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NON-CONTACT METHOD OF MEASURING SURFACE TEMPERATURE

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A non-contact method is proposed for measuring the surface temperature of an object using a standard radiator and standard object having optico-physical properties identical to those of the monitored object. Placed co-planarly with the monitored object in the field of view of an optoelectronic system (OES) is a standard object, the temperature of which is regulated and measured, and a standard radiator, whose normal spectral emissivity and temperature are known. In addition, the OES has its three fixed points, at which it registers the normal emissivity of the standard object, monitored object, and standard radiator (SR). The main distinction of the proposed method from the known ones is that the limits or tolerances for the nature of reflection and the quantitative parameters of reflection of the monitored object make no difference. The obtained analytical expression is an equation of the non-contact method of measuring the surface temperature of the monitored object, which can be applied for any spectral range of operation of the OES. A metrological analysis of the proposed method is made using a monochromatic optoelectronic system working at wavelengths of 0.65, 2.0, 5.0, 14.0, and 50.0 μm for the temperature of the monitored object, *T*, equals to 400, 700, and 1000 K. Based on the analysis of the results the requirement for the implementation of the proposed method of measuring the surface temperature has been formulated, which says that the choice of an optoelectronic system for measuring the surface temperature of objects should be preceded by a methodological and metrological analysis of the optico-physical properties of the monitored object, the surrounding background, and the OES itself.

Keywords: pyrometry, non-contact/contactless method, measurement, temperature, mathematical model, monitored object, standard object, standard radiator, methodical and metrological analysis, monochromatic mode, optoelectronic system, background light.

БЕСКОНТАКТНЫЙ МЕТОД ИЗМЕРЕНИЯ ТЕМПЕРАТУРЫ ПОВЕРХНОСТИ ОБЪЕКТА

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Предложен бесконтактный метод измерения температуры поверхности объекта с использованием эталонного излучателя и эталонного объекта, имеющего тождественные с контролируемым объектом оптико-физические свойства. В поле зрения оптико-электронной системы (ОЭС) планарно с контролируемым объектом установлены эталонный объект, температуру которого регулируют и измеряют, и эталонный излучатель, нормальная спектральная излучательная способность которого и температура известны. Причем ОЭС имеет три фиксированных положения, при которых она регистрирует нормальное излучение эталонного объекта, контролируемого объекта и эталонного излучателя. Принципиальное отличие предложенного метода от известных состоит в том, что на характер отражения и количественные параметры отражения контролируемого объекта не накладываются ограничения и не принимаются допущения. Получено аналитическое выражение, являющееся уравнением бесконтактного метода измерения температуры поверхности контролируемого объекта, и применимо для любого спектрального диапазона работы ОЭС. Выполнен метрологический анализ предложенного метода при использовании монохроматической ОЭС, работающей на длинах волн, равных 0.65, 2.0, 5.0, 14.0 и 50.0 мкм; температура *T* контролируемого объекта составляла 400, 700 и 1000 К. Анализ результатов позволил сформулировать требование к реализации предложенного метода измерения температуры поверхности, состоящее в том, что выбору оптико-электронной системы для измерения температуры поверхности объектов должен предшествовать методический и метрологический анализ оптико-физических свойств объекта контроля, окружающего его фона и самой ОЭС.

Ключевые слова: пирометрия, бесконтактный метод, измерение, температура, математическая модель, объект контроля, эталонный объект, излучатель, методический и метрологический анализ, монохроматический режим, оптико-электронная система, фоновая засветка.

Introduction

One of the current trends of scientific achievements application in technological processes is using non-contact methods (procedures) and techniques of monitoring the temperature state of objects at all stages of their life cycle and determining the physical properties of materials [1–4]. These procedures are associated with the non-contact measurement of temperature, *T*, of the surface of related objects, which is the main information parameter.

It should be noted that the implementation of pyrometric methods of temperature measurement is far from being a trivial task. It is the multiparameter description of electromagnetic energy radiated by the object that complicates the building of a physical model of the temperature measurement procedure and its mathematical description [1, 4, 5].

The physical complexity of non-contact methods (procedures) of measuring the temperature of an object is caused by the fact that the intrinsic thermal radiation is characterized not only by temperature, but also by spectral and temperature dependences of the normal emissivity ε_{λ_n} of the surface of the monitored object, by the state of the surface, and other factors. (Here and further λ is the wavelength of electromagnetic radiation; the index λ indicates spectral dependence of the corresponding parameter, and the index *n* indicates emissivity propagation along normal towards the surface of a monitored object).

It is worth noting that there is a wide range of semi-transparent materials often referred to as partially transparent materials for thermal radiation, which in certain regions of thermal radiation spectrum have a small absorption coefficient and can pass radiation falling upon them, or have intrinsic radiation, over long distances. These materials include almost all dielectrics and semiconductors: oxides, fluorides, chlorides, selenides, tellurides, germanium, silicon, gallium arsenide, indium antimonide, as well as most of organic substances. Non-contact temperature measurement of objects made of such materials requires specific methodological and technical support. So, we will not consider this issue here [6, 7].

The mathematical complexity of non-contact methods of temperature measurement is explained by the essential nonlinearity of the dependence of the monochromatic radiant flux density on the wavelength and temperature, which is defined by the Planck radiation law.

A non-contact measurement method

The optoelectronic systems available on the market of instruments and devices are not well fit to the quantitative measurement of the surface temperature of an object, in terms of both the optical-physical properties of the material from which the monitored object is made, and the background light, the optical-physical properties of an OES and the medium between the monitored object and the OES [8]. Thus, the methodological support of pyrometric and thermal imaging systems is a topical issue today.

The total thermal radiation of the object, the emissivity of which differs from "one", consists of its intrinsic radiation and the radiation reflected by the object, depending on the optico-physical parameters of the monitored object, the surrounding background and the medium between the object and the optoelectronic system of temperature measurement.

One of the main factors influencing the metrological parameters of the results of measuring the surface temperature of the monitored object is its background light [9–15]. It is noteworthy that the background light sometimes makes it difficult to obtain reliable information [14, 15].

Based on the analysis of physical processes of the non-contact procedure of measuring the object temperature, *T*, several ways of reducing radiation effect of the background light have been formulated. They are:

1. The surface radiation reflected by the object is reduced. (This can be achieved either by covering the object with a coating having a reflection coefficient close to "zero" or by choosing such spectral range of the optoelectronic system, within which the reflection coefficient of the object is small.)

2. The background radiation is reduced. (This can be achieved when an object is placed in a chamber, the inner surface of which is coated, for example, by gold, which provides background radiation not exceeding 0.05 in a wide spectral range.)

3. The background temperature is lowered. (This can be realized in practice, for example, by putting the object inside a chamber, the cooling of which can be arranged.)

4. The measuring (reduction, compensation) of the background radiant flux reflected from the object and its further subtraction from the total radiation flux.

The first three approaches are rather well studied. And the fourth one will be analyzed here. To this end a method of measuring the surface temperature of a monitored object using a standard radiator is proposed in [16].

A perfect blackbody model is commonly taken as an SR [17, 18]. As a standard object it is suggested [16] that an additional object be taken, which has optico-physical and thermophysical properties identical with the monitored object. Provided the temperature measurement procedure is geometrically correct, that is, the monitored object, the standard object and the OES are properly located, the conditions of radiation and reflection of energy of the objects will be the same.

Fig. 1 shows a scheme of non-contact method of measurement of the surface temperature T of Monitored Object 2, the normal spectral emissivity ε_{λ_n} of the surface of which is known.

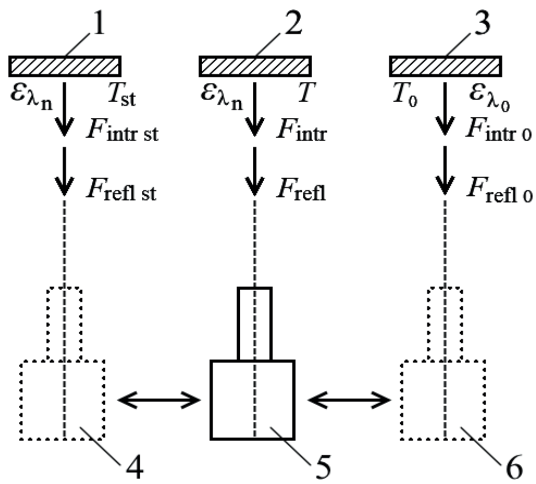

Fig. 1. The scheme of a non-contact method of measuring the surface temperature of an object using a standard radiator and a standard object.

In the field of view of OES 5, co-planarly with Monitored Object 2, is placed Standard Object 1, the temperature of which T_{st} is regulated and measured, as well as Standard Radiator 3 with the known normal spectral emissivity ε_{λ_0} and temperature T_0. The OES has three set positions 4, 5 and 6, at which it registers the normal emissivity of the standard object, monitored object and SR.

The total integral radiation flux F_Σ produced by the monitored object is a sum of the intrinsic radiation flux F_{intr} and the reflected radiation flux F_{refl}, which can be written using the Planck law as the following expression:

$$F_\Sigma = F_{intr} + F_{refl} = \int_0^{+\infty} \frac{\varepsilon_{\lambda n} \cdot C_1}{\lambda^5 \left(\exp\left(C_2 / \lambda T\right) - 1\right)} d\lambda + F_{refl}, \quad (1)$$

where $C_1 = 3.7413 \cdot 10^{-16}$ W·m^2, and $C_2 = 1.4388$ m·K – the first and second Planck constants.

In order to register radiation flux, an optoelectronic system is used. Usually it is either a pyrometer or a thermal imaging system with a related radiation receiver and data processing system.

The output signal of the OES is determined not only by the parameters accounted for in expression (1), but also by other parameters: K – OES design parameter, $\Delta\lambda$ – spectral range (from λ_1 to λ_2) of the OES operation, S_λ – the volt-watt sensitivity of the OES radiation receiver, τ_λ – transmissivity of the OES and the medium between the object and the OES [19, 20].

The total integral flux of the standard object $F_{\Sigma\ st}$ is also a sum of the intrinsic flux $F_{intr\ st}$ and the reflected flux $F_{refl\ st}$, i.e.

$$F_{\Sigma\ st}=F_{intr\ st}+F_{refl\ st}=\int_0^{+\infty}\frac{\varepsilon_{\lambda n}\cdot C_1}{\lambda^5\left(\exp\left(C_2/\lambda T_{st}\right)-1\right)}d\lambda+F_{refl\ st} \quad (2)$$

Since the monitored object and the standard object have identical optico-physical and thermophysical properties, the radiation flux reflected by them are equal, that is, $F_{refl}=F_{refl\ st}$.

When the temperature of the standard object T_{st} decreases (it is regulated and measured), a quantitative structure change of the radiation flux $F_{\Sigma\ st}$, occurs. Specifically, the intrinsic radiation flux decreases compared with the reflected radiation flux. To make the analysis simpler, we can assume that the reflected characteristics of objects do not depend on their temperature. The temperature of the standard object T_{st} is lowered up to the temperature, at which the intrinsic radiation flux, $F_{intr\ st}$, is much less than the reflected radiation flux $F_{refl\ st}$, that is, $F_{intr\ st} \ll F_{refl\ st}$.

The expression (2) takes the following form:

$$F_{\Sigma\ st}=F_{refl\ st}. \quad (3)$$

Then the difference between the flows F_Σ and $F_{\Sigma\ st}$, calculated by formulas (1) and (3), forms the output signal of the OES, ΔU, which is defined by this formula:

$$\Delta U=K\cdot\int_{(\Delta\lambda)}\frac{\varepsilon_{\lambda n}\cdot C_1\cdot\tau_\lambda\cdot S_\lambda}{\lambda^5\left(\exp\left(C_2/\lambda T\right)-1\right)}d\lambda\cdot \quad (4)$$

The total radiation flux of the standard radiator, $F_{\Sigma 0}$, is the sum of the intrinsic radiation flux $F_{intr\ 0}$ and the reflected radiation flux $F_{refl\ 0}$. As a rule, the spectral normal emissivity ε_{λ_0} of the SR is close to “one” (actually no less than 0.98). This allows to determine the output signal of the OES, U_0, without an essential error, by the following expression:

$$U_0=K\cdot\int_{(\Delta\lambda)}\frac{\varepsilon_{\lambda 0}\cdot C_1\cdot\tau_\lambda\cdot S_\lambda}{\lambda^5\left(\exp\left(C_2/\lambda T_0\right)-1\right)}d\lambda. \quad (5)$$

The ratio of the output signals of the OES, ΔU and U_0, can be written as follows:

$$\frac{\Delta U}{U_0}=\frac{\int\limits_{(\Delta\lambda)}\frac{\varepsilon_{\lambda_n}\cdot\tau_\lambda\cdot S_\lambda}{\lambda^5\left(\exp\left(C_2/\lambda T\right)-1\right)}d\lambda}{\int\limits_{(\Delta\lambda)}\frac{\varepsilon_{\lambda_0}\cdot\tau_\lambda\cdot S_\lambda}{\lambda^5\left(\exp\left(C_2/\lambda T_0\right)-1\right)}}. \tag{6}$$

The obtained expression (6) is an equation for a non-contact method for the determination of the surface temperature of the monitored object, T.

In the monochromatic approximation, equation (6) can be used to obtain an analytical expression for determining the surface temperature of the object under test.

In the monochromatic approximation from equation (6) the analytical expression is derived, determining the temperature of the monitored object surface.

$$T=\frac{C_2}{\lambda\cdot\ln\left(1+\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}}\cdot\frac{e^{\frac{C_2}{\lambda T_0}}-1}{\Delta U/U_0}\right)}. \tag{7}$$

The proof of correctness of obtained equation (7) is that at $\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}}=\frac{\Delta U}{U_0}$ the equality $T=T_0$ is fulfilled, that is, the temperature of the monitored object and the temperature of the standard radiator are equal. In terms of mathematics, this follows from equation (7). In terms of physics, it shows that no background light is available and ΔU is in fact an output signal of the OES, which is proportional to the intrinsic radiation flux of the monitored object.

Metrological analysis

A metrological analysis of the proposed method has been carried out using the small perturbations method [19, 20] for the determination of the temperature of an object, implementing monochromatic OES, with λ = 0.65, 2.0, 5.0, 14.0, and 50.0 μm for the following parameters: the temperature T of the monitored object is equal to 400 K, 700 K, 1000 K; $\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}}$ = 0.1, 0.5, 0.9, and 1.0; $\frac{\Delta U}{U_0}$ = 0.1, 0.5, 0.9, 1.0, and 1.5; the absolute error Δλ of the wavelength of the OES, λ, equals to 0.01 μm for λ= 0.65 μm; and 0.1 μm for the rest of the wavelengths λ; the relative errors δT_0=3%, δ $\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}}$ =5% and δ $\frac{\Delta U}{U_0}$ =2% for the determination of T_0, $\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}}$ and $\frac{\Delta U}{U_0}$, respectively.

The selection of the temperature T_0 of the standard radiator is better to be made proceeding from the condition that $\frac{\Delta U}{U_0}$ ~1, at which the signals ΔU and U_0 are commensurable. In this case, the distortions in the receiving and amplifying paths of the OES signals, ΔU and U_0, will be identical. The use of the scale of ratios significantly reduces the systematic errors in determining the signals ΔU and U_0.

The calculations, for which the results are presented in the table, have been obtained for the given parameters and the ratio of OES output signals $\frac{\Delta U}{U_0}=1$.

The impact of inaccuracy of parameters knowledge on the determination of the error of temperature

λ, μm	T, K	$\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}}$	T_0, K	δT_λ, % $\Delta\lambda = 0.01$ or $\Delta\lambda = 0.1$, μm	δT_{T_0}, % $\delta T_0 = 3\%$	δT_ε, % $\delta(\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}}) = 5\%$	δT_U, % $\delta(\frac{\Delta U}{U_0}) = 2\%$	θ, %
0.65	400	0.1	384	−1.52	2.88	0.08	−0.03	3.6
		0.5	395	−1.52	2.96	0.09	−0.04	3.7
		0.9	399	−1.52	2.99	0.09	−0.04	3.7
		1.0	400	−1.52	3.00	0.09	−0.04	3.7
	700	0.1	652	−1.52	2.79	0.14	−0.06	3.5
		0.5	685	−1.52	2.93	0.15	−0.06	3.6
		0.9	698	−1.52	2.99	0.15	−0.06	3.7
		1.0	700	−1.52	3.00	0.15	−0.06	3.7
	1000	0.1	906	−1.52	2.71	0.20	−0.08	3.4
		0.5	970	−1.52	2.91	0.21	−0.09	3.6
		0.9	995	−1.52	2.99	0.22	−0.09	3.7
		1.0	1000	−1.52	3.00	0.22	−0.09	3.7
2.0	400	0.1	355	−4.76	2.65	0.24	−0.10	6.0
		0.5	385	−4.76	2.89	0.26	−0.11	6.1
		0.9	398	−4.76	2.98	0.27	−0.11	6.2
		1.0	400	−4.76	3.00	0.27	−0.11	6.2
	700	0.1	572	−4.76	2.44	0.39	−0.16	5.9
		0.5	656	−4.76	2.81	0.45	−0.18	6.1
		0.9	693	−4.76	2.97	0.47	−0.19	6.2
		1.0	700	−4.76	3.00	0.48	−0.19	6.2
	1000	0.1	758	−4.76	2.26	0.52	−0.21	5.8
		0.5	912	−4.76	2.73	0.62	−0.25	6.1
		0.9	986	−4.76	2.96	0.67	−0.27	6.2
		1.0	1000	−4.76	3.00	0.68	−0.27	6.2
5.0	400	0.1	303	−1.96	2.26	0.52	–0.21	3.4
		0.5	365	−1.96	2.73	0.62	–0.25	3.8
		0.9	394	−1.96	2.96	0.67	–0.27	4.0
		1.0	400	−1.96	3.00	0.68	–0.27	4.0
	700	0.1	450	−1.96	1.94	0.77	–0.31	3.2
		0.5	600	−1.96	2.58	1.02	–0.41	3.6
		0.9	683	−1.96	2.93	1.15	–0.46	4.1
		1.0	700	−1.96	3.00	1.18	–0.47	4.2
	1000	0.1	561	−1.96	1.76	0.95	–0.38	3.1
		0.5	812	−1.96	2.50	1.35	–0.54	3.8
		0.9	967	−1.96	2.91	1.58	–0.63	4.3
		1.0	1000	−1.96	3.00	1.62	–0.65	4.4

End of the table

λ, μm	T, K	$\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}}$	T_0, K	δT_λ, % $\Delta\lambda = 0.01$ or $\Delta\lambda = 0.1$, μm	δT_{T_0}, % $\delta T_0 = 3\%$	δT_ε, % $\delta(\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}}) = 5\%$	δT_U, % $\delta(\frac{\Delta U}{U_0}) = 2\%$	θ, %
14.0	400	0.1	214	−0.71	1.71	1.02	−0.41	2.4
		0.5	319	−0.71	2.48	1.47	−0.59	3.3
		0.9	385	−0.71	2.91	1.73	−0.69	3.9
		1.0	400	−0.71	3.00	1.78	−0.71	4.0
	700	0.1	290	−0.71	1.56	1.36	−0.54	2.5
		0.5	504	−0.71	2.43	2.12	−0.84	3.8
		0.9	663	−0.7	2.91	2.53	−1.00	4.5
		1.0	700	−0.71	3.00	2.61	−1.03	4.6
	1000	0.1	349	−0.7	1.54	1.59	−0.63	2.7
		0.5	674	−0.71	2.46	2.55	−1.01	4.1
		0.9	937	−0.71	2.92	3.03	−1.19	4.9
		1.0	1000	−0.71	3.00	3.12	−1.23	5.0
50.0	400	0.1	118	−0.20	1.56	1.85	−0.73	2.8
		0.5	254	−0.20	2.51	2.98	−1.17	4.5
		0.9	371	−0.20	2.93	3.47	−1.37	5.2
		1.0	400	−0.20	3.00	3.56	−1.40	5.4
	700	0.1	159	−0.20	1.69	2.30	−0.91	3.3
		0.5	410	−0.20	2.63	3.59	−1.41	5.1
		0.9	643	−0.20	2.95	4.03	−1.58	5.8
		1.0	700	−0.20	3.00	4.10	−1.61	5.9
	1000	0.1	196	−0.20	1.81	2.61	−1.03	3.7
		0.5	563	−0.20	2.70	3.91	−1.54	5.5
		0.9	913	−0.20	2.96	4.29	−1.68	6.0
		1.0	1000	−0.20	3.00	4.34	−1.70	6.11

The calculated results showing the effect of the errors of knowledge of the initial parameters on the error of determining the temperature T are presented as rather small relative errors δT_λ, δT_{T_0}, δT_ε, and δT_U. The selected values of errors almost comply with those obtained using modern measuring instruments. Therefore, the results presented in the table can be considered as evaluation data. Since these functions are almost linear for small variations of arguments, the obtained results can be used, with appropriate weighting factors, in real measurement conditions.

The total systematic error θ of determination of the surface temperature of an object with a confidence probability of 0.95 is calculated by the formula $\theta = 1{,}1 \cdot \sqrt{\sum_{i=1}^{m} \left(\delta T_i\right)^2}$, %, where m is the number of varying parameters ($m = 4$) [21].

While analyzing the obtained results, certain facts have been established.

The relative errors $\delta\lambda$ of knowledge of the wavelength λ of the OES operation are almost equal to the relative errors δT_λ of determining the object temperature T. For example, the relative errors $\delta\lambda$ equaling 1.5, 5.0, 2.0, 0.7, and 0.2% for the wavelength λ equaling 0.65, 2.0, 5.0, 14.0, and 50.0 μm give relative errors δT_{λ} of determining the object temperature T equaling 1.5, 4.8, 2.0, 0.7, and 0.2%, respectively.

The similar case is with the effect of the inaccuracy of knowledge of the standard radiator temperature T_0 on the error of determination of the monitored object temperature T. Moreover, at $\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}} = \frac{\Delta U}{U_0}$, the relative errors δT_0 и δT_{T_0} are equal. For the rest modes of determining the temperature of an object, the difference between the errors of δT_0 and δT_{T_0} does not exceed several percent. For example, at $\frac{\Delta U}{U_0} = 1$ and $\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}} = 0.9$, a three-percent relative error in determining the temperature T_0 of the standard radiator gives an error of δT_{T_0} equaling ~ 2.9%, which does not depend on the level of the measured temperature T. This means that δT_0 and δT_{T_0} are nearly equal.

The influence of the inaccuracy of knowledge of the ratio of emissivity $\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}}$ of the monitored object and the standard radiator on the error in determining the temperature T of the monitored object significantly depends on the wavelengths of the OES operation. For example, at $T = 700$ K, $\frac{\Delta U}{U_0}$ and $\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}} = 0.9$, a five-percent relative error in the determination of $\frac{\varepsilon_{\lambda_n}}{\varepsilon_{\lambda_0}}$ results in δT_{ε} equaling 0.15, 0.47, 1.15, 2.53 and 4.03% for wavelengths λ equaling 0.65, 2.0, 5.0, 14.0, and 50.0 μm, respectively.

In the implementation of the proposed method of temperature measurement an important parameter is the ratio q of the registered by the OES intrinsic radiation flux $F_{\text{intr st}}$ of the monitored object, the coefficient of reflection of which is R_{λ}, and the background radiation flux $F_{\text{refl st}}$ reflected by the monitored object, the temperature of which is T_{b}, and the emission is $\varepsilon^{*}_{b_{\lambda}}$ [22]. The expression for q can be written in the following form:

$$q = \frac{\Phi_{\text{intr st}}}{\Phi_{\text{refl st}}}$$

or

$$q = \frac{\int\limits_{\lambda_1}^{\lambda_2} \varepsilon_{\lambda_n} \frac{C_1 \cdot \tau_{\lambda} \cdot S_{\lambda}}{\lambda^5 \left(\exp\left(\frac{C_2}{\lambda \cdot T_{\text{st}}} \right) - 1 \right)} d\lambda}{\int\limits_{\lambda_1}^{\lambda_2} R_{\lambda} \cdot \varepsilon^{*}_{b_{\lambda}} \frac{C_1 \cdot \tau_{\lambda} \cdot S_{\lambda}}{\lambda^5 \left(\exp\left(\frac{C_2}{\lambda \cdot T_{\text{b}}} \right) - 1 \right)} d\lambda}. \tag{8}$$

For monochromatic mode of the OES, the expression (8) takes this form:

$$q=\frac{\int_{\lambda_1}^{\lambda_2}\varepsilon_{\lambda_n}\frac{C_1\cdot\tau_\lambda\cdot S_\lambda}{\lambda^5\left(\exp\left(\frac{C_2}{\lambda\cdot T_{\mathrm{st}}}\right)-1\right)}d\lambda}{\int_{\lambda_1}^{\lambda_2}R_\lambda\cdot\varepsilon^*_{b_\lambda}\frac{C_1\cdot\tau_\lambda\cdot S_\lambda}{\lambda^5\left(\exp\left(\frac{C_2}{\lambda\cdot T_{\mathrm{b}}}\right)-1\right)}d\lambda}=\frac{\varepsilon_{\lambda_n}}{\varepsilon^*_{b_\lambda}\cdot R_\lambda}\cdot\frac{\exp\left(\frac{C_2}{\lambda\cdot T_{\mathrm{b}}}\right)-1}{\exp\left(\frac{C_2}{\lambda\cdot T_{\mathrm{st}}}\right)-1}. \quad (9)$$

Assuming that $R_\lambda=1-\varepsilon_{\lambda_n}$, the obtained expression for q can be written as follows:

$$q=\frac{\varepsilon_{\lambda_n}}{\varepsilon^*_{b_\lambda}\cdot\left(1-\varepsilon_{\lambda_n}\right)}\cdot\frac{\exp\left(\frac{C_2}{\lambda\cdot T_{\mathrm{b}}}\right)-1}{\exp\left(\frac{C_2}{\lambda\cdot T_{\mathrm{st}}}\right)-1}. \quad (10)$$

The calculation of the function $q=f(T_{\mathrm{st}})$ made by formula (10) at T_{b}=300 K is shown in Fig. 2.

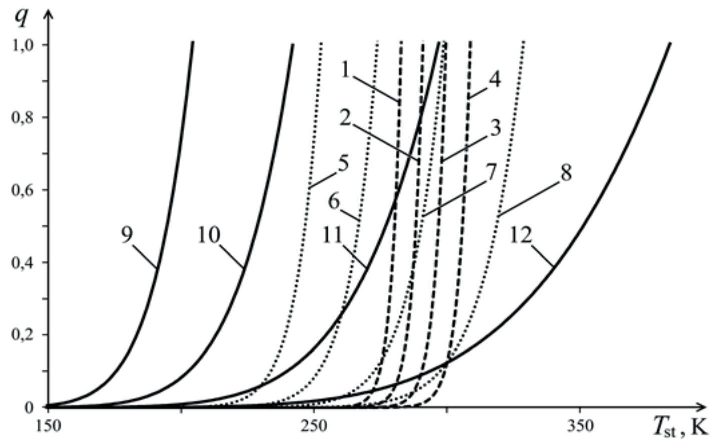

Fig. 2. The dependence of the ratio of the registered by the OES intrinsic radiation flux of the object and surrounding background radiation flux reflected by it on the temperature of the standard object T_{st}:

λ = 0.65 μm: 1 – ε_{λ_n} = 0.9 and $\varepsilon^*_{b_\lambda}$ = 0.1; 2 – ε_{λ_n} = 0.9 and $\varepsilon^*_{b_\lambda}$ = 0.9; ε_{λ_n} = 0.5 and $\varepsilon^*_{b_\lambda}$ = 0.1;

3 – ε_{λ_n} = 0.5 and $\varepsilon^*_{b_\lambda}$= 0.9; ε_{λ_n} = 0.1 and $\varepsilon^*_{b_\lambda}$= 0.1; 4 – ε_{λ_n} = 0.1 and $\varepsilon^*_{b_\lambda}$= 0.9

λ = 2.0 μm: 5 – ε_{λ_n} = 0.9 and $\varepsilon^*_{b_\lambda}$= 0.1; 6 – ε_{λ_n} = 0.9 and $\varepsilon^*_{b_\lambda}$ = 0.9 and ε_{λ_n} = 0.5 and $\varepsilon^*_{b_\lambda}$ = 0.1;

7 – ε_{λ_n} = 0.5 and $\varepsilon^*_{b_\lambda}$ = 0.9 and ε_{λ_n} = 0.1 and $\varepsilon^*_{b_\lambda}$ = 0.1; 8 – ε_{λ_n} = 0.1 and $\varepsilon^*_{b_\lambda}$ = 0.9

λ = 5.0 μm: 9 – ε_{λ_n} = 0.9 and $\varepsilon^*_{b_\lambda}$ = 0.1; 10 – ε_{λ_n} = 0.9 and $\varepsilon^*_{b_\lambda}$ = 0.9 and ε_{λ_n} = 0.5 and $\varepsilon^*_{b_\lambda}$= 0.1;

11 – ε_{λ_n} = 0.5 and $\varepsilon^*_{b_\lambda}$ = 0.9 and ε_{λ_n} = 0.1 and $\varepsilon^*_{b_\lambda}$ = 0.1; 12 – ε_{λ_n} = 0.1 and $\varepsilon^*_{b_\lambda}$ = 0.9.

At least two conclusions can be made from Fig. 2.

Conclusion One. The less the background radiation, the deeper cooling of the object is required. For example, at ε_{λ_n} = 0.9 and q = 0.05 for $\varepsilon^*_{b_\lambda}$ equaling 0.1 and 0.9, the object has to be cooled to temperatures of 169 K and 194 K, respectively. And at ε_{λ_n} = 0.1 and q = 0.05 for $\varepsilon^*_{b_\lambda}$ equaling 0.1 and 0.9, the object has to be cooled to temperatures of 227 K and 274 K, respectively.

Conclusion Two. The more radiation of the object, the greater the steepness of the curve $S = \frac{dq}{d_{\mathrm{T\ st}}}$ of the function $q=f(T_{st})$. For example, at ε_{λ_n} = 0.9 and $\varepsilon^*_{b_\lambda}$ equaling 0.1 and 0.9, the steepness of the curve S is 0.041 1/K and 0.029 1/K, respectively. And at ε_{λ_n} = 0.1 and $\varepsilon^*_{b_\lambda}$ equaling 0.9, the steepness of curve S is 0.020 1/K and 0.013 1/K, respectively.

Findings

A mathematical model of the method is proposed for determining the surface temperature of an object using a standard radiator and a standard object which has optico-physical properties identical with the monitored object. The proposed method differs from the known ones in that the nature of reflection and qualitative parameters of reflection from the monitored object do not depend on any limits or tolerances.

Applying the small perturbations method, a metrological analysis of the proposed method of determining the surface temperature for monochromatic optoelectronic systems has been made.

Optoelectronic instrument making has been rapidly developing as a knowledge-intensive manufacturing area [23–26]. And in order to choose a certain OES to be used for measuring the surface temperature of objects, a methodological and metrological analysis of the optico-physical properties of the monitored object, its surrounding background and the OES itself has to be made.

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