Reduction of uncertainty with non-contact measurement of temperature

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Abstract. The results of calculated theoretical and experimental studies aimed at justifying the use of calibrators, allowing to take into account the uncertainties associated with the difficulty of taking into account the radiation coefficients of controlled surfaces in non-contact pyrometric temperature measurements are given in the work. The relevance of the research is related to the requirements for ensuring the accuracy of non-contact temperature measurements at the level of instrumental errors of pyrometers declared by their manufacturers. Currently, pyrometric measurements are used in virtually all industries and this causes the relevance of the presented research results and proposed technical solutions. The functional scheme of the calibrator using replaceable surface samples is proposed, the temperature of which is measured by pyrometers.

1. Introduction
Accounting for uncertainties associated with methodological errors caused by difficulties in accurately taking surface radiation coefficients represent a significant problem in pyrometric measurements in industrial conditions. Universal quantitative estimates of such errors are difficult due to the variety of conditions for using the difference in temperature control over the thermal radiation of surfaces. In work [1], the influence of errors in the a priori specification of the operating coefficients of pyrometers and thermal imagers on the accuracy of non-contact temperature measurement was studied. The results of calculations of errors based on the energy balance at the radiation receiver presented in showed that there is a significant dependence of the errors on the values of the measured temperature of the monitoring object.

An analysis of the methods for calculating the coefficient in the practice of pyrometric measurements showed that to introduce corrections into the pyrometer on the actual emissivity of the surface of the material of the test object, it is most practical to use the radiation coefficient of a sample of a given material with a known temperature. This conclusion made it possible to propose a specialized device presented in the work - a calibrator, with the help of which it is possible to reduce errors in contactless temperature measurements caused by uncertainties associated with unknown emission factors of controlled surfaces.

2. Problem definition
At present, in pyrometry, tables are used with the numerical values of these coefficients either for one surface temperature value when measuring the surface temperatures to take into account the radiation coefficients, or for a narrow range of controlled temperatures. At the same time, it is known that the change in the values of these coefficients depends significantly on the temperature of the controlled surface and the spectral range of the recorded radiation. At present, the dependence of the change in the emissivity on temperature is presented only in publications for particular measurement conditions. At the same time, it should be noted that installations for measuring the radiation coefficient from temperature and type of materials exist only in research laboratories and are not included in GOSTs.
(state standards) for metrological provision in pyrometry. In the absence of information on the spectral range of sensitivity of a particular model of a pyrometer, the use of tabulated coefficients may lead to a significant error in the non-contact temperature measurement, especially for materials with low emissivity.

In this paper, using the example of an aluminum surface on the basis of computational studies, it is shown that the emission coefficient of aluminum varies significantly from temperature and wavelength, which proves the necessity of taking these changes into account in measurement practice. The results of the investigations are used as a basis for the development of the pyrometric calibrator, which, when applied, significantly reduces the errors associated with the uncertainties in taking into account the radiation coefficient in contactless temperature measurements.

3. Theory
It is known that metals have a small emissivity that increases with increasing metal temperature [3]. This is explained by the fact that the conductivity of metals increases with heating, which is accompanied by a decrease in the reflection coefficient of electromagnetic radiation. In this case, the radiation coefficient will be calculated as:

\[
\varepsilon(\lambda) = 1 - \rho(\lambda),
\]

where \( \rho \) is the reflection coefficient.

In [2], the equation based on the spectral emissivity \( \varepsilon(\lambda, T) \) holds for most metals:

\[
\varepsilon(\lambda, T) = 0.365\sqrt{\rho[1 + \alpha(T - 293)](1/\lambda)} - 0.067\rho[1 + \alpha(T - 293)](1/\lambda) + 0.006\sqrt{(\rho[1 + \alpha(T - 293)](1/\lambda))^3},
\]

where \( \rho \) - is the resistivity of the metal; \( \alpha \) - is the temperature coefficient of the change in the resistivity of the metal; \( \lambda \) - is the wavelength of the electromagnetic radiation.

In this paper, a graphical solution of equation (2) is obtained for aluminum at temperatures of 100, 200 and 500 °C, which is shown in Fig. 1. Calculations are given in app. A.

![Figure 1](image)

**Figure 1.** The calculated spectral dependence of the radiation coefficient of aluminum \( \varepsilon(\lambda) \) at temperatures of 100, 200 and 500 °C in the spectral range from 3 to 14 µm

\( \lambda \) - wavelength

From the dependencies shown in Fig. 1. It can be seen that, in a wide spectral range, the emission coefficient of aluminum varies significantly from temperature and wavelength. For \( \varepsilon(\lambda) \) (3 µm) = 0.33 and example, at a temperature of 100 °C, it was \( \varepsilon(\lambda) \) (3 µm) = 0.44 and \( \varepsilon(\lambda) \) (14 µm) = 0.175, and at 500 °C, respectively, (14 µm) = 0.245. Under real conditions of measurement, the dependence of \( \varepsilon(\lambda) \) under the influence of technological processes of material processing, roughness, oxidation and surface contamination. Consequently, the use of solutions of equations (1) and (2) in the algorithm for
the operation of the pyrometric converter is not a sufficient condition for taking into account the real radiation coefficient.

The integrated emission coefficient is determined in accordance with the international standard for the classical method of the ratio of the radiation power $F_A$ that hits the radiation receiver from the aluminum surface at a known temperature $T$ to the radiation power of the $F_{BB}$ radiation coming from the emitter of the type of the blackbody model (BB) at the same temperature $T$. For example, for a temperature $T = 100 \, ^\circ C$ it can be calculated as:

$$\varepsilon_A(273 + 100) = \frac{F_A(273+100)}{F_{A_{BB}}(273+100)} = \frac{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \varepsilon_A(\lambda,T) (r(\lambda,T) - r(\lambda,T_0)) d\lambda}{\int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} (r(\lambda,T) - r(\lambda,T_0)) d\lambda}$$

where $\varepsilon_A(\lambda,T)$ – is spectral emission factor of aluminum; $\lambda_{\text{max}} - \lambda_{\text{min}} = \Delta \lambda$ - is spectral range of sensitivity of the radiation receiver; $r(\lambda,T)$ - is the spectral density of the radiation brightness - the Planck function; $r(\lambda,T_0)$ - spectral brightness of the receiver.

The dependences of the integrated emission coefficient of aluminum $\varepsilon_A(\lambda,T)$ obtained for formula (3) for the spectral ranges $\Delta \lambda = 7-14 \, \mu m$ and $\Delta \lambda_s = 3-5.5 \, \mu m$ are shown in Fig. 2.

In the literature [3] for strongly oxidized aluminum, the integral coefficient $\varepsilon_A = 0.2...0.25$ is given in the temperature range 150 ... 500 \, ^\circ C without indicating the type of radiation receiver. These data approximate the calculated values obtained for the spectral range $\Delta \lambda = 7-14 \, \mu m$, shown in Fig. 3.5, where $\varepsilon_A = 0.2...0.283$ in the temperature range 100 ... 500 \, ^\circ C. However, for relatively short-wavelength radiation receivers with a spectral sensitivity $\Delta \lambda_s = 3-5.5 \, \mu m$ in this same temperature range, the coefficient $\varepsilon_{AS} = 0.281...0.386$ (Fig. 2).

The error in measuring the temperature $\Delta T = T_{\text{meas}} - T_{\text{true}}$, determined by an erroneous setting of the radiation coefficient parameter, can be determined from equation (3) by taking $\varepsilon_A$ as a constant value. When setting the emissivity of aluminum determined by the black body at 100 \, ^\circ C, $\varepsilon_A = 0.2$ and performing measurements with a pyrometer with $\Delta \lambda = 7-14 \, \mu m$, the calculated absolute error of measurement $\Delta T(T_{\text{true}})$, shown in Fig. 3.6, was 130 \, ^\circ C at an aluminum surface temperature of 500 \, ^\circ C. For the short-wave range, $\Delta \lambda_s = 3-5.5$ or 60 \, ^\circ C respectively.
Calculation studies carried out for aluminum, the results of which are presented in Fig. 4, show that if the temperature of the measured surface is 10 °C in the range of measured temperatures of 100-500 °C, when the reference value of the integrated radiation coefficient is used, the measurement error will be 1-2 °C.

4. Experimental results

Based on the results of the analysis of the presented errors in the measurement of the temperature of materials with a low emissivity (ε< 0.3) a pyrometric converter with a calibration according to the black body model formulated a proposal on the need to calibrate pyrometric measurements using the model of a pyrometric calibrator (MPC) with samples of materials of controlled surfaces.

Under the condition of uncertainty ε(λ, T), it is proposed to calibrate the pyrometers not according to the emitter of the type of the black body model, but according to the MPC. At such an installation, the
pyrometer will be graded taking into account the ambiguous dependence of the effective emissivity on temperature, texture of the surface and the spectral range of the sensitivity of the pyrometer.

In Fig. 5. The functional diagram of the proposed model of the pyrometric calibrator is presented. Temperature change of the sample of the controlled surface (SCS) is checked by the heater (H). The temperature of the heated surface is set by the temperature regulator (TR) with the help of the temperature controller (TC) and is controlled by the temperature of the sample measured by the contact temperature sensor (TS) by means of the meter (M). Thus, the system has an automatic control system with negative feedback.

In the design of the calibrator, it shall be possible to replace the samples of the inspection object material, which allows the use of a calibrator for various samples of materials when measured in production conditions.

The possibility of replacing samples of the inspection object material should be provided in the calibrator design, which allows the use of a calibrator for various material samples when measured in production conditions.

The paper presents the results of experimental studies on the estimation of the parametric measurement error associated with the error in setting the effective emissivity.

For the Pyrometer OptrisCTL T15 (Germany) with \( \Delta \lambda = 8-14 \ \mu m \), having a calibration on the black body, correction of the readings to the effective emissivity was carried out. The dependence of \( \varepsilon_{ef}(T) \) on the temperature of the aluminum surface measured by the contact method in the calibrator is shown in Fig. 6. In accordance with the classical radiometric method of measuring the emissivity [3], the lower limit of the temperature range of measurements is taken as \( T = T_{py} + 20 ^\circ C \).
Figure 6. The experimental dependence of $\varepsilon_{\text{ef}}(T)$ on the temperature of the aluminum surface at a radiation receiver temperature $T_{\text{py}} = 20 \, ^\circ\text{C}$ and an ambient temperature $T_0 = 24 \, ^\circ\text{C}$.

The results of experimental studies of the methodical measurement error arising when the correction to the effective emissivity factor $\varepsilon_{\text{ef}}(T) \pm \Delta \varepsilon$, made using the model of a pyrometric calibrator are inaccurately presented are shown in Fig. 7.

Figure 7. Absolute measurement error $\Delta T$ of the OptrisCTL15 pyrometer in the case of an error in the setting of the radiation coefficient parameter $\Delta \varepsilon = \pm 0.1$ and $\Delta \varepsilon = \pm 0.01$.

Based on the results of the experiment, the relative methodological error in measuring the surface temperature of the OptrisCTL15 pyrometer at the minimum error in setting the parameter of the radiation coefficient $\Delta \varepsilon = \pm 0.01$ in the temperature range 40-200 °C was $\delta_{\text{met}} = 0.5...4\%$ with the declared instrument error $\delta_{\text{in}} = 1\%$. In the absence of correction for the background radiation $\varepsilon_{\text{ef}}(T)$ and setting the value of the parameter, the radiation coefficient $\varepsilon = 0.259$, determined at 107 °C, the
pyrometer readings are overestimated in the lower temperature range by 7.4% at 40 °C and underestimated by 2% in the upper range.

For the FlirE60 (US) thermal imager with \( \Delta \lambda = 7-14 \, \mu\text{m} \), the measurement error was investigated, associated with an increase in the integral emissivity of aluminum from temperature. The results of the experiment are shown in Fig. 8. At an ambient temperature of 24.1 °C, according to the diffuse reflector method, a conditioned reflected temperature of 26 °C is determined. The measured temperature values are entered in the thermal imager settings. The emissivity of the aluminum surface at a temperature of 100 °C, measured by the contact method in the calibrator, was \( \varepsilon = 0.25 \) for this model of the thermal imager.

\[\delta, \%\]
\[\text{T, °C}\]

**Figure 8.** Relative measurement errors \( \delta \% \) with the FlirE60 thermal imager at \( \varepsilon = 0.25 \).

According to the results of the experiment shown in Fig. 9, the relative methodological error in measuring the temperature of the aluminum surface by the FlirE60 thermal imager was \( \delta (50) = -3.5\% \) with a decrease in the temperature of the test object by 50 °C relative to the temperature at which the radiation coefficient was determined, and \( \delta (200) = +2.4\% \) with an increase in temperature by 100 °C, respectively.

5. Discussion of the results

The results of experimental studies have shown that to reduce uncertainty in pyrometric measurements of temperature, it is necessary to determine the dependence of the integral radiation coefficient on temperature. Otherwise, the methodical error of measurements can reach one hundred percent or more. Although the instrumental error of pyrometers calibrated on the black body declared by their manufacturers may not exceed a fraction of a percent. The introduction of correction factors corresponding to radiation temperatures from the experimental dependences of \( \varepsilon(T) \) during the measurement is technically difficult [4,5].

The results of calculations for two spectral intervals for the sensitivity of the radiation detector at the surface temperatures of the control object \( T = 60, 100, \) and \( 500 \) °C are shown in Fig. 9. Analysis of these dependencies allowed us to justify the requirements for the error \( \Delta T \) of the temperature of the sample of the controlled surface for pyrometers with different spectral sensitivity. At \( T = 60 \) °C and \( \Delta \lambda = 3-5.5 \, \mu\text{m} \), the calculated error was 1.1, 0.2 and 0.1 °C for the radiation coefficient \( \varepsilon = 0.1, 0.5 \) and 0.95, respectively. The calculated error for a pyrometer with a spectral sensitivity \( \Delta \lambda = 7-14 \, \mu\text{m} \), shown in Fig. 3.3. a, with a discreteness \( \Delta \varepsilon = 0.01 \) was 1.4, 0.3 and 0.15 °C at the radiation coefficient \( \varepsilon = 0.1, 0.5 \) and 0.95 respectively.
Figure 9. Calculated values of the requirements for the absolute error of maintaining the temperature $T$ of the sample of the monitored surface as a function of its integral emissivity to correct for the radiation coefficient with a discreteness $\Delta \varepsilon = 0.01$ in the readings of the pyrometer with spectral sensitivity a) $\Delta \lambda = 7-14 \mu m$ b) $\Delta \lambda = 3-5.5 \mu m$.

Conclusions
The results of the presented studies prove the existence of a measurement accuracy problem related to the difficulties in taking into account the radiation coefficients of controlled surfaces in the case of noncontact pyrometric temperature control. The conclusion is made about the advisability of using the developed calibrator to take into account the emission factors of the controlled surfaces in order to reduce uncertainty in contactless measurement of temperature. This proposal will allow the calibration of pyrometers in the conditions of their operation, taking into account the uncertainty of the emissivity of the control surfaces.

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