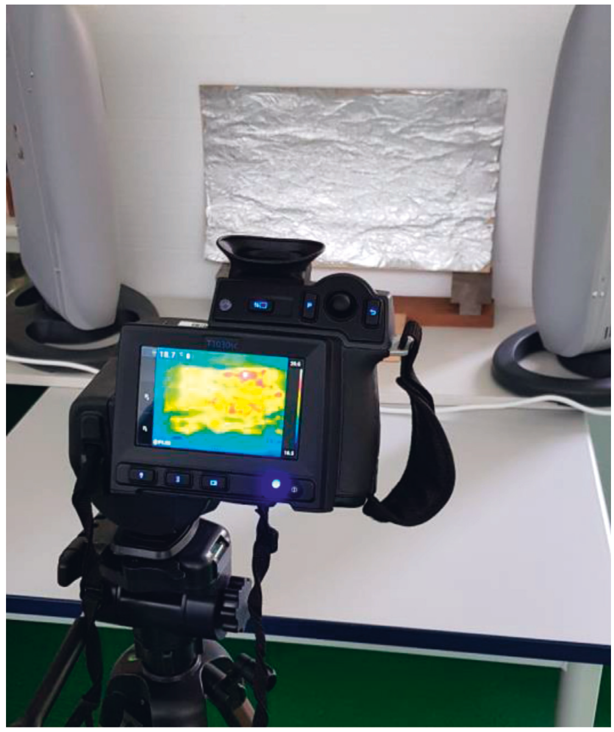


Figure 3: Experiment for measuring the apparent reflected temperature.

(a) (b)

Figure 4: Wood samples with electrical insulating black adhesive tape on half of the observed face. (a) Inland mountains pine. (b) Coast pine.

(1) Introduce the emissivity value (black adhesive tape, 0.970)

(2) Focus the sample surface (the whole face, black tape zone plus naked zone)

(3) Record the sample face thermogram

(4) Export the thermogram using proper software (e.g., FLIR Tools+ [20])

(5) Get the emissivity through the analysis of thermogram (adjust the emissivity in the naked zone to equal both temperatures)

Other details of the procedure, with adaptations, can be found in [23, 24]. The thermograms were analysed using image processing software to determine the average temperature of the sample surface.

The face of each sample was heated to about 20°C above room temperature. The heating time is not relevant, and the aim is to increase the analysis surface temperature 10°C to 20°C over the ambient temperature. After that, the face was observed and the thermograms were obtained. The procedure was performed after each heating process. Three heating systems, representative of the three modes of heat transfer were applied in the tests: radiation (Experiment 1), conduction (Experiment 2), and convection (Experiment 3). The reflective mode of the active thermography was used. In all experiments, the heated face of the sample was the face covered by the black adhesive tape (nondetachment of the tape was checked). The same face of the sample was used in all tests. For each sample and each heating mode, two thermograms were sequentially registered. For each thermogram, one emissivity value was determined.

2.3.1. Experiment 1. In Experiment 1, a radiant heating system was used with two halogen heaters of 3×400 W power, placed at a 45° angle to the sample (Figure 5).

2.3.2. Experiment 2. In Experiment 2, the surface of the sample face was heated with a contact (conduction) heating system using a thermostatic heating plate. A schematic and thermogram of this system are shown in Figure 6.

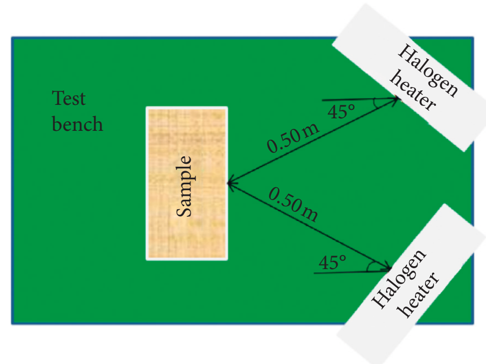
2.3.3. Experiment 3. In Experiment 3, the sample surface was heated by blowing hot air on the face of the sample (convection heating) using an APU (air processing unit) (Figure 7).

In order to confirm that the temperature was equal on both sides, that is, on the side with tape and the side of the wood without tape, a thermocouple type K was used after the heating process and before the thermograms were performed. This was done for each sample.

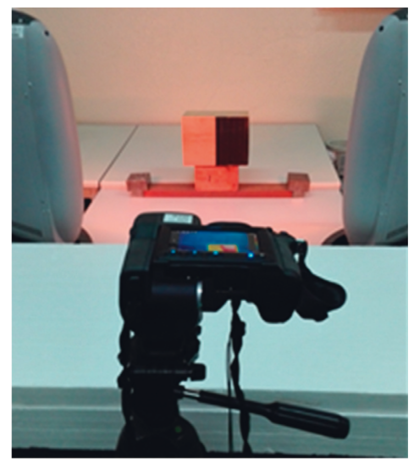
The sample was placed on a bench, and the thermal camera was fixed to a tripod. The camera lens was fixed perpendicular to the plane of the sample surface as shown in the diagram in Figure 8. Then, the observations were made.

The ambient conditions between the thermal camera and the sample were surveyed by using the thermohygrometer FLIR MR 176. As referred above, the emissivity values were determined using FLIR Tools+ software [20]. The image processing software is necessary to determine the average temperature of the sample surface. In fact, since wood is a very heterogeneous natural material, the thermographic evaluation was performed over the whole area and not at one point. The larger the area, the more representative the average temperature of the surface under observation. Thus, measuring should be avoided at a single point, since it is not representative [23, 24]. The area was calculated to get a sufficiently large and representative sample observation of temperature [23]. For this purpose, we used a square/rectangle function to open an analysis box (Figure 9) from the side covered by the tape in order to determine the average surface temperature in the area with the tape. This procedure was repeated on the opposite side of the exposed wood. Thus, by varying the emissivity value, it was possible to vary the temperature value read on the exposed side of the lumber. Then, the value of the emissivity was fixed. When the temperatures were equal, the value of the emissivity meter matches the value of the sample surface emissivity, which in fact corresponds to the emissivity value of the sample at room temperature.

The values of emissivity and surface temperature for each sample were determined by the analysis of a square of 100×100 pixels and a rectangle of 200×100 pixels on the thermogram. These two cases were performed to verify if the area of 100×100 pixels is sufficiently representative of the average measured temperatures. These two cases were performed for all thermograms applying the three methods of heating. In Figure 9(b), we can observe thermograms with the design of the two areas of analysis. The thermograms

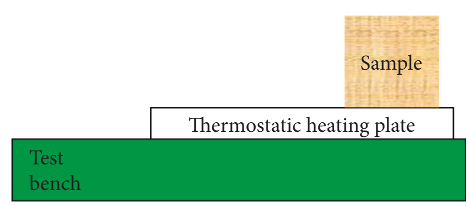


(a)

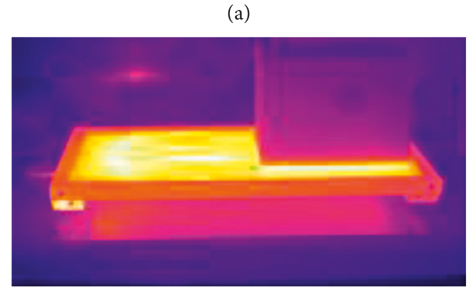


(b)

Figure 5: Experiment 1: radiant heating. (a) Schematic of the experimental setup (top view). (b) Test system installation (general view).



(a)



(b)

Figure 6: Experiment 2: conduction heating. (a) Schematic of the experimental setup (lateral view). (b) Thermogram of the process of heating.

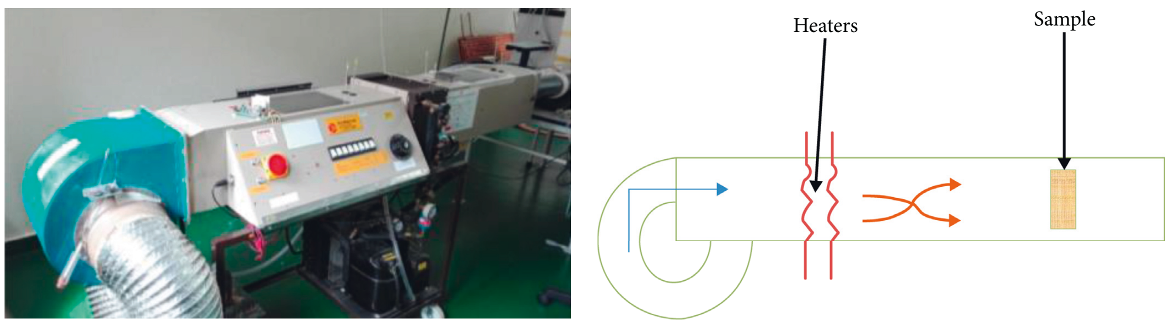


Figure 7: Experiment 3: convection heating. (a) Schematic of the experimental setup. (b) Air processing unit (APU) (general view).

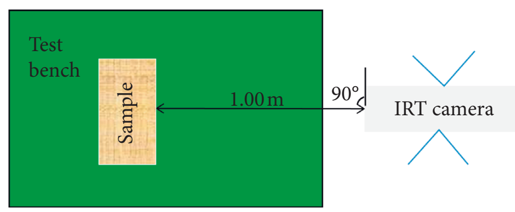


Figure 8: Schematic of the observation of the experimental setup (top view).

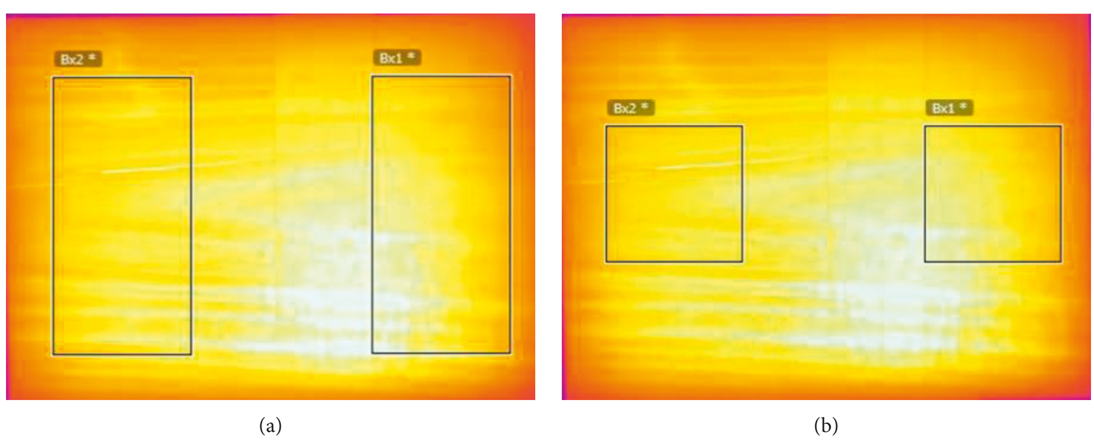


Figure 9: The geometry of the areas for thermograms analysis: (a) square 200 × 100 pixels; (b) rectangle 100 × 100 pixels.

refer to the inland mountains pine sample in the contact heating mode (conduction).

The values correspond to the emissivity of the wood sample conditioned by the registered ambient conditions. For each sample and heating process, two thermograms were made.

The water content of the samples was determined to ensure that it is similar in both samples. It is relevant because of water contents influence emissivity measures [24, 25]. To determine the water content, equation (1) was used, and each sample was weighed. W_{Wet} represents the wet weight, and W_{Dry} represents the dry weight [26].

At the end of the experiments, the samples were heated at 100°C during 48°h, and successive weightings were performed until the value was constant (dry weight):

$$\text{water content}\,(\%) = \left(\frac{\left(W_{\text{Wet}} - W_{\text{Dry}}\right)}{W_{\text{Dry}}}\right) \times 100. \qquad (1)$$

3. Results and Discussion

3.1. Results. The laboratory ambient conditions are shown in Table 2, and the conditions of the samples are shown in Table 1. It should be noted that the emissivity values of the samples were analyzed under the referred ambient conditions (Tables 3 and 4).

3.2. Discussion. The wood samples used in this work were only sawn, and they were not polished or sanded, such as in many wood constructions and structures (untreated wood and wood where the treatment has deteriorated or disappeared are very common in practice). Wood is a heterogeneous material and has zones with protruding veins that produce a heterogeneous contact with the heating plate. The protruding veins heat up faster than the remaining surface, resulting in heterogeneous heating of the surface. As

Table 2: Laboratory ambient conditions.

Ambient temperature (°C)	Relative humidity (%)	Reflected temperature (°C)	Light intensity (Lux)
20	50	21.5	1.45

Table 3: Emissivity values of the coast pine sample.

Experiment	Heating mode	200 × 100 pixels		100 × 100 pixels	
		ε	Average surface temperature (°C)	ε	Average surface temperature (°C)
1	Radiation	0.99	39.40	0.99	39.10
		0.99	39.30	0.99	39.10
2	Conduction	0.95	45.10	0.94	44.70
		0.95	44.20	0.94	43.80
3	Convection	0.97	34.20	0.97	34.30
		0.98	33.90	0.98	34.10

Table 4: Emissivity values of the inland mountains pine sample.

Experiment	Heating mode	200 × 100 pixels		100 × 100 pixels	
		ε	Average surface temperature (°C)	ε	Average surface temperature (°C)
1	Radiation	0.91	40.70	0.91	40.80
		0.91	40.90	0.91	40.80
2	Conduction	0.96	42.00	0.96	42.00
		0.95	41.70	0.95	42.10
3	Convection	0.91	36.00	0.91	36.10
		0.92	35.60	0.92	35.80

a result, the emissivity values obtained in this procedure may differ from those obtained with the other heating modes. Thus, for the coast pine sample, the values of emissivity obtained by radiation and convection heating were between 0.97 and 0.99; these values are concordant with each other. The values determined by conduction deviate from the previous ones, and they are between 0.94 and 0.95. For the inland mountains pine sample, the values of emissivity obtained by the processes of heating by radiation and convection are between 0.91 and 0.92. The values determined for the emissivity during the conduction heating process are between 0.95 and 0.96.

The emissivity values measured by the three heating processes are close to each other: they are all above 0.90. They are similar to the values found in the literature for the emissivity of the wood. However, the values in the two samples exposed to the same heating process are not the same. This highlights the heterogeneity of trees within the same species. One of the features is density diversity.

Rice [12] reports values between 0.89 and 0.92 using different species of wood and their products. It points out that producers of infrared temperature measurement equipment recommend values between 0.94 and 0.95 for wood in general under general conditions [12]. The manufacturer FLIR presents an emissivity table in the user manual of the T10XX thermal camera [18] for the spectral window of this machine. An emissivity of 0.88 is reported for the oak sample planed at 70°C. Four different pine samples, also heated at 70°C, showed a range of emissivity 0.81–0.89. However, comparison of these results against the values reported in the literature is difficult because the above values refer to different experimental conditions, or the conditions are not mentioned in the literature, such as the temperature and relative humidity, characteristics of the thermal camera, spectral window, and conditions of the sample itself (surface finish, water content, density, and wood species).

According to the ASTM standard [19], for the determination of emissivity using expeditious methodologies, it is assumed that both parts of the face of the surface under analysis have the same temperature value over time. However, as soon as the sample is moved away from the place where it is being heated, it begins a cooling process. It is a transient phenomenon. In the process of observing, first the temperature of the side in which the emissivity is known is read; then this temperature value is used to determine the emissivity on the other side where the emissivity is unknown. This cannot be done because it is not possible to obtain the same temperature value for both sides since the instant of time is different and the cooling process is continuous. Thus, to be able to carry out the observation at the same instant for both sides, the analysis was made using the thermograms captured (and saved) because it is possible to “freeze” the instant of recording time. In fact, the problem of the phenomenon being transient and therefore varying rapidly with time is no longer a difficulty—the time spent to estimate the emissivity after heating is also not relevant. The emissivity value was determined by defining and comparing, in each thermogram, the “bounded areas”. This procedure, developed by the authors, was made to minimise errors in the emissivity values determination. Actually, it traditionally takes a lot of time during the transient cooling regime, and the temperature measures are based on a single or few points.

It should be noted that the higher the temperature difference between the sample surface and the ambient temperature, the more accurate the values obtained for the emissivity [19]. The need to raise the surface temperature values is only a process for thermal contrast about the ambient temperature. With a thermal jump of only 10–20°C, the determined values of emissivity are valid for the ambient temperature.

The proposed ETA method can be applied, with some adaptations, to *in situ* measurements. Further details can be found in [23, 25]. It can also be applied to wood with or without surface treatment. Despite many IRT analyzes are only qualitative, for analysis of wood health, due to the reduced thermal contrast commonly found, more refined measurements are required in which a correct emissivity plays a predominant role.

The emissivity tables are useful since, in most cases, the determination of the emissivity parameter *in situ* is very difficult or impossible. Thus, it is a need to have tables that are as close as possible to the conditions that are normally found *in situ*. Then, the characteristics of the samples and the ambient conditions in which the experiments are performed should be mentioned.

The most suitable heating processes are radiation and convection. The radiation heating is, as a rule, easier to implement and provides uniform heating of the observation zone. It can be applied in the laboratory or in situ. For practical reasons, it may be easier to use an easy-to-use convective system, e.g., a hot air blower or even a hairdryer. In this case, it is important to take into account the distance and the exhaust opening, in order to ensure that the airflow provides, as far as possible, uniform heating of the surface to be observed. Conduction heating requires that the surfaces of the sample under study should not have large roughness or protrusions so as to allow the entire surface of the sample face to be uniformly heated, which is hardly gotten (Figure 9(b)).

4. Conclusions

In quantitative thermography, precise knowledge of emissivity is essential for accurate temperature readings. In the literature, there are few studies on the emissivity values for wood materials reporting their specificities as well as the ambient conditions. Thus, a standardized emissivity list for different wood species under different ambient conditions is yet to be elaborated. The methodology outlined in this study, the ETA method, is effective and expeditious. In fact, applying the software to "freeze" the thermograms and performing image processing to obtaining temperature values for comparison and determination of emissivity proved to be an expeditious and effective tool in relation to the conventional method, particularly for transient phenomena. It represents a valid contribution in this field.

The most suitable heating processes are radiation and convection. Conduction heating requires that the surfaces of the sample under study should not have large roughness or protrusions. This is critical to ensure that the entire surface of the sample is uniformly heated. However, it is not easy to guarantee especially for in situ tests.

Regarding the process of measuring the emissivity using a square of 100×100 pixels and a rectangle of 200×100 pixels, it is concluded that the values obtained in both cases are very similar, showing that a square of 100×100 pixels is a sufficient representative area.

This work helps and calls attention to the IR camera users on the importance of the procedures to minimise errors when working with thermograms. It is noted that the results and conclusions of this study were only tested under the environmental and the test conditions discussed.

Data Availability

All equipment and materials used in this work are described and presented (photographs), and the technical manuals are referenced. The method has been described in detail and is reproducible. All relevant results obtained were presented and discussed. Other details can be requested.

Disclosure

Part of this study was submitted to patent preregistration.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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