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Thermography Applications in the Study of Buildings Hygrothermal Behaviour

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1. Introduction

Infrared thermography (IRT) can be defined as the science of acquisition and analysis of data from non-contact thermal imaging devices. The process of thermal imaging has simplified over the years with the availability of efficient, high resolution infrared cameras that convert the radiation sensed from the surfaces into thermal images (Rao, 2008). Thermography literally means "writing with heat", just as photography implies "writing with light". The invisible infrared radiation emitted by bodies is converted into temperature and displayed as thermal images, the thermographs.

Infrared thermography is a powerful tool for engineers, architects and consultants for use in evaluating existing buildings and structures. Infrared thermography is a fast and reliable tool to assist in identifying potential problems in existing buildings.

Infrared thermography offers several advantages in condition surveying. Recent developments in thermography and image processing made the technique a valuable addition to the repertoire of nondestructive testing methods. Thermography is a non-contact, non-destructive technique. While the potential exists, thermography has not yet been utilized extensively in the assessment of monuments and ancient structures. Condition surveys by conventional techniques cannot detect the presence and source of moisture readily, require access to the surfaces, and are expensive and time consuming. On the other hand, IRT offers a rapid method for assessing large surfaces without the need of a scaffold to reach the area under investigation.

2. A brief history of infrared thermography

Thermography has a long history, although its use has increased dramatically with the commercial and industrial applications of the past fifty years. Sir William Herschel, an astronomer, discovered infrared in 1800. He built his own telescopes and was therefore very familiar with lenses and mirrors. Knowing that sunlight was made up of all the colours of the spectrum, and that it was also a source of heat, Herschel wanted to find out which colour(s) were responsible for heating objects. He devised an experiment using a prism, paperboard, and thermometers with blackened bulbs where he measured the temperatures of the different colours. Herschel observed an increase in temperature as he moved the

thermometer from violet to red in the rainbow created by sunlight passing through the prism. He found that the hottest temperature was actually beyond red light. The radiation causing this heating was not visible; Herschel termed this invisible radiation "calorific rays". Today, we know it as infrared.

Approximately thirty years after the infrared discovery the first detector using this type of radiation was developed. This first infrared detector was based in the same principles of the thermocouples and it was referred as “Thermopiles”. In 1880, the discovery of bolometers (materials whose electrical resistance changes with temperature) allowed a significant improvement in sensitivity for infrared rays detection.

Between 1870 and 1920, the technology advance allowed the development of the first quantum detectors, based on the interaction between radiation and matter. The detection nature was changed, because the electrical signal created by the effect of thermal radiation finished and now there is a direct conversion of radiation into electrical signals. With this type of detector the response time was reduced considerably and measurement accuracy was increased.

Between the decades of 30 and 60 several infrared detectors were developed, essentially for military purposes. The wavelengths range that the infrared detectors were sensitive depended on the materials used in its manufacture: Lead sulphide (PbS) sensitive in the range between 1.5 to 3 μm; Indium antimonide (InSb) sensitive in the range between 3 to 5 μm; and Mercury - Cadmium - Tellurium (HgTeCd) sensitive in the range between 8 to 14 μm. All these detectors were working with optical-mechanical scan systems and requiring cryogenic cooling.

The first commercial infrared cameras appeared in the end of 60's. In the '90s a new generation of equipment with array detectors appeared in the market. These new equipments allowed a simultaneous temperature reading at different points and did not require cryogenic cooling systems.

An infrared camera is a non-contact device that detects infrared energy (heat) and converts it into an electronic signal, which is then processed to produce a thermal image on a video monitor and perform temperature calculations. Heat sensed by an infrared camera can be very precisely quantified, or measured, allowing you to not only monitor thermal performance, but also identify and evaluate the relative severity of heat-related problems. Recent innovations, particularly detector technology, the incorporation of built-in visual imaging, automatic functionality, and infrared software development, deliver more cost-effective thermal analysis solutions than ever before. Digital image storage produces calibrated thermal images that contain over 78000 independent temperature measurements that can be measured at any time.

2.1 Infrared thermography applied to building physics

It is essential that studies be performed to evaluate the performance of building materials, especially nowadays when new materials and techniques with unknown characteristics are often being used. These studies are a step towards improving technical solutions and regulations to ensure the building’s durability and to guarantee user comfort and satisfaction.

Most material pathologies are related with temperature action. Therefore, measuring a material's temperature is crucial for understanding the causes of those defects. The use of non-destructive techniques to test a building material may be very useful by making it possible to evaluate a material behaviour without destroying it and without interfering with the users' life (Avdelidis and Moropoulou, 2004; Grinzatoa *et al*., 1998 and Haralambopoulos and Paparsenos, 1998).

Infrared thermography is a non-destructive testing technology that can be used to determine the superficial temperature of objects. Cameras collect infrared radiation emitted by the surface, convert it into electrical signals and create a thermal image showing the body's superficial temperature distribution (NEC, 1991). In this process, each shade expresses a specific temperature range (see Figure 1).



Fig. 1. Thermogram and visible image of the Carmo Church's façade covered with "azulejos" (ceramic tile) in Porto.

This technology has been applied to buildings for a couple of decades, to evaluate the building performance. According to Hart (1991) thermography can be used to detect insulation defect, air leakage, heat loss through windows, dampness and "hidden details" (subsurface pipes, flues, ducts, wall ties, etc.). It can also be used for examination of heating systems and preventive maintenance.

Despite thermography's potential uses to buildings, its application to building materials has not been greatly studied yet. The parameters that may affect measurements aren't completely understood and interpreting the results becomes difficult and confusing.

The main objective of this work was to evaluate the applicability of thermography in order to study the behaviour of building materials. To do so, some simple experiments were carried out at the Building Physics Laboratory (LFC) of the Engineering Faculty of Porto University (FEUP).

A sensibility study was performed with LFC's equipment to evaluate how measurements are influenced by emissivity, environmental conditions (temperature and relative humidity), colour and reflectivity. It was also possible to visualise the wetting and drying process of specimens, as water evaporation is an endothermic reaction inducing local surface cooling. And, lastly, the comfort of some interior floor coatings was evaluated by comparing thermal images obtained from the sole of a barefoot after having been in contact with different materials.

3. Fundaments of infrared thermography

3.1 The electromagnetic spectrum and the infrared rays

Infrared energy is part of the electromagnetic spectrum and behaves similarly to visible light. It travels through space at the speed of light and can be reflected, refracted, absorbed, and emitted. The wavelength (λ) of infrared energy is about an order of magnitude longer than visible light, between 0.7 and 1000 μm. Other common forms of electromagnetic radiation include radio, ultraviolet, x-ray and γ-ray (see Figure 2).

The electromagnetic spectrum is the range of all possible frequencies of electromagnetic radiation. It is the characteristic distribution of electromagnetic radiation emitted or absorbed by that particular object. The electromagnetic spectrum extends from low frequencies used for modern radio to gamma radiation at the short-wavelength end, covering wavelengths from thousands of kilometers down to a fraction of the size of an atom. The long wavelength limit is the size of the universe itself, while it is thought that the short wavelength limit is in the vicinity of the Planck length, although in principle the spectrum is infinite and continuous.

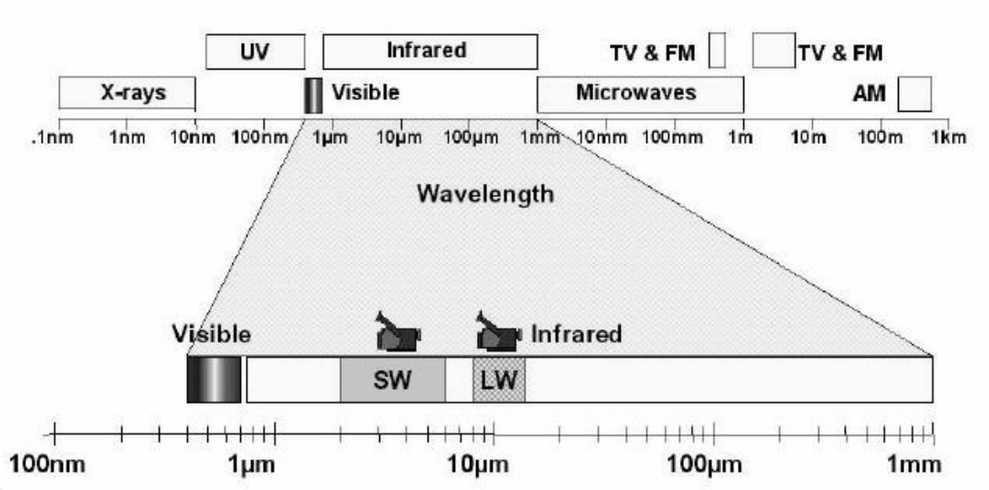


Fig. 2. Electromagnetic Spectrum.

The infrared part of the electromagnetic spectrum covers the range from roughly 1000 μm to 0.75 μm. It can be divided into three parts: far-infrared, from 1000 μm to 20 μm, mid-infrared, from 20 μm to 1.5 μm and near-infrared, from 1.5 μm to 0.75 μm.

3.2 Radiation emitted by a surface

The study of the radiation emitted by real surfaces is related with the concept of blackbody. A blackbody is an ideal surface that absorbs all incident radiation, regardless of wavelength and direction. The blackbody is a diffuse emitter and no other surface can emit more radiation than it, for a certain temperature and wavelength (Incropera and Witt, 2001).

Although there are no perfect absorbers or emitters, in a practical point of view there are two possible ways to guarantee the blackbody behaviour:

- A cavity with a small aperture, whose inner surface is at uniform temperature. If radiation enters the cavity it can be considered almost entirely absorbed as it will experience many reflections before coming out.
- A surface coating with very high absorbance.

The spectral emissive power of the blackbody is ruled by the Plank distribution (Gaussorgues, 1999):

$$\frac{dR(\lambda,T)}{d\lambda} = \frac{2.\pi.h.c^2.\lambda^{-5}}{\exp\left(\frac{h.c}{\lambda.k.T}\right)-1} \tag{1}$$

where $dR(\lambda,T)/d\lambda$ is the spectral radiance or emissive power per unit area of the blackbody and wavelength, h is the Planck constant (h=6.626176x10^{-34} Js), k is the Boltzmann constant (k=1.380662x10^{-23} J/K), c is the speed of light (c=2.998x10^{8} m/s), λ is the wavelength (m) and T is the temperature (K).

The Planck distribution can be plotted as a family of curves, considering a certain temperature (see Figure 3). From the Planck distribution it is possible to note that the emissive power is zero when the wavelength is zero, it increases continuously with wavelength until a maximum is achieved, corresponding to a wavelength λ_{max}. At any wavelength the emitted radiation increases with temperature (Incropera and Witt, 2001).

The value of the wavelength λ_{max}, corresponding to the maximum emissive power for a certain temperature, is given by the Wien Law that is plotted by the curve in Figure 4.

$$\lambda_{max} = \frac{2898}{T} \tag{2}$$

According to Eq. (2), the maximum spectral emissive power is displaced to shorter wavelengths with increasing temperature. For solar radiation, emitted at a temperature around 6 000 K, the maximum emissive power occurs for a wavelength around 0.50 μm, in the middle of the visible spectrum. For blackbodies emitting at a temperature near the temperature of terrestrial surfaces, around 300K, the peak emission occurs at 10 μm and for the liquid nitrogen (T = 77 K) the peak emission occurs at 40 μm, both in the infrared spectrum.

The Stefan-Boltzmann law results from the integration of the Planck distribution in the domain [λ = 0; λ = ∞] and it allows calculating the total amount of radiation emitted by the blackbody at a certain temperature T (in every direction and over all wavelength) (Incropera and Witt, 2001).

$$R_t = \sigma.T^4 \tag{3}$$

where R_t is the total blackbody spectral radiance, σ is the Stefan-Boltzmann constant ($\sigma = \left(2.\pi^5.k^4\right)/\left(15.c^2.h^3\right) = 5.67\times10^{-8}$ W/m^{2}K^4) and T is the temperature (K).

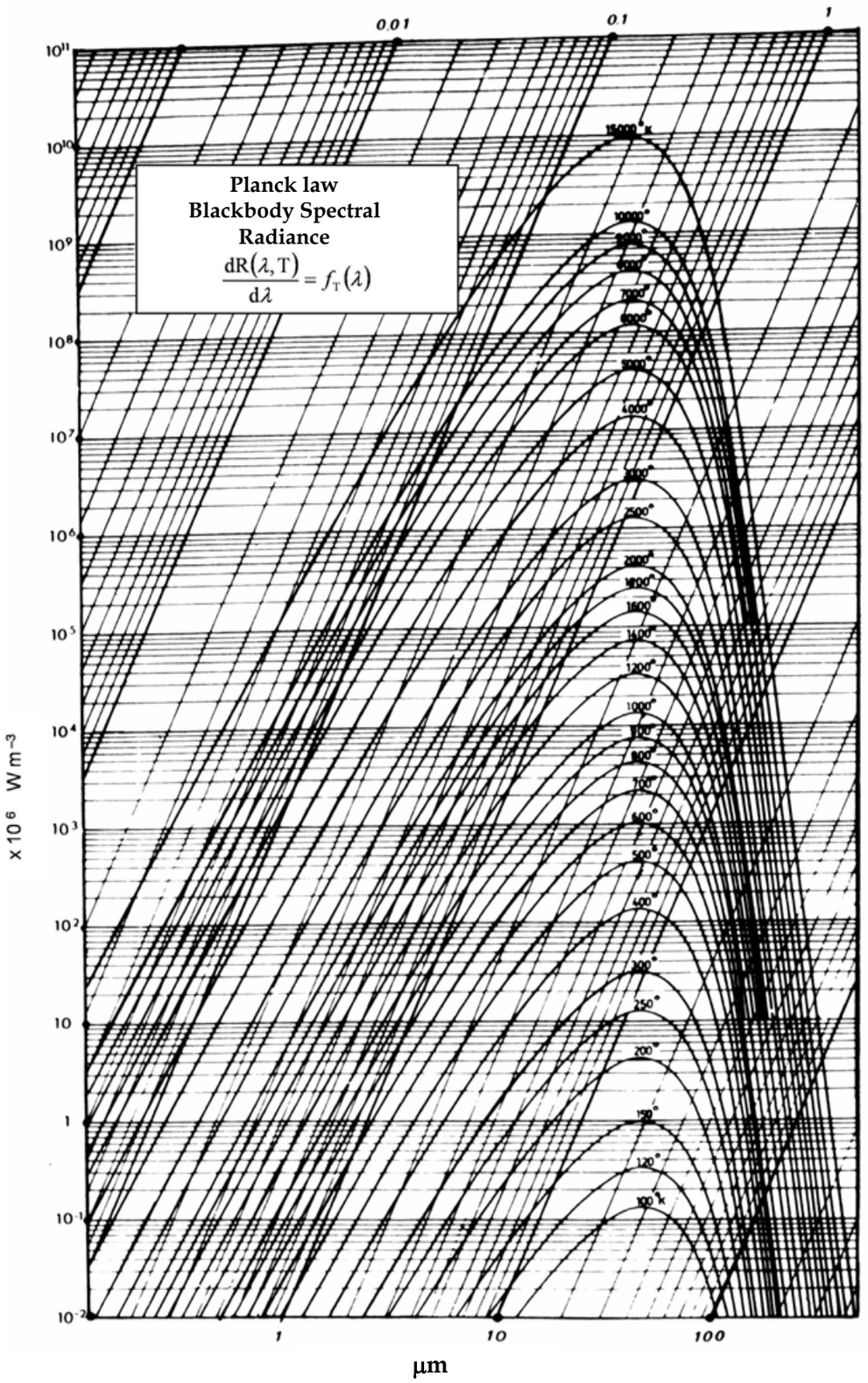


Fig. 3. Blackbody spectral radiance by Planck law.

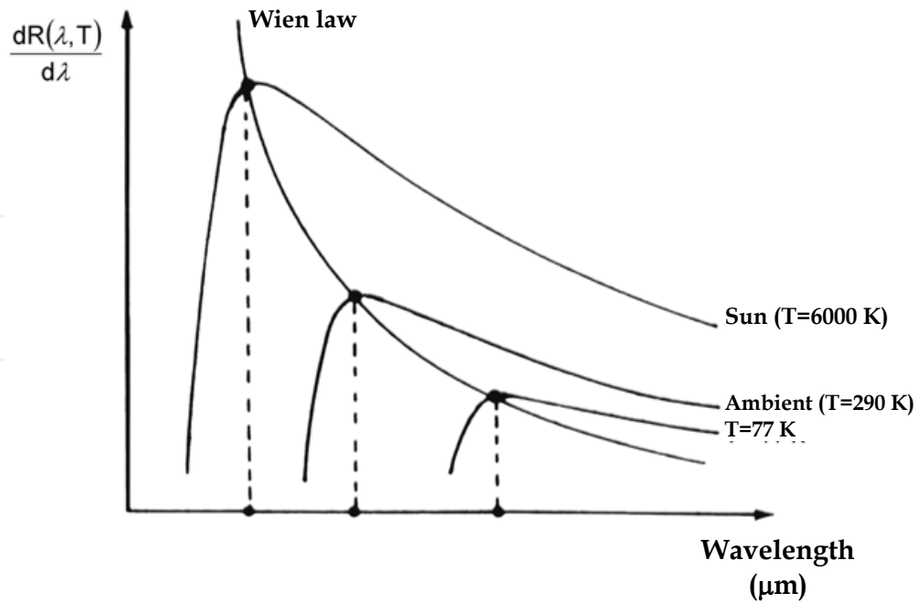


Fig. 4. Wien law (Gaussorgues, 1999).

Normally real surfaces don't behave like a blackbody. The property that traduces the emissive capacity of a real surface is emissivity (ε) that can be defined as the ratio of the radiation emitted by the surface to the radiation emitted by a blackbody at the same temperature (Incropera and Witt, 2001).

$$\varepsilon(\lambda) = \frac{\frac{dR(\lambda,T)}{d\lambda}}{\frac{dR_{cn}(\lambda,T)}{d\lambda}} \tag{4}$$

When the spectral component of the radiant energy interacts with a semitransparent surface, part of the radiation may be reflected, absorbed and transmitted (see Figure 5). The reflectivity (ρ) is a property that determines the fraction of the incident radiation that is reflected by the surface, the absortivity (α) is a property that determines the fraction of the irradiation absorbed by the surface and the transmissivity (τ) is the property that determines the fraction of the irradiation that is transmitted through the surface. Theses parameters depend on the wavelength, but for the same wavelength they are equal to one (Hagentoft, 2001).

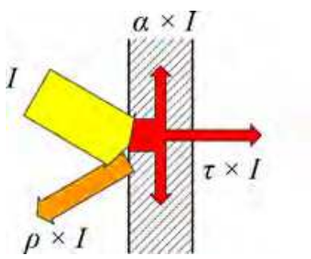


Fig. 5. Radiant energy interacting with a semitransparent surface.

$$\alpha(\lambda) + \rho(\lambda) + \tau(\lambda) = 1 \tag{5}$$

where $\alpha(\lambda)$ is the spectral absorption for a given wavelength, $\rho(\lambda)$ is the reflection spectrum for a given wavelength and $\tau(\lambda)$ is the spectral transmittance for a given wavelength.

According to the Kirchhoff Law, at thermal equilibrium, the emissivity of a surface equals its absorptivity (Incropera and Witt, 2001).

$$\alpha(\lambda) = \varepsilon(\lambda) \tag{6}$$

Considering Kirchhoff Law, Eq. (5) can be rewrited as:

$$\varepsilon(\lambda) + \rho(\lambda) + \tau(\lambda) = 1 \tag{7}$$

Some materials present specific values for these parameters:

Blackbody	$\varepsilon(\lambda) = 1$	$\rho(\lambda) = 0$	$\tau(\lambda) = 0$
Transparent surface	$\varepsilon(\lambda) = 0$	$\rho(\lambda) = 0$	$\tau(\lambda) = 1$
Perfect mirror	$\varepsilon(\lambda) = 0$	$\rho(\lambda) = 1$	$\tau(\lambda) = 0$
Opaque surface	$\varepsilon(\lambda) + \rho(\lambda) = 1$		$\tau(\lambda) = 0$
Grey body	$\varepsilon(\lambda) =$ constant		

The non-blackbody emitters for which the emissivity is constant regardless wavelength are called grey bodies. The total amount of radiation emitted by the grey body can be calculated using the Stefan-Boltzmann law and considering the emissivity of the surface, ε.

$$R_t = \varepsilon.\sigma.T^4 \tag{8}$$

3.3 The surface emissivity affecting infrared thermography measurements

Emissivity depends on the wavelength (λ), direction (θ) and temperature (T).

$$\varepsilon = f(\lambda, \theta, T) \tag{9}$$

Generally, for solid materials spectral emissivity don't varies significantly but for liquids and gases the fluctuations are more obvious. For metals, spectral emissivity reduces with wavelength and for non-metals it tends to increase.

The angular dependence of emissivity implies different apparent emissivity's for a non-plane surface. For non-metals the emissivity is high and almost doesn't change for angles between 0^o and about 60^o from the perpendicular. After 70^o its value quickly declines. For metal the emissivity values are lower and practically constant between 0^o and 40^o, increasing rapidly for higher angles.

Most materials used in buildings are characterized by having emissivity independent from the direction (diffuse surface) and wavelength (a behavior that is similar to the grey body). For that reason, for these materials emissivity can be assumed as constant, for a certain temperature, being quantified considering the normal to the surface and all wavelengths (Hart, 1991):

$$\varepsilon_t = \frac{\int_0^\infty \varepsilon(\lambda)\frac{dR(\lambda,T)}{d\lambda}.d\lambda}{\int_0^\infty \frac{dR(\lambda,T)}{d\lambda}.d\lambda} = \frac{1}{\sigma T^4}\int_0^\infty \varepsilon(\lambda)\frac{dR(\lambda,T)}{d\lambda}.d\lambda \quad (10)$$

The emissivity calculated by Eq. (10) is termed total emissivity and is defined as the ratio of the total energy emitted by the surface to the total energy emitted by a blackbody at the same temperature. Metals present lower values for total emissivity that increases with temperature. Oxide formation on the metal surface changes considerably emissivity. Non-metals have higher total emissivity, normally above 0.80, decreasing with temperature.

Over the temperature range experienced by buildings, from -10º C to 60º C, the temperature dependence of the emissivity can be, however, ignored and there are several databases of emissivity values in the literature. Table 1 presents some examples for metals and non-metals.

Material	Temperature (º C)	Emissivity
Stainless steel	25 - 100	0.79 – 0.80
Steel, non-oxidized, polished	100	0.07 – 0.08
Aluminum, non-oxidized, polished	0 - 100	0.03 – 0.06
Water	0 - 100	0.93 – 0.98
Concrete	-	0.92 – 0.94
Ceramic	21	0.93
White paper	20	0.70 – 0.95
Limestone	38	0.95
Human skin	32	0.98

Table 1. Emissivity of some materials.

Although the availability of emissivity values in the literature, for more accurate results it may be necessary to know the real value of total emissivity for the surface under study. In these cases, some simple methods can be used to define its value.

One of the most common methods consist in measuring the surface temperature using, for example, a thermocouple and adjust the emissivity value of the surface in a manner that the temperature measured by the infrared camera is equal to the one obtained by the thermocouple.

It is also possible to cover on the surface some tape with very high absorption or to paint black a small area of it. After thermal equilibrium is achieved, the temperature on the coated surface is measured, considering emissivity close to 1, as well as the surface that is not coated with the tape or the paint. As the temperature on the two surfaces must be similar, emissivity of the surface must be adjusted until equal values are achieved.

3.4 Other factors affecting infrared thermography measurements

The material reflectivity may cause some problems in infrared radiation measurements. The energy captured by the receptor, resulting from the radiation emitted by the body at temperature T_0, results by the following three effects (see Fig. 6):

- The body reflects a fraction of the energy emitted by the atmosphere, equal to the enegy emitted by a blackbody at temperature T_a.
- If the body is partially transparent, transmits a fraction of the radiation emitted by the background, equal to the energy emitted by a blackbody at temperature T_f.
- The body emits radiation to be at temperature T_0.

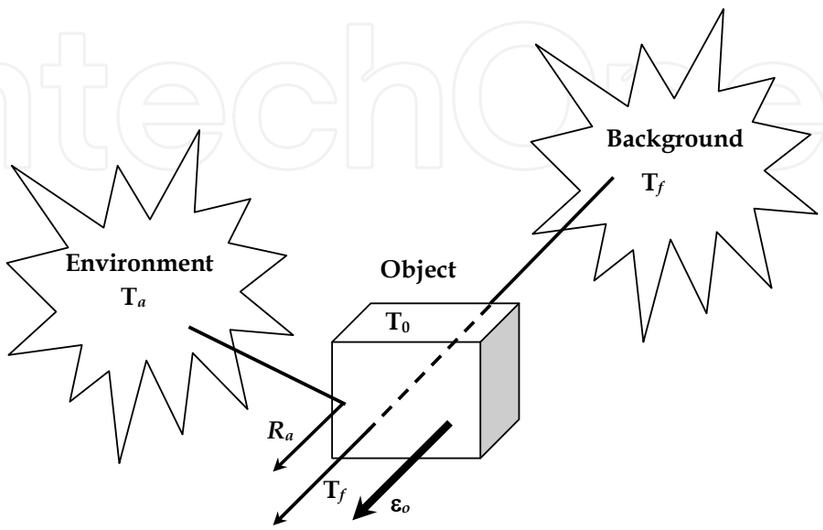


Fig. 6. Factors affecting infrared thermography measurements.

If the purpose of measuring is to determine the object temperature, T_0, from the detected infrared radiation in a spectral range, $\Delta\lambda$, then:

$$R_{\text{det}} = \int_{\Delta\lambda} \rho_a(\lambda)\frac{dR(\lambda,T_a)}{d\lambda}.d\lambda + \int_{\Delta\lambda} \tau_f(\lambda)\frac{dR(\lambda,T_f)}{d\lambda}.d\lambda + \int_{\Delta\lambda} \varepsilon_0(\lambda)\frac{dR(\lambda,T_0)}{d\lambda}.d\lambda \qquad (11)$$

To determine T_0 it is necessary to know the first two terms of Eq. (11) and the body spectral emissivity, $\varepsilon_0(\lambda)$. However, this problem may be simplified if the body is opaque, $\tau_f(\lambda) = 0$, which neglect the second term of Eq. (11). On the other hand, if T_0 is greater than T_a, the first term of Eq. (11) may be neglected, and we only need to know the body emissivity, $\varepsilon_0(\lambda)$.

However, if the body is surrounded by other bodies at different temperatures, greater than the object in study, the term related to its emission, function of its temperature T_0 and emissivity ε_0, is affected by an error due to reflection by this body of the radiation emitted by objects that surround him, with temperature T_a and emissivity ε_a. If ρ_a is the reflection factor of the body in study, the new term is proportional to T_a, ε_a and ρ_a, and assumes a great importance if T_a is greater than T_0 and ρ_a not equal to zero (Gaussorgues, 1999).

Although thermal reflections are common, they can be easily identify during the measurements, as their appearance in the thermal image, as cold or hot areas, will change its relative position depending on the angle of the camera. Once identified, their sources can be eliminated. If surfaces have very low emissivity, like metals, the thermal image will be almost made up of reflected radiation. In this case, the entire counter reflected radiation must be considered in other to estimate the surface temperature. Other solution is to change

the surface characteristics, by covering it with paint or tape prior to the measurement (Hart, 1991).

The atmosphere presence between the emission source and the sensor causes disturbances in the measurement. In addition to the attenuation resulting from propagation in the atmosphere, the temperature gradients and turbulence create inhomogeneities in the air refractive index, which cause degradation of image quality. The atmospheric attenuation is the cause of major problems during the measurement because it entails a systematic error, which depends on the spectral range used, the observation distance and weather conditions. For these reasons, the measurements taken at distances great than 10 m should be corrected.

The thermal image of an object depends on the heat transfer between the surface and surroundings. If there are no external heat sources, the surface temperature of a building element is a function of temperature difference between inside and outside and the heat resistance of the various layers.

It is very important to know all the building element layers, the physical phenomenon of heat transfer and ensure that no unexpected thermal influences appeared. On the other hand, if the temperature difference between inside and outside increase the heat flow across the building element increase and the thermal image shows areas with lower thermal resistance. The temperature difference should be taken into account during the results analyse.

The convective heat flux, through or around the buildings, is a result mainly from heating and cooling areas, chimney effect and wind. The upward movement of warm air from radiators or other heat sources and and the cold air down from the windows, can cause distortions in surface temperatures. The chimney effect causes infiltrations on the lower floors and exfiltrations on the upper floors. This phenomenon causes the cooling of the walls on the lower floors and heating the upper floors.

The wind, blowing at a significantly speed, also affects the thermal images. The positive pressure on the façade facing the wind originates air infiltration and negative presures on the remaining façades cause air exfiltration. It is not necessary for the air to completely cross the building envelope to affect surface temperatures, since the air flow on the outer surface of the façade reduces its surface thermal resistance, cooling it down. This effect is differential, since the cooling is higher at the corners.

As the wind or the stack effect, also the mechanical pressurization or depressurization of a building distorts the distribution of surface temperatures of the building element. The pressurization increases the defects when viewed from the outside and smoothes them when viewed from the inside. The opposite occurs when the building is depressurized. The pressure difference in the façade is therefore quite relevant when conducting thermographic testing. In some cases, buildings can even be pressurized or depressurized mechanically, just to highlight the flaws and make them easier to detect.

For a study inside a building, air draughts directed to the area to be measured resulting for example from an open window or vents should be avoided.

The moisture resulting from surface condensation also has a considerable effect on the temperature of the studied element, as it changes the local transmission of heat and causes

evaporative cooling. This phenomenon is more severe in areas where there are construction defects, such as thermal bridges or lack of thermal insulation. It is essential to take account of their existence in a later analysis.

A strange heat source and perhaps the most important from the outside is the sun. On clear days, the heat radiated by the sun to the building's façade conceals completely the results of heat transfer through the surrounding. The information obtained inside can also be affected, not only due to heating of the exterior façade, which changes the normal flow of heat from inside to the outside, but also due to the direct effect of sunlight on the surface under study, through the windows. To avoid this interference, the windows must be totally shaded some time before the test begins.

Even on a cloudy day, the diffuse solar radiation can affect the thermal patterns of the exterior of the building. For these reasons, the tests usually are performed outside at night, while the tests conducted indoors take place at night or on overcast days.

The existence of heat sources near the measurement area, such as radiators, artificial lights, vehicles, equipment and people running, may affect the results. The severity of the interference from these sources depends on their radiative power and reflection from the surface under study. The radiation emitted by people is not usually a problem, unlike radiators, lights and machinery, which must be disconnected before the test begins and then have to be taken into consideration when analyzing the results.

The existence of shadows on the building, resulting from the presence of other buildings, trees or other neighboring elements can lead to wrong conclusions if not taken into account when analyzing the results, since highly complex phenomena can provoque change in the heat transfer to the façade.

The distance is another parameter that affects the thermal image, not only because it influences the atmospheric attenuation, but also because the resolution of the thermograms decreases with the distance between the equipment and the object. Each point of the thermogram corresponds to a specific area of the object surface. With increasing distance, each point corresponds to a larger area of the surface and the radiation captured by the equipment becomes a real average of the radiation emitted, lowering the detail level. The ambient temperature can influence the performance of thermal imaging equipment, since when is too low or too high infrared radiation detection systems become less stable.

The transparent bodies or partially transparent in the infrared range, such as glass and some plastics, can also create measurement problems. For example, when the radiation of a transparent surface is captured by the infrared equipment, the image obtained results from the energy emitted and reflected from the surface, plus a portion of energy transmitted through it. The real surface temperature is different of the temperature obtained by the thermographic images, since it contains a portion of the resulting radiation that crosses it.

4. Sensibility case-studies

Several parameters affect thermographic measurements, namely, emissivity, reflectivity, environmental conditions, colour and others (Hart, 1991 and Chown and Burn, 1983). To evaluate the influence of some of these parameters, simple tests were carried out using the LFC's thermography equipment, both in laboratory and "in situ".

One of the laboratory tests consisted of partially immersing two identical specimens of cellular concrete in water followed by a drying period. The tests were performed under steady state conditions, in two climatic chambers with different temperatures and relative humidity. Thermal images were obtained during each test, using four different values of emissivity: 0.62, 0.85, 0.91 and 0.95.

As expected (Hart, 1991; Chown and Burn, 1983; Chew 1998 and Gaussorges, 1999), the results showed that emissivity variation induced changes in the thermal images, during both absorption and drying (see Figure 7). By looking at the thermal images it was possible to say that the images obtained with emissivity 0.62 were quite different from the remaining ones. The differences between the other thermograms (emissivities 0.85, 0.91 and 0.95) were not very significant. However, thermal images obtained with emissivity 0.85 were generally clearer (Barreira and Freitas, 2007 and Barreira, 2004). Thus, if the study aims for a qualitative evaluation of the results, that is, an analysis of superficial temperature differences, the selected emissivity value is not very important (Hart, 1991). Nevertheless, a judiciously selected emissivity value may simplify the interpretation of the thermal image.

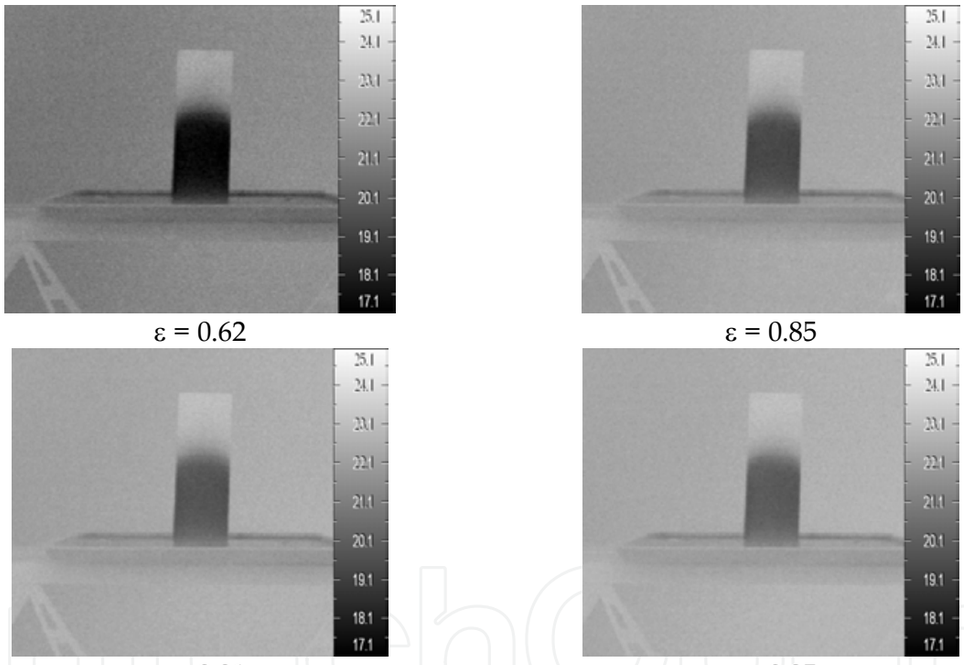
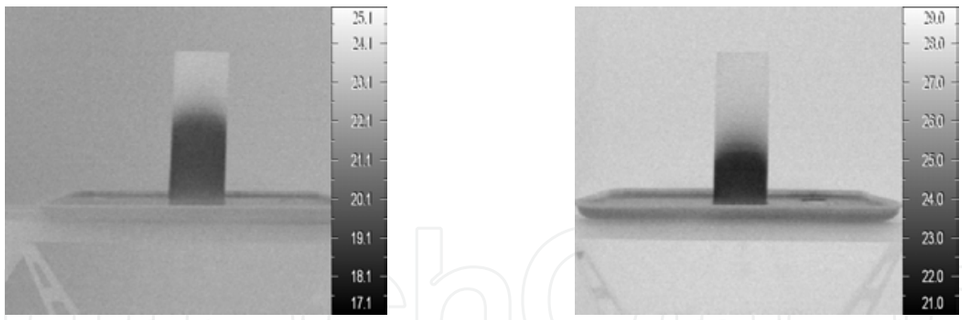


Fig. 7. Thermograms of a cellular concrete specimen after 168 hours of absorption obtained with different emissivities.

Variations in environmental conditions (temperature and relative humidity) also induced changes in the thermal images obtained in the same period (see Figure 8), not only because the environmental conditions may interfere with infrared detection, but especially because superficial evaporation is susceptible to their influence (Barreira and Freitas, 2007 and Barreira, 2004).

At the end of the drying period, the specimen's edges could no longer be distinguished from the image's background (see Figure 9) because their respective temperatures were very similar (Barreira and Freitas, 2007 and Barreira, 2004). Only objects whose temperature



T = 20º C and RH = 60% T = 25º C and RH = 40%

Fig. 8. Thermograms of a cellular concrete specimen after 168 hours of absorption using emissivity 0.85.

varies at least 1º C from the environmental temperature can be detected using thermography. Therefore, this technology cannot be used to study objects in thermal equilibrium or in hygroscopic domain (Hart, 1991 and Santos and Matias, 2002), which may thus restrict thermography to the study of building materials. For example, it is possible to detect thermal resistances from a radiant floor (Barreira and Freitas, 2003), but only if the system is on, inducing temperature variations between the resistances and the background (see Figure 10).

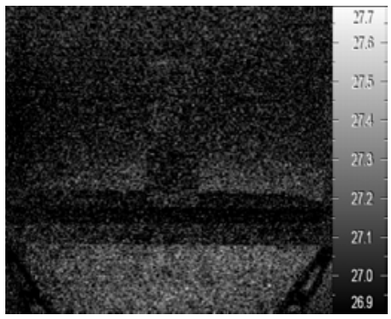
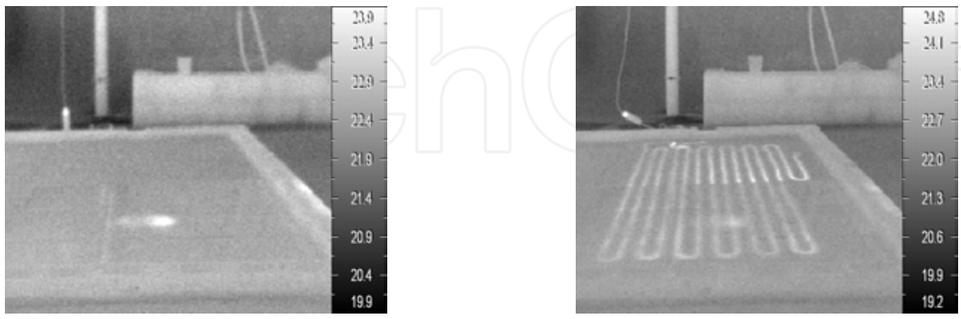


Fig. 9. Thermogram of a cellular concrete specimen after 792 hours (end of the drying period) using emissivity 0.85.



Floor in thermal equilibrium Floor after the system is switched on

Fig. 10. Thermograms of a radiant floor, before and after the system is switched on.

Reflectivity and colour are two important parameters since they may mask defects in building materials or components. Reflectivity is especially important for materials with low emissivity since reflectivity is complementary of emissivity in opaque materials. As such, an

object with low emissivity induces a greater superficial temperature variation due to thermal reflection (Hart, 1991). Figure 11 shows the effect of reflectivity on the thermal image of a ceramic floor. The hotter area in the bottom left of the image results from the ceramic surface's thermal reflection (Barreira and Freitas, 2003).

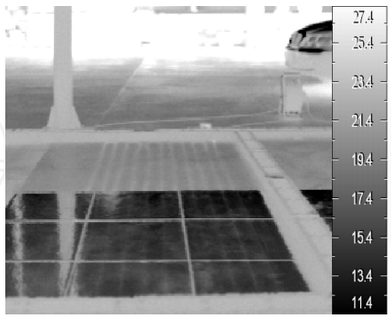
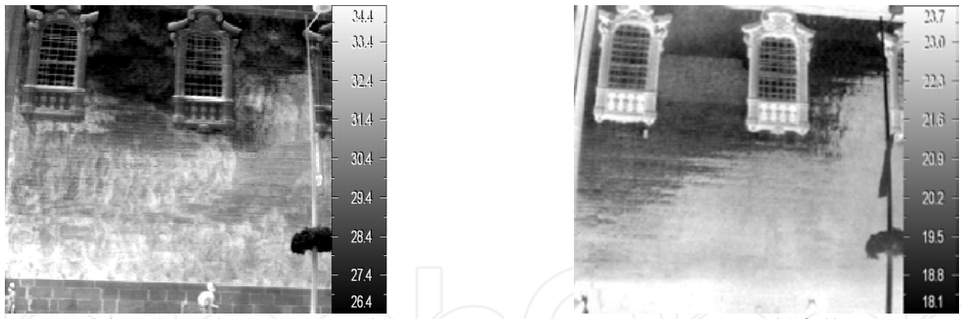


Fig. 11. Thermogram of a ceramic floor coating exhibiting thermal reflection.

Colour's significant influence on thermographic measurements became quite obvious when thermal images were obtained at the Carmo Church in Porto – Portugal. The Carmo Church's east façade is covered with "azulejos" (hand-painted ceramic tiles). The colouring varies between white and several shades of blue (see Figure 1). The thermal images revealed remarkable temperature differences caused by the colour variation. Colour had a greater influence when temperature differences were more pronounced. When temperature differences decreased at the end of the day (see Figure 12), the influence of colour became less important (Barreira and Freitas, 2004a).



At midday (incident sun rays) At nightfall

Fig. 12. Thermograms of Carmo Church's façade covered with "azulejos" in Porto – Portugal.

4.1 Capillarity absorption and drying of building materials

A cellular concrete specimen was used to visualise capillarity water absorption and subsequent drying. The main properties of cellular concrete can be found in Table 2. The test was performed in a climatic chamber, under steady state conditions of temperature and relative humidity.

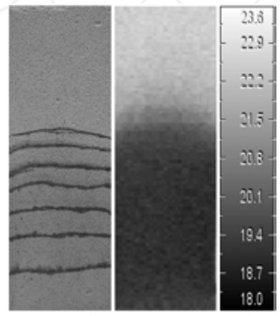
During the absorption period, the specimen's water level was visually observed and thermographically detected by its superficial temperature variation (see Figure 13). The temperature varied because of surface evaporation that, being an endothermic reaction, induced local cooling (Santos and Matias, 2002). The visible top water level was shown as

Density	525 kg/m³
Open porosity [volume]	66%
Critical moisture content	0.24 kg/kg
Capillary saturation moisture content	0.50 kg/kg
Specific heat capacity	1050 J/kg·K
Thermal conductivity	0.3 W/m·K

Table 2. Main properties of cellular concrete measured at Building Physics Laboratory (Freitas, 1992).



Specimen at 2 hours

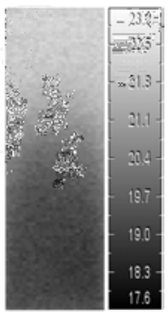


Specimen at 408 hours (end of absorption)

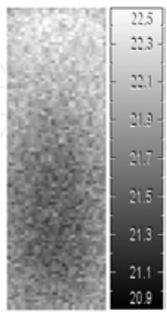
Fig. 13. Thermograms obtained during absorption.

the upper limit of the darker shade. The intermediate shades, from dark to light, showed the "wet" to "dry" transition in the specimen's surface.

The drying period began immediately after the specimen was removed from the water. In the first hours of drying, the thermograms still showed significant superficial temperature differences. However, as drying progressed, the colder area decreased and the lighter shades enlarged. This fact revealed faster drying rates along the specimen's top and vertical edges (Barreira and Freitas, 2004a). At the end of the test, superficial temperature was almost uniform and therefore moisture distribution was not perceptible (see Figure 14).



Specimen at 442 hours



Specimen at 578 hours



Specimen at 794 hours (end of drying)

Fig. 14. Thermograms obtained during the drying period.

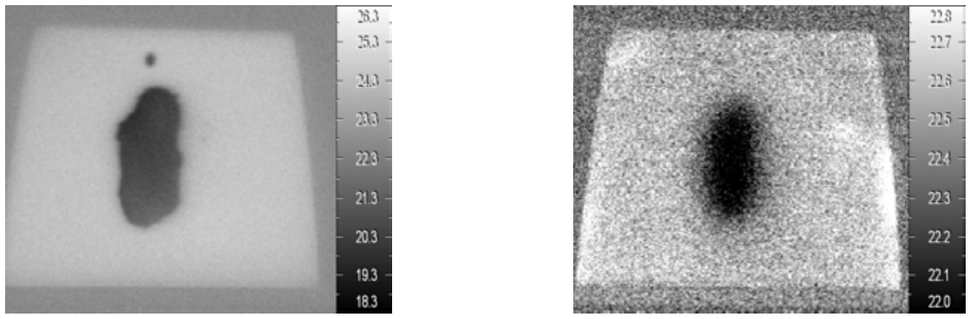
It may thus be said that thermography allows visualising superficial temperature variations due to rising capillarity. During the drying period, superficial temperature variations may

also be detected. Nevertheless, a decrease in moisture induces small superficial temperature variations which are therefore difficult to detect (Barreira and Freitas, 2004a).

4.2 Wetting and drying of building materials

A cellular concrete specimen (see Table 2) was used to visualise wetting and drying. Inside a climatic chamber, water was dropped on the specimen for one hour, at a rate of 11 drops per minute. After the wetting process, the drying period started immediately under the same environmental conditions.

After a one-hour wetting period, a stained area was visually observed and thermographically detected through the superficial temperature variation. The intermediate shades, from dark to light, showed the "wet" to "dry" transition in the specimen's surface (see section 4.1). During the first day of drying the thermograms still showed significant superficial temperature differences. After 48 hours of drying the colder area decreased considerably as the lighter shades enlarged (see Figure 15). This revealed faster drying along the "wet" area's edges (Barreira and Freitas, 2005).

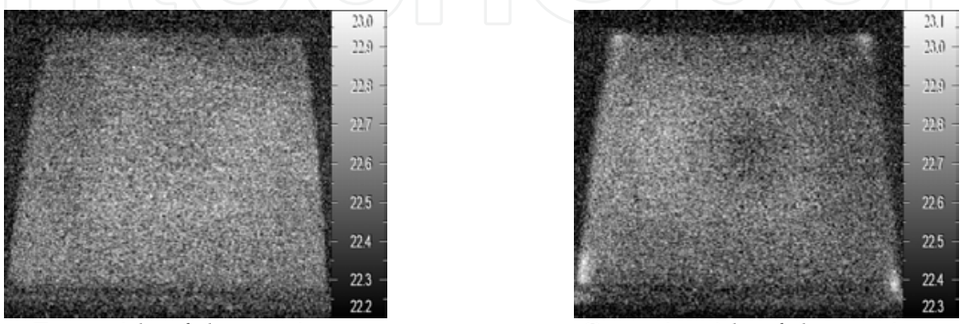


Specimen after 1 hour of wetting Specimen after 48 hours of drying

Fig. 15. Thermograms obtained during the drying period.

The test was concluded when moisture detection was hampered by the small superficial temperature differences. However, at the end of the test, the opposite side of the specimen still showed superficial temperature variation, as sketched in Figure 16 (Barreira and Freitas, 2005).

Although thermography is a mean of evaluating the specimen's approximated drying time, it only detects superficial moisture (Barreira and Freitas, 2005).



Front side of the specimen Opposite side of the specimen

Fig. 16. Thermograms at the end of the drying period.

4.3 Evaluating the thermal comfort of floor coatings

The comfort of interior floor coatings is very important for the well-being of building users, especially in bedrooms and bathrooms where people commonly walk barefoot. Although comfort depends on floor and environmental temperatures, it is also determined by the material's thermal characteristics, namely, thermal diffusivity and effusivity.

Thermography was used to evaluate the comfort of some interior floor coatings by comparing effects from barefoot contact with six different materials. The floor coatings under comparison were carpet, cork, vinyl, wood, ceramic tile and granite (see Table 3). The tests were performed inside a climatic chamber, with temperature and relative humidity similar to a dwelling's environmental conditions. Two different contact periods were adopted: 1 minute to assess initial discomfort and 2 minutes to study discomfort progress over time (Barreira and Freitas, 2004b).

Material	Density [kg/m³]	Specific heat capacity [J/kg·K]	Thermal conductivity [W/m·K]	Thermal diffusivity (a) (*) [m²/s]	Thermal effusivity (b) (**) [W·s½/m²·K]
Cork	150	2008	0.04	$0.13 \cdot 10^{-6}$	110
Wood	500	1500	0.14	$0.19 \cdot 10^{-6}$	324
Ceramic tile	2000	753	1.10	$0.73 \cdot 10^{-6}$	1 287
Granite	2650	837	3.97	$1.79 \cdot 10^{-6}$	2 967

(*) Obtained using Eq. (12); (**) Obtained using Eq. (13)

Table 3. Thermal properties of some materials (Hagentoft, 2001 and SQUARE ONE, 2005).

Before starting the tests, a thermogram was obtained from the sole of a barefoot to show its superficial temperature when the shoe was taken off. This thermogram indicated the foot's standard temperature (see Figure 17). Several thermal images of the sole of the barefoot were collected after the foot was placed in contact with the respective materials.

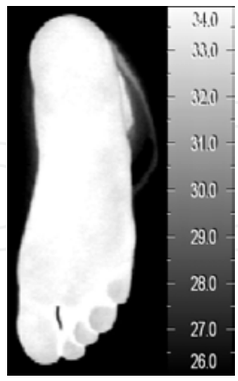


Fig. 17. Thermogram of the foot's standard temperature.

After being in contact with the different materials for 1 minute, the foot's superficial temperature was always less than its standard temperature and decreased according to the respective materials (see Figure 18). Contact with the carpet induced a higher superficial temperature of the foot sole, followed by cork, wood, vinyl, ceramic tile and, lastly, granite (see Table 4).

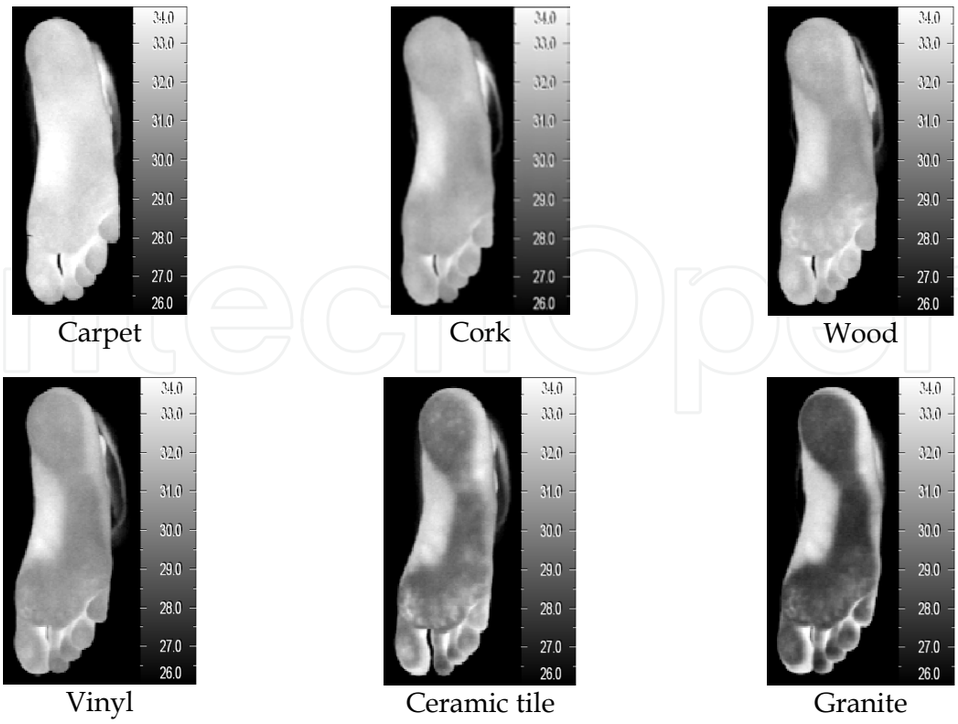


Fig. 18. Thermograms after 1 minute of contact.

Material	Average temperature (° C)	
	1 minute of contact	2 minutes of contact
Standard	*33.5*	
Carpet	32.6	32.7
Cork	31.6	32.6
Wood	31.5	32.5
Vinyl	31.0	32.3
Ceramic tile	30.5	30.6
Granite	29.6	30.1

Table 4. Average superficial foot temperature after 1 and 2 minutes of contact.

After being in contact with the materials for 2 minutes, the foot's superficial temperature was inferior to its standard temperature. The foot's temperature variations resulting from contact with carpet, cork, wood and vinyl were very similar. The ceramic tile and granite induced lower superficial temperatures (see Figure 19). However, the foot's superficial temperature was always higher than its temperature after having been in contact with each material for 1 minute (see Table 4).

Variations in the superficial foot temperature induced by contact with the various floor coatings are caused by the respective material's heat transference characteristics. Contact between the barefoot and the material induces an exchange of heat from the foot's higher temperature to the floor coating's lower temperature, until reaching a thermal equilibrium. This heat transference depends essentially on thermal diffusivity and effusivity (see Table 3).

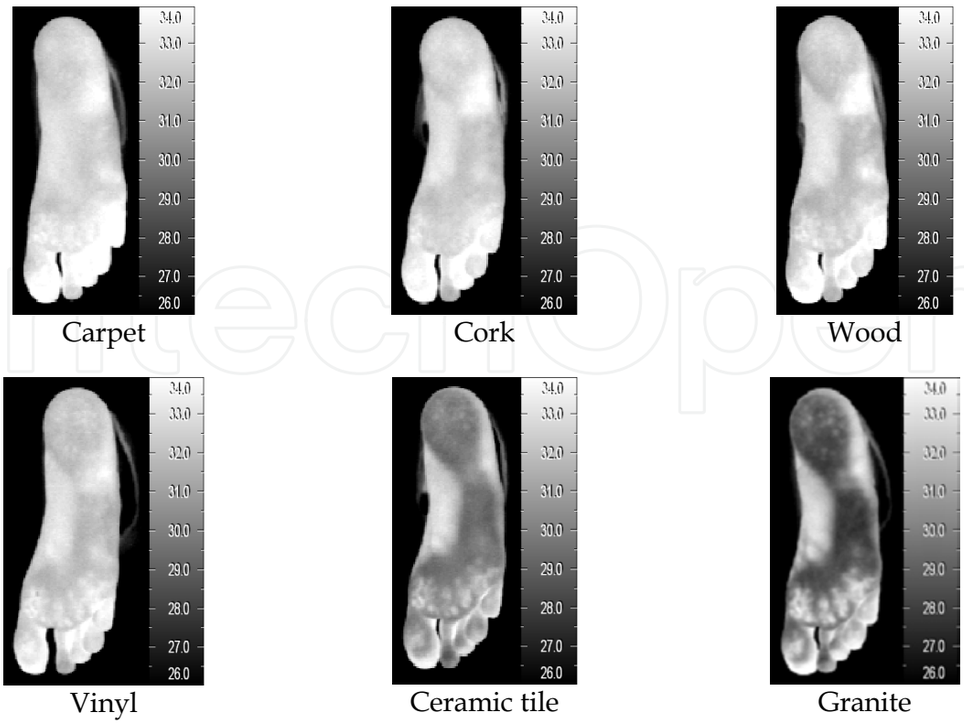


Fig. 19. Thermograms after 2 minutes of contact.

Thermal diffusivity (a) expresses heat transfer inside the material (Hagentoft, 2001). The higher its value, the quicker the heat is exchanged between the foot and the material, which causes more discomfort in the initial contact and induces lower superficial foot temperature.

$$a = \frac{\lambda}{\rho.c} \tag{12}$$

where λ is the thermal conductivity [W/m·K], ρ is the density [kg/m^3] and c is the specific heat capacity [J/kg·K].

Carpet has a lower diffusivity, and thus its contact with the foot induced higher superficial temperature and less initial discomfort. On the contrary, granite has the highest diffusivity and was the most uncomfortable floor coating (Barreira and Freitas, 2004b).

Thermal effusivity (b) expresses the material's capacity to absorb and store heat (Hagentoft, 2001). The higher its value, the greater the heat storage capacity and the longer it takes to reach the thermal equilibrium. The initial discomfort therefore lasts longer.

$$b = \frac{\lambda}{\sqrt{a}} \tag{13}$$

Carpet, cork, wood and vinyl have low effusivity. After 2 minutes of contact, they induced similar superficial foot temperatures that were the closest to the thermal equilibrium temperature. Ceramic tile and granite have higher effusivity and therefore induced lower superficial temperatures and caused discomfort for a longer period (Barreira and Freitas, 2004b).

5. Conclusions

Thermography is a non-destructive testing technology with much potential, but its application to building materials has not been greatly studied yet. Research studies developed at the Building Physics Laboratory (LFC) revealed that emissivity is an essential parameter, since it greatly influences thermographic measurements and may restrict application of this technology to buildings. However, if the study aims for a qualitative analysis of the results, the selected emissivity value is not very important. It was also possible to confirm that thermography cannot be used to study objects in thermal or hygroscopic equilibrium, as temperature differences between the object and the environment must be significant. Colour and thermal reflection must also be considered during thermographic testing, as they may mask the results and cause misinterpretation.

Thermography allowed studying the wetting and drying process of building materials. Temperature differences due to superficial water evaporation provided a means of recognising "wet" and "dry" areas. It was also possible to evaluate a material's approximate drying time since small superficial temperature variations indicate that moisture is rather significant. Thermography, however, detects only superficial moisture.

Thermography was also used to evaluate the comfort of some interior floor coatings. Thermal images were obtained from the sole of a barefoot after having been in contact with different floor materials. Since the superficial temperature variation, after contact between the foot and the material, is related with discomfort, a comparison of thermograms revealed the various material comfort levels.

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7. References

Avdelidis, N.P.; Moropoulou, A. (2004). Applications of infrared thermography for the investigation of historic structures. *Journal of Cultural Heritage*, Vol. 5, N.º 1, pp. 119-127.

Barreira, E. & Freitas, V.P. (2003). Thermal Images Obtained from Different Solutions of Radiant Floor. Internal Report LFC/IC 134.2003, LFC, FEUP, Porto, Portugal (in Portuguese).

Barreira, E. & Freitas, V.P. (2004a). Infrared Thermography Applications in the Study of Building Hygrothermal Behaviour. *CIB W40 Meeting*, Caledonian University, Glasgow.

Barreira, E. & Freitas, V.P. (2004b). Thermal Comfort Evaluation of Floor Coatings Using Infrared Thermography . *Construlink International Journal*, Vol. 3, No. 8, pp. 30–38 (in Portuguese).

Barreira, E. & Freitas, V.P. (2005). Barreira, E. & P. de Freitas, V. Importance of Thermography in the Study of ETICS Finishing Coatings Degradation Due to Algae and Mildew Growth. *Proceedings of the 10th International Conference On Durability of Building Materials and Components* (10DBMC), CSTB, Lyon.

Barreira, E. & Freitas, V.P. (2007). Evaluation of building materials using infrared thermography. *Construction and Building Materials*, Vol. 21, N.º 1, pp. 218-224.

Barreira, E. (2004). Thermography Applications in the Study of Buildings Higrothermal Behaviour. MSc Theses, Porto, FEUP, Portugal (in Portuguese).

Chew, M.Y.L. (1998). Assessing building facades using infra-red thermography. *Structural Survey*, Vol. 16, N.º 2, pp. 81-86.

Chown, G.A. & Burn, K. N. (1983). Thermographic identification of buildings enclosure defects and deficiencies. *Canadian Building Digest* 229, Canada, NRC-IRC.

Freitas, V.P. (1992). The Moisture Migration in Buildings Walls – Analysis of the Interface Phenomenon. PhD Theses, Porto, FEUP, Portugal (in Portuguese).

Gaussorgues, G. (1999). La thermographie infrarouge – Principes, Technologies, Applications. Fourth Édition, Edition TEC & DOC, Paris, France.

Grinzatoa, E.; Vavilovb, V.; Kauppinen, T. (1998). Quantitative infrared thermography in buildings. *Energy and Buildings*, Vol. 29, N.º 1, pp. 1-9.

Hagentoft, C. (2001). Introduction to Building Physics. Student Litteratur, Sweden.

Haralambopoulos, D.A.; Paparsenos, G.F. (1998). Assessing the thermal insulation of old buildings - The need for in situ spot measurements of thermal resistance and planar infrared thermography. *Energy Conversion and Management*, Vol. 39, N.º 1-2, pp. 65-79.

Hart, J.M. (1991). A practical guide to infra-red thermography for building surveys. Garston, Watford, BRE.

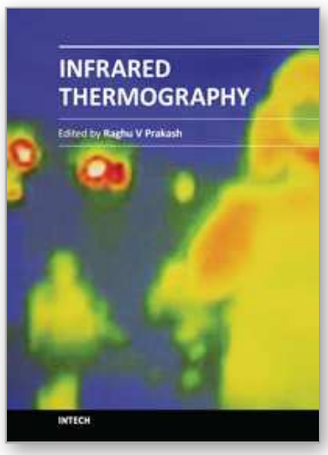
Incropera, F.P.; Witt, D. P. (2001). Fundamentals of Heat and Mass Transfer. John Wiley & Sons.

NEC San-ei Instruments, Ltd (1991). TH1 101 Thermo Tracer – Operation Manual, Japan.

Rao, P. (2008). Infrared thermography and its applications in civil engineering. *The Indian Concrete Journal*, Vol. 82, N.º 5 , pp. 41-50.

Santos, C.P. & Matias, L. (2002). Application of Thermography for Moisture detection - A laboratory research study. *Proceedings of the XXX IAHS World Congress on Housing*, Coimbra, Portugal.

SQUARE ONE (2005). Research PTY LTD Properties of materials (http://www.squ1.com/index.php).



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Infrared Thermography (IRT) is commonly as a NDE tool to identify damages and provide remedial action. The fields of application are vast, such as, materials science, life sciences and applied engineering. This book offers a collection of ten chapters with three major sections - relating to application of infrared thermography to study problems in materials science, agriculture, veterinary and sports fields as well as in engineering applications. Both mathematical modeling and experimental aspects of IRT are evenly discussed in this book. It is our sincere hope that the book meets the requirements of researchers in the domain and inspires more researchers to study IRT.

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