BRIGHTNESS TEMPERATURE MEASUREMENT BY A WIDE-BAND PYROMETER

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The notion of integral brightness temperatures measured by an optical wide-band pyrometer is introduced. A relationship between these temperatures and between the brightness temperatures and a thermodynamical one is shown, a comparison is made, the procedure of their determination is discussed.

Brightness pyrometry relies on a comparison of the signals of a pyrometer sighted to an investigated object and a black body reference emitter. If a spectral channel of the pyrometer is sufficiently monochromatic, then the pyrometer signals are used to compare spectral radiances (SR) of the object and the reference emitter, which allows determination of the brightness temperature. The determination is based on equating the SR of a real body at a temperature T to that of a black body at a brightness temperature T_b

$$\varepsilon(\lambda, T) L(\lambda, T) = L(\lambda, T_b).$$

The brightness temperature T_b measured by the monochromatic pyrometer depends on the wavelength of the recorded radiation and in the Wien approximation is related to the thermodynamic temperature as

$$\frac{1}{T} - \frac{1}{T_b} = \frac{\lambda}{C_2} \ln \varepsilon(\lambda, T). \quad (1)$$

A pyrometer signal having a wide spectral band of detection is proportional [1, 2] to

$$F = \int_0^\infty \varepsilon(\lambda, T) L(\lambda, T) \psi(\lambda) d\lambda. \quad (2)$$

With the appropriate calibration of $\psi(\lambda)$, the quantity F represents the detected radiation flux with allowance for the optical circuit characteristics and the receiver response.

In the wide-band pyrometer signal the SR is integrated according to (2) and therefore it is impossible to directly compare the SR's of an object and a standard emitter and to determine a monochromatic brightness temperature. Substitution of a monochromatic flux in calculations for a real detected wide-spectrum radiation flux by introducing the effective wavelength [1-3] or correcting factors [3-5] inevitably leads to the use of some rigorously unjustified assumptions since the introduced parameters depend on the temperature and the spectral dependence of the emissive power, with the latter usually being unknown. A wide-band pyrometer records the spectrum-integrated radiance from which one may strictly, without any assumptions, determine the integrated brightness temperature. Unlike monochromatic pyrometry, several (not one) brightness temperature determinations may be made by a wide-band instrument which are analyzed in the present work.

In some temperature range specified by reference emitter parameters, a pyrometer signal from the object radiation may be assigned to the appropriate heating mode of a black body which provides the same pyrometer signal as from the object. In this case the blackbody temperature will be assumed as the conventional temperature of an object and is called the effective brightness temperature. As a mathematical tool for determination of this temperature, the following equality serves

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$$\int_0^\infty \varepsilon(\lambda, T) L(\lambda, T) \psi(\lambda) d\lambda = \int_0^\infty L(\lambda, S_e) \psi(\lambda) d\lambda. \quad (3)$$

If the pyrometer is calibrated against the black body at its several temperatures, then a set of these values and corresponding pyrometer readings may be used to construct a calibration curve. The temperature determined by this curve is thermodynamic for a black body and the effective brightness temperature S_e for a non-black body.

If the measured temperature values are outside the black body calibration range, then instead of direct levelling of pyrometer signals, relative measurements are made to determine the ratio of recorded radiation fluxes from an investigated body and the blackbody at the given calibration temperature

$$K = F/F_0 = \int_0^\infty \varepsilon(\lambda, T) L(\lambda, T) \psi(\lambda) d\lambda \Big/ \int_0^\infty L(\lambda, T_0) \psi(\lambda) d\lambda.$$

Equality (3) allows one to represent K as a ratio of black body radiation fluxes with temperatures S_e and T_0:

$$K = \int_0^\infty L(\lambda, S_e) \psi(\lambda) d\lambda \Big/ \int_0^\infty L(\lambda, T_0) \psi(\lambda) d\lambda.$$

Solving this integral equation for S_e numerically, one may calculate the effective brightness temperature by the measured ratio K. For the case given, the procedures of black body temperature determination in terms of the effective wavelengths and the correcting factor [3] are also fully applicable. In the calculation formulas one must only substitute S_e for T; i.e., the methods and formulas considered in [3] as applied to a non-black body will give the effective brightness temperature values.

While the brightness temperature for a narrow monochromatic radiation band is a function of the temperature, the emissive power of an object, the radiation wavelength, the effective brightness temperature S_e also depends on the pyrometer properties prescribed by the function $\psi(\lambda)$. Thus, this convectional temperature is not only characteristic of an emitting object but it also includes the effect of the pyrometer properties. In contrast to monochromatic measurements, the effective brightness temperature S_e is related with T and emissivity $\varepsilon(\lambda, T)$, not through the simple expression (1), but through the more complicated integral equation (3), which contains the apparatus function $\psi(\lambda)$ of the pyrometer. Such brightness temperatures are used in [5], however the authors have not given their definition and considered them as ordinary brightness temperatures measured by a monochromatic pyrometer.

The integral relationship (3) between thermodynamic and effective brightness temperatures is simplified when the correcting factors are used to take account of the spectral channel non-monochromaticity of the pyrometer [4, 5]. In this case relation (3), in the Wien approximation, acquires the form

$$\ln[R_n(\lambda, T)\varepsilon(\lambda, T)] - C_2/(\lambda T) = \ln R(\lambda, S_e) - C_2/(\lambda S_e).$$

Whence the thermodynamic and effective brightness temperatures are related as

$$\frac{1}{T} - \frac{1}{S_e} = \frac{\lambda}{C_2} \ln\left[\frac{R_n(\lambda, T)}{R(\lambda, S_e)} \varepsilon(\lambda, T)\right]. \quad (4)$$

On passing from integral to monochromatic relations, λ may be chosen to correspond both to the maximum $\psi(\lambda)$ and to any value of λ in the spectral response range of the pyrometer. Variation of λ entails a change in $R_n(\lambda, T)$, $R(\lambda, S_e)$ and, in the case of non-gray bodies, in $\varepsilon(\lambda, T)$ as well, but the whole expression in the r.h.s. of (4) remains constant. For wide-band pyrometry, equality (4) plays the same role as (1) for monochromatic measurements.

The necessity of performing iterations for S_e calculation in the case of relative measurements poses complications when applying the procedure considered. In practice non-monochromaticity of the spectral channel is often neglected and the temperature is calculated as if the intensity of monochromatic radiation has been recorded. In this case some conventional temperature is obtained which will be referred to as a quasi-brightness one. The quasi-brightness temperature of an object is the temperature of the black body at which the ratio of SR of the black body to that at the calibration temperature for the chosen wavelength λ is the same as the ratio of the signals of the wide-band pyrometer sighted to the object and the calibration emitter

$$K = F/F_0 = L(\lambda, S_q)/L(\lambda, T_0). \quad (5)$$

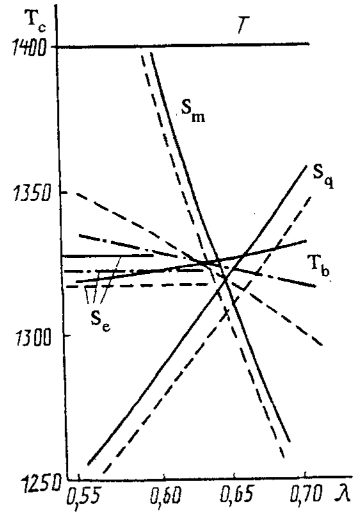

Fig. 1. Different types of brightness temperatures (K) versus radiation wavelength (μm) at T = 1400 K for bodies with different emissivity dispersion: dashed curves, $\Delta\varepsilon = -0.1$; dot-dash curves, $\Delta\varepsilon = 0$; solid curves, $\Delta\varepsilon = 0.1$.

Whence a simple formula for S_q is obtained which does not require an iteration process

$$\frac{1}{S_q} = \frac{1}{T_0} - \frac{\lambda}{C_2} \ln K. \tag{6}$$

Substituting integral expressions for F and F_0 into (5) in terms of SR and correcting factors and using the Wien formula, we obtain the relationship between thermodynamic and quasi-brightness temperatures:

$$\frac{1}{T} - \frac{1}{S_q} = \frac{\lambda}{C_2} \ln \left| \frac{R_n(\lambda, T)}{R(\lambda, T_0)} \varepsilon(\lambda, T) \right|. \tag{7}$$

Unlike the effective brightness temperature, the quasi-brightness temperature values depend on the choice of the wavelength in the recorded range and also on the calibration temperature, therefore it is necessary to take into account values of T_0 when comparing the measurement results obtained at different calibration temperatures.

Thus, determination of a quasi-brightness temperature is a simpler procedure than the effective brightness temperature determination but it is ambiguous because of the arbitrary choice of T_0. Introduce one more type of an integrated brightness temperature devoid of this drawback.

The weighted mean brightness temperature of an object measured by a wide-band pyrometer is the temperature of the black body at which its spectral radiance at a wavelength λ is equal to the weighted mean (by an apparatus function of the pyrometer) radiance of an object.

The weighted mean brightness temperature is determined from the equality

$$\int_0^\infty \varepsilon(\lambda, T) L(\lambda, T) \psi(\lambda) d\lambda \Big/ \int_0^\infty \psi(\lambda) d\lambda = L(\lambda, S_m), \tag{8}$$

which relates S_m and T via λ and $\psi(\lambda)$ and may serve for conversion from S_m to T vice versa.

Experimental determination of the weighted mean brightness temperature involves measurement of the ratio of pyrometer signals from the emitting object and the black body at the known temperature T_0. Replacing the integral expressions for the signals by their monochromatic analogs, we arrive at

$$K \doteq F/F_0 = L(\lambda, S_m)/[R(\lambda, T_0) L(\lambda, T_0)].$$

TABLE 1. Types of Temperatures Calculated by (11) with Substitution of Different Coefficients G

G	T_c
1	S_q
$R(\lambda, T_0)$	S_m
$R(\lambda, T_0)/R(\lambda, S_e)$	S_e
$R(\lambda, T_0)/R_n(\lambda, T)$	T_b
$R(\lambda, T_0)/[R_n(\lambda, T)\,\varepsilon(\lambda, T)]$	T

TABLE 2. Calculation Results for Different Types of Conventional Temperatures

T	S_q	S_m	S_e	T_b
800	784,6	798,2	773,3	775,1
1000	961,4	982,1	959,2	961,4
1200	1133,9	1162,7	1142.3	1144,9
1400	1302,3	1340,5	1322,7	1325,5
1600	1467,1	1515,7	1500,4	1503,5
1800	1628,2	1688,3	1675,6	1678,8
2000	1785,9	1858,5	1848.2	1851,4

Substituting the Wien function, we arrive at

$$\frac{1}{S_m} = \frac{1}{T_0} - \frac{\lambda}{C_2} \ln [KR(\lambda, T_0)]. \tag{9}$$

The correcting factor $R(\lambda, T_0)$ in this formula depends on the choice of the wavelength λ, the apparatus function $\psi(\lambda)$ of the pyrometer, and the calibration temperature T_0. It may be calculated beforehand. Then in the process of measurements one may very easily and quickly calculate S_m at the given λ and measured K and since it does not require numerical integration and iterations.

In order to simplify the relationship between T and S_m (8), we employ the procedure used earlier and obtain a relation similar to (4) and (7)

$$\frac{1}{T} - \frac{1}{S_m} = \frac{\lambda}{C_2} \ln [R_n(\lambda, T)\,\varepsilon(\lambda, T)]. \tag{10}$$

All the integral brightness temperatures considered are functions not only of the thermal condition of an object (T, ε) but also of the apparatus function $\psi(\lambda)$ of the pyrometer. These temperatures are related to a thermodynamic temperature through integral equations (3), (5), (8) or the correcting factors and spectral emissive powers at a concrete wavelength (4), (7), (10). The latter relations may be used to derive equations relating integral temperatures between each other, which allows one to pass from one temperature to another. For this, knowledge of $\varepsilon(\lambda, T)$ is not required. Use of any integral temperatures is equally justified for characterization of the thermal condition of an object.

The relations between brightness temperatures T_b, S_e, S_q, and S_m dependent on the choice of a wavelength inside a spectral range of radiation detection may be illustrated by calculating the triangular apparatus function (Fig. 1). Spectral characteristics of the pyrometer have been assumed the same as in [3] ($\lambda_0 = 0.63$ μm, $\psi(\lambda) = 1 - |\lambda - \lambda_0|/\Delta\lambda$, $\Delta\lambda = 0.1$ μm). The spectral dependence of the emissive power has been described by the linear function $\varepsilon(\lambda) = \varepsilon(\lambda_0) + (\Delta\varepsilon/\Delta\lambda)(\lambda - \lambda_0)$. Calculation has been conducted for $\varepsilon(\lambda_0) = 0.4$, $T_0 = 100$ K, T = 1400 K.

The possibility of variation of λ inside the spectral range of radiation detection is such that any of the integral brightness temperatures may be equated to the monochromatic brightness temperature. S_q and S_m highly depend on the choice of λ and may be both higher and lower than the brightness temperature T_b. The effective brightness temperature values are intermediate between T_b values for the extreme points of the working spectral range of the pyrometer. As a consequence of these specific features, it is reasonable to use the effective brightness temperature to characterize the thermal condition of an object.

For temperature determination based on measurement of the ratio of registered radiation fluxes at the measured and calibration temperatures we propose the following generalized formula resulting from analysis of the present work:

$$\frac{1}{T_c} = \frac{1}{T_0} - \frac{\lambda}{C_2} \ln (GK). \tag{11}$$

Dependent on the choice of the coefficient G, the calculation by (11) gives different types of T_c (Table 1). When no information on emissivity is available, only the first three variants of the calculation are possible, the results of which produce the integrated brightness temperatures S_e, S_q, S_m. To determine T_b or T, it is necessary to know $\epsilon(\lambda, T)$ in the registered spectrum.

The results of calculation by (11) for a gray ($\varepsilon = 0.4$) body (Table 2) allow a comparison of different types of conventional temperatures. Spectral characteristics of the pyrometer have been prescribed the same as those in the calculation presented in Fig. 1. A transition to monochromatic parameters has been carried out for $\lambda = 0.63$ μm. The calibration temperature is $T_0 = 1000$ K.

For the temperature range considered the weighted mean brightness temperature exceeds all the remaining conventional temperatures. In connection with the fact that the quasi-brightness temperature values depend on the calibration temperature, the relations between S_q and T_b depend on elevation of the thermodynamic temperature of an object relative to the calibration temperature. When the thermodynamic temperature of the object is lower than the calibration temperature, $S_q > T_b$. At a body temperature equal to the calibration temperature, non-monochromaticity of a spectral channel does not manifest itself in the results of quasi-brightness temperature measurements, and we obtain $S_q = T_b$. In the case of measurements in a wide temperature range of non-black bodies, S_e values are closest to the brightness temperature T_b.

When the object emissivity is unknown, a wide-band pyrometer allows rigorous, without any assumptions, determination only of integrated brightness temperatures S_e, S_q, S_m. Thermodynamic and monochromatic brightness temperatures may be measured by the wide-band pyrometer provided $\varepsilon(\lambda, T)$ is known. All the types of integrated brightness temperatures may be equally used to characterize the thermal condition of an object and with the apparatus function $\psi(\lambda)$ being known, a one-to-other type transition is possible. It seems most reasonable to use the effective brightness temperature since it is unique for the entire recorded interval and stands closer to the monochromatic brightness temperature at the maximum wavelength of the apparatus function of the pyrometer.

NOTATION

$L(\lambda, T)$, spectral radiance of the black body at temperature T and radiation wavelength λ; ε, $\varepsilon(\lambda, T)$, emissive power (coefficient of directional thermal radiation); $C_2 = 1.4388 \times 10^{-2}$ m·K, pyrometric constant; T_c, T_b, conventional and brightness temperatures, respectively; $\psi(\lambda)$, apparatus function of the pyrometer calculated as the product of the spectral coefficient of transmission of the pyrometer optical system by the spectral response of its radiation detector; S_e, S_q, S_m, integral brightness temperatures (effective, quasi-brightness, mean weighted); T_0, temperature of a reference emitter with calibration of the pyrometer; $K = F/F_0$, ratio of the detected radiation flux F from the body with temperature T to the flux F_0 from the black body with the calibration temperature T_0; $R(\lambda, T_0)$, $R(\lambda, S_e)$, $R_n(\lambda, T)$, correcting factors for radiation of the black body with temperature T_0, S_e and the non-black body with temperature T; λ_0, $\Delta\lambda = \int_0^\infty \psi(\lambda)d\lambda$, maximum wavelength and half-width of the apparatus function; $\Delta\varepsilon$, variation of the radiative power over the section $\Delta\lambda$; G, methodical coefficient.

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