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Determining the infrared reflectance of specular surfaces by using thermographic analysis

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ABSTRACT

Specular surfaces as glass, mirrors and metals are commonly used in solar devices and in building facades. Determining the temperature distribution of such kind of surfaces allows estimating their thermal losses and detecting hot spots and temperature gradients that provokes material stress and rupture. In this sense, thermography is a non-contact measurement technique that is capable to quickly scan and record these surface temperature distributions, but when specular materials are inspected the infrared reflectance becomes a crucial parameter. This work describes a methodology to measure the reflectance of specular materials for different incidence angles in the infrared range 8 μm–14 μm, by using a thermographic camera and an infrared radiation source. The methodology includes the analysis of errors in the estimation of the reflectance and how to select the temperature of the source that minimizes these errors. The method is applied to different specular surfaces commonly used in building facades and solar devices, whose infrared specular reflectances are estimated for different incidence angles. The obtained results are analyzed in order to provide valuable information for in-situ thermographic measurements of specular surfaces.

1. Introduction

Specular surfaces as glass, mirrors and metals are commonly used in solar devices and in building facades. In solar devices they are used mostly as transparent covers (air and water solar heaters, heat pipes, solar absorber for linear Fresnel devices, photovoltaic modules, solar cookers, etc.) and as reflecting surfaces in solar concentrating devices (glass mirrors and aluminum sheets in Fresnel and CPC devices). In buildings, specular surfaces appear in windows, glazed and mirrored facades, glazing of Trombe walls, metallic facade covers, and so on. Determining the temperature distribution of such kind of surfaces allows to estimate their thermal losses, a very important parameter both, in building and solar applications, that influences the thermal performance and energy consumption of buildings and the efficiency in the case of solar devices (Albatici and Tonelli [1]). The knowledge of the surface temperature field also allows detecting hot spots and temperature gradients provoking material stress and rupture. Thermography is a non-contact measurement technique that is capable to quickly scan and record surface temperature distributions. A thermographic camera works by detecting the radiant energy, typically over a restricted range of wavelengths, emitted by the object of interest and by using Planck's radiation law to relate this energy to temperature. An optical system focuses the energy onto the detector, and a filter is used to select the appropriate wavelength range. This thermal energy is transformed into a visible image, where a color or a gray level is used to represent the point temperature. Nowadays, the application of thermography in buildings and solar devices is a usual qualitative diagnosis technique, but in quantitative applications the accuracy of the measurements depends on knowing the limitations and possible errors influencing the results. Thermography is an ideal measurement technique when the surfaces are inaccessible to other measure devices (as in the facades of high rise buildings), when surfaces receive high solar radiation levels that make unavailable the use of conventional contact sensors (as in the case of the absorbers of solar concentrators), for applications at urban level as when measuring heat island effects (Chudnovsky et al. [2]), to estimate the infrared reflectance of selective surfaces as the case of glasses treated to reflect a high portion of the infrared spectrum, etc. The quantitative infrared thermography in buildings is a very useful technique currently under development. Some valuable researches include the quantitative evaluation of thermal bridges in buildings (Asdrubali et al. [3]), who can estimate the thermal bridge effect as a percentage

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Nomenclature

$e\%$	percentage relative error of the reflectance measurement (unitless)
$S_0(T)$	signal produced by the infrared sensor (V)
S_{sen}	electrical signal produced by sensor (V)
T_a	air temperature (°C)
T_r	apparent temperature of the source reflected on the target (°C)
T_s	source temperature (°C)
T_{surr}	surrounding temperature (°C)
T_t	target temperature (°C)
U	Overall heat transfer coefficient (W m^2 K^{-1})

Greek symbols

ε'	emittance set in the infrared camera when measuring the reflected image (unitless)
ε_λ	spectral emittance (unitless)
ε_t	target emittance in work camera range (unitless)
ε_s	source emittance in work camera range (unitless)
θ	incidence angle for infrared radiation (°)
λ	wavelength (μm)
ρ_t	target reflectance in work camera range (unitless)
σ	Stefan–Boltzman constant (5.6697 × 10^{-8} W m^2 K^{-4})
τ_a	air transmittance (unitless)
$\Delta\rho_t$	absolute error of the reflectance measurement (unitless)
ΔT_s	absolute error when measuring T_s (°C)
ΔT_r	absolute error when measuring T_r (°C)
ΔT_a	absolute error when measuring T_a (°C)

increase of the wall transmittance by measuring the air temperature and by analyzing the corresponding thermogram. Other studies deal with the quantitative determination of the overall heat transfer coefficient (*U*-value) of building envelopes through infrared thermography: Fokaides and Kalogirou [4] proposed a technique to estimate U by measuring the wall temperature with an infrared camera and they determined the *U*-value of typical building construction in Cyprus. Recently, Lehmann et al. [5] performed a quantitative analysis of the individual influence of different parameters on the thermal images of building facades and developed a procedure to evaluate these images considering the thermal characteristics of the building itself and the climatic history preceding the infrared thermography. Marinetti and Cesaratto [6] proposed a transient method for emissivity measurement, which is based on the spectral response of the IR sensor and does not require emissivity references and reflected temperature knowledge. The authors used an IR camera operating in the mid-wave band (3–5 μm). Results showed that for outdoor measurements, the influence of emissivity was stronger than in the indoor case.

The mentioned studies deal with diffusing targets. The application of infrared thermography for specular targets is complex because the reflection of infrared radiation is angle-dependent, while in perfectly diffuse surfaces this reflected radiation is isotropic and it is spread homogeneously in all directions. For specular targets, some valuable studies were carried out by several researchers in the last decades. Argiriou et al. [7] measured the brightness concentration distribution in the focal plane of a solar parabolic dish using a standard infrared thermography equipment. Bazilian et al. [8] used thermographic techniques to investigate the thermal effects of a residential-scale building integrated photovoltaic cogeneration system. More recently, Pfänder et al. [9] developed a methodology for infrared temperature measurements on solar trough absorber tubes by using a solar-blind approach. Datcu et al. [10] present a method to quantify the reflected flux of opaque walls by using an infrared mirror, which allows large surface temperature measurements by infrared thermography under near-ambient conditions with improved accuracy. Krenzinger and De Andrade [11] studied the errors and their consequences when performing outdoor glass thermographic thermometry of solar energy devices. They proposed and experimentally validated a correction method for outdoor thermographic measurements that includes the estimation of a thermographic equivalent sky temperature. The authors applied the methodology to measurements of photovoltaic modules exposed to clear and cloudy skies. The present paper is based on the Krenzinger and De Andrade [11] research, and it extend their results to other surfaces as metallic ones, providing also a method to estimate the optimum source temperature and the analysis of the measurement error.

Thermographic measurement of specular surfaces is not straightforward. Specular reflection is mirrorlike, that is, the incident angle is equal to the reflected angle with both angles and the normal to surface lying on the same plane. Thus, the contribution of the reflected energy to the thermal image produced by a thermographic camera is an important parameter that should be accounted for. Pfänder et al. [9] highlights two main limitations for the accurate temperature determination when using infrared sensors on solar irradiated surfaces: reflected infrared energy from sunlight and errors due to the uncertainty in the emittance of the radiating object. The authors studied the application of thermography in the tubes of a solar absorber and they indicate that reflection errors are often dominant for measurements under concentrated solar radiation and that a reliable temperature measurement is only possible if the thermal radiance considerably exceeds the reflected radiance. When this is not the case, as for example when glazed surface at near ambient temperature are inspected, the knowledge of infrared reflectance is important for the analysis and processing of the thermal image. Thus, in quantitative applications of thermography, the estimation of the infrared reflectance provides vital information in order to correct the measurements provided by the camera. It is also important for specular materials to know the behavior of the reflectance with the incidence angle in order to correct the measurements that were taken with incidence angles different from the normal direction, and for surfaces that are not plane.

This work describes a methodology to measure the reflectance of specular materials for different incidence angles in the infrared range 8 μm–14 μm, by using a thermographic camera and an infrared radiation source. The methodology includes the analysis of errors in the estimation of the reflectance and how to select the temperature of the source that minimizes these errors. The method is applied to different specular surfaces commonly used in building facades and solar devices, whose infrared specular reflectances are estimated for different incidence angles. The obtained results are analyzed in order to provide valuable information for in-situ thermographic measurements of specular surfaces.