THE PROBLEM OF ACCURACY FOR RADIATION PYROMETERS

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We examine the effect of the temperature of the ambient medium on the accuracy with which measurements are performed with a radiation pyrometer using a lead sulfide photoresistor. It is demonstrated that in coordinating the quantitative calibration to a specific temperature for the ambient medium, we achieve an extremely high confidence coefficient for the measurements ($0.9 < \alpha < 0.999$).

The working model of the IKR-1 radiation pyrometer (an infrared radiometer) [1], developed at the Northwest Polytechnic Correspondence Institute, was used to measure the "effective emittance" ε_{eff} of certain electrotechnical materials.

The quantity ε_{eff} is understood to refer to a coefficient relating the value of the signal (the reading of the given pyrometer), produced by the nonblack body being observed, to the signal given off by some arbitrary standard with a high emissivity (a metal plate coated with a special black diffusion stain), exhibiting the same true temperature as the body under observation. Here we have in mind the fact that the pyrometer uses a selective radiation receiver with a fully specified spectral sensitivity distribution, i.e., a PbS photoresistor with an extremely small area of 0.28 mm^2 for the sensitive surface, operating without special cooling, at an ambient-medium temperature t_{amb}.

It goes without saying that the value of ε_{eff} for each specific nonblack body must be a function of its temperature, as well as of the temperature t_{amb} of the ambient medium, affecting the sensitivity of the photoresistor.

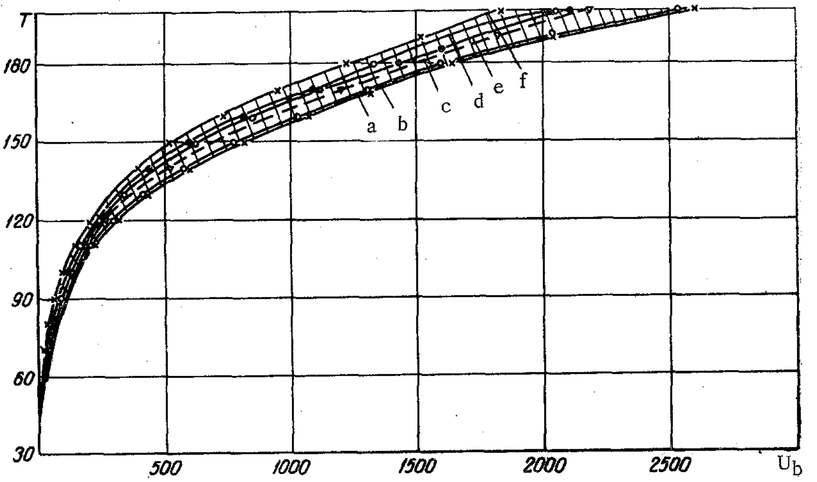

Fig. 1. Calibration curve for the IKR-1 radiation pyrometer $U_b = f(T)$ on the basis of an arbitrary black standard: a) series 1-1'; b) 2-2'; c) arithmetic mean; d) series 3-3'; e) 4-4'; f) 5-5'.

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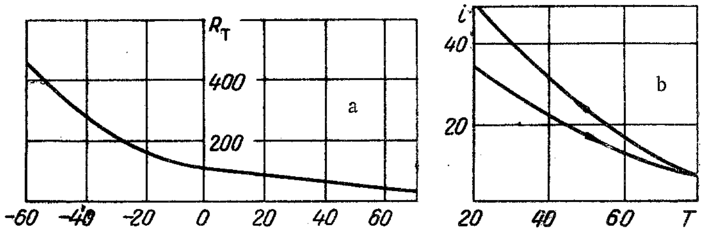

Fig. 2. Effect of temperature on the parameter of a PbS photoresistor: a) on the dark resistance (R_T, kΩ); b) on the photocurrent (i, μA) for 10 V, 200 lx.

The value of ε_{eff} was determined [2] from the formula

$$\varepsilon_{\text{eff}} = \frac{U_T}{U_{\text{b}}} = \frac{\int\limits_0^\infty r_{\lambda T}\, \varepsilon_{\lambda T}\, S_\lambda d\lambda}{\int\limits_0^\infty r_{\lambda T}\, S_\lambda d\lambda}. \qquad (1)$$

In measuring the signal U_T and U_b, we subtracted from these the value of U_n, the total noise level in the measuring circuit. In the measurements, the temperature of the test specimen and of the standard plate varied from the temperature of the ambient air by as much as 200°C. The preliminary calibration of the device, in steps of 10°C, using the standard plate to produce a relationship $U_b = f(T)$, was accomplished by a series of measurements, involving the gradual raising of the temperature of the plate and its subsequent cooling, and 20 such measurement series were performed. The results of the measurements are shown in Fig. 1. The cross-hatched zone shows the scattering of the points, while the dashed line corresponds to the arithmetic mean for all of the measurements. Analysis of the observations shows a reduction in time for the signal, given identical temperatures for the standard plate. This fact can be explained by the gradual rise in the temperature of the PbS photoresistor as the medium surrounding the resistor is heated (for example, as a consequence of the effect of the radiation from the amplifier tubes). Indeed, we know [3] that PbS photoresistors exhibit an extremely pronounced temperature dependence. Thus, Fig. 2a shows the effect of temperature on the dark resistance of the photoresistor, while Fig. 2b shows the effect of temperature on the magnitude of the photocurrent. In the illuminated state, the nature of the change in photoresistor resistance is the same as in darkness. The photocurrent temperature coefficient TKΔi over the entire working range of temperatures is negative and amounts to 1.5% per 1°C.

A second calibration of the pyrometer was undertaken to verify the above assumption, and during the course of this calibration we measured the temperature t_{amb} of the ambient medium in the immediate vicinity of the photoresistor and we accumulated data coordinated to $t_{\text{amb}} = 19$, 20, and 22°C. Figure 3 shows the results of these measurements.

It would be very important to determine the magnitude of the errors and the reliability of the measurements carried out during the first and second calibrations of the instrument. With this purpose in mind, we calculated the confidence coefficient for the measurements by the following procedure [4]:

1) We determined the mean square error from the formula

$$s_n = \frac{\sqrt{\sum\limits_1^n (\bar{x} - x_i)^2}}{n-1}. \qquad (2)$$

Given a sufficiently large number n of observations, S_n^2 (selective variance) approaches the magnitude of the general measurement variance σ^2

$$\lim_{n\to\infty} s_n^2 = \sigma^2; \qquad (3)$$

2) we determined the variation factor (the relative magnitude of the mean square error) w from the formula

$$w = \frac{s_n}{\bar{x}} \cdot 100\%;$$

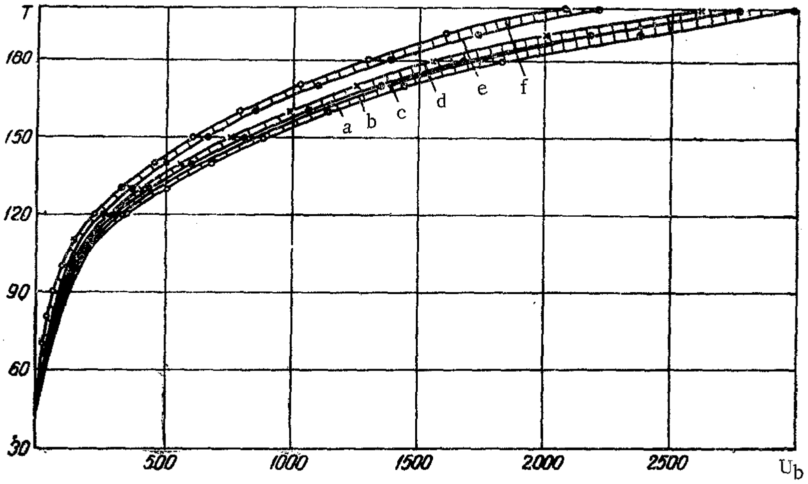

Fig. 3. Calibration curve for the IKR-1 radiation pyrometer for various t_{amb}: a) 19° (a reduction in T); b) 19° (increase in T); c) 20° (increase in T); d) 20° (reduction in T); e) 22° (increase in T); f) 22° (reduction in T).

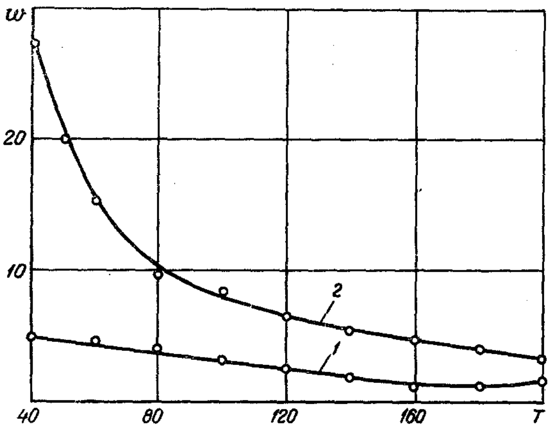

Fig. 4. Variation factor w as a function of temperature T for the observed standard plate: 1) t_{amb} = 19°C; 2) 22°C.

3) we determined the confidence interval

$$\bar{x} - \Delta x < x < \bar{x} + \Delta x, \qquad (5)$$

where x is the true value of the quantity measured;

4) we determined the confidence coefficient (or reliability factor) α:

$$\alpha = P(\bar{x} - \Delta x < x < \bar{x} + \Delta x). \qquad (6)$$

The significance of this expression lies in the fact that the measurement result, with a probability equal to α, does not exceed the limits of the confidence interval from $\bar{x} - \Delta x$ to $\bar{x} + \Delta x$. The quantity α was determined from tables relating the Student coefficient

$$t_{\alpha,n} = \frac{\Delta x \sqrt{n}}{s_n} \qquad (7)$$

with the number of observations n [4].

As an example, Table 1 shows a scheme for the calculation of one of the values for the temperature of the standard plate, given a specific temperature for the ambient medium.

We know that in the actual practice of investigating measurement errors and the magnitude of a random error it is a common practice to base the estimates on the standard error which corresponds to the confidence coefficient $\alpha = 0.68$, at which the measurement reliability is regarded as completely satisfactory. It is sufficient for the qualitative measurements to correspond to $\alpha = 0.9$ or 0.95. Only for measurements which specify an extremely high degree of reliability is it sometimes necessary to specify a confidence coefficient of $\alpha = 0.999$ [4].

As a result of the calculation of the confidence coefficient for the measurement on the basis of the indicated method for the first calibration (without consideration of changes in t_{amb}) we found that the quantity α ranges within the limits from 0.7 to 0.98, which exceeds the measurement standard $\alpha = 0.68$ and is satisfactory. For the second calibration, coordinated with the determined values of t_{amb}, the calculation of the confidence coefficient yields values of α that do not go beyond limits from 0.9 to 0.999, which indicates high reliability for the measurements. Calculation of the variation factor w as a function of temperature t for the obseved standard plate yields the result shown in Fig. 4. We note a pronounced increase in the value of w in the region of reduced temperatures, corresponding to a region of low spectral sensitivity for the photoresistor. It is obvious that for higher temperatures of the observed objects the reliability of the measurements must increase.

TABLE 1. Scheme for the Calculation of the Confidence Coefficient for the Measurements

x_i	$\bar{x}-x_i$	$(\bar{x}-x_i)^2$
168	—1,8	3,24
172	—5,8	33,6
171	—4,8	23,0
162	4,2	17,6
160	6,2	38,4
164	2,2	4,84

$$\sum_{1}^{n}(\bar{x}-x_i)^2 = 120,7.$$

Selective variance $s_n^2 = \sum_{1}^{n}(x - x_i)^2/(n-1) = 24.1.$

Variation factor $w = S_n/\bar{x} = (4.91/166.2)\cdot 100 = 2.95\%$, $\Delta x = 6$; confidence interval $160.2 < x < 172.2.$

Student coefficient

$$t_{\alpha,n} = \Delta x\sqrt{n}/s_n = 6\sqrt{6}/4.91 = 2.99.$$

From the table of Student coefficients: for $\alpha = 0.95\ldots$, $t_{0.96;6} = 2.6$; for $\alpha = 0.98\ldots$, $t_{0.98;6} = 3.4$. Consequently, $0.95 < \alpha < 0.98.$

It follows from the above that the accuracy of the measurement results obtained with the radiation pyrometer using a PbS photoresistor as the radiation receiver – operating without cooling – is markedly affected by the temperature regime. However, even for the measurements in which the temperature of the ambient medium varies by 3° (for example, from 19° to 22°C) we have an acceptable measurement reliability which is characterized by the value of the confidence coefficient α between 0.7 and 0.98 (for a measurement standard of $\alpha = 0.68$).

In this case, if the calibration of the radiation pyrometer is coordinated to completely determined values of the temperature for the ambient medium, the confidence coefficient α rises to extremely high values (0.9 to 0.999), indicating high reliability for the measurements.

NOTATION

t_{amb}	is the temperature of the ambient medium, °C;
ε_{eff}	is the effective emittance;
U_T	is the signal from the radiation of the test specimen, mV;
U_b	is the signal from the arbitrary black standard, mV;
U_n	is the total noise level for the measuring circuit, mV;
$r_{\lambda T}$	is the spectral brightness distribution for the arbitrary black standard at a temperature T;
ε_λ	is the spectral distribution for the relative emittance of the test specimen at a temperature T;
S_λ	is the spectral distribution of the PbS photoresistor sensitivity;
s_n	is the mean square error;
$\bar{x}$	is the arithmetic mean value of the x_i signals, obtained for an identical standard-plate temperature, mV;
n	is the number of observations;
s_n^2	is the selective measurement variance;
σ^2	is the general measurement variance;
w	is the variation factor (the relative magnitude of the mean square error), %;
x	is the true value for the measured quantity, mV;
α	is the confidence coefficient (reliability factor);
$t_{\alpha,n}$	is the Student coefficient.

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