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Research Article

Optimization of Wavelength Selection for a Two-Color Pyrometer Based on the Flux Ratio and Planck's Law on Real Body

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Abstract

This article examines a methodical analysis for optimizing the wavelength selection used for the two channels of a bichromatic pyrometer. Temperature measurement via pyrometry relies on analyzing the radiation emitted by a body at various wavelengths, enabling non-contact thermal assessment. Several laws mathematically characterize this thermal radiation: Lambert's law, which states that radiance is independent of the emission direction, and Planck's law, which allows for the calculation of the body's radiation energy density. The bichromatic pyrometer utilizes distinct wavelengths; it consists of two separate spectral filter channels and two detectors with different spectral sensitivities, each followed by its own analog processing electronics. The two signals representing the thermal radiation undergo this analog processing before being combined through digital processing. A crucial step is selecting the wavelengths for the two spectral filters. Depending on the approach, calculations for a bichromatic pyrometer can be based either on the flux ratio combined with Wien's approximation or on the flux ratio combined with Planck's law, with each approach offering a different level of compensation for emissivity variations. In our case, the second method, that is to say the flux ratio using Planck's law will be used. This method applies Planck's law to a real body by modeling emissivity as a second-degree polynomial. By varying the ratio value, we can calculate pairs of wavelengths based on their difference; this difference is then evaluated against relative errors to determine how to optimize the selected wavelengths. Optimizing wavelength selection in the bispectral system, by using two wavelengths simultaneously, improves the accuracy of temperature estimation and enables more reliable modeling of the materials' spectral behavior.

Keywords

Wavelength, Two-Color Pyrometer, Temperature, Emissivity, Luminance, Planck's Law

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1. Introduction

Precise temperature measurement is crucial for high-temperature industrial processes such as steelmaking and foundry operations. Optical pyrometry, which measures temperature without contact by analyzing thermal radiation, offers speed and safety. However, its accuracy is limited by complex variations in the material's emissivity. This radiative property depends on the wavelength, surface condition, and composition of the material [1-3]. A two-color pyrometer employs two optical filters for two different wavelength ranges. The selection of these two wavelengths plays a significant role in minimizing measurement errors.

2. Methodology

2.1. Physical Modeling of Thermal Radiation According to Planck's Law

According to Planck's law, the spectral radiance of a black body depends only on its temperature and wavelength [4]:

$$L_0(\lambda, T) = \frac{2hc^2}{\frac{hc}{\lambda^5(e^{(\lambda kT)}-1)}} \quad (1)$$

where h =6,6255×10^{-34}Js: constant of Planck,
k =1,38×10^{-23} JK^{-1}: constant of Boltzmann,
c =2,996×10^{8} ms^{-1}: Speed of electromagnetic waves in a vacuum [5].

A real material is characterized by emission that depends on the spectral emissivity ε(λ, T). In this case, Planck's law thus becomes the product of the blackbody radiance and the emissivity:

$$L(\lambda, T) = \varepsilon(\lambda, T). L_0(\lambda, T) \quad (2)$$

Kirchhoff described a relationship between emissivity and absorptivity. This relationship holds for opaque bodies [5-7].

$$\varepsilon(\lambda) = 1 - \rho(\lambda) \quad (3)$$

With $\rho(\lambda)$ is the spectral reflectivity.

2.2. Theoretical Foundations of Thermal Radiation

A blackbody serves as the reference for all emitting bodies; it absorbs all incident light and perfectly emits the full spectrum of radiation [3-6].

Depending on the emissivity model, which may be monochromatic or total, as well as directional or hemispherical. its value is between 0 and 1. The emission of a real body depends entirely on its emissivity, as described by Equation (2). A heated body emits radiation in the ultraviolet and infrared ranges; these represent the thermal radiation utilized in pyrometry to detect the body's temperature.

2.3. Analysis of Heat Transfer Modes

The study distinguishes between the three modes of heat transfer: conduction, convection, and radiation. At high temperatures, radiation becomes the dominant mode, justifying the use of optical techniques for thermal measurement. Interactions between the radiation emitted by the object, the environment, and the intervening atmosphere are taken into account to assess their impact on the measurement [5].

2.4. Infrared Detection Technologies

In the field of detection technology, there are two main categories: photonic detectors and thermal detectors. The choice of detector determines the measurable temperature range and the overall accuracy of the system [6].

The radiation from the object is detected by two detection systems that each other has their specification in term of spectral sensitivity. The flux cannot detect directly by those detectors but an optical filter system allows two different spectra to pass through and converge them respectively towards the detector system [6, 7].

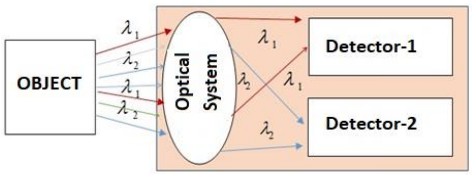

Figure 1. *Optimal principle of bichromatic pyrometer [8].*

3. Various Bichromatic Estimation Models

Three models will be presented and compared. Each model accounts for a polynomial representation up to the second order of the spectral variations in the measurement chain's overall transfer function (including emissivity). The first model is based on the flux ratio using the Wien approximation; it is thus inspired by the model used in dual-wavelength (bi-spectral) thermometry. The second model relies solely on the flux ratio, assuming Planckian emission [8-12].

3.1. Multispectral Method Based on the Flux Ratio and the Wien Approximation

The Temperature via Non-Linear model (TNL) is the model and the suffix TXY indicates the parameters to be estimated. This method will be referred to as the TNL.TXY method [11-

14]. The same naming convention will be used for the other methods.

Letting (λ) denote the overall transfer function of the measurement chain, the flux (λ_i) received by the detector at wavelength λ_i, under the Wien approximation [1, 15, 16], is expressed as:

$$L_{\lambda_i}(T) = f(\lambda_i)\frac{C_1\lambda_i^{-5}}{-1+e^{\frac{c_2}{\lambda_i T}}}, \forall\lambda_i \ll c_2 \quad (4)$$

with $C_1 = 2hc^2$ and $C_2 = \frac{hc}{k}$

3.2. Multispectral Method Based on the Flux Ratio and Planck's Law

The approach is analogous to that developed in the first method, except that Planck's law is used instead of the Wien approximation; consequently, we cannot express the temperature Rij as a function of the flux ratio [15]. Thus, the proposed model is written as:

$$\mathrm{R}(a_0, a_1, a_2) = \frac{L_i}{L_j} \quad (5)$$

$$\mathrm{R}(a_0, a_1, a_2) = \left(\frac{a_0+(\lambda_j-\lambda_m)a_1+(\lambda_j-\lambda_m)^2 a_2}{a_0+(\lambda_j-\lambda_m)a_1+(\lambda_j-\lambda_m)^2 a_2}\right)\left(\frac{\lambda_j}{\lambda_i}\right)^{-5}\left(\frac{-1+e^{\frac{c_2}{\lambda_j T}}}{-1+e^{\frac{c_2}{\lambda_i T}}}\right) \quad (6)$$

3.3. Multispectral Method Based on Planck's Law

The multispectral method based on Planck's law for real bodies is a technique for determining an object's temperature by analyzing its electromagnetic radiation at multiple wavelengths [16, 17]. Planck's law describes the intensity of radiation emitted by a black body as a function of temperature T and wavelength λ:

$$L(\lambda, \mathrm{T}) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1} \quad (7)$$

where h is Planck's constant,

c is the speed of light,

k is Boltzmann's constant.

By measuring the spectral intensity at different wavelengths, λ_1 and λ_2, one can establish a flux ratio:

$$R(\lambda_1, \lambda_2, T) = \frac{I(\lambda_1, T)}{I(\lambda_2, T)} = \frac{\lambda_1^5 e^{\frac{\mathrm{hc}}{\lambda_2 \mathrm{kT}}}-1}{\lambda_2^5 e^{\frac{\mathrm{hc}}{\lambda_1 \mathrm{kT}}}-1} \quad (8)$$

This ratio is then used to solve the equation for T, thereby making it possible to determine the object's temperature. This method is effective in contexts requiring high precision, such as infrared thermography and astrophysics [18].

4. Results of the Various Presentations of the Calculations

The spectral flux radiated by the steel at T = 1373.15 K is calculated using Planck's law using Equation (2). By measuring the spectral intensity at different wavelengths, λ_1 and λ_2, a flux ratio represented in Equation (6) can be established.

For each value of λ_2 ranging from 0.7 to 2.5 µm, that is the near-infrared band, the corresponding wavelength λ_1 is determined numerically by solving this ratio. Calculations show that λ_1 is always less than λ_2.

4.1. Selection of the Two Wavelengths Based on the Ratio of the Two Fluxes

The analysis of wavelength selection optimization for the bichromatic pyrometer focuses on determining the optimal separation between the two wavelengths used to measure the temperature of molten steel at 1373.15 K. The principle relies on measuring the ratio of radiant fluxes at two closely spaced wavelengths (λ_1 and λ_2). The objective is to identify wavelength pairs that minimize measurement error while remaining within the technologically feasible range of 0.7 µm to 3 µm. The wavelength differences are illustrated in the figure below for flux ratios of 0.25, 0.50, 0.75, and 0.90.

4.2. Flux Ratio Versus the Difference Between the Two Wavelengths

The figure below is derived using the results from Section 4.1 regarding the selection of the two wavelengths based on the flux ratio and Equation (6). The ratio of the two spectral radiances (based on Planck's law applied to a real body) is expressed as a function of the separation between the two wavelengths, λ_1 and λ_2.

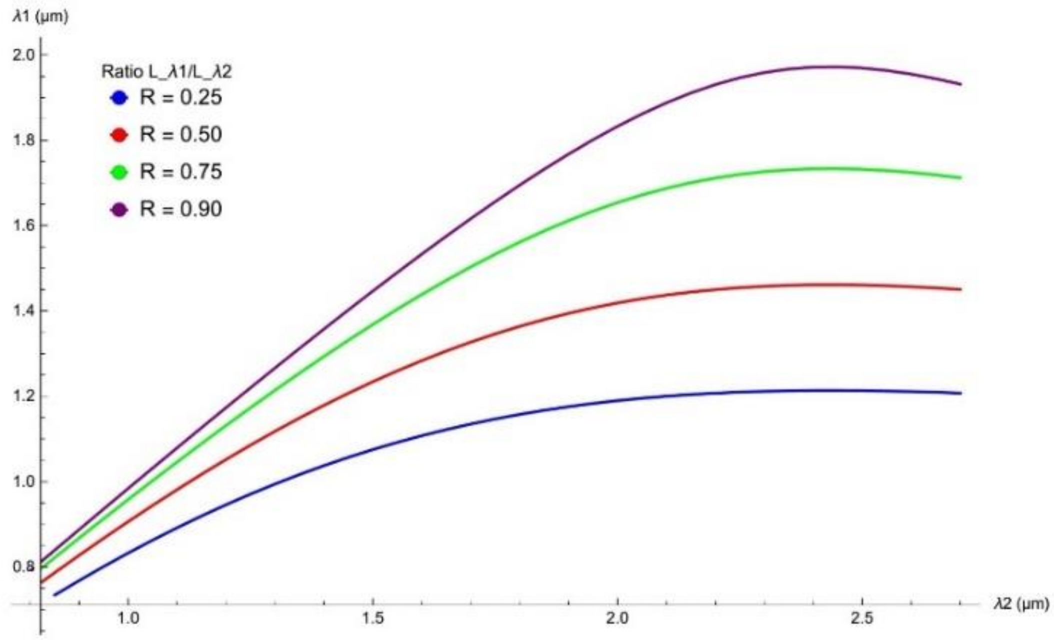

***Figure 2**. Optimal pairs (λ_1, λ_2) for different values of the ratio of the two fluxes.*

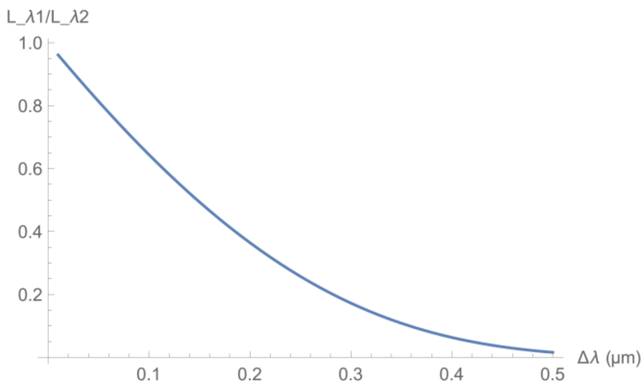

***Figure 3**. Ratio of the two fluxes as a function of Δλ, with λ_2 fixed at 1.2 µm.*

4.3. Measurement Sensitivity

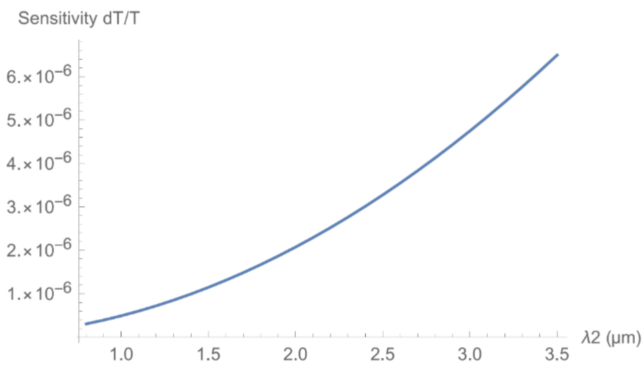

***Figure 4**. Ratio relative error dT/T as a function of λ_2.*

The amplification factor for measurement errors in the luminance ratio is plotted as a function of the choice of λ_2, since the value of the first wavelength depends on the second. Understanding the characteristics of this error is important for determining the optimal values for both wavelengths [17, 18].

5. Discussion of the Results

For each λ_2, the corresponding λ_1 is determined such that the flux ratio L_λ1/L_λ2 equals 0.25, 0.50, 0.75, or 0.90. The closer the ratio of the two fluxes generated at wavelengths λ_1 and λ_2, respectively is to the upper limit (i.e., close to 1), the more linear the curve of the difference $\lambda_2 - \lambda_1$ becomes for λ_2 values below 2.5 µm. Within this λ_2 range, lower ratios exhibit less linearity in the difference between the two wavelengths compared to ratios close to 1.

The ratio decreases almost exponentially with Δλ:

1) For Δλ = 0.01 µm, the ratio is 0.95, very close to 1; the risk of error is high, as the two signals are nearly equal.
2) For Δλ = 0.18 µm, R = 0.45; this allows for an optimal value regarding the two wavelengths.
3) For Δλ = 0.5 µm, R = 0.05; noise immunity reaches its lower limit because the ratio of the two fluxes from the two wavelengths is too low.

At wavelengths below 2 µm, the sensitivity follows a nonlinear polynomial curve with very low relative error. Preferably, the second wavelength λ_2 lies within the near-infrared band, and λ_1 is calculated and based on its value. The goal is to achieve a configuration that offers the best compromise between thermal sensitivity (significant variation of luminance with the temperature T), emissivity stability (λ_1 and λ_2 being close), low sensitivity to measurement errors, and, above all, the availability of detectors in the relevant spectral band.

6. Conclusions

The method achieves a theoretical temperature accuracy of around 0.1%, which is sufficient for the industrial control of steelmaking processes.

It follows that the higher the flux ratio, the more one error term can be disregarded relative to the other, thereby reducing the error in the temperature measurement.

While the two-color pyrometer is not the most theoretically accurate method for real bodies, it represents the optimal solution from a techno-economic standpoint. It offers the best balance between measurement speed, implementation cost, and partial robustness against signal disturbances (provided these are non-selective). It is therefore the preferred choice for industrial process control, where speed and simplicity are paramount.

Optimizing the selection of wavelengths minimizes measurement errors while addressing the requirements of the various criteria.

Abbreviations

TNL	Temperature via Non-Linear Model
TXY	Parameters T, X, et Y to Be Estimated

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Author Contributions

Ratianarivo Paul Ezekel: Conceptualization, Investigation, Methodology, Resources, Visualization, Writing – original draft, Writing – review & editing

Andrianjanahary Olinirina Theophile: Data curation, Resources, Software

Rastefano Elisee: Project administration, Supervision, Validation

Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Ratianarivo Paul Ezekel is a professer at Polytechnical High School of Antsirabe, Vakinankaratra University, Electronic Engineering Department. He completed his PhD in Electronic Divices et Systems Engineering from Antananarivo University in 2018, and his Master of Engineering in Automatic Electronic Systems from Polytechnical High School of Antananarivo in 2010. Recognized for his exceptional contributions, Dr. Ratianarivo Paul Ezekel has been known as the chef department of electronic engineering at Polytechnical High School of Antsirabe.

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Ratianarivo Paul Ezekel: Electronic system, Instrumentation, Embedded systems, programmable system, spintronic.

Andrianjanahary Olinirina Theophile: Electronic system, Instrumentation, Embedded systems.

Rastefano Elisee: Semiconductor, electronic system, signal processing, spintronic.