

Measurement of emissivity of low-emissivity coatings using a thermographic camera

Medida de emisividad de recubrimientos bajo emisivos mediante cámara termográfica

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ABSTRACT:

The development of low-emissivity coatings has gained prominence in recent years due to their various applications in the architectural and industrial sectors. This is due to their ability to optimize energy efficiency by reflecting infrared radiation while allowing the passage of visible light. When working with these types of coatings, it is essential to measure their emissivity. Therefore, this work presents a method to determine the emissivity of these coatings using a thermographic camera, addressing the limitations of traditional spectroscopic methods.

Key words: Low-emissivity coatings, emissivity, thermographic camera.

RESUMEN:

El desarrollo de recubrimientos de baja emisividad ha ganado relevancia en los últimos años debido a sus diversas aplicaciones en los sectores arquitectónico e industrial. Esto se debe a su capacidad para optimizar la eficiencia energética al reflejar la radiación infrarroja mientras permiten el paso de la luz visible. Al trabajar con este tipo de recubrimientos, es esencial medir su emisividad. Por ello, este trabajo presenta un método para determinar la emisividad de estos recubrimientos utilizando una cámara termográfica, abordando las limitaciones de los métodos espectroscópicos tradicionales.

Palabras clave: Recubrimientos bajo emisivos, emisividad, cámara termográfica.

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1. Introduction

Low-emissivity coatings are applied to building glass surfaces, as they allow visible solar radiation to enter while reflecting the infrared component of solar radiation, as well as thermal infrared. These coatings exhibit high transmittance in the visible range and high reflectance in the infrared range [1-3].

Due to these properties, they enhance the energy performance of buildings, keeping interiors warm in cold climates and cool in warm climates (See Fig.1). They are also useful in greenhouses, allowing the passage of visible light but not infrared radiation. Typically, these coatings are composed of two dielectric layers and one metal layer, usually silver.

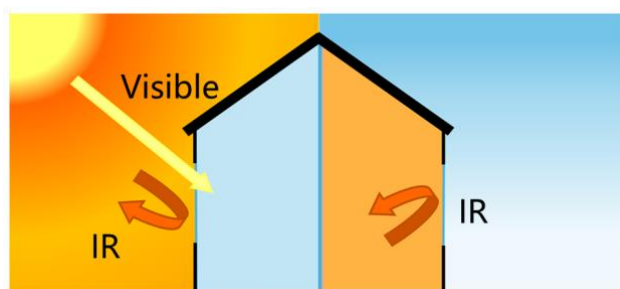


Fig.1. Diagram of the functioning of low-emissivity coatings. Left: summer, right: winter.

To achieve energy performance with these coatings, it is important to know their emissivity, which is often determined through direct measurements with an emissometer or through spectral reflectance measurements in the infrared with a spectrometer. This last method is more common and is based on the principle that, as detailed below, for these coatings, because of the absorbance of the glass in the infrared, transmittance is negligible, so reflectance and emissivity sum to 1:

$$\varepsilon = 1 - R \quad (1)$$

However, this method has a main drawback: for low-emissivity coatings, the associated error can be significant. For example, for the same sample at a given temperature, we obtain two reflection measurements, 99.1% and 99.4%, with a difference due to possible systematic error such as the overestimation or underestimation of the reflectance due to degradation of the calibration reference sample, or due to the misalignment of the measurement system.

The absolute difference between these measurements is 0.3%, which is negligible in relation to the measurements. However, when determining the emissivity applying Eq. (1), we get values of 0.9%

and 0.6%. Although the absolute difference is still 0.3%, the first value is 50% higher than the second, making the relative error no longer negligible.

In previous studies on the optical properties of low-emissive coatings, it was found that a qualitative estimation of emissivity could be obtained by using a thermographic camera. However, most of these methods are either qualitative in nature, rely on complex measurement systems, or show significant limitations when applied to low-emissivity coatings, often resulting in inaccurate measurements [4-7]. This study aims to design and optimize a simple configuration that allows quantitative emissivity measurement for several low-emissivity coatings, directly measuring the radiation emitted by samples with a thermographic camera FLIR AX8, instead of measuring the complementary of emissivity, the reflectance.

Additionally, we aim to develop a method that efficiently classifies the samples based on their emissivity without the need for additional calculations, as it is required with the spectrometer method.

2. Methods

In this section, the emissivity of three low-emissivity coating samples marketed by the Spanish company Ariño Duglass [8], named SuperE, AN62, and AS50, as well as a gold sample (See their structure in Table 1), will be determined using two different methods: traditional reflectance coefficient measurements with a spectrometer and measurements with a thermographic camera. The aim is to compare the results from both methods in order to establish a model that allows us to determine the emissivity based on the apparent temperature measurements obtained with the thermographic camera.

TABLE 1. Structure of the low emissivity coating samples. [9]

Sample	Structure	Thickness (nm)
SuperE	Glass/SnO ₂ -Ag-Ti-SnO ₂	Glass/29-10-1-45
AN62	Glass/SnO ₂ -Ag-Ti-SnO ₂	Glass/24-16-1-49
AS50	Glass/SnO ₂ -Ag-Ti-SnO ₂	Glass/33-21-2-55
Gold	Glass/Au	Glass/80

2.a. Emissivity determination from reflectance with a spectrometer

In this subsection, the procedure to determine the emissivity of a low-emissivity coating from the reflectance coefficients measurements obtained with the spectrometer is detailed.

Theoretical background

This method is based on black body theory, which states that all surfaces of bodies, by being at a certain temperature, emit electromagnetic radiation. A black body is one that absorbs (and emits) all the radiation that falls on it, meaning that there is no reflection or transmission through it [10, 11]. The radiation from a black body, E , at a temperature, T , and for a wavelength, λ , can be described by Planck's equation:

$$E(\lambda, T) = \frac{2hc^5}{\lambda^2} \frac{1}{\exp \frac{hc}{\lambda kT} - 1} \quad (2)$$

where h is the Planck's constant, c is the speed of light and k Boltzmann's constant.

The laws explained earlier apply to the case of the black body; however, real objects rarely follow these laws over a wide range of wavelengths. This is due to three processes: absorption of a fraction of the incident radiation, α (absorptance); reflection of a fraction, R (reflectance); and transmission of a fraction, τ (transmittance). These factors depend on the wavelength, and by energy conservation, their sum equals one:

$$\alpha(\lambda) + R(\lambda) + \tau(\lambda) = 1 \quad (3)$$

According to Kirchhoff's law, for any material in thermal equilibrium, the spectral emissivity, $\varepsilon(\lambda)$, and the spectral absorptance, $\alpha(\lambda)$, are equal: $\varepsilon(\lambda) = \alpha(\lambda)$. Therefore, for materials with negligible transmittance,

$\tau(\lambda) \approx 0$, such as low-emissivity coatings in the thermal infrared, the spectral emissivity can be determined from the spectral reflectance:

$$\varepsilon(\lambda) = \alpha(\lambda) = 1 - R(\lambda) - \tau(\lambda) \approx 1 - R(\lambda) \quad (4)$$

Taking this into account, along with the black body radiation spectrum, Eq. (2), we can integrate over the spectrum to determine the emissivity for a given temperature, T :

$$\varepsilon(T) = \frac{\int_0^\infty E(\lambda, T)[1 - R(\lambda)]d\lambda}{\int_0^\infty E(\lambda, T)d\lambda} \quad (5)$$

Measurement procedure

Taking this into account, to determine the emissivity of low-emissivity coatings, it is necessary to perform reflectance measurements using a spectrometer, in our case *Spectrum 100 FT-IR Spectrometer* from *PerkinElmer*. Next, it is necessary to apply Eq. (5). It is important to highlight that, as mentioned earlier, for these coatings, transmittance is negligible, so this is why it is only necessary to measure the reflectance [12]. Note that for each sample, three measurements were taken in a spectral range from 5 to 50 μm .

2.b. Emissivity measurement with a thermographic camera

For the measurement of emissivity in this subsection, it will be necessary to have a thermographic camera, in our case the FLIR AX8, along with its associated software. Additionally, a heating plate will be required to heat the samples, thus ensuring a temperature difference between the samples and the environment. We will also use a thermocouple to measure the temperature of the plate.

Operation and specifications of the thermographic camera

A thermographic camera is a device that measures temperature and provides a thermal image of objects without the need of contact, based on the thermal radiation emissions from these objects, which increase as the object's temperature rises. In this way, it allows us to obtain the apparent temperature of a sample, that we will relate to its emissivity.

The camera we will use, the model FLIR AX8, has a resolution of 0.1°C and it can measure within a range of 10°C to 180°C. Its spectral detection range is between 6 and 15 μm ; however, the responsivity, $S(\lambda)$, which has been provided by the camera designer, varies across this range. It is important to note that, since the spectral range is narrow, the emissivity in this wavelength range does not depend on temperature [13].

The total radiation power received by the camera, W_{tot} , can be expressed as:

$$W_{tot} = \varepsilon_{obj}\tau_{atm}W_{obj} + (1 - \varepsilon_{obj})\tau_{atm}W_{refl} + (1 - \tau_{atm})W_{atm} \quad (6)$$

Where the term $\varepsilon_{obj}\tau_{atm}W_{obj}$ is the radiation power from the object, being ε_{obj} and τ_{atm} the emissivity of the object and the transmissivity of the atmosphere and W_{obj} the power emitted by a black body at the temperature of the object, T_{obj} ; $(1 - \varepsilon_{obj})\tau_{atm}W_{refl}$ the radiation power from the environment reflected through the object's surface, being W_{refl} the power emitted by a black body at the temperature of the surroundings; and $(1 - \tau_{atm})W_{atm}$ the radiation power from the atmosphere, being W_{atm} the power emitted by a black body at the temperatures of the atmosphere, T_{atm} .

When the radiation power from a black body, W , at a temperature T_{source} strikes the detector, it generates an output signal, U , related to W by an unknown constant C . However, we know that this signal is proportional to the power emitted by the black body, weighted by the camera's responsivity $S(\lambda)$:

$$U \propto \int_0^\infty E(\lambda, T)S(\lambda)d\lambda \quad (7)$$

Through a fitting process, we can obtain the polynomial dependence of the signal as a function of temperature, as we can see in Fig. 2.

Knowing the dependence of U on the temperature, we can rewrite Eq. (6) as follows:

$$U_{tot} = \varepsilon_{obj}\tau_{atm} U_{obj} + (1 - \varepsilon_{obj})\tau_{atm}U_{refl} + (1 - \tau_{atm})U_{atm} \quad (8)$$

where U_{tot} , U_{obj} , U_{refl} and U_{atm} are the respective signals associated with W_{tot} , W_{obj} , W_{refl} and W_{atm} .

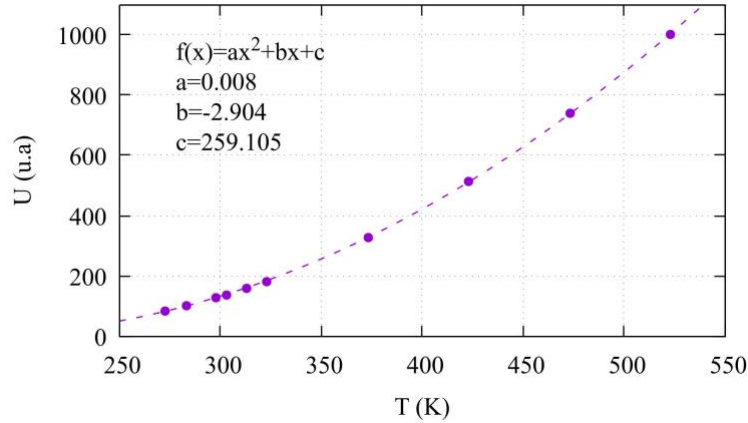


Fig.2. Fitting of the camera's output signal as a function of temperature.

Thus, the camera generates a signal from the received radiation power, U_{tot} . By providing the temperature of the atmosphere, T_{atm} , and the surroundings, T_{refl} , the camera calculates U_{atm} and U_{refl} applying the fitting procedure shown in Fig. 2. With these values, along with the emissivity of the object, ε_{obj} , and the transmittance of the atmosphere, τ_{atm} , the camera obtains U_{obj} by rearranging Eq. (8). Using the inverse process of the fitting procedure in Fig. 2, the camera determines the object's temperature, T_{obj} , which is the output value provided by the camera. Note that measurements with the camera are performed using a software associated with the camera.

Note that in the setup used, which will be detailed later, the camera-object distance is less than one meter. Consequently, the contribution of atmospheric radiation is negligible, implying $\tau_{atm} = 1$, therefore Eq. (8) becomes:

$$U_{tot} = \varepsilon_{obj}U_{obj} + (1 - \varepsilon_{obj})U_{refl} \quad (9)$$

Derivation of the emissivity formula

The operation of the camera to determine a body's temperature has been explained. However, the aim of this work is to determine the emissivity, so we are going to derive the formula to determine it.

To do this, we must first assume that on the heating plate we have a sample with emissivity, ε'_{obj} , that we want to determine. We provide the camera with random values for emissivity, ε_{obj} , and ambient temperature T_{refl} , such that if we measure the apparent temperature of the sample, we will obtain a value, T_{obj} that is either lower or higher than its actual temperature, T'_{obj} . The total signal received by the camera will be given by Eq. (9), where U_{refl} and U_{obj} are the signals corresponding to the temperatures T_{refl} and T_{obj} .

Now, if the emissivity provided to the camera is the actual emissivity of the sample, ε'_{obj} , and the ambient temperature we have set is the actual one, T'_{refl} , the temperature reported by the camera would be the temperature of the sample, T'_{obj} . The radiation reaching the camera, and thus the generated signal, would remain the same, since even though we have varied the parameters, the sample is still at the same temperature. The expression for this case is the following:

$$U_{tot} = \varepsilon'_{obj} U'_{obj} + (1 - \varepsilon'_{obj}) U'_{refl} \quad (10)$$

with U'_{obj} and U'_{refl} being the signals associated with T'_{obj} and T'_{refl} . If we equate the equations from the total signals, U_{tot} , from Eq. (9) and Eq. (10), we can isolate the value of the emissivity of the sample that we want to determine, ε'_{obj} :

$$\varepsilon'_{obj} = \frac{\varepsilon_{obj}(U_{obj} - U_{refl}) + U_{refl} - U'_{refl}}{U'_{obj} - U'_{refl}} \quad (11)$$

Measurement procedure

Next, we are going to establish the procedure for measuring emissivity. First, it will be necessary to cover the heating plate with a layer of aluminum foil to prevent overheating of the camera, as aluminum is low emissive. This also reduces the effect of radiation from the plate. Next, the camera is placed on a stand, raising the front part of the camera by about 45° to avoid camera reflections. In terms of height, it is situated approximately 70 cm away, as this reduces variation in the measurements. It is also important to note that the samples should be measured in the same position. The setup for the measurements is shown in Fig. 3.

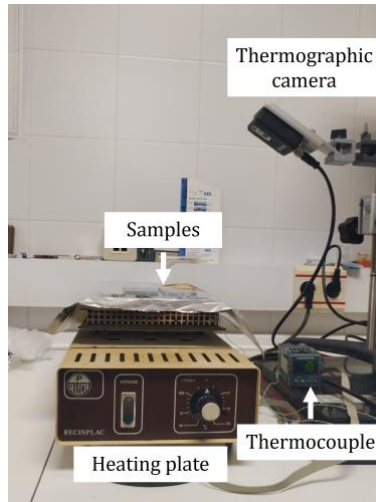


Fig.3. Setup for emissivity measurement with a thermographic camera.

The measurement process is as follows: an arbitrary emissivity ε is set in the camera program, and an ambient temperature, T_{refl} , which, as explained before, does not have to match the actual temperature. A glass sample is placed on the heating plate, along with the coatings we want to measure, since the actual temperature of the samples, T'_{obj} , is measured by placing a surface thermocouple on the glass surface. Using the camera, the apparent temperature of each sample, T_{obj} , and the actual ambient temperature, T'_{refl} , are measured at the beginning of each measurement.

With these temperatures, the corresponding signals are obtained: U_{refl} , U'_{obj} , U_{obj} and U'_{refl} , according to the fit shown in Fig. 2. Using these signals and the emissivity set in the camera, ε_{obj} , the emissivity value is obtained by applying Eq. (11).

Note that the measurements were made allowing the sample temperature to stabilize for about three hours, reaching a value of 110°C since it was determined that the emissivity measurements were better when taken this way.

3. Results

This section presents the results obtained in the emissivity measurement process of the SuperE, AN62, AS50, and gold samples using both measurement methods, which allow establishing a model that relates

them. Finally, to verify the validity of this model, emissivity measurements will be performed on three new samples called AS40, DAG66, and Bronze.

3.a. Analysis of results

In Table 2, we can observe the emissivity results obtained with the spectrometer and with the thermographic camera. As we can see, the results obtained with the camera are higher than those obtained with the spectrometer (except gold), which we will consider as valid. These differences may be due to the fact that, when measuring with the camera, we might have disregarded some radiation contribution, such as an internal contribution from the camera, which may have heated during the measurements.

Note that the error associated with the camera measurements is due to the variation in emissivity when modifying the apparent temperature of the samples, T_{obj} by 0.1 °C, which is the variation in apparent temperature measurements when at a stable temperature. In the case of the spectrometer error, it is given by the standard deviation, as three measurements were taken with the spectrometer.

TABLE 2. Comparison of emissivity measured with the spectrometer and with the thermographic camera.

Sample	Spectrometer	Thermographic camera
SuperE	0.05208 ± 0.00012	0.063 ± 0.004
AN62	0.0334 ± 0.0002	0.040 ± 0.004
AS50	0.0233 ± 0.0009	0.030 ± 0.004
Gold	0.013 ± 0.002	0.003 ± 0.004

However, we can observe that these measures do allow us to qualitatively rank the emissivity values. In fact, this can be done simply by taking the apparent temperature of the samples, as we can see in Fig. 4, where the highest apparent temperature is that of the gold sample.

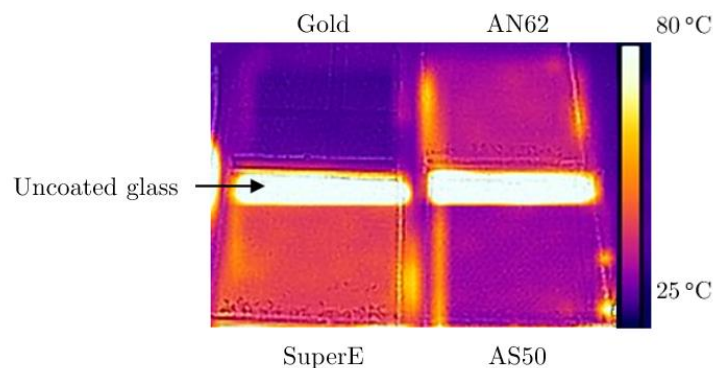


Fig.4. Image taken with the thermographic camera. Comparison of apparent temperatures.

3.b. Model establishment

In Fig. 5, we can observe a representation of the emissivity obtained with the camera as a function of that obtained with the spectrometer.

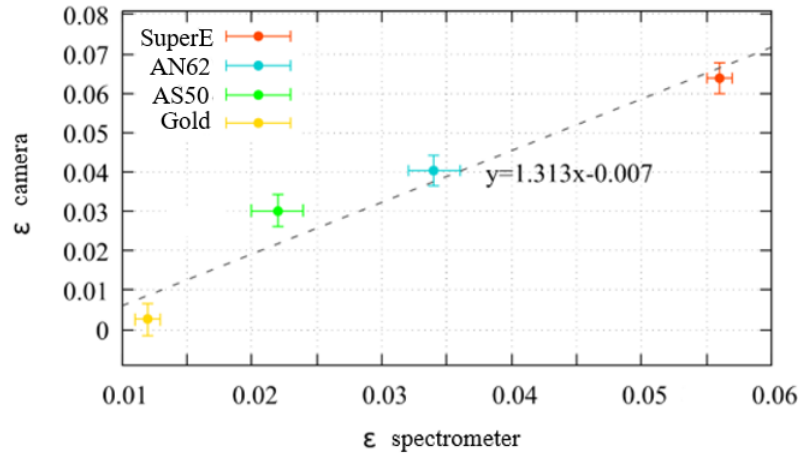


Fig.5. Representation of the emissivity obtained with the camera as a function of that obtained with the spectrometer for the samples SuperE, AN62, AS50 and gold.

We will consider this linear dependence and propose a model for determining emissivity that requires prior calibration, given by the adjustment of the samples with known emissivity, in our case SuperE, AN62, AS50, and gold. This provides us with a linear fit with slope m and intercept n . Once the adjustment is made, the emissivity of the test samples—AS40, Bronze, and DAG66—will be determined using the camera, and will be denoted as ϵ_c . The corrected emissivity, ϵ_a , will be given by the following expression:

$$\epsilon_a = \frac{\epsilon_c - n}{m} \quad (12)$$

3.c. Model validation

Taking the above into account, we determined the emissivity of the three validation samples and compared them with their actual values in Table 3.

TABLE 3. Comparison of the corrected emissivity of the validation samples with the spectrometer emissivity.

Sample	Spectrometer	Thermographic camera
AS40	0.036 ± 0.004	0.038 ± 0.009
DAG66	0.0328 ± 0.0005	0.035 ± 0.009
Bronze	0.0694 ± 0.0014	0.066 ± 0.012

We can observe that the results obtained with the camera are within less than one σ of error from those of the spectrometer. Regarding the error of the corrected emissivity, it is determined by the calibration fit error.

Finally, in Fig. 6, we represent the emissivities of the verification samples alongside the fit from Fig. 5, and as we can see, the three points align with the expected results, enabling us to confirm that the linear dependency model we proposed is valid.

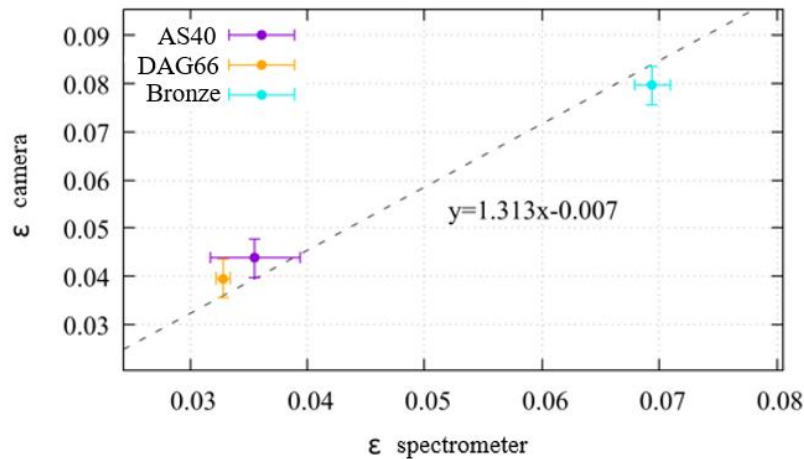


Fig.6. Representation of the emissivity obtained with the camera as a function of that obtained with the spectrometer for the validation samples AS40, DAG66 and Bronze.

4. Conclusions

With the completion of this work, a measurement procedure has been designed, and a model has been established. This model allows measuring the emissivity of low-emissivity coatings, obtaining valid results, without the need to measure reflectance, by directly measuring the radiation emitted by the sample.

This procedure presents several advantages over the spectrometer. The first advantage is that, without needing to perform any calculations, simply by measuring the apparent temperature of the samples, they can be ordered based on their emissivity. It is also important to note that, unlike the spectrometer, the thermographic camera allows for simultaneous emissivity measurements. Additionally, the necessary equipment for this method (heating plate and thermographic camera) is more affordable than the spectrometer.

As for potential improvements for future work, it is suggested to try to estimate at which fixed temperatures the best results are obtained after allowing the samples to stabilize.

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