Understanding the Radiation Thermometers

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Abstract. Radiation thermometers use the laws of thermal radiation to compute the temperature as a function of the measured spectral radiance. The more precise calculations involve the integration of Planck’s Law, which turns the mathematical developments more complex. In this article, whenever possible we use the concept of monochromatic radiation thermometers, which has the advantage of facilitating mathematical developments and allowing the reader to obtain more easily an overview of the instrument behaviour. In addition, we deal with three important types of thermometers: total radiation, spectral band, and ratio thermometers. Some concepts such as radiance and exitance were also presented.

Keywords: Radiation thermometers, Radiation thermometry, Thermal radiation

1. Introduction

The thermal radiation emitted by the ideal blackbody surface has the following properties: i) does not depend on any material medium to propagate, ii) propagates in vacuum at a high speed (the speed of light in the vacuum) and iii) can be associated with the blackbody spectral radiance which is a function only of temperature and wavelength. These factors together suggest the development of a non-contact measuring instrument that can detect the thermal radiation of a surface and calculate its temperature from its thermal radiation.

This instrument is what we call a radiation thermometer (RT), also called an infrared pyrometer or simply pyrometer. Using the word pyrometer as a radiation thermometer is already widespread, however, it is necessary to warn the reader that on the internet one can find this term with other meanings. We can find, for example, analog pyrometer referring to an analog indicator with scale graded in temperature or pyrometer referring to a thermocouple, thus, the use of radiation thermometer expression is preferable and avoids ambiguity.

For radiation thermometer measurement, a target whose temperature is to be determined emits thermal radiation that travels along a certain path until it reaches an optical system of the instrument, which directs the radiation to a detector. This generates an electronic signal as a function of the radiation received. Then, the output signal of the detector receives processing, and the temperature of the target is calculated.

The optical system can contain various components such as lenses, filters, apertures, limiters, mirrors, etc. The main purpose of the optical system is to ensure that only the radiation coming from the target reaches the detector.

The set is a radiometer and after the signal processing and conversion of this signal into temperature according to some calibration algorithm, it is possible to speak in RT. Figure 1 illustrates the temperature measurement through the RT.
Figure 1 – Temperature measurement using a radiation thermometer. 1) Target; 2) Atmosphere; 3) Lens; 4) Filter; 5) Detector; 6) Signal processing; 7) display

In [1], RT is defined as a radiometer calibrated to indicate the blackbody temperature. This blackbody temperature indicated by the RT is also called apparent temperature or radiance temperature, which is generally not equal to the actual surface temperature being measured unless this is a blackbody surface. This is a fundamental problem of radiation thermometry: to get a good approximation of the actual temperature from the radiance temperature. We will see next some techniques to address this problem.

There are several types of RT. It is possible to select a radiation thermometer according to several criteria, such as portability, temperature range, spectral range, the ratio between target size and distance to the target, type of detector, and possibility of emissivity adjustment (instrumental emissivity).

For a given surface whose temperature we want to measure, the lower the temperature is, the lower will also be the radiant energy emitted by this surface and, in general, thermometers require a larger target size. At temperatures not too high, for example, typical room temperature, the detectors of radiation thermometers need to operate at longer wavelengths at which thermal radiation is predominantly emitted. To advance the study of the radiation thermometers it is interesting address some fundamental concepts related to heat transfer by thermal radiation.

2. Fundamentals Concepts
Surfaces usually emit thermal radiation in several directions toward an imaginary hemisphere above the surface. This makes the spherical coordinate system more suitable for presenting the mathematical definitions of thermal radiation fluxes.

In a spherical coordinate system, let \( dA \) be an element of area on the plane \( \theta = \pi/2 \), centered at the origin (Figure 2).

Figure 2 – Thermal radiation emitted by \( dA \) in the direction of \( \vec{r} \) and elements of spherical coordinate system.
In this system, the coordinates \((r, \theta, \phi)\) define the position of any point, where \(r\) is the magnitude of the position vector \(\vec{r}\) that leaves the origin of the coordinate system and ends at the point \((r, \theta, \phi)\). The angle \(\theta\) is the polar or zenith angle, and \(\phi\) is the azimuth angle. These angles define the direction of \(\vec{r}\) what we can also call the \((\theta, \phi)\) direction. The thermal radiation considered is the portion that leaves the surface \(dA\) in the \((\theta, \phi)\) direction.

2.1. Radiance

We define the spectral radiance \(L_\lambda\) of the surface \(dA\) in the \((\theta, \phi)\) direction as the radiant flux \(dq\) emitted at the wavelength \(\lambda\), propagating from \(dA\) in the direction \((\theta, \phi)\), per unit of projected area in this direction, per unit of solid angle around this direction and per unit of wavelength range around \(\lambda\). Formally, we can write:

\[
L_\lambda = \frac{dq}{dA \cos(\theta) d\Omega d\lambda},
\]

where \(dq\), called radiant flux or radiant power (unit W), is the time rate at which radiant energy propagates from the surface area \(dA\), \(d\Omega\) is the solid angle element, expressed in the steradian unit (sr). \(L_\lambda\) can be conveniently expressed in the unit \(W/(m^2 \text{sr} \mu\text{m})\), since the wavelength of the thermal radiation is commonly written in unit \(\mu\text{m}\).

If we integrate the spectral radiance at all wavelengths, in the \((\theta, \phi)\) direction, we obtain the total radiance, \(L\), which unit is \(W/(m^2 \text{sr})\).

2.2. Exitance

We define the spectral exitance, \(M_\lambda\), as the spectral radiative heat flux, with wavelength \(\lambda\), which leaves a surface in all directions, entering a hypothetical hemisphere above the surface. The spectral exitance has unit \(W/(m^2 \mu\text{m})\). The radiative heat flux is defined as radiant flux across an element area \(dA\) in all directions. From Eq. (1), we can define the spectral exitance as:

\[
M_\lambda = \int_{\text{hem}} L_\lambda(\lambda, \theta, \phi) \cos(\theta) \, d\Omega.
\]

If we consider the contribution of spectral exitance in all wavelengths, we will have the total exitance \(M\), in units \(W/m^2\), which corresponds to the radiative heat flux transferred from a surface in all directions above this surface.

It is worth considering the case where the surface is perfectly diffuse, a characteristic present in blackbodies. In this case, the spectral radiance is independent of the direction so we can write the spectral and total exitance as:

\[
M_\lambda = \pi L_\lambda
\]

\[
M = \pi L
\]

The exitance includes emitted, reflected, and transmitted radiant flux. The exitance due to only the thermal radiation emitted by the surface is called self-exitance or emitted exitance. Some authors, notably in the texts of heat transfer [2,3], use different denominations such as radiation intensity for radiance, radiosity for exitance and emissive power for self-exitance, however, in this text, we will adopt the standard terms used in the metrological literature.

2.3. Irradiance

Another heat flux we should consider in the study of thermal radiation is the irradiance that is the radiative heat flux incident on a surface from all directions above that surface. We will represent the spectral and total irradiance by \(E_\lambda\) and \(E\), respectively.

The mathematical evaluation of irradiance is done in a similar way to the exitance, except that we need to consider the radiant flux incident on the surface and not the one coming out of it. Thus, we can...
use Eq. (2), changing $M_\lambda$ by $E_\lambda$ and considering the incident radiance as function of incident azimuthal and zenith angles. The unit is also $W/m^2$.

2.4. The Blackbody

To calculate some radiative heat fluxes such as spectral exitance of real surfaces, it is necessary to quantify the spectral radiance used, however, to make this task easier, an ideal radiant surface was defined. This surface was named blackbody.

The German physicist Gustav Kirchhoff called an ideal absorber and emitter of a black body, a term that nowadays is more common to find it written as a single word, blackbody.

We can cite the following characteristics of a blackbody surface [1]:

- It is the best absorber because it absorbs all incident radiation, independent of the angle of incidence and of the wavelength.
- It is the best emitter because it emits the maximum heat flux at any direction and wavelength at a given temperature.
- It is a perfectly diffuse surface, also called an isotropically diffuse surface or a lambertian surface.
- Its spectral radiance is a function of wavelength and temperature, but it is independent of direction.

2.5. The Emissivity

If we intend to capture the thermal radiation of a surface to evaluate its temperature through a radiation thermometer, it is important to understand how this surface emits thermal radiation in comparison to a blackbody.

The total hemispheric emissivity $\varepsilon(T)$ of this material is a property that compares the radiation emitted by the surface of the material in all directions and at all wavelengths with that which would be emitted by a surface of a blackbody, both at the same temperature, that is,

$$\varepsilon(T) = \frac{M_{em}(T)}{M_b(T)}$$

in which $M_{em}$ is the total self-exittance and $M_b$ is the blackbody total exitance.

At this point, we emphasize that in all equations in this text where the temperature appears, we are referring to the SI temperature unit, Kelvin, unless we explicitly specify another unit.

We also can be interested in the behavior of the radiative properties of materials as a function of wavelength and propagation direction. In this case we use the spectral and directional words, respectively. For instance, the directional spectral emissivity $\varepsilon'_\lambda$ is defined:

$$\varepsilon'_\lambda(\lambda, \theta, \phi, T) = \frac{L_{\lambda,em}(\lambda, \theta, \phi, T)}{L_{\lambda,b}(\lambda, T)}$$

where the prime, $\lambda$ and $b$ modifiers represent the directional, spectral, and blackbody properties, respectively.

The reader should note in the fraction’s denominator of Eq. (6) that the spectral radiance of the blackbody does not depend on the coordinates $\theta$ and $\phi$. This is a consequence of the lambertian surface property of blackbodies.

3. Thermal Radiation Detectors

The thermal radiation detectors can be classified, relating to the physical phenomenon involved in the detection process, as thermal and quantum detectors. The latter are also known as photodetectors.

Thermal detectors absorb radiant energy and then increase the temperature of the sensing element, which alters some of its temperature dependent property. The measurement of this property allows calculating the temperature of the source of thermal radiation. These detectors are characterized by
absorption of radiation over a wide spectral range, excellent linearity, and slow response speed in relation to quantum detectors. Among the thermal detectors are thermopiles, bolometers and pyroelectric detectors whose temperature-dependent properties are, respectively, electromotive force, electric resistance, and surface electric charge [4].

Thermopiles usually operate in a subrange between 2 μm and 18 μm. A typical commercial configuration comprises the spectral range from 8 μm to 14 μm with a measurement range from −30 °C to 900 °C. Uncooled microbolometers have been used in the manufacture of detectors for thermal imagers. Such a typical commercial configuration used in thermal imagers comprises a spectral range from 7.5 μm to 13 μm with temperature range from −40 °C to 500 °C.

In quantum detectors, the photons of thermal radiation are absorbed by electrons from the crystalline structure of the detectors resulting in phenomena of quantum nature such as the photoelectric effect. These detectors have higher response speeds than thermal detectors. Typically, quantum detectors without forced cooling used in radiation thermometry are Si, Ge, InGaAs and PbS photodiodes. Si photodiodes are preferably used for high-temperature measurement.

A typical radiation thermometer with a Si photodiode has a spectral range from 0.8 μm to 1.1 μm and a temperature range between 600 °C and 3000 °C. Photodetectors of InSb or HgCdTe (commonly referred to as Mercury Cadmium Telluride MCT), cooled by liquid nitrogen, are used for low-temperature measurement [5].

4. Total Radiation Thermometers

Total radiation thermometers are based on the Stefan-Boltzmann law which relates the total exitance to the temperature of a blackbody:

\[ M_b(T) = \sigma T^4, \]  

(7)

where \( \sigma \) is the Stefan-Boltzmann constant. Because the surface being measured is not a real blackbody, we need to use its emissivity as a reduction factor:

\[ M_{em} = \varepsilon \sigma T^4. \]  

(8)

Considering negligible the reflected exitance of the surface compared to its self-exitance, the apparent or total radiance temperature, \( T_t \), showed by the total radiation thermometer is related to the real temperature \( T \) by the following:

\[ \varepsilon \sigma T^4 = \sigma T_t^4 \]  

(9)

and therefore, the actual temperature can be obtained:

\[ T = \varepsilon^{-1/4} T_t. \]  

(10)

Differentiating \( T \) in relation to \( \varepsilon \), it can be shown that

\[ \frac{\delta T}{T} = -\frac{1}{4} \frac{\delta \varepsilon}{\varepsilon}, \]  

(11)

where \( \delta \) implies small variation. The result in Eq. (11) shows that the relative uncertainty in temperature is one-quarter of the relative uncertainty in the emissivity, i.e., an uncertainty of 10% in emissivity leads to an uncertainty of 2.5% in temperature. At a temperature of 1000 K, this implies an uncertainty of 25 K.

5. Spectral Band Radiation Thermometers

We have seen that the total radiation thermometers calculate the radiance temperature based on Stefan-Boltzmann’s Law. The spectral band radiation thermometer uses the blackbody spectral radiance to get the radiance temperature. This measured spectral radiance \( (L_m) \) comprises the components due reflections in the target surface \( (L_\rho) \), the radiance emitted by the surface \( (L_e) \) and the radiance of the detector by itself \( (L_d) \). Thus, we can write
\[ L_m = L_s + L_p - L_d. \]  
\[ L_m = L_s + L_p - L_d. \] (12)

Considering that the RT has an emissivity setting \( \varepsilon_i \) where the user must set the estimated surface emissivity, we can rewrite Eq. (11) as:

\[ \varepsilon_i L_b(\lambda, T_m) = \varepsilon(\lambda) L_b(\lambda, T) + (1 - \varepsilon) L_b(\lambda, T_p) - L_b(\lambda, T_d) \]  
\[ \varepsilon_i L_b(\lambda, T_m) = \varepsilon(\lambda) L_b(\lambda, T) + (1 - \varepsilon) L_b(\lambda, T_p) - L_b(\lambda, T_d) \] (13)

where \( T_m \) is the measured (apparent) temperature, \( T \) is the real target temperature, \( T_p \) is the surrounding temperature (or the environment temperature in the place where the thermometer is), \( T_d \) is the temperature of the detector and \( L_b \) is the blackbody spectral radiance, which is:

\[ L_b(\lambda, T) = \frac{c_{1L}}{\lambda^5} \left( \frac{c_2}{e^{c_2/\lambda T} - 1} \right) \]  
\[ L_b(\lambda, T) = \frac{c_{1L}}{\lambda^5} \left( \frac{c_2}{e^{c_2/\lambda T} - 1} \right) \] (14)

where \( c_{1L} \) is the first radiation constant for spectral radiance and \( c_2 \) is the second radiation constant. We can get the values of these constants and other physical fundamental constants from [6]. We also are considering that the output of detector is proportional to the Planck’s Law and \( \varepsilon(\lambda) \) is the spectral emissivity of the target.

If \( T_d \) has a typical value about 25 °C and the target is at a temperature about 200 °C or greater, than we can neglect the last term of Eq. (13). Let us suppose we can neglect the \( T_p \) term, which is reasonable if \( T_p \) is much smaller than \( T \) or if the target has high emissivity. Then, Eq. (13) turns into

\[ \varepsilon_i L_b(\lambda, T_m) = \varepsilon(\lambda) L_b(\lambda, T). \]  
\[ \varepsilon_i L_b(\lambda, T_m) = \varepsilon(\lambda) L_b(\lambda, T). \] (15)

If \( c_2/(\lambda \cdot T) \gg 1 \) we can use the Wien approximation for spectral radiance. For example, if \( c_2/(\lambda \cdot T) \gg 5 \), the Wien’s Law leads to an error less than 1 %. Then, using the Wien’s approximation and setting \( \varepsilon = 1 \), we can easily calculate the real temperature \( T \):

\[ T = \left[ \frac{1}{T_m} + \frac{\lambda}{c_2} \ln \varepsilon(\lambda) \right]^{-1}. \]  
\[ T = \left[ \frac{1}{T_m} + \frac{\lambda}{c_2} \ln \varepsilon(\lambda) \right]^{-1}. \] (16)

Differentiating \( T \) with respect to the spectral emissivity we get the relative uncertainty in the surface temperature as a function of the relative uncertainty in its spectral emissivity:

\[ \frac{\delta T}{T} = -\frac{\lambda T}{c_2} \frac{\delta \varepsilon(\lambda)}{\varepsilon(\lambda)}. \]  
\[ \frac{\delta T}{T} = -\frac{\lambda T}{c_2} \frac{\delta \varepsilon(\lambda)}{\varepsilon(\lambda)}. \] (17)

Figure 3 illustrates the difference between the real target temperature and the measured apparent temperature as a function of the emissivity of the target for a total RT and for a spectral band RT operating at different wavelengths. The temperature of the target surface is 1000 K. In the figure, it is possible to note that if the surface is a blackbody, all the thermometers returns the correct temperature, however, if the surface has an emissivity equal to 0.95, the total RT would present an error greater than 12 °C.

If it is not possible to use the Wien approximation and it is also not appropriate to use the average value of the nominal spectral range of the thermometer, which is the case for wide spectral range thermometers, such as 8 μm to 14 μm, The Planck’s Law can be approximated by the Sakuma-Hattori equation. A good reference for this case can be found in [7].
Figure 3 – Corrections to the apparent temperature as a function of the emissivity of the target

6. The ratio thermometer

The ratio thermometer calculates the target temperature from the ratio of signals generated at two different wavelengths. This thermometer is an excellent option when the spectral emissivity of the target (surface of interest) has grey behavior and then, emissivity is independent of the wavelength in the spectral band of the RT. In this case, it is possible to calculate the temperature independent of the emissivity value.

The ratio thermometer also is called radiance ratio thermometer, dual wavelength thermometer, two-color thermometer. This last terminology is inappropriate because it can lead to the interpretation that the thermometer operates only on the spectrum of visible light, which is not always true. In this text, we will adopt the term ratio thermometer.

The signal $S_i$ related to the spectral band $\lambda_i$, $i \in \{1, 2\}$, is:

$$S_i = C \varepsilon_i L_b \lambda_i (\lambda_i, T), \quad (18)$$

where $C$ is a proportionality constant. The ratio of signals $r$ becomes

$$r = \frac{S_1}{S_2} = \left(\frac{\lambda_2}{\lambda_1}\right)^5 \frac{\varepsilon_1}{\varepsilon_2} \cdot \exp \left[\frac{c_2}{T} \left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\right], \quad (19)$$

in which we use the Wien approximation. The last equation can easily be solved for $T$:

$$\frac{1}{T} = \frac{1}{T_r} + \frac{\lambda_1 \lambda_2}{c_2 (\lambda_2 - \lambda_1)} \ln \frac{\varepsilon_2}{\varepsilon_1}, \quad (20)$$

where $T_r$ is the ratio temperature, the apparent temperature got by the ratio thermometer when the target has a grey surface.

The ratio temperature is

$$T_r = \frac{c_2 (\lambda_2^{-1} - \lambda_1^{-1})}{\ln \left[r \left(\frac{\lambda_1}{\lambda_2}\right)^5\right]}, \quad (21)$$

If the surface is grey, the last term in (20) vanishes and the ratio temperature equals the target temperature. The latter term in (20) therefore represents the error in $T_r^{-1}$ if the emissivity is different in the two wavelengths used by the thermometer.
7. Conclusions
For the measurement of temperature through thermal radiation, we must carry calculations involving integration with limits between the spectral ranges of the detectors. These calculations become much more complex than when Wien’s Law is used instead of Planck’s Law. Moreover, depending on the spectral range of the thermometer and the temperature to be measured, it is possible to use Wien’s Law with errors less than 1%, which is why we gave some examples using this Law and not Planck’s.

The total radiation thermometer uses Stefan-Boltzmann’s Law for the calculation of temperature. These thermometers have greater sensitivity to uncertainties in the target’s emissivity than the spectral band thermometers.

Ratio thermometers operate in two distinct spectral bands. They are useful when we do not have a very precise estimate of the target’s emissivity, but we know that the emissivity does not vary between the spectral ranges of operation of the thermometer. The ratio thermometer can calculate the temperature without dependence of the emissivity of the target.

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