METHOD OF INCREASING ACCURACY OF INFRARED TEMPERATURE MEASUREMENT

МЕТОД ПІДВИЩЕННЯ ТОЧНОСТІ ВИМІРЮВАННЯ ТЕМПЕРАТУРИ ЗА ІНФРАЧЕРВОНИМ ВИПРОМІНЕННЯМ

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Abstract. Object temperature diagnostics by means of infrared temperature measurements as well as measurements of temperature gradients are considered. Values of the surface temperature carry information about the internal structure, defects and their location of measured object. This information becomes quite important for preventive measures and repairs of technical objects.

The world production of infrared thermometers and pyrometers, thermal imagers and infrared cameras is quite significant. These measuring devices are small-sized, with low power consumption at comparatively high performance and the possibility of real-time processing information. It contributes to expanding the radiation thermometers and infrared cameras application in industry. However, low accuracy of infrared temperature measurements can lead to inadequate decisions caused by inefficient analyze of thermograms. The lack of correct information about values of impact factors including an emissivity coefficient in industrial conditions becomes a decisive.

Therefore, enhancing the accuracy of temperature/temperature gradient measurements of object surface and developing of temperature measurement methodology in production cycles becomes more and more important.

Key words: Radiation thermometer, Emissivity, Background radiation, Infrared radiation, Measurement accuracy.

Анотація. Із метою технічного діагностування об'єктів проаналізовано результати вимірювання температури за інфрачервоним випромінюванням та визначено градієнт температури поверхні об'єкта дослідження. Обидва показники інформують про особливості зовнішньої та внутрішньої будови об'єктів, наявні дефекти та їх розташування. Як результат, така інформація є важливою під час планування та проведення профілактичних заходів, виконання ремонту чи організації подальших уточнювальних досліджень.

На світовому ринку багато компаній виробляє радіаційні термометри, тепловізори та інфрачервоні камери. Це зумовлено використанням доступних та високотехнологічних матричних детекторів випромінювання і мікропроцесорів, а також можливістю розроблення інтерактивного та доступного користувачеві програмного забезпечення. Власне тому ці вимірювальні прилади малогабаритні, характеризуються низьким енергоспоживанням із високою продуктивністю і можливістю опрацювання інформації у режимі реального часу. Це сприяє розширенню їх використання у промисловості.

Проте низька точність вимірювання температури за інфрачервоним випроміненням може призвести до хибного трактування термограм, формування помилкових висновків та прийняття неправильних рішень. Це пов'язано з відсутністю достовірної інформації про значення факторів впливу в реальних умовах функціонування об'єктів дослідження, а саме коефіцієнта випромінення поверхні досліджуваного об'єкта, пропускання проміжного середовища та фонового випромінення.

Саме тому важливим є підвищення точності вимірювання температури та градієнта температур у промисловості, зокрема, за допомогою розроблення методів вимірювання, які можна використовувати в реальних умовах.

Ключові слова: радіаційний термометр, випромінювальна здатність, фонове випромінювання, інфрачервоне випромінювання, точність вимірювань

Introduction

In industry, medicine and research, the application of infrared radiation thermometers and infrared cameras for temperature measurement and temperature gradient analysis is expanding. It allows also thermal monitoring, state diagnostics, and detection of defects. The advantages of using the infrared radiation thermometers and infrared cameras [1] are following:

- wide range of measuring temperatures – 50÷2500 °C;
- short duration of measurements – ~10^{-6} s;
- ability of moving objects measurements including the measurements in aggressive environment and under high electrical potential.

However, the problem of radiation temperature measurement seems to be insufficient accuracy.

Purpose of the article

The aim of the current work is to improve the accuracy of infrared temperature measuring means while operation by studying their peculiarities.

1. Radiation temperature measurements. Analysis of accuracy problem

1.1. Difference of radiation temperature measurement process in different measurement conditions

According to the Planck's law the output signal of the radiation thermometer in ideal operating conditions $S_{id}(l,T_{bb})$ is presented by equation [2–5]:

$$S_{id}(l,T_{bb}) = \int_{l_1}^{l_2} \left(R(l) \cdot C_1 l^{-5} (e^{\frac{C_2}{l T_{bb}}} - 1)^{-1} \right) dl \,, \quad (1)$$

where $l_1 - l_2$ is the spectral band of optical system of infrared thermometer; $R(l)$ is the spectral sensitivity; T_{bb} is the temperature of black body object; C_1 and C_2 are the constants.

However, in conditions of calibrating and measuring processes such factors influence on results obtained with help of radiation thermometer and infrared camera [6] as:

- the lack of reliable information about the surface emissivity factor;
- the effect of background radiation;
- the impact of intermediate environment.

The output signal of the radiation detector in calibration condition $S_c(l,T_{bbc})$ is presented by:

$$S_c(l,T_{bbc}) = \int_{l_1}^{l_2} R(l) \cdot t(l,T_{amb}) \left[e(l,T_{bbc}) \cdot C_1 l^{-5} (e^{\frac{C_2}{l T_{bbc}}} - 1)^{-1} + (1 - e(l,T_{bbc}) \cdot C_1 l^{-5} (e^{\frac{C_2}{l T_{bg}}} - 1)^{-1} \right] dl \approx$$
$$\approx \int_{l_1}^{l_2} R(l) \cdot t(l,T_{amb}) e(l,T_{bbc}) \cdot C_1 l^{-5} (e^{\frac{C_2}{l T_{bbc}}} - 1)^{-1} dl \,, \quad (2)$$

where $t(l,T_{amb})$ is the transmission factor of intermediate environment in real conditions; $e(l,T_{bbc})$ is the real emissivity factor of the reference black body cavity; T_{bg} is the temperature of background radiation in operation conditions.

The output signal of the radiation detector in this condition $S_{rc}(l,T_{ob})$ looks like:

$$S_{rc}(l,T_{ob}) = \int_{l_1}^{l_2} R(l) \cdot t(l,T_{amb}) \left[e(l,T_{ob}) \cdot C_1 l^{-5} (e^{\frac{C_2}{l T_{ob}}} - 1)^{-1} + (1 - e(l,T_{ob}) \cdot C_1 l^{-5} (e^{\frac{C_2}{l T_{bg}}} - 1)^{-1} \right] dl \,, \quad (3)$$

where $e(l,T_{ob})$ is the emissivity of the object's surface. Really, the temperature T_{ob}, the emissivity factor $e(l,T_{ob})$ of object's surface and the transmission factor of intermediate environment $t(l,T_{amb})$ are unknown. Values of different impact factors of radiation temperature measurements, presented in Table 1, concerned the probable operation conditions.

Table 1

Values of different influent factors of radiation temperature measurements

Radiation temperature measurement condition	Object's emissivity factor $e(l,T)$	Temperature of background radiation T_{bg}, °C	Transmission coefficient of intermediate environment $t(l,T_{amb})$
Ideal condition of radiation temperature measurement	Blackbody surface $e(l,T_{bb})$ =1.00	0	1.00
Condition of radiation thermometer calibration	Blackbody cavity surface $e(l,T_{bbc})$ 0.99	20 ± 2 °C	1.00
Real condition of radiation temperature measurement	Real object's surface $e(l,T_{ob})$ $0.3 < \varepsilon < 1$	0 °C < T_{bg} < 5000 °C	$0.8 < \tau < 1$

Difference between ideal output signals in calibration and real measurement conditions causes the significant errors of measurement results. This fact restricts the widespread use of the radiation thermometers in practical temperature measurements in industry, scientific research and medicine.

1.2. The simulation results of output signals depending of values of the influence factors

The simulation results of temperature dependence of output signal (for radiation detector of radiation thermometer or infrared camera) depending of deference values of the influence factors (emissivity factor ε, temperature of background radiation T_{bg} and transmission coefficient of intermediate environment τ) are presented in Fig. 1. It demonstrates that due to the influence factors, the value of the signal deviates from the ideal.

There fore, under the influence of emissivity factor ε, temperature of background radiation T_{bg} and transmission coefficient of intermediate environment τ the measured temperature differs from the true value. The temperature error somewhere is at least tens of percent.

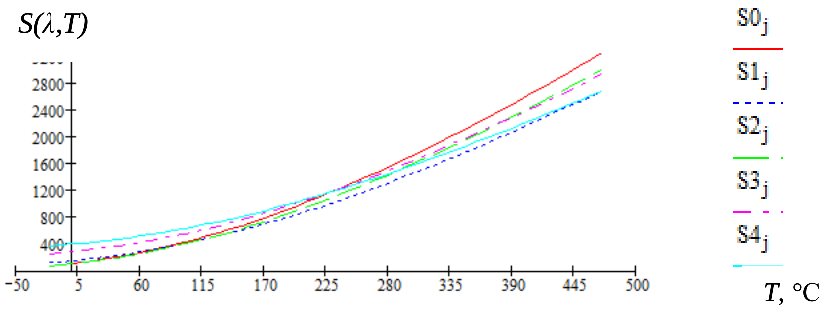


Figure 1. Temperature dependency graphs of the detector's output signal for different conditions:
$S0_j$: ε=1.00, τ=1.00, T_{bg}=0 °C;
$S1_j$: ε=0.85, τ=0.95, T_{bg}=100 °C;
$S2_j$: ε=0.95, τ=0.97, T_{bg}=0 °C;
$S3_j$: ε=0.85, τ=0.99, T_{bg}=250 °C;
$S4_j$: ε=0.75, τ=0.97, T_{bg}=250 °C.

1.3. The uncertainty component of type B of radiation temperature measurement method

The influence of uncertainty parameters of type B of radiation thermometry is examined in [7–9]: the instrument uncertainty components (the noise of detector; the spectral sensitivity changes in optical receiving system and non-linearity of conversion; the influence of external temperature; changes in spatial and temperature sensitivity) and the uncertainty components of measurement method.

The main uncertainty components of type B, caused by the peculiarities of the infrared radiation measurement method, are described by the equation [7], [10]:

$$u_{B(method)}(S(l,T))=\sqrt{C_e^2u^2(e(l,T_{ob}))+C_t^2u^2(t(l,T_{amb}))+C_{T_{bg}}^2u^2(l,T_{bg})}, \quad (4)$$

where C_e is the sensitivity coefficient of the influence of the object's surface emissivity; C_t is the sensitivity coefficient of the influence of the intermediate environment transmission; $C_{T_{bg}}$ is the sensitivity coefficient of the influence of the background radiation; $u(e(l,T_{ob}))$ is the uncertainty component of infrared radiation temperature measurement of the influence of the emissivity; $u(t(l,T_{amb}))$ is the uncertainty component of infrared radiation temperature measurement of the influence of intermediate environment; $u(l,T_{bg})$ is the uncertainty component of radiation temperature measurement of the influence of background radiation.

We have investigated the uncertainty of the infrared radiation temperature measurements in operating conditions. The modelling of uncertainty of non-contact temperature measurement method demonstrates that in the range 50–500 °C the uncertainty can reach tens and hundreds of degrees. Fig. 2 presents separate results of the simulation of radiation measurement uncertainty. It makes possible to give the quantitative assessment of the accuracy, to compare the results and to evaluate the influence of various factors on the obtained results.

The multiband measurement methods [11–15] and testing methods [16] enable to process the spectral information on the influential factors and to determine them. The application of multiband measurement methods allows the increasing the accuracy of infrared radiation temperature measurement. Unfortunately, these methods make it possible to determine only the value of emissivity, but ignore the information about the influence of background radiation and the intermediate environment on the temperature measurement results [17, 18].

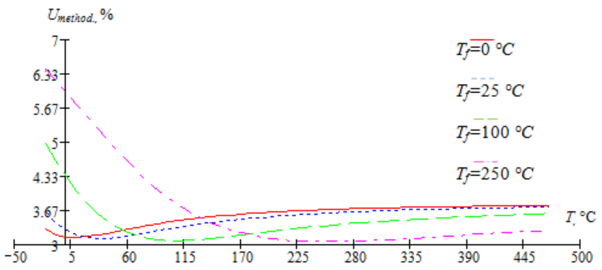


Figure 2a. Graph of relative uncertainty dependence on the influence of background radiation at ε=0.75 and τ=0.95

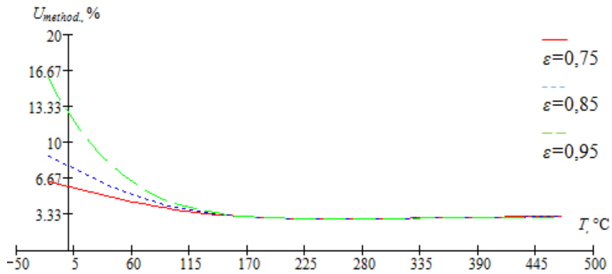


Figure 2b. Graph of relative uncertainty dependence on the influence of the radiation coefficient at T_{bg} =250 °C and τ=0.99

Thus, for increasing the accuracy of radiation temperature measurements explorer has to know full information about impact factors. While operating the values of these factors are unknown. As a result, a new approach is needed.

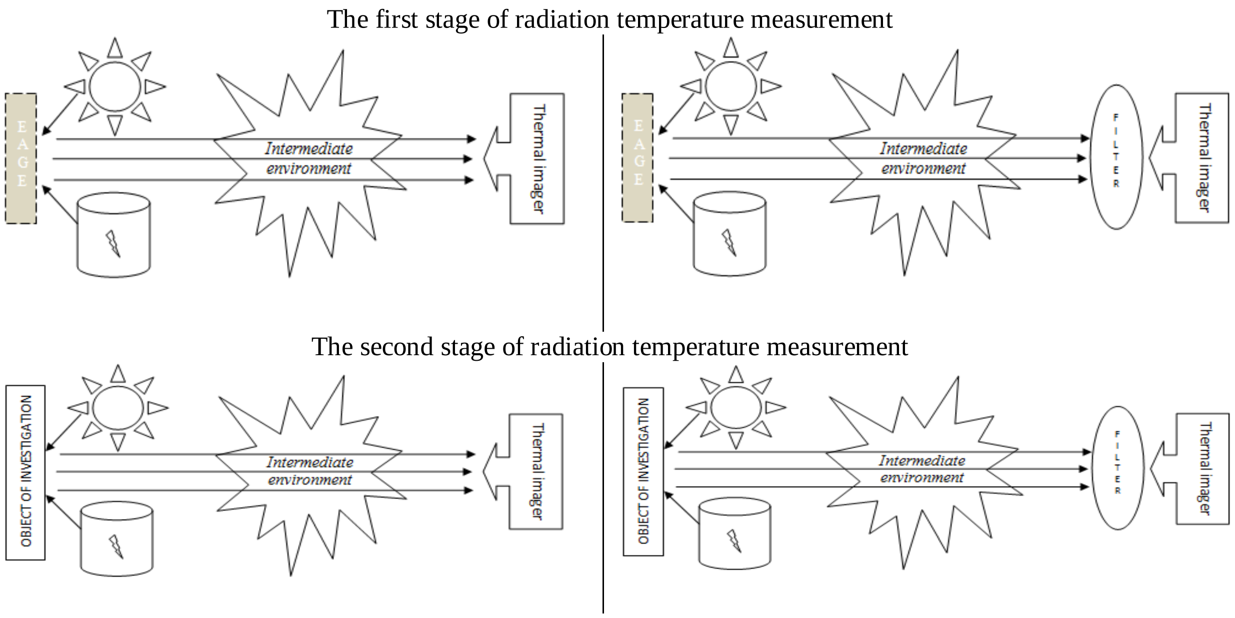


Figure 3. Scheme for implementing the method of increasing the infrared radiation temperature measurement accuracy

2. Method of increasing of IR temperature measurement accuracy in operating conditions

We propose the method of temperature measurement in two spectral bands. It is implemented with using the temperature information-measuring system, which consists of radiation thermometers, a system of external filters, a computer and a reference grey body.

2.1. Scheme for implementing the method (Fig. 3)

2.2. Sequence of implementation of the method

The researched method the method is two-step.

1. First, we determine the transmission coefficient of intermediate environment and the temperature of background radiation. Two color (or two spectral bands) radiation thermometer measures the temperature T_{rgb} of the reference grey body with emissivity factor e_{rgb}. The values of transmission coefficient t and background radiation temperature are calculated by the values of the output signals of the radiation detector in the mentioned

bands. The system of output signals equations in both spectral bands $S_{p,q}^{11}(l)$ and $S_{p,q}^{21}(l)$ looks like (5). When the system of equations is solved, we obtain the values of the influential factors that characterize the research conditions. Then, we carry out the calculation and enter into the radiation thermometer the data on transmission coefficients and temperature of background.

$$\begin{cases} S_{p,q}^{11}(l) = t\ \ (e_{rgb}\int\limits_{l_{11}}^{l_{21}} C_1 l^{-5}(e^{\frac{C_2}{lT_{rgb}}}-1)^{-1}dl + (1-e_{rgb})\int\limits_{l_{11}}^{l_{21}} C_1 l^{-5}(e^{\frac{C_2}{lT_{dg}}}-1)^{-1}dl) \\ S_{p,q}^{21}(l) = t\ \ (e_{rgb}\int\limits_{l_{12}}^{l_{22}} C_1 l^{-5}(e^{\frac{C_2}{lT_{rgb}}}-1)^{-1}dl + (1-e_{rgb})\int\limits_{l_{12}}^{l_{22}} C_1 l^{-5}(e^{\frac{C_2}{lT_{bg}}}-1)^{-1}dl) \end{cases}. \quad (5)$$

Implementation of the first stage of the method involves the following actions:

- formation of a measuring system: a reference grey body, a filter installation with two spectral bands $\lambda_{11}\div\lambda_{21}$ and $\lambda_{12}\div\lambda_{22}$; a radiation thermometer or infrared camera, a computer;
- heating the reference grey body to a temperature T_{rgb};
- process of measuring the surface temperature of the reference grey body in two spectral bands $\lambda_{11}\div\lambda_{21}$ and $\lambda_{12}\div\lambda_{22}$;
- registration of output signals of the radiation thermometer in two spectral bands $S_{p,q}^{11}(l)$ and $S_{p,q}^{21}(l)$;
- formation of equations (5);
- solving the equations (5) and determining the transmission coefficient of intermediate environment t and the temperature T_{rgb}. of background radiation while measuring.

2. Second, we determine the values of the emissivity coefficient e_{ob} and the object's surface temperature T_{ob} for two color radiation thermometer that measures the surface temperature of the object. The values of the emissivity coefficient and surface temperature are calculated by the output signals of the radiation detector in two spectral bands. As a result, we obtain the system of two equations of output signals for both spectral bands $S_{p,q}^{12}(l)$ and $S_{p,q}^{22}(l)$:

$$\begin{cases} S_{p,q}^{12}(l) = t\ \ (e_{p,q}\int\limits_{l_{11}}^{l_{21}} C_1 l^{-5}(e^{\frac{C_2}{lT_{p,q}}}-1)^{-1}dl + (1-e_{p,q})\int\limits_{l_{11}}^{l_{21}} C_1 l^{-5}(e^{\frac{C_2}{lT_f}}-1)^{-1}dl) \\ S_{p,q}^{22}(l) = t\ \ (e_{p,q}\int\limits_{l_{12}}^{l_{22}} C_1 l^{-5}(e^{\frac{C_2}{lT_{p,q}}}-1)^{-1}dl + (1-e_{p,q})\int\limits_{l_{12}}^{l_{22}} C_1 l^{-5}(e^{\frac{C_2}{lT_f}}-1)^{-1}dl) \end{cases}. \quad (6)$$

Implementation of the second stage involves the following actions:

- process of measuring the surface temperature of the object in two spectral bands $\lambda_{11}\div\lambda_{21}$ and $\lambda_{12}\div\lambda_{22}$;
- registration of output signals of the radiation thermometer in two spectral bands $S_{p,q}^{12}(l)$ and $S_{p,q}^{22}(l)$;
- formation of a system (6);
- solving this system (6) and determining the values of the emissivity coefficient e_{ob} and of object's surface temperature T_{ob}.

While solving the appropriate system (6), we obtain the value of the emissivity e_{ob} and temperature T_{ob} in operating conditions. The solution of these equations systems is carried out by a microprocessor, which controls the operation of the measuring system. To determine the true temperature value T_{ob}, the microprocessor automatically enters the values of the influential factors t , T_{bg}, e_{ob}. Herewith, it is important to use a linear or linearized calibration function IR detector of radiation thermometer [18].

When this method is applied to IR camera, the true values of the object's surface point temperatures can be calculated. As a result, it provides the possibility to receive a thermogram with the temperatures distribution of the object's surface temperature field. It enables not only to carry out a qualitative analysis of thermo grams, and also a quantitative analysis of the object's surface thermal field.

The results of simulation confirming the possibility of the studied method are presented below (Table 2). We can see that the algorithm of the proposed method gives the possibility of obtaining values that are in line with the actual values of the temperature.

Table 2

Results of simulation of the method of increasing accuracy of IR temperature measurement

Temperature values, °C	Values of influencing factors			Calculated temperature values, °C	Absolute deviation, °C	Relative deviation (for K)
	ε	τ	T_{bg}, °C			
–20	0.80	0.90	21	–15.3999	4.6001	1.8171
10	0.95	0.93	250	28.8647	18.8647	6.6625
30	0.99	0.95	–10	26.2828	–3.7172	–1.2262
100	0.75	0.97	0	78.1421	–21.8579	–5.8577
250	0.90	0.99	100	235.9553	–14.0447	–2.6846
470	0.85	1.00	50	423.5431	–46.4569	–6.2514
–20	0.75	0.90	250	80.5711	100.5711	39.7279

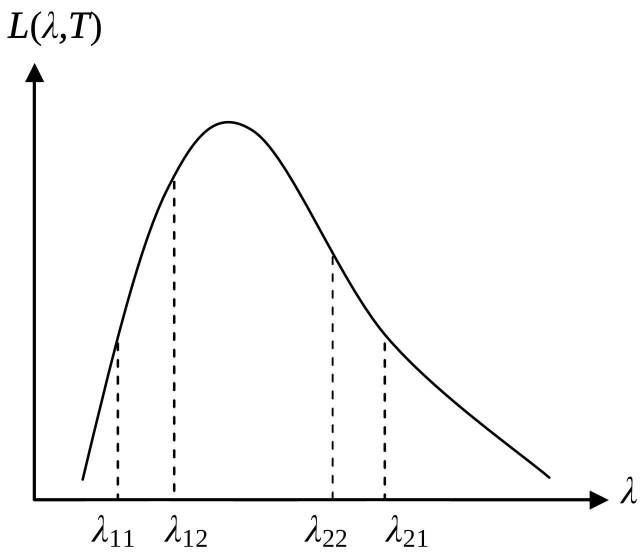


Figure 4. Working spectral bands based on the "band in band" principle on the example of the radiation intensity according to Planck's law

The studied method of can increase the accuracy of contactless temperature measurements by one order in comparison to the existing measurement methods indicated by the manufacturers.

2.3. Spectral channels formation principles

To implement the measurements in two spectral bands, it is necessary to select them. We propose to choose these bands basing on the "band in band" principle. The meaning of this approach is graphically depicted in Fig. 4.

It can be achieved in the following ways by using:

- the thermal imagers operating in several spectral bands or by conducting the measurements using two thermal imagers (for example, IRE Cooled IR Cameras – IRE-320M and IRE-640M / BB) that operate in different spectral bands;
- an additional bandpass filter to reduce the width of the working spectral band of the thermal imager optical system (for example, if the spectral band of the radiation thermometer is 8÷14 µm, the bandpass filter can be used to narrow it to 8÷10 µm).

During the calculation of the output signals of the radiation receivers in the range of 8÷14 µm and 8÷10 µm, the difference between the values of the signals is sufficient and increasing with the temperature of investigated object's surface (for the ideal value of the output signal of the thermal imager according to Planck's law). The results of calculations are presented in Fig. 5.

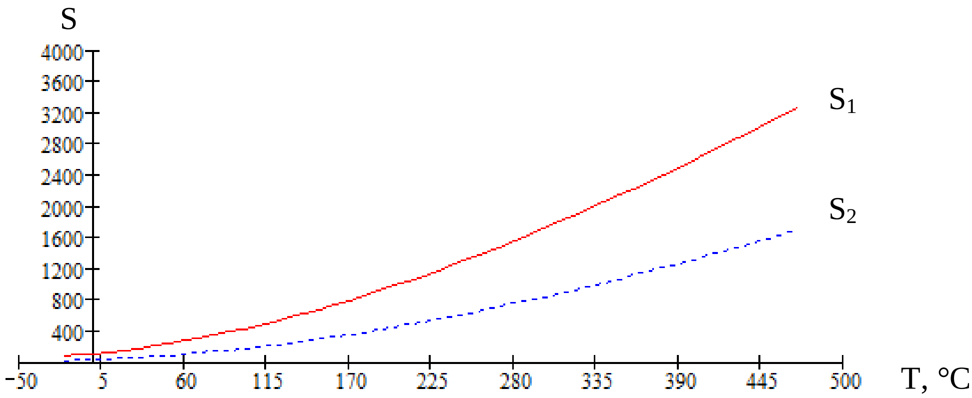


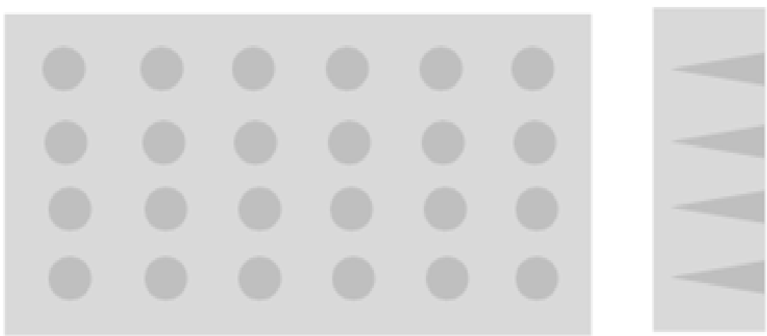
Figure 5. Graphs of the output signal values S_1 and S_2 of the thermal imager radiation receiver according to Planck's formula for spectral bands 8÷14 μm and 8÷10 μm

So, performing of measurements based on the "band in band" principle that means simultaneous observation of the object in different spectral bands, gives more information about object.

2.4. Reference grey body

For the realization of this method, we developed the design of reference grey emitter [19]. It has the following characteristics: plane design; the properties of surface emissivity $\varepsilon(\Delta\lambda,\Delta T)<1$, $\varepsilon(\Delta\lambda,\Delta T)$=const, $\varepsilon(t)$=const; and homogeneity of surface temperature. It is possible to correct the surface emissivity of the extended area grey emitter by the following methods: oxidation of the metal surface or deposition of coatings with different emissivity, mechanical surface treatment, and selection of geometry of the surface. For example, the formation of a surface can be implemented by creating the cone-shaped cavities on the plane of the extended area grey emitter or by 3D printing of such surface (Fig. 6).

Achieving a stable surface structure provides the minimum drift of emissivity values at a wide its range.



a *b*

Figure 6. The surface of an extended area grey emitter with drilled cones: a – the top view; b – the side view

The expediency of using such shape is due to the cone property to provide multiple reflections of radiation that enters in its cavity. It helps to sustain the high emissivity coefficient by reducing the reflection coefficient of the area of grey emitter surface.

The considered emissivity coefficients of the grey emitter surface with cones can be altered due to the choice of different materials for this surface, changes in the number of drilled conical cavities, in the radius and depth of cones.

Conclusions

The considered method can be used for IR temperature measurement under the operating conditions. It provides the correction of the emissivity and the transmission coefficient as well as the background radiation temperature can be inputted into the output signal of radiation receiver. The application of this method for infrared cameras provides the possibility to obtain a thermogram with the real temperature distribution of the thermal field of investigated object's surface and to conduct a quantitative analysis of the results of thermal imaging research at increasing the accuracy of IR temperature measurements. The formation of spectral bands based on the principle of "band in band" allows using only one additional filter for the implementation of two-band filtration in this method. The development of method in thermal imagers and IR cameras supplemented by output signals of the object and reference grey body in two spectral bands processing gives the possibility to introduce the temperature corrections to each point of the temperature field, obtaining the real values of the temperatures. This achieves the transition from qualitative to quantitative measurements with definite accuracy.

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Conflict of interest

The conflict of interest during the writing, preparation and publication of the article is absent, as well as the mutual claims of co-authors.

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