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THERMAL MEASUREMENTS

A METHOD OF MEASURING TRUE TEMPERATURES BY BICHROMATIC PYROMETRY

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A method of measuring the true temperature of bodies with unknown and variable emissive power during heating and cooling is considered. The method is based on the fact that the spectral emissive power depends on the temperature. The necessary number of spectral components is minimized by employing relative laser reflectometry, the use of which does not require that the radiating surface should obey Lambert's law. The results of measurements of the true temperature and spectral emissive powers of specially manufactured high-melting point metals are presented. The overall error of a measurement of the true temperature does not exceed 1%.

Key words: *bichromatic pyrometry, reflectometry, spectral emissive power, true temperature.*

The main difficulties in determining and eliminating the effect of the emissive power on line when measuring temperature are well known. In practice, methods of measuring the true temperature based on the excessive amount of information in the spectrum of natural radiation [1–4] are used, for which it is necessary to know tens or hundreds of spectral components. A large number of pyrometers are based on the use of reflectometry. However, their Achilles heel is the need for the radiating surface to obey Lambert's law, which is not obeyed in practice for actual bodies. Hence, reflectometry methods are used fairly rarely.

A new method was considered in [5] which enables one, in principle, to determine the true temperature from the self-radiation of actual bodies without preliminary calibration and hence to realize the thermodynamic temperature scale without using a black body. Physically, the method is based on the change in the properties of a material resulting from the fact that the emissive power of the spectral components depends on the temperature [6–8]. However, in these publications, it was assumed that one has a priori knowledge of the spectral emissive power for some temperature, which eliminates the possibility of using the method in practice.

It was shown in [5] that if the emissive power depends on the temperature, then by varying the number N of unknown values of T_j and measuring the corresponding intensities of the spectrum of the thermal radiation in M spectral intervals for each of these values, one can always obtain the required number $N + \sum_{i=1}^{M} m_i$ of equations to determine all the unknowns, where m_i is the number of unknowns at each spectral intensity.

In addition to the temperatures T_1 and T_2, the apparatus functions ξ_i and the emissive powers $\varepsilon(\lambda_i, T_j)$ occur in a number of the unkowns in the form of the products $\xi_i\varepsilon(\lambda_i, T_j)$, and also the coefficients of the power polynomial α_i, β_i, ..., γ_i, which approximate the temperature dependence of the emissive power:

$$\varepsilon(\lambda_i, T_1) = \varepsilon(\lambda_i, T_2) + \alpha_i(T_1 - T_2) + \beta_i(T_1^2 - T_2^2) + \ldots + \gamma_i(T_1^n - T_2^n).$$

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These coefficients occur in the equation in the form

$$\alpha_i/\varepsilon(\lambda_i, T_2),\ \beta_i/\varepsilon(\lambda_i, T_2),\ \ldots,\ \gamma_i/\varepsilon(\lambda_i, T_2).$$

Hence

$$MN \geq N + \sum_{i=1}^{M} m_i\,.$$

This method enables one, without any calibration, to measure the true temperatures of a body during heating and cooling. When there is a linear dependence on the temperature, the number of unknowns in each spectral intensity is reduced to three. Then, in order to determine the true temperature it is necessary to make measurements in two parts of the spectrum for four values of the temperature or in three spectral intervals for three values of the temperature. We will then, naturally, have eight equations with eight unknowns or nine equations with nine unknowns.

Consequently, this method enables one to measure the true values of unknown temperatures T_{tj}, by eliminating the effect of both the apparatus constant and the emissive power, but without determining the latter. If one first uses a graduated pyrometer in this method, i.e., one simultaneously measures the brightness temperature T_{bj}, the emissive power can easily be found from the routine relation for the difference in the inverse values of the temperatures:

$$\varepsilon(\lambda_i, T_j) = \exp[C_2(T_{bj} - T_{tj})/\lambda_i T_{bj} T_{tj}],$$

where $C_2 = hc/k$; h is Planck's constant; c is the velocity of light; and k is Boltzmann's constant.

This method works more accurately the greater the temperature range employed. However, for wide ranges the temperature dependence may turn out to be extremely nonlinear, which, in turn, increases the number of unknowns and, consequently, leads to an increase in the required number of equations and to a considerable sharpening of the requirements imposed on the signal/noise ratio.

Because the emissive power depends only slightly on the temperature, the signal/noise ratio is decisive in this method. In order to reduce the required number of values of the temperatures and spectral intervals, we employed the method of relative reflectometry in the pyrometric system considered [9, 10]. The distinguishing feature of the relative reflectometry method is that there is no need for the radiating surface to obey Lambert's law.

The bichromatic pyrometer described below, each of the two channels of which is calibrated in brightness temperatures T_{b1} and T_{b2}, contains a built-in two-wave laser reflectometer, which measures the ratio of the directional reflection coefficients $\rho^*(\lambda_1, T_1)/\rho^*(\lambda_1, T_2)$ and $\rho^*(\lambda_2, T_1)/\rho^*(\lambda_2, T_2)$ for two values of the temperatures T_1 and T_2 at two wavelengths λ_1 and λ_2. It is obvious that

$$\rho^*(\lambda_1, T_1)/\rho^*(\lambda_1, T_2) = x_1\rho(\lambda_1, T_1)/x_1\rho(\lambda_1, T_2);$$

$$\rho^*(\lambda_2, T_1)/\rho^*(\lambda_2, T_2) = x_2\rho(\lambda_2, T_1)/x_2\rho(\lambda_2, T_2),$$

where $\rho(\lambda_1, T_1)$, $\rho(\lambda_1, T_2)$, $\rho(\lambda_2, T_1)$, and $\rho(\lambda_2, T_2)$ are the normal reflection coefficients and x_1 and x_2 are coefficients which take into account the scattering of the radiation due to the surface roughness. If the surface obeys Lambert's law, we have $x_1 = x_2 = 1$, and hence from Kirchhoff's law we have

$$\rho^*(\lambda_1, T_1)/\rho^*(\lambda_1, T_2) = [1 - \varepsilon(\lambda_1, T_1)]/[1 - \varepsilon(\lambda_1, T_2)].$$

We will introduce the following notation:

$$A = 1 - \rho^*(\lambda_1, T_1)/\rho^*(\lambda_1, T_2); \tag{1}$$

$$B = 1 - \rho^*(\lambda_2, T_1)/\rho^*(\lambda_2, T_2). \tag{2}$$

We will write the difference of the inverse values of the brightness temperatures at two wavelengths, measured by the pyrometer, in the form

$$T_b^{-1}(\lambda_1)_1 - T_b^{-1}(\lambda_2)_1 = \lambda_1/C_2 \ln\varepsilon(\lambda_1, T_1) - \lambda_2/C_2 \ln\varepsilon(\lambda_2, T_1);$$

$$T_b^{-1}(\lambda_1)_2 - T_b^{-1}(\lambda_2)_2 = \lambda_1/C_2 \ln\varepsilon(\lambda_1, T_2) - \lambda_2/C_2 \ln\varepsilon(\lambda_2, T_2)$$

or, involuting,

$$J_1 = \varepsilon(\lambda_1, T_1)/\varepsilon(\lambda_2, T_1)^{\lambda_2/\lambda_1}; \tag{3}$$

$$J_2 = \varepsilon(\lambda_1, T_2)/\varepsilon(\lambda_2, T_2)^{\lambda_2/\lambda_1}. \tag{4}$$

Hence, we obtain four equations (1)–(4) for determining the four unknown emissive powers.

If $\lambda_2 = 2\lambda_1$, we obtain a simple solution in the form of a quadratic equation

$$\varepsilon(\lambda_2, T_2)^2[J_1(1-B)^2 - J_2(1-A)] + J_1 2B(1-B)\varepsilon(\lambda_2, T_2) + J_1 B^2 - A = 0. \tag{5}$$

In this method it is not the absolute values of the reflection coefficients that are used but their ratios. This enables the necessary measurement accuracy to be obtained comparatively simply. However, the temperature dependence of the emissive power is fairly weak and we need to be convinced that changes in the effective wavelengths due to the temperature have no appreciable effect on the results of the measurements (or they can be taken into account). It is well known that the effective wavelength λ_{effi} is a hyperbolic function of the temperature.* As a result of exhaustive investigations [12, 13], the expression for λ_{eff} can be represented in the form

$$\lambda_{effi} = \lambda_{0i}(1 + \mu_i/T),$$

where

$$\mu_i = D\Delta\lambda_i^2/\lambda_{0i}^3(1 - 6\Delta\lambda_i^2/\lambda_{0i}^2); \tag{6}$$

where D is a coefficient which takes into account the form of the spectral characteristic (the filter + detector), for a Gaussian form $D = 0.18$; $\Delta\lambda_{0i}$ is half the width of the spectral characteristic; and λ_{0i} is the center wavelength.

Hence, the self-radiation signal can be written as

$$\ln U(\lambda_i, T_j) = \ln \xi_i C_1 \lambda_{0i}^{-5} - 5\mu_i/T_j + \ln\varepsilon(\lambda_i, T_j) - C_2/\lambda_{0i}(1 + \mu_i/T_j)T_j,$$

where $C_1 = 2\pi c^2 h$.

Equations (3) and (4) then become

$$\ln J_1 = \ln[\varepsilon(\lambda_1, T_1)^{\lambda_{01}}/\varepsilon(\lambda_2, T_1)^{\lambda_{02}}] - 5(\mu_1\lambda_{01} - \mu_2\lambda_{02})/T_1 - C_2/(T_1 + \mu_1) + C_2/(T_1 + \mu_2); \tag{7}$$

$$\ln J_2 = \ln[\varepsilon(\lambda_1, T_2)^{\lambda_{01}}/\varepsilon(\lambda_2, T_2)^{\lambda_{02}}] - 5(\mu_1\lambda_{01} - \mu_2\lambda_{02})/T_2 - C_2/(T_2 + \mu_1) + C_2/(T_2 + \mu_2). \tag{8}$$

* The first communication on the hyperbolic relation, as pointed by Foote [11], was by Natting in 1908. For different forms of the spectral characteristic, the temperature dependence of the effective wavelength was obtained in a form convenient for calculation by Coats and confirmed by Svet in the papers indicated.

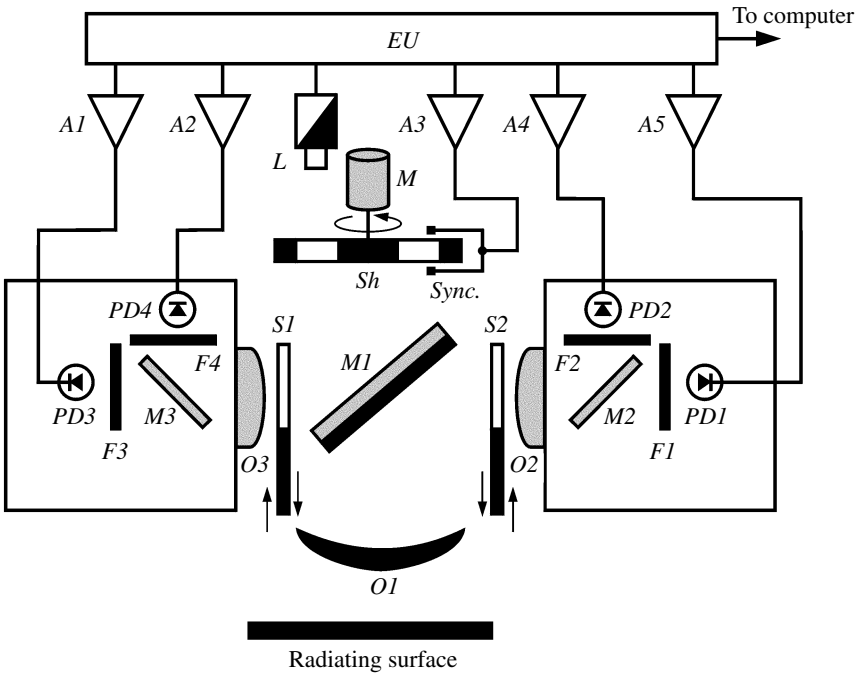

Fig. 1. Sketch of the experimental pyrometer.

It follows from (7) and (8) that terms with the coefficient $C_2 = 14388$ μm·K introduce the main error. To eliminate this error, it is necessary to put $\mu_1 = \mu_2 = \mu$. Then the error $\delta = 5\mu/T(\lambda_{01} - \lambda_{02})$ remains uneliminated.

In an experimental pyrometer the half-width of the self-radiation band $\Delta\lambda_1$ at a wavelength $\lambda_1 = 0.53$ μm was chosen from the minimum required signal/noise ratio: $\Delta\lambda_1 = 0.05$ μm. The calculation from (6) with $\mu_1 = \mu_2$ gives $\mu = 3.1116 \cdot 10^{-3}$.** Hence, the half-width of the band $\Delta\lambda_2 = 0.1953$ μm.

We constructed interference filters from these data and the spectral characteristics of the silicon photodiodes employed.

The basic arrangement of the experimental pyrometer is shown in the figure. Here the beam from a continuous two-wave laser *L**** ($\lambda_1 = 0.53$ μm and $\lambda_2 = 1.06$ μm) is modulated by a rotating shutter *S* and is incident on the radiating surface (the metal filament of a lamp) through a half-silvered mirror *M1* and an exit lens *O1*. The reflected radiation of the laser, simultaneously with the self-radiation of the surface, on passing through the lens *O1*, is reflected from the half-silvered mirror *M1* and is incident, through the screen *S2* and the lens *O2*, on the beam-splitting mirror *M2* and the filters *F1* (0.53 μm) and *F2* (1.06 μm). It then falls on the photodetectors *PD1* and *PD2*, and then enters the preamplifiers *A4* and *A5* and the electronic unit *EU*. The intensity of the laser radiation at the two wavelengths is monitored from the radiation reflected from the beam-splitting mirror *M3* and incident on the detectors *PD3* and *PD4* with corresponding filters *F3* and *F4*. When the screen *S2* is closed, one can monitor the dark current of the detectors *PD1* and *PD2*. The closed screen *S1* correspondingly enables one to monitor the dark current of the detectors *PD3* and *PD4*.

The spectral emissive power was measured at two brightness temperatures. To determine the latter, the "self-radiation" channels were first calibrated against a black body.

The signals of the self-radiation and the reflected radiation are processed in the electronic unit taking the dark current into account. To increase the signal/noise ratio in the reflected-signal channel, synchronous detection is employed, which

** For this value of μ, the uneliminated error does not exceed 10^{-6}.

*** The aluminum–yttrium laser with the splitting crystal was provided by Dr. A. N. Magunov (N. P. Lebedev Institute of Physics of the Academy of Sciences).

TABLE 1. Emissive Power of the Metals

Metal	$\varepsilon(\lambda_1, T_1)$	$\varepsilon(\lambda_2, T_1)$	$\varepsilon(\lambda_1, T_2)$	$\varepsilon(\lambda_2, T_2)$
Tungsten	T_1 = 1825 K		T_2 = 2580 K	
	0.462	0.374	0.446	0.302
Tantalum	T_1 = 1790 K		T_2 = 2350 K	
	0.470	0.267	0.442	0.308
Rhenium	T_1 = 1800 K		T_2 = 2955 K	
	0.435	0.35	0.405	0.35

is ensured by pulses from the synchronizer *Sync*. From the electronic unit the signals of the self-radiation from the surface of a filament lamp and the laser signals reflected from this surface are applied to a computer, which also carries out the algorithm for determining the emissive power.

The emissive power was measured on samples of tungsten, rhenium and tantalum. The samples were used in the form of vacuum lamps**** with a filament of width 5 mm made of the metal being tested. In the calculations, naturally, the losses introduced by the glass envelope of the lamp were taken into account. These metals were chosen since there are fairly reliable data on their emissive powers at the wavelengths (0.53 μm and 1.06 μm) employed in the pyrometer [14–16]. In addition, as we know from the literature, tantalum does not have an *x*-point while rhenium has an *x*-point at a wavelength of about 1 μm, which practically corresponds to one of the wavelengths of the pyrometer. When using the *x*-point, at which the emissive power is independent of the temperature, and $\lambda_2/\lambda_1 = 2$ the number of unknowns is reduced. In this case,

$$\varepsilon(\lambda_2, T_1) = \varepsilon(\lambda_2, T_2) = \varepsilon(\lambda_2, T) = A/[J_1 - J_2(1 - A)].$$

From the measured brightness temperatures and the emissive power coefficients calculated using algorithm (5), we determined the true temperatures, the values of which are presented in Table 1.

The errors in measuring the emissive power with the experimental pyrometer exceeded the errors achieved in [14–16], and amounted to 6–8%. However, these errors enable us to obtain an error in measuring the true temperature with the experimental pyrometer of $\Delta T/T<1\%$.

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**** The lamps with high-melting point metals were developed by Professor N. S. Vdovin (Saransk State University).

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