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Accurate determination of the total hemispherical emittance and solar absorptance of opaque surfaces at elevated temperatures

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ABSTRACT

In many applications such as solar power conversion technologies, radiative heat transfer plays a significant role in the energy balance. For accurate performance predictions of solar power conversion devices the total hemispherical emittance and solar absorptance of surfaces need to be known with high accuracy. Often times the emittance of a surface is calculated from indirect spectral bidirectional or directional-hemispherical reflection measurements at room temperature which can significantly underestimate the total hemispherical emittance. Here, we report a simple steady-state calorimetric method to directly measure the total hemispherical emittance of opaque surfaces at elevated temperatures with a maximum experimental uncertainty of 5%. The method is further expanded to directly measure the solar absorptance of the surface at elevated temperature using a solar simulator. We show experimental total hemispherical emittance and solar absoprtance results for various surfaces such as machine polished copper and stainless steel and several spectrally selective solar absorbers. We describe a methodology to characterize solar absorbers and apply it to a cermet-based spectrally selective solar absorber.

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1. Introduction

Radiation is a relevant heat transfer mechanism in countless applications such as high temperature industrial processes, heat management in buildings, space applications, and solar power conversion [1–3]. The far-field radiated power from a blackbody is related to its temperature by the Stefan–Boltzmann law and is diffusely emitted in the form of electromagnetic waves with a temperature-dependent wavelength spectrum [4–6]. However, real materials typically radiate at a fraction of the blackbody's emissive power. This fraction is defined as the emissivity which typically is a function of the material's temperature and the wavelength and direction of the emitted electromagnetic waves [7]. Equivalently, the absorptivity is the optical material property that determines the fraction of irradiated power absorbed by a real surface relative to a blackbody. Whereas the emissivity and absorptivity are pure material properties, oftentimes those properties are affected by the condition and structure of the surface (oxide layer, surface roughness, subwavelength multilayer thin films) in which case one uses the terminology emittance and absorptance, respectively. The temperature, wavelength, and directional dependences of the optical properties make their measurement difficult and numerous techniques have been developed each with their own ranges of applicability, advantages and shortcomings [7,8]. The techniques to measure the emittance can loosely be separated into three groups: reflection, radiometric emission, and calorimetric emission measurements.

With reflection measurement methods the emittance (absorptance) is obtained indirectly from the measured reflectance based on the relation for opaque materials, $\varepsilon=\alpha=1-\rho$ with ε, α, and ρ being the emittance, absorptance, and reflectance, respectively. However, this already leads to one of the main shortcomings of these techniques when used for low-emittance samples because a small relative error in the measured reflectance results inevitably in a significantly larger relative error in emittance [9]. Nevertheless, there are various absolute and relative techniques used to measure the spectral bidirectional, spectral directional-hemispherical or spectral hemispherical-directional reflectance using monochromatic or polychromatic light sources [2,7,10–15]. Here, we use the term "spectral" to refer to the reflectance or emittance at a single wavelength, as opposed to the term "total" which refers to the property averaged over a given spectrum (e.g. a blackbody spectrum at a given temperature, or the AM1.5G solar spectrum). Reflectance measurements are described by the angular distributions of first the incident spectrum, and then the measured reflection; for example, a directional-hemispherical measurement has a single-direction incident spectrum, but the reflection is the sum over all outgoing angles. To obtain the directional-hemispherical or hemispherical-directional

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reflectance the techniques are based on integrating sphere, integrating mirror or heated cavity reflectometers or they use a hemispherical diffuse light source [16–20]. Oftentimes, the measurements require a reference standard and are performed with the sample at room temperature and only for one angle, thus calculating the total hemispherical emittance for the sample at elevated temperature can result in significant errors.

In order to avoid the challenges of an indirect measurement, radiometric methods are used to directly measure the spectral directional emittance of opaque or partially transparent samples using a spectrometer by comparing their emission spectra to that of a blackbody reference [21–26]. The experimental systems used for these techniques are typically quite complex; their three major challenges are measuring only the radiation emitted by the sample, ensuring sample temperature uniformity, and accurately measuring the sample temperature. Whereas steady-state radiometric methods need a reference and are limited to relatively high temperatures to minimize errors from ambient radiation reflecting off of the sample, periodic radiometric methods can eliminate this effect and the directional emittance can be directly calculated by comparing to a reference. By adding a simultaneously performed periodic hemispherical-directional reflection measurement the directional emittance can be obtained without a reference [27]. Instead of measuring the spectral directional emittance at several angles, radiometric techniques based on the Land Surface Pyrometer can directly measure the spectral hemispherical emittance [28,29].

However, those techniques have rather large uncertainties and if the total hemispherical emittance is of primary interest, calorimetric methods performed under vacuum are considered to have the highest measurement accuracies due to their direct and absolute nature [30]. These techniques can either be steady-state or transient with some of their main challenges being to minimize parasitic heat losses and to perform accurate temperature measurements [31]. In transient techniques the emittance is obtained by relating the cooling curve to the radiative heat loss, assuming that the heat capacity is known as a function of temperature [32–37]. Radiative or inductive heating of the sample is typically preferred over electrical heating. It is also common to coat the complete specimen with the sample material to minimize parasitic heat losses. For sample surfaces deposited on flat sheet metal substrates such as for solar selective coatings the parasitic heat losses from the back side and through the supports can be minimized with a rather complex heated radiation shield requiring sophisticated temperature control [38].

Steady-state techniques relate the radiative heat loss, and thus the total hemispherical emittance, directly to the electrical power input required to maintain a sample at a constant elevated temperature, thus eliminating the uncertainty from an additional heat capacity measurement. In this type of experiment the thermodynamic equilibrium between the system and its surroundings is of great importance because transients can introduce large measurement errors [31]. In some techniques the sample-heater assembly is suspended on pillars and while the sample surface faces a blackbody surrounding at constant lower temperature, the back side and supports are surrounded by a heated radiation shield at sample temperature to minimize parasitic heat losses [39–43]. Similarly, concentric vacuum tube configurations are used with the sample surface deposited on the outside of the inner tube and an electrical heater embedded on the inside. Guard heaters at the tube ends minimize the edge effects [44,45]. Other techniques sandwich a thin electrical heater between two samples and suspend the assembly inside a vacuum chamber. The main challenges of these methods are to establish a uniform sample temperature and to measure the temperature accurately while minimizing the edge and wire heat losses [46–48]. It is particularly challenging to minimize the edge and wire heat losses for samples with low emittance due to the finite thickness of the sample-heater assembly needed to ensure temperature uniformity.

Here we develop a simple steady-state calorimetric method that determines the total hemispherical emittance of flat opaque samples with a maximum error below 5% by calibrating for the aforementioned inevitable parasitic heat losses. We also introduce a technique to probe internal thermal resistances of the assembly in order to validate (1) the assumption of consistent parasitic heat losses in experimental runs; and (2) the accuracy of our sample temperature measurement which can be one of the main sources of errors in those methods [31]. To demonstrate the method we measured various samples including machine-polished copper, machine-polished stainless steel, and solar absorbers with spectrally selective surfaces deposited on copper and stainless steel substrates at steady-state set temperatures ranging from 100 to 500 °C. The method is further expanded to also measure the solar absorptance at elevated temperatures using a solar simulator [43]. The absorptance of a reference black paint (HE6) is measured at temperatures from 100 to 300 °C [49]. Finally, a methodology is proposed to characterize spectrally selective solar absorbers.

2. Measurement methods, theory, and systems

The developed techniques are steady-state calorimetric methods in which the electrical input power can directly be related to the total hemispherical emittance or the solar absorptance of a sample surface at elevated temperatures. The methods are based on particular forms of the more general heat balance expression for a sample suspended in an evacuated blackbody surrounding,

$$C\frac{\partial T}{\partial t} = -A_s\varepsilon_s(T_s)\sigma {T_s}^4 + A_s\int_0^\infty \alpha_{s,\lambda}(T_s)E_{b,\lambda}(T_{amb})d\lambda + \alpha_{s,sol}Q_{sol} + P_H - Q_p \quad (1)$$

where the left-hand side is the unsteady term with C being the heat capacitance of the system, and $\partial T/\partial t$ the change in temperature with time which is zero when the system reaches a steady state. The first term on the right-hand side corresponds to the emitted radiation from the sample surface at temperature T_s with area, A_s, total hemispherical emittance, ε_s, and σ being the Stefan–Boltzmann constant. The second term is the irradiance from the blackbody surrounding absorbed by the sample surface. It is expressed in terms of the wavelength integral of the spectral hemispherical absorptance, $\alpha_{s,\lambda}$, of the sample at T_s multiplied by the spectral blackbody emissive power, $E_{b,\lambda}$, of the surrounding at temperature T_{amb}. This will take into account the effect of non-gray properties of a sample. The third term accounts for possible incident solar radiation power, Q_{sol} being absorbed by the sample surface with the solar spectrum weighted absorptance, $\alpha_{s,sol}$. Furthermore, an electrical heater power input, P_H, balances the net heat flow from the sample surface and the parasitic heat losses, Q_P which includes wire heat conduction as well as possible back side and edge radiation.

2.1. Total hemispherical emittance measurement technique

Whereas typical steady-state calorimetric techniques try to minimize the parasitic heat losses, the method developed here calibrates for those heat losses by performing three consecutive measurements (Fig. 1). The method requires two similar heater assemblies (1 and 2) to which two identical samples (1 and 2) are attached. For the first two experiments (subscripts 1 and 2) the sample-heater assemblies 1 and 2 are consecutively suspended in a large vacuum chamber acting as a blackbody surrounding at uniform temperature, T_{amb}. In each measurement, the required electrical power input, P_H, to balance the sample-heater assembly heat losses is measured for various steady-state set temperatures, T. The heat losses include the radiation from the sample, Q_S, and the parasitic heat losses, Q_P. The latter consist of the wire heat conduction from I/V leads, Q_L, and

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