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A new wavelength selection criterion for two-color pyrometer interfered with participating media

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ABSTRACT

Two-color pyrometry is well established and widely applied to surface temperature measurements. However, its accuracy degrades significantly when the transmission path between the object surface and the pyrometer is full of high concentration participating media, which attenuates the surface radiation signal to the pyrometer. To improve measurement accuracy, a theoretical optimization wavelength selection criterion for two-color pyrometry working with the interference of a participating medium is established on the basis of the Plank's law and Wien's approximation. The closer to zero the criterion value is, the smaller the measuring error is. Therefore, the optimum choice of operating wavelengths combination for two-color pyrometer is obtained through intercomparison of the criterion values. Evaluation of the practical applicability of the new criterion is performed by employing an analytical radiation thermometry model considering radiative attenuation and augmentation in participating media. Theoretical estimations confirm that the new criterion has good applicability and scientific quality considering two typical media ordinarily encountered in engineering applications: water vapor and water mist. This selection criterion not only provides solid reference information for the proper selection of wavelengths combination, but also helps one to better understand the fundamentals of measurement errors for two-color pyrometer interfered with participating media. The analyses in the paper provide the necessary theoretical supports for the design and application of a two-color pyrometer.

1. Introduction

Surface temperature is one of the most important characteristics of scientific, industrial, and military targets. Accurate surface temperature measurement thus acts as a key role in target detection, monitoring, and diagnosis processes [1–4]. The radiometric determination of temperature is of great practical importance and is widely used in science and industry in those instances in which thermocouples, resistance thermometers or other sensors are found to be unsuitable [5].

One of the great advantages of radiation thermometers is that they can measure temperature at a distance. However, this involves using the intervening space between the object and the thermometer as the transmission path for the radiation, but unfortunately most gases and particles are not transparent [6]. The participating medium across the transmission path can attenuate the amount the radiant flux received by the radiation detector due to absorption and scattering. Participating medium emission, which is closely related to absorption by referring to Kirchhoff's law, can increase the apparent spectral radiance [7]. Consequently, the effects of the participating medium produce corresponding erratic and inaccurate surface temperature measurements that vary unpredictably according to the aforementioned effects.

The problem can often, but not always, be reduced by using thermometers that operate at shorter wavelengths provided that the radiative participating media is not spectral selective [8,9]. It is noted that this method could not remove the problem. Additionally, there are many situations where longer operating wavelengths may prove advantageous, such as the case of cooler objects. As a consequence, it is meaningful to put forward a general analytical method or criterion to investigate and remove the effect of participating media on radiometric temperature measurements.

In applications when there is additional attenuation caused by the presence of an unwanted medium, such as smoke or steam, it is very common to use a two-color pyrometer to correct for the losses because the reduction in signal due to additional attenuation is possibly cancelled out partly in many applications by ratioing the electrical outputs from the two photo-detectors [10,11]. As Tenney [12] indicated, two-color pyrometers do not necessary provide more accurate results than monochromatic pyrometers. The extent of the cancellation depends on

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the selected pyrometer wavelengths [13]. Regarding to the wavelength selection criterion in two-color pyrometers, A. Tapetado et al. [14] presented the separation between single wavelengths channels has to be large enough to minimize the temperature error and to allow the separation of both channels without overlapping. At the same time, they have to be close enough to ensure a constant emissivity [13]. However, these principles are put forward without consideration of the thermal radiation attenuation caused by participating media. If high temperature participating media are presented in the field-of-view of the pyrometer with significant concentrations, a novel wavelength selection criterion considering the application of a computed correction for such effect is needed.

Many previous theoretical studies [11–13] concerning two-color pyrometers involve the discussion of the thermal radiation attenuation caused by participating media. They have claimed that the measured temperature is not affected by any signal attenuation as long as the attenuation is the same across the two chosen wavelength bands. While the theoretical analyses elaborated in the following section certify that two-color ratio pyrometer does not always measure the true temperature of a gray-body, although the signals of both channels attenuate equally.

A new optimal wavelength selection criterion for eliminating the interference of participating media is developed in the present work on the basis of the *Plank's law* and *Wien's approximation*. The applications of this criterion are threefold: first, this criterion is instructive to select the most suitable wavelength for radiation thermometry in the case of non-negligible medium within the field of view; second, theoretical analyses of the measurement uncertainty based on the wavelength selection criterion are useful in better understanding the intrinsic causes of it; third, this criterion is the fundamental factor for evaluating the performance of a two-color pyrometer working in participating media and applicable for system design and application.

This paper is organized as follows. First, a theoretically optimal wavelength selection criterion for two-color pyrometer working in participating medium is established on the basis of the *Plank's law* and Wien's *approximation*. Subsequently, to evaluate the applicability of the new criterion, numerical simulations considering radiative attenuation and augmentation in participating media are carried out. Finally, the main conclusions of this work are briefly given.

2. Measurement principles of two-color pyrometer

A pyrometer is a non–contact device that intercepts and receives thermal radiation from an emitting target surface, converting the output signal into a measuring temperature value. An equation for the quantitative mathematical relationship between the measured thermal radiation $E_\lambda(T)$ and its thermo-physical temperature T can be derived from *Planck's law* [15]:

$$E_\lambda(T)=\frac{2\pi\varepsilon_\lambda hc_0^2}{n^2\lambda^5\left[e^{hc_0/n\lambda kT}-1\right]} \tag{1}$$

where $h=6.626\times10^{-34}$ J·s is known as Plank's constant, n is the refractive index, ε_λ is the monochromatic emissivity of the measured object, $c_0=2.998\times10^8$ m/s is known as speed of light in vacuum, $k=1.3806\times10^{-23}$ J/K is known as Boltzmann's constant, and λ is the wavelength.

In two-color pyrometry, temperature is derived by measuring the ratio of the detector signals obtained in two different wavebands of the incoming radiation. If the wavebands are represented by the two wavelengths λ_1 and λ_2, on which the emissivity of the target are $\varepsilon_{\lambda1}$ and $\varepsilon_{\lambda2}$. The measurement temperature is determined by the ratio of $E_{\lambda1}(T)$ to $E_{\lambda2}(T)$. In this case, the temperature is given by the following equation:

$$\frac{E_{\lambda_1}(T)}{E_{\lambda_2}(T)}=\frac{\varepsilon_{\lambda_1}}{\varepsilon_{\lambda_2}}\cdot\frac{\lambda_2^5\left[e^{hc_0/n\lambda_2kT}-1\right]}{\lambda_1^5\left[e^{hc_0/n\lambda_1kT}-1\right]} \tag{2}$$

Considering the spectral response of a real pyrometer is not a monochromatic wavelength but a narrow band, on which the radiation energy is large enough to be detected, therefore the radiation thermometer model should be written in spectral waveband form. By integrating Eq. (2) over a spectral waveband $\Delta\lambda$ results in the following equation:

$$\frac{E_{\Delta\lambda_1}(T)}{E_{\Delta\lambda_2}(T)}=\frac{\int_{\Delta\lambda_2}\lambda_2^5\left[e^{hc_0/n\lambda_2kT}-1\right]/\varepsilon_{\lambda_2}\,d\lambda}{\int_{\Delta\lambda_1}\lambda_1^5\left[e^{hc_0/n\lambda_1kT}-1\right]/\varepsilon_{\lambda_1}\,d\lambda} \tag{3}$$

Since Eq. (3) is a transcendental equation, a dichotomy search method is applied to solve this equation to obtain the target surface temperature T.

3. Optimal criterion for wavelengths selection

Because of participating medium absorption, emission and scattering, there is a huge possibility of an error of unpredictable sign and magnitude in the radiometric temperature measurement occurring when high concentration media exist in the field of view of a pyrometer. In such case an important property that requires to be considered in designing or selecting a pyrometer is its sensitivity, which describes the change in the thermometer output produced by a change in the target temperature. The choice of the working waveband is largely determined by the thermometer sensitivity, although it also depends on the efficiency of the optical system and the detectivity of the detector. Through this sensitivity analysis, a criterion for selecting the optimal spectral pass-band of a two-color pyrometer to minimize the effects of the participating media will be presented.

The sensitivity of a two-color pyrometer can be obtained by differentiating Eq. (2) with respect to T. If *Wien's approximation* [16] is used for $E_\lambda(T)$, one obtains [17]:

$$\Delta T=\frac{\lambda_1\lambda_2}{\lambda_1-\lambda_2}\frac{T^2}{c_2}\frac{\Delta R(\lambda_1,\lambda_2)}{R(\lambda_1,\lambda_2)} \tag{4}$$

where $R(\lambda_1, \lambda_2)$ is the radiance ratio of the incoming radiation at the two wavelengths, $\Delta R(\lambda_1, \lambda_2)$ represents the difference between the measured and true values of $R(\lambda_1, \lambda_2)$, and it can be expressed as follows,

$$\Delta R(\lambda_1,\lambda_2)=\frac{E_{\lambda_1}(T)-\Delta E_{\lambda_1}(T)}{E_{\lambda_2}(T)-\Delta E_{\lambda_2}(T)}-\frac{E_{\lambda_1}(T)}{E_{\lambda_2}(T)} \tag{5}$$

where $c_2=hc_0/k=1.4388\times10^4$ μm·K, $\Delta E_\lambda(T)$ represents the difference between the detected spectral radiance and true value caused by the participating media, $E_\lambda(T)$ stands for the true radiation without attenuation.

Let ϕ_λ be the ratio of attenuated radiation energy to the true radiation energy. It can be expressed as follows,

$$\phi_\lambda=\frac{\Delta E_\lambda(T)}{E_\lambda(T)} \tag{6}$$

Substituting Eqs. (5) and (6) into Eq. (4) we obtain the following relationship between the temperature measurement error (ΔT) and the attenuation ratio coefficient (ϕ_λ):

$$\Delta T=\frac{T^2}{c_2}\cdot\frac{\lambda_1\lambda_2}{\lambda_1-\lambda_2}\cdot\left(\frac{1-\phi_{\lambda_1}}{1-\phi_{\lambda_2}}-1\right) \tag{7}$$

This equation indicates that the essence of the measuring error for two-color pyrometer interfered with participating media is the separation of the two attenuation ratio coefficients. Factor $T^2\lambda_1\lambda_2/[c_2(\lambda_1-\lambda_2)]$ is only an error amplification coefficient proportional to $\lambda_1\lambda_2/(\lambda_1-\lambda_2)$ and target temperature T. The advantage of working at