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Spectral-brightness pyrometry: Radiometric measurements of non-uniform temperature distributions

I.P. Gulyaev [a,b,*], A.V. Dolmatov [b]

[a] Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Institutskaya Str. 4/1, Novosibirsk 630090, Russia
[b] Ugra State University, Chekhova Str. 16, Khanty-Mansiysk 628012, Russia

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ABSTRACT

The paper proposes spectral-brightness pyrometry (SBP) as a new approach to measure the temperature field dynamics on the emitting body surface. The brief review of modern methods of pyrometry – radiometric temperature measurements – is presented. Their properties are analyzed in the Wien's approximation. The SBP combines the high resolution on temperature, time, and space typical for the brightness pyrometry instruments, and small methodical error of temperature measurements of materials with unknown emissivity intrinsic for spectral pyrometers. The peculiarity of this method is calibration of the brightness pyrometer – thermal vision camera – directly during the measurement process using the integral thermal radiation spectrum of the object. The mathematical model of the SBP measurement system is proposed, the technique of data processing based on this model is verified. The examples of practical implementation of the SBP method for the determination of temperature field dynamics of objects with unknown emissivity are presented.

1. Introduction

It would be hard to overestimate the importance of temperature measurements based on the spectrum of objects thermal radiation. These tasks are solved both in advanced sciences, from astrophysics to micro- and nano-world studies, and in everyday industrial practice. Despite such a wide range of problems, the differences of them are pure quantitative, i.e. the order of measured temperatures, operational region of electromagnetic radiation spectrum, the type of utilized photo-detectors. The pyrometric methods offer the advantages of non-contact measurements with minimal influence on the investigated object, high spatial and temporal resolution of control instruments, and wide range of measurable temperatures.

It can be argued that the methodology of most optical pyrometry types used today was developed about a hundred years ago [1] and since then there have been few fundamental changes in its scientific base. In general, the development of optical temperature measuring instruments followed the emergence of new photo-detecting elements (photomultipliers, photodiodes, CMOS and CCD arrays, etc.) and digital acquisition systems. The first brightest pyrometers of the early 1900s [2], based on the principle of a "disappearing filament", as well as later instruments measuring the absolute brightness of thermal radiation at a certain wavelength, were extremely widespread due to simplicity and high sensitivity, but they had a significant drawback - the measured "brightness" temperature of the surface with low emissivity significantly differs from its true temperature. The appearance of multi-wave and spectral photo-detecting devices in the middle of the 20th century has made it possible to increase the accuracy of measurements, to control the presence of a non-thermal signal component, even to make estimates of the material emissivity spectral dependence. However, in fact, the method of measuring the temperature, including the utilization of Wien's auxiliary coordinates, was borrowed from a well-developed approach of two-color pyrometry [3].

The aim of present work is to introduce a new approach of spectral-brightness pyrometry, which combines the best qualities of known methods of radiometric temperature measurements. For this purpose, we present a systematic overview of the main pyrometric methods, in which we consider their strengths and weaknesses.

2. Thermal radiation

All the pyrometric methods are based on the law of thermal radiation. Bodies emit light as a result of atoms and molecules

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* Corresponding author at: Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Institutskaya Str. 4/1, Novosibirsk 630090, Russia.
E-mail address: gulyaev@itam.nsc.ru (I.P. Gulyaev).

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Nomenclature

λ	radiation wavelength
T	body temperature
$r(\lambda, T), b(\lambda, T)$	spectral radiance (spectral brightness) of the black body and a real body
ε	material emissivity

Constants

$c = 2.998 \cdot 10^8$ m/s speed of light in vacuum,
$h = 6.626 \cdot 10^{-34}$ J·s Plank's constant,
$k = 1.38 \cdot 10^{-23}$ J/K Boltzmann's constant,
$C_1 = 3.7418 \cdot 10^{20}$ W·nm^4·m^{-2} first radiation constant,
$C_2 = 14.388 \cdot 10^6$ nm·K second radiation constant.

transition from the states with higher energy into the states with lower energy. Population of high-energy levels can be provided by the equilibrium thermal motion of atoms and molecules which is characterized in terms of body temperature or by the external action, such as radiation, chemical reactions, electric current, etc. In the first case, the body radiation is called thermal, in the second – the luminescence. At the turn of the XIX – XX centuries, Max Plank obtained the law of equilibrium thermal radiation of an absolute black body, using the concept of the discrete energy levels of radiating oscillators and the Boltzmann's theorem of the energy level population. The black body is an idealized object which completely absorbs the incident radiation, and real bodies correspond to it to some extent only. The Plank's law determines the power of electromagnetic radiation into the semi-space from a black body unit area in the unit wavelength range (*spectral brightness*) [4]:

$$r(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{\exp(hc/\lambda kT) - 1} \left[\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{m}}\right]. \tag{1}$$

In practice, when the wavelength is measured in nanometers, and object area in millimeters, it is convenient to use the values of pyrometric (radiation) constants: $C_1 = 2\pi hc^2 = 3.7418 \cdot 10^{20}\ \mathrm{W} \cdot \mathrm{nm}^4/\mathrm{m}^2$, $C_2 = hc/k = 14.388 \cdot 10^6\ \mathrm{nm} \cdot \mathrm{K}$. When the condition $C_2/\lambda T \gg 1$ is satisfied, unity in the denominator can be neglected, and formula (1) takes on the form called the Wien's approximation:

$$r(\lambda, T) = \frac{C_1}{\lambda^5} \cdot \exp(-C_2/\lambda T) \quad \left[\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{nm}}\right]. \tag{2}$$

In Fig. 1 hatching shows the range of temperatures and wavelengths of radiation in which the difference between formulas (1) and (2) is less than 1% - the Wien's region. Thus, for =500 nm, the Wine approximation is correct up to temperatures $T < 6000$ K, for =1.5 μm - up to $T < 2000$ K. The same figure exemplifies the black body thermal radiation spectrum at 2000 K calculated by the Plank's (1) and Wien's (2) formulas. The Wien's region features the exponential dependence of the spectral brightness of the radiation on the temperature, which provides high sensitivity of measuring instruments and allows to reach high measurements accuracy (error below 0.1%). Further analysis of the pyrometry methods is presented by the authors for this very region.

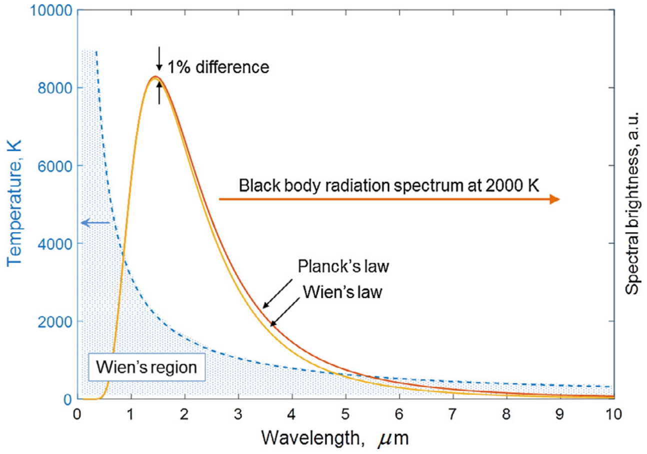

Fig. 1. The Wien's region in the coordinates «radiation wavelength – source temperature» and black body radiation spectrum at 2000 K.

Individual features of the atomic and crystalline structure of materials, which determine the availability of energy electronic levels, lead to the fact that the spectrum of thermal radiation of real bodies $b(\lambda, T)$ differs from the spectrum of the black body $r(\lambda, T)$. The dimensionless value of the material spectral emissivity $0 \leqslant \varepsilon(\lambda, T) \leqslant 1$ is defined by the relation

$$\varepsilon(\lambda, T) = b(\lambda, T)/r(\lambda, T). \tag{3}$$

The emissivity is the radiation property of a material. In the general case, it depends on the radiation wavelength, body temperature, its surface condition, observation angle and other properties. For most metals in the optical wavelength range (400–800 nm), the normal emissivity decreases with increasing wavelength and increases with increasing temperature, and its typical values lie in the range 0.3–0.5 [5]. Those bodies which emissivity does not depend on the wavelength are referred to as «grey bodies». For example, coal is a grey body in a wide range of wavelengths with a value of $\varepsilon = 0.8$—0.9 [6]. Calibration and verification of pyrometric instruments use reference radiation sources– black body models providing values $\varepsilon \approx 0.99$, as well as temperature lamps with a tungsten ribbon, for which the emissivity properties are well studied [5,7].

3. Review of up-to-date pyrometry methods

Having the formulas (1) or (2) available, it is possible to determine the temperature of the black body by measuring the intensity of its radiation in one or several wavelength ranges. The determination of the temperature of real objects is complicated by the fact that their radiation can significantly differ from Planck's law due to an arbitrary dependence $\varepsilon(\lambda)$. For this reason, all the pyrometric methods operate with conventional (observed) temperatures, for the determination of which the results of observations of the real object are compared to intensity of the radiation of the blackbody.

3.1. Brightness pyrometry

In the brightness pyrometry method (also called single color pyrometry), the intensity of the monochromatic radiation of an object at a selected wavelength $b(\lambda_0)$ is measured. The *brightness temperature* T_{br} of an object is the temperature at which the black body has the same spectral brightness at the selected wavelength λ_0 as the body under consideration at the true temperature T:

$$b(\lambda_0, T) = r(\lambda_0, T_{br}). \tag{4}$$

Using the formulas (2)–(4), one can easily define the relation between the brightness and true temperatures of the studied body: