



Research Article

Efficiency of Multispectral Pyrometer Technology in the Infrared Spectral Band According to Planck's Law on the Real Body in the Case of Oxidized Steels

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Abstract

This research is based on a theoretical analysis of thermal radiation, the fundamental laws of Planck and Kirchhoff, and multispectral processing methods using nonlinear models. Accurate high-temperature measurement is a major challenge in many scientific and industrial fields, including thermal processes, metallurgy, energy, and fundamental research. Planck's law gives the relation between radiation, temperature and wavelength. That law can be used to determine temperature by pyrometry method. Besides Planck's law for the black body multiplied by the emissivity will give the expression of the real body. Uncertainty in emissivity is the main source of error in conventional pyrometric measurements. In our case, the polynomial model of emissivity only goes up to the second order. To reduce the influence of emissivity and improve measurement reliability, several approaches have been developed, including monochromatic, bichromatic, and multispectral pyrometry based on Planck's law. The characteristics of chromatic luminance in the near and mid-infrared bands highlight the high potential of pyrometry for measuring high temperatures in complex environments. Compared to traditional approaches, this pyrometry technology offers greater robustness to variations in emissivity and environmental uncertainties. Luminance across the infrared spectral band and a temperature range provides improved linearity. This linearity highlights the strength of using infrared radiation for remote temperature sensing. The mid-infrared zone offers greater stability and a closer relationship between luminance, temperature, and wavelength in temperature detection for oxidized steel.

Keywords

Wavelength, Pyrometry, Spectrum, Temperature, Luminance, Emissivity, Infrared

1. Introduction

Infrared pyrometry is based on the fundamental principle that anybody with a temperature above absolute zero emits electromagnetic radiation whose intensity and spectral distribution depend on its temperature. However, the relationship between the measured radiation and the actual temperature is

strongly influenced by the radiative properties of materials, particularly emissivity [1-3].

Applying the infrared spectral length allows for the characterization of chromatic radiance according to Planck's law [4, 5].

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2. Methodology and Law of Radiation

2.1. Physical Model

Multispectral pyrometry modeling is based on the fundamental laws of thermal radiation. Planck's law describes the spectral radiance of a black body at temperature T [6-8].

$$L_0(\lambda, T) = \frac{2hc^2\lambda^{-5}}{e^{\left(\frac{hc}{\lambda T}\right)} - 1} \tag{1}$$

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

For a real material, the measured luminance is weighted by the spectral emissivity $\epsilon(\lambda, T)$.

$$L(\lambda, T) = \epsilon(\lambda, T) \cdot L_0(\lambda, T) \tag{2}$$

Kirchhoff's fundamental relationship linking emissivity and absorptivity is written, for an opaque body [9].

$$\epsilon(\lambda) = 1 - \rho(\lambda) \tag{3}$$

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

In multispectral pyrometry, the temperature is estimated from the measured fluxes [10, 11].

For materials with non-linear emissivity, such as steels, that is to say, emissivity does not depend on wavelength. In that case, the emissivity can be modelled as a second-degree polynomial.

$$\epsilon_\lambda = a\lambda^2 + b\lambda + c \tag{4}$$

The parameters a, b, and c are to be estimated during the measurement [12-14].

2.2. Different Regions of the Infrared Spectrum

The infrared range covers wavelengths from 0.8µm to 1000µm. It is generally divided into 2 sub-ranges: near and mid for thermography.

Table 1. Different region of the infrared spectrum for thermography [15].

| Near infrared | Mid infrared |
|-----------------|----------------|
| 0.8 µm - 2.5 µm | 2.5 µm - 25 µm |

2.3. Theoretical Foundations of Thermal Radiation

The methodology is based primarily on the study of the physical principles of thermal radiation. The electromagnetic radiation emitted by a heated body extends from the ultraviolet to the infrared, with a spectral distribution governed by Planck's law. The black body serves as the reference model, representing an ideal emitter that absorbs and emits perfectly across the entire spectrum [16].

For a real material, the spectral radiance is weighted by an emissivity coefficient, ranging from 0 to 1. This emissivity can be defined in different forms: monochromatic or total, directional or hemispherical [17]. In pyrometry, directional monochromatic emissivity plays a central role, as it directly relates the measured radiance to the actual surface temperature.

2.4. Infrared Detection Technologies

The methodology includes a comparative analysis of the different infrared detector technologies used in pyrometry. Photonic and thermal detectors are studied according to their spectral range, sensitivity, and signal-to-noise ratio [18]. The choice of detectors determines the measurable temperature range and the overall accuracy of the system.

3. Results of Chromatic Curve

Using equation (2) which describes that the measured luminance is weighted by the spectral emissivity $\epsilon(\lambda, T)$, we obtain the characteristic curves of oxidized steels, i.e. the emissivity does not vary as a function of length or temperature.

3.1. Curve in the Near-Infrared Spectrum

The near-infrared spectrum lies between the 0.8 µm and 2.5 µm band. The characteristic luminance curves according to Planck's law for real bodies whose emissivity is such a polynomial form are plotted from temperatures from 0 K up to 2500 K. They are obtained by choosing the wavelengths 0.9 µm, 1.35 µm, 1.75 µm and 2.25 µm in the near-infrared spectral band.

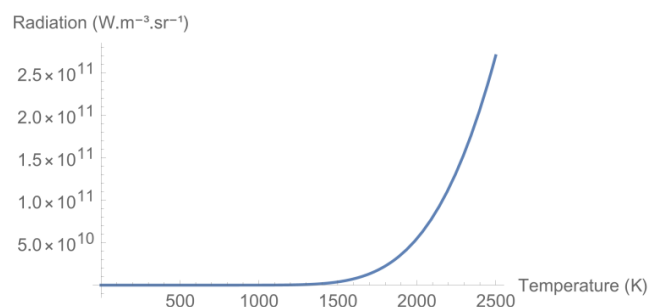


Figure 1. Radiation emitted for Oxidized Steel at a wavelength of 0.9 µm.

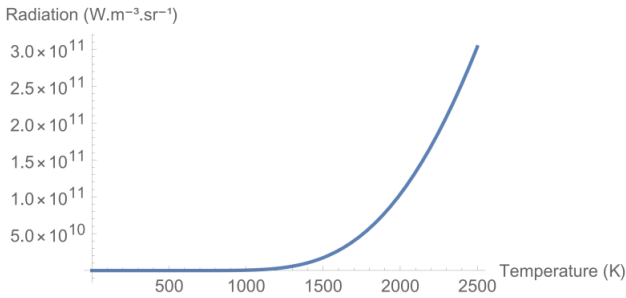


Figure 2. Radiation emitted for Oxidized Steel at a wavelength of 1.35 μm .

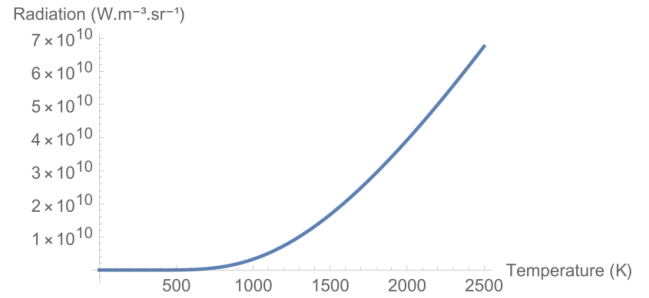


Figure 5. Radiation emitted for Oxidized Steel at a wavelength of 3 μm .

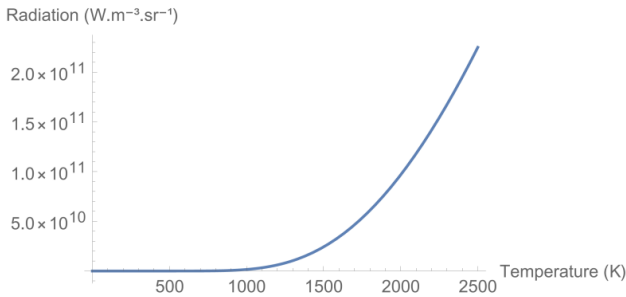


Figure 3. Radiation emitted for Oxidized Steel at a wavelength of 1.75 μm .

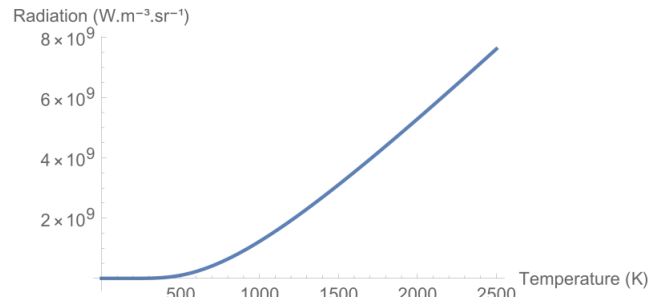


Figure 6. Radiation emitted for Oxidized Steel at a wavelength of 6 μm .

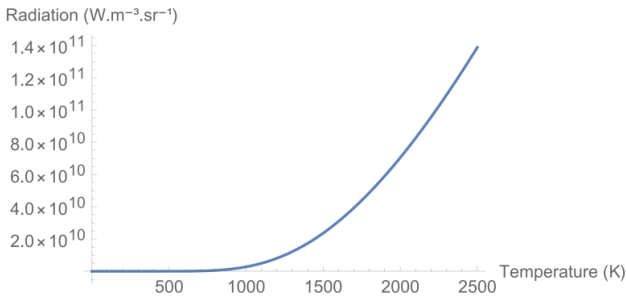


Figure 4. Radiation emitted for Oxidized Steel at a wavelength of 2.25 μm .

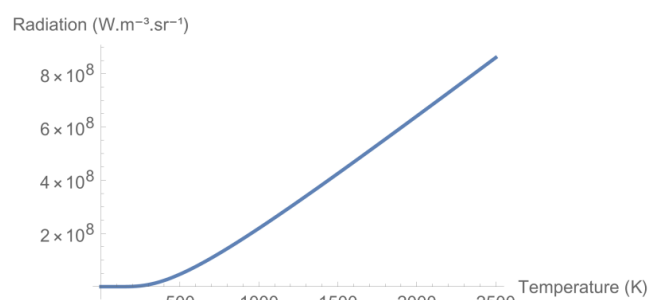


Figure 7. Radiation emitted for Oxidized Steel at a wavelength of 11 μm .

3.2. Curve in the Mid-Infrared Spectrum

The mid-infrared spectrum lies between the 2.5 μm and 25 μm band. The characteristic luminance curves according to Planck's law are plotted from temperatures from 0 K up to 2500 K. They are obtained by applying the wavelengths 3 μm , 6 μm , 11 μm , 14 μm , 18 μm , 22 μm , and 24 μm .

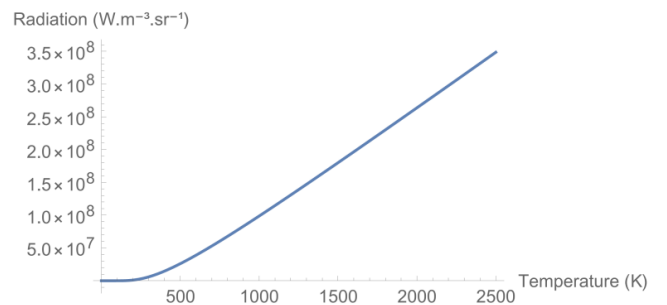


Figure 8. Radiation emitted for Oxidized Steel at a wavelength of 14 μm .

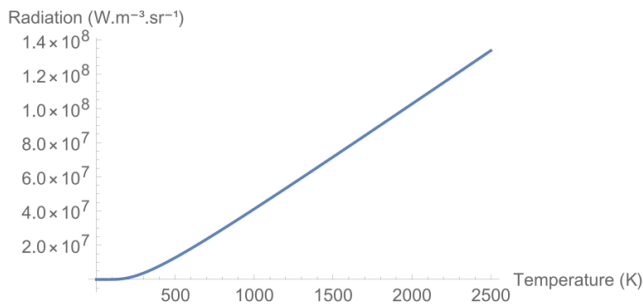


Figure 9. Radiation emitted for Oxidized Steel at a wavelength of 18 μm .

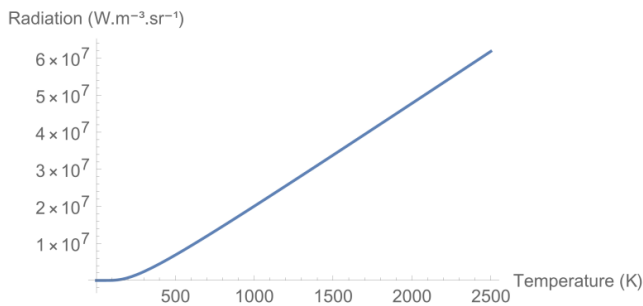


Figure 10. Radiation emitted for Oxidized Steel at a wavelength of 22 μm .

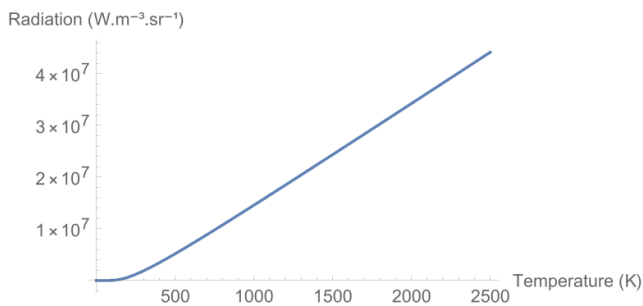


Figure 11. Radiation emitted for Oxidized Steel at a wavelength of 24 μm .

4. Discussion

These curves allow for a direct comparison of the performance of different spectral ranges within the framework of multispectral pyrometry.

In the near-infrared range, low radiation is observed at temperatures below 1000 K, and the signal sensitivity in this region is very low. However, above these temperatures, the sensitivity becomes high, indicating the effectiveness of the measurement at high temperatures. The influence of stray radiation on the observed radiation is minimal.

The spectral band between 2.5 μm and 25 μm exhibits better overall stability, but with low thermal sensitivity at low temperatures. The curves representing luminance in this region are almost linear except at temperatures below approximately

200 K, which explains the linear relationship between chromatic luminance and temperature for wavelengths above 200 K.

The results show that the choice of wavelengths has a decisive influence on the accuracy of multispectral pyrometry. Sequential selection makes it possible to identify groups of optimal wavelengths that minimize the uncertainty in the estimated temperature. The wavelengths selected differ depending on the temperature range considered and the spectral domain studied.

5. Conclusions

In the infrared range, characterized by long wavelengths, spectral radiance varies more slowly with temperature. This shallow slope indicates reduced thermal sensitivity.

The infrared spectrum offers several major advantages: improved measurement stability, low sensitivity to external disturbances, and less influence from rapid spectral variations in emissivity.

Below 200 K, a compensation system is highly recommended to reduce the influence of ambient fluxes.

The near-infrared region is very effective for detecting high temperatures in oxidized steels, while the mid-infrared exhibits a good linear relationship between temperature, wavelength, and chromatic radiance.

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Author Contributions

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

Tiavina Razafindratsira: Data curation, Funding acquisition, Resources

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 professor at Polytechnical High School of Antsirabe, Vakinankaratra University, Electronic Engineering Department. He completed his PhD in Electronic Devices 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.



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Research Field

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

Tiavina Razafindratsira: Electronic system, Instrumentation, Embedded systems.

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