REMOTE METHOD FOR MEASURING THE TEMPERATURE OF OBJECTS IRRADIATED BY LATERAL SOURCES

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UDC 536.52

Relations are proposed for calculating the true temperature of bodies from indications of radiation pyrometers sited on a reference object and the object being measured, and the possibilities for efficient use of these relations are analyzed.

Remote methods for measuring temperature in most cases are complicated by the destabilizing influence of re-reflected radiant fluxes.

The well-known methods for taking into account the influence of re-reflected light on the indications of radiation pyrometers [1] are based on the concept of external bodies surrounding the objects being measured. This concept under real conditions, as a rule, is not well defined, which decreases the effectiveness of the techniques proposed. This made it necessary to search for possibilities of replacing the concept of the temperature of surrounding bodies by a parameter with a concrete physical meaning.

We shall use the radiation temperature of a reference object, consisting of a small plate at the surface of the object being measured, as such a parameter. The plate was prepared from a material whose characteristic spatial distribution of reflected radiation under identical angular irradiation conditions is the same as for the object being measured.

We shall examine a variant of a pyrometric system with a cooled reference object, when its characteristic radiation can be neglected. The principle for performing the measurements can be based, for example, on the well-known two-radiometer method [2]. For the radiometers, we shall take two radiaton pyrometers with identical spectral sensitivities. One of them is sited on the object being measured and the other on the cooled reference object.

From the definition of the radiation temperature of the object being measured T_x^r, if its coefficient of reflection equals the coefficient of reflection of the reference object, we find

$$H_{xs}\int\limits_{\lambda=0}^{\infty}\Psi_\lambda I_\lambda(T_x^r)\,d\lambda=H_{xs}\int\limits_{\lambda=0}^{\infty}\Psi_\lambda\varepsilon_{x_\lambda}I_\lambda(T_x)\,d\lambda+H_{0s}^r\int\limits_{\lambda=0}^{\infty}\Psi_\lambda I_\lambda(T_0^r)\,d\lambda,$$

from where, using the equality $H_{xs} = H_{0s}$,

$$I_\lambda(T_x^r)=\varepsilon_{x_\lambda}I_\lambda(T_x)+I_\lambda(T_0^r). \tag{1}$$

Integrating relation (1) over the independent variable λ, we obtain $c_0\theta_x^r = \varepsilon_x c_0\theta_x + c_0\theta_0^r$. From here, the equation sought for calculating the true temperature of the object being measured has the form

$$T_x=\sqrt[4]{(T_x^r)^4-(T_0^r)^4/\varepsilon_x}. \tag{2}$$

It can be shown that if the reflection coefficient of the measured and reference objects are not equal, Eq. (2) is changed as follows:

$$T_x=\sqrt[4]{\frac{(T_x^r)^4-(T_0^r)^4\dfrac{\rho_x}{\rho_0}}{\varepsilon_x}}. \tag{3}$$

Cooling the reference object, for example, with the help of flowing water, complicates the pyrometric system and creates obstacles to miniaturizing it and, therefore, it makes it

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 43, No. 5, pp. 811-817, November, 1982. Original article submitted July 23, 1981.

0022-0841/82/4305-1275$07.50

difficult to decrease the noise that it contributes to the measuring system. For this reason, we shall examine a variant of the pyrometric system with an uncooled reference object. For this case, if the reflection coefficients of both objects are equal,

$$H_{\lambda 0} \int\limits_{\lambda=0}^{\infty} \Psi_\lambda I_\lambda (T^{\mathrm{r}}_x)\, d\lambda = H_{xs} \int\limits_{\lambda=0}^{\infty} \Psi_\lambda \varepsilon_{x_\lambda} I_\lambda (T_x)\, d\lambda + H_{0s} \int\limits_{\lambda=0}^{\infty} \Psi_\lambda I_\lambda (T^{\mathrm{r}}_0)\, d\lambda - H_{\rho s} \int\limits_{\lambda=0}^{\infty} \Psi_\lambda I_\lambda (T_0)\, \varepsilon_{0_\lambda} d\lambda,$$

from where

$$T_x = \sqrt[4]{\frac{(T^{\mathrm{r}}_x)^4 - (T^{\mathrm{r}}_0)^4}{\varepsilon_x} + (T_0)^4}\,. \tag{4}$$

The temperature T_x is calculated from relation (4) if T_0 is measured, for example, with the help of a thermocouple caulked directly into the material of the reference object.

If the optical characteristics of the measured object differ from those of the reference object, then a more general relation is valid

$$T_x = \sqrt[4]{\frac{(T^{\mathrm{r}}_x)^4 - (T^{\mathrm{r}}_0)^4 \dfrac{\rho_x}{\rho_0}}{\varepsilon_x} + \frac{\varepsilon_0 \rho_x}{\varepsilon_x \rho_0} (T_0)^4}. \tag{5}$$

The magnitudes of the reflection coefficients ρ_x and ρ_0 depend on the spatial redistribution of temperature on the sources irradiating the measured object. Due to the choice of properties of the reference object, the ratio ρ_x/ρ_0 remains, in this case, constant. However, the quantity ρ_x/ρ_0 varies due to the temperature variations on the reference and investigated objects. The properties of the reference object permit determining this ratio from the known values of their spatially integrated reflection coefficients. The dynamics of the latter can be investigated with the help of a well-known procedure [3]. Nevertheless, it must be remembered that in a correct approach, the ratio $\rho x/\rho_0$ includes not simply the reflection coefficients, but their instrumental values, i.e., determined relative to the instruments used, specific bench complexes or commercial units. Often the temperature of the measuring object differs greatly from the temperature of the reference. For this reason, when partial radiation pyrometers are used, their selective optics excludes the possibility of using the integral reflection coefficients obtained with the help of the technique in [3].

The situation with the emission coefficients is analogous. But we investigated the dynamics of the instrumental emission coefficients of different objects outside the heating chamber on setups of the GOST 1209-71 type [4]. In so doing, the object was heated by irradiating it from the back or by connecting it directly to the current leads instead of the filament emitter. For the instrumental emission coefficient, we took the ratio of the output signal of the pyrometer, sited on the object being studied, to its rated calibration signal.

The techniques of and results of studying the dynamics of instrumental coefficients are the key to generalizing the method being examined. Indeed, even approximate information on the absolute values and changes in the ratio $\varepsilon_0\rho_x/\varepsilon_x\rho_0$ permit giving the initial values of these ratios, analyzing them in computers together with the extracted information on the radiation temperatures and, in so doing, to estimate the true temperature of the measured object using an iterative method.

The measurement and monitoring of the instrumental reflection coefficients is a problem that requires a special analysis. First it is necessary to choose the reflection standards. For this reason, we shall consider only the method with an arbitrary standard. For the arbitrary reflection standard we adopted the reflection coefficient at the temperature maximum of the reflectivity of the reference object with a clean, dust-free, and uncomtaminated surface. The numerical value 1 is arbitrarily assigned to this reference. The arbitrary instrumental reflection coefficient of objects in this case is the numerical value of the output signal of the pyrometer sensing the radiation beam reflected by the object to the output signal of the pyrometer sited on the cooled reference. The difference from ρ_x/ρ_0 is compensated by the ratio of the arbitrary coefficients, although for tuning and normal functioning of the pyrometric system it is not necessary to fix the reflection coefficients to absolute scales.

The main obstacle to miniaturizing the uncooled reference object is the relatively large size of the field of view of commercial radiation pyrometers. The reference object must overlap the field of view of the pyrometer sited on it.

In principle, the diameter of the field of view of the pyrometer can be decreased to 0.007 mm. However, for most commercial pyrometers, it exceeds 35 mm [4, 5]. For this reason, in order to choose the correct diameter of the reference object and to estimate the measurement error due to its incomplete overlapping of the field of view of the pyrometer, it is necessary to know the viewing characteristics of radiation pyrometers. An exact knowledge of these characteristics is also necessary to choose the correct stopping down aperture of the armature of the viewing aperture in the walls of the heating chamber when developing procedures and techniques.

The viewing characteristics of radiation pyrometers are the dependence of the diameters of the fields of view on distance to the measuring object and the distribution function of the energy sensed according to the field of view of the receiver. It is not difficult to calculate these characteristics for total radiation pyrometers. The index of refraction of the optical materials from which the lens of the partial radiation pyrometers is made is dispersive. For this reason the contribution of the ring-shaped zones in the field of view to the total output signal of the partial radiation pyrometer greatly depends on the temperature of the object being viewed. Due to aberrational phenomena, the distribution of the radiation energy sensed over the field of view of such a pyrometer is not amendable to a simple mathematical description. The well-known computational models [6, 7] contain simplifications. For this reason, the distribution function $\delta(t, d, l)$ of the radiation energy sensed from the field of view is more conveniently found experimentally.

We determined experimentally the distribution $\delta(t, d, l)$ for all modifications of the TERA-50 telescope of the most widely used commercial radiation pyrometer of the type RAPIR. The experiments were performed on a special stand, whose construction corresponded to GOST 12091-71, according to the procedure described in [8].

The generalized interpretation of the experimental data led to cumbersome relations with comparatively low accuracy. In order to increase the accuracy, the experimental results were analyzed with fixed distances most often encountered in commercial practice l. For the TERA-50 telescope with low temperature calibration R_5 and a distance to the diffuse object $l = 1000 \pm 10$ mm, the following relation was obtained:

$$\delta(d, t) = (118 - A)\exp\{(-3.49 - B)\exp[(-0.0258 - C)d]\}, \tag{6}$$

where the chromatic abberational complexes A, B, and C were calculated as periodic functions of temperature: $A = 0.0272t + 4.1 \sin[\pi(+0.81-0.00624t)]$, $B = 0.00877t + 1.05 \sin[\pi(0.89-0.00658t)]$, $C = 0.000098t-\{0.0000261t-0.001815-0.001603 \sin[\pi(0.775-0.005t]\} \sin[\pi(132-t) : (32 + 1.545t-91.2\cdot10^{+6}t^{-3})]$. The function $\delta(t, d)$ (5%) can be calculated to within ±5% from this relation with fixed d (mm) and t. In measuring T_p^o, this error involves an error in Δt_o^r not exceeding ±1%.

The results of the investigations showed that as the degree to which the surface of the viewed object deviates from a lambertian state increases, the diameters of the fields of view of the partial radiation pyrometers increase. In addition, the distribution functions on nonlambertian objects depend on the spatial distribution of the lateral irradiators. For this reason, it is best to estimate the field of view of the pyrometer on the reference object relative to the specific bench complex of tests or commercial units directly on site using an experimental method.

We did this, for example, by estimating the ratio of the output signals of the telescope sited alternately on the reference object, stopped down relative to the cold object, practically completely absorbing diaphragm (lamp black covering), and on the same unstopped reference object known to overlap the field of view of the telescope. The diameter of the diaphragm, corresponding to the value of this ratio equal to one, was taken as the necessary diameter of the reference object. In this case, the diameter of the reference object can be chosen as smaller than necessary, while the estimate, related to the decreased diameter compared to the required value, can be made from the ratio of the corresponding output signals of the pyrometer.

The required diameter of the reference object can also be decreased by stopping it down outside the heating chamber. In this case, the diameter of the reference object is easily matched to the diameter of the iris diaphragm stopping it down, if we use almost completely the absorbing screen placed behind the reference object. The screen is introduced into the chamber at the time of the measurements. This eliminates its being heated to the temperature level of the sensitivity of the pyrometer. When the diameter of the iris diaphragm is de-

TABLE 1. Indications of the Pyrometric System with Varying Conditions of Heating of an Offset Mold in the Heating Chamber with Halogenic Incandescent Lamps of the Type KG 220-1000

Air temp., °C	Air velocity, m/sec	Temp. of the offset mold, °C	Output signal of the system, mV
25	0,0	235	1,22
25	0,5	235	1,20
50	1,0	235	1,21
100	5,0	235	1,23

creased, the matching moment arrives if the presence of the screen does not change the output signal of the pyrometer. The numerical value of the distribution function for different temperature levels of irradiators is estimated as the ratio of the output signal from the stopped down reference object to the output signal from the nonstopped down reference object, overlapping the field of view of the pyrometer. It is not difficult to calculate the magnitude of the total output signal of the pyrometer from the known values of the distribution function and the output signal from the stopped down reference object.

As follows from what was said above, in order to perform correctly remote measurements of temperature of objects affected by the reflected radia from fluxes, it is necessary to perform a large number of tedious supplementary investigations. For cases when it is desirable to avoid such investigations, we developed a less general purely instrumental measurement method. The essence of this method is as follows. Two identical pyrometers, connected into a counter measuring circuit, are used. One of them is sited on the measured object and the other on the water-cooled reference object, made of the same material. The output signal of the second pyrometer compensates the ballast component of the output signal of the first pyrometer, since the reemission characteristics of both objects coincide in many cases. The system can be calibrated directly according to the measuring object in real stands or commercial units.

We estimated the efficiency of such a system experimentally in a thermal setup with regulated forced circulation of air and ventillation of the heating chamber. In this case, we used two identical radiation pyrometers based on layered thermobatteries [9]. The output signals of the thermocouple caulked into the material of the measured object, a heat-treated offset mold, and the radiation pyrometers were measured with F116-2 microvolt—microampere meters. The uniformity of cooling of the reference object was ensured by paper layers between its back surface and the water-cooled holder.

The velocity of the airflow in the chamber of the thermal setup varied in the range 0-5 m/sec. The air temperature varied in the range 15-100°C. Different rates of heating of the offset mold were achieved by varying the temperature and velocity of air in the chamber up to the same temperature 235°C.

It was established that the output signal of the instrumental pyrometric system does not depend on the conditions of heating of the offset printing mold in the chambers of the thermal setups and is uniquely related to the temperature of the mole.

There are no fundamental difficulties in estimating the magnitude of the corrections to the indications of the instrumental pyrometric system, which is necessary due to aging of the reference object. For this, it should be remembered that the reference object must be replaced by a new one and the output signals should be compared.

It is in principle possible to use efficiently the instrumental pyrometric system without forced cooling of the reference object, if the reflectivity of its surface does not change with temperature and time or if the law governing this change is known. For this, it is enough to calibrate the pyrometer beforehand according to a reference object outside the heating chamber and to introduce the appropriate corrections, using the indications of the thermocouple caulked into the reference object.

Part of the experimental data is presented in Table 1.

In our opinion, there is no hope that the same high accuracy of measurements will be obtained using the system with a more appreciable temperature dependence of the reflectivity of the surface of the offset mold.

NOTATION

H_{xs}, H_{os}, mutual surfaces of irradiation of the output opening of the pyrometer from the measuring object and the reference object; Ψ, spectral sensitivity function of the pyrometer; T_x, T_o, T_x^r, T_o^r, absolute, true, and radiation temperatures of the measured object and of the reference object; λ, wavelength of the spectral band; $I_\lambda(T)$, Planck function of absolute temperature; $\varepsilon_{x\lambda}$, $\varepsilon_{o\lambda}$, spectral emissivities of the measured object and reference object in a direction normal to the surface; c_o, Stefan–Boltzmann constant; $\theta_x = (T/100)^4$, reduced temperature; ε_x, ε_o, integral emissivities of the measured and reference objects in a direction normal to the radiation surface, measured relative to the radiation pyrometer; ρ_x, ρ_o, reflection coefficients of the measured and reference objects in a direction normal to the irradiation surface, measured relative to the radiation pyrometer; t, temperature of the object in degree Celsius; d, diameter of the central circular zone in the field of view of the radiation pyrometer; l, distance from the input aperture of the pyrometer to the measured object; $\delta(t, d, l)$, energy distribution function of the radiation, sensed from the central circular zone in the field of view of the pyrometer.

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