

Simulation of the influence of multiple reflections of background radiation on the thermography results

Abstract: The paper investigates the effect of background radiation on the accuracy of temperature measurement by infrared radiation and defines the requirements to neglect multiple reflections of radiation. The theoretical analysis is confirmed by the results of modeling the temperature measurement radiation errors.

Streszczenie: W artykule przeprowadzono analizę wpływu promieniowania tła na dokładność pomiaru temperatury promieniowaniem podczerwonym. Zdefiniowano wymagania dotyczące możliwości pominięcia wielokrotnych odbić promieniowania. Analizę teoretyczną potwierdzono wynikami modelowania błędów radiacyjnych pomiaru temperatury. (Symulacja wpływu wielokrotnych odbić promieniowania tła na wyniki pomiarów termowizyjnych)

Keywords: intensity of radiation, background radiation, multiple reflections of radiation, radiation temperature measurement

Słowa kluczowe: intensywność promieniowania, promieniowanie tła, wielokrotne odbicia promieniowania, pomiar temperatury promieniowania.

Introduction

According to the theoretical principles of infrared thermometry [1, 2], the Planck's law determines the temperature dependence of the spectral intensity of surface radiation:

$$(1) L(\lambda, T) = \int_{\lambda_1}^{\lambda_2} C_1 \cdot \lambda^{-5} \cdot \left(e^{\frac{c_2}{\lambda \cdot T}} - 1 \right)^{-1} d\lambda,$$

Where: $C_1=3.7417749 \cdot 10^{-16} \text{ Wt}\cdot\text{m}^2$, $C_2=0.01438769 \text{ mK}$, $\lambda_1 - \lambda_2$ – wavelength range.

But in real conditions of experiment, three factors affect a radiation temperature measurement process and cause the methodological error in measurement results [3,4,5,6]:

- the dependence of the radiation intensity from the surface of the object on the value of the emissivity coefficient;
- the influence of reflected background radiation on the radiation intensity from the object surface ;
- the influence on the radiation intensity from the object the property of intermediate environment, in particular the near-Earth atmosphere with impurities present as particles of industrial dust and precipitation.

In this article, we analyze in detail the effects of infrared radiation from surrounding objects in the object-background system.

For monochromatic radiation, the interdependence between the radiation coefficient, the reflection coefficient and the transmission coefficient is defined as $\rho + \varepsilon + \tau = 1$.

For real objects, the relation between the radiative and reflective properties of the surface is described by Kirchhoff's law [1,2]:

$$(2) \rho = 1 - \varepsilon.$$

The transmission rate of opaque objects is zero. This means that the background radiation acts only on the object surface of a few microns thick, without distorting the internal temperature.

Therefore, the intensity of radiation from the surface of the object and the effective intensity of radiation differ.

As a result, the methodological error of non-contact measurement of temperature by radiation occurs. It is caused by the influence of the background radiation

reflected from the surface of the object by surrounding objects.

Sources of background radiation include:

- reflected radiation from other parts of the object,
- radiation of foreign objects in the object-background system;
- environmental radiation.

It is especially necessary to note the influence of the reflected radiation of the Sun as an absolutely black body with a temperature of about 6000 K with a maximum of radiation at a wavelength of 0.8 μm [1,2].

It should also be emphasized that the radiative properties of the objects of background are also subjects to Kirchhoff's law (1).

This causes multiple reflections of radiation in the object-background. This methodological error component is the result of the influence of the multiply reflected background radiation on the object surface [7,8,9]:

$$(3) L_{ef} = L_{ob} + L_{bg} = L_{ob} + L_{mbg} + L_{mob} + L_a,$$

where: L_{ob} - radiation intensity of the object surface; L_{bg} - radiation intensity of the background objects; L_{mbg} - radiation intensity of the background objects multiply reflected in the object-background system; L_{mob} - radiation intensity of the object multiply reflected in the object-background system; L_a - radiation intensity of the atmosphere.

Aim of the research.

The aim of the article is to create a mathematical model and study the effect of multiple reflections of background radiation on the results of radiation temperature measurements.

Main material of the research.

This part investigates the influence of multiple reflections of radiation on the measurement results as illustrated by monochromatic radiation.

The intensity of radiation from the object surface (neglecting the influence of background radiation) is determined by the formula:

$$(4) \quad L = \varepsilon \cdot L_{ob},$$

where: L — the radiation intensity of the black body with temperature T .

The radiation intensity from the object with only a single reflection of the background radiation is defined as [62]:

$$(5) \quad L_{1B} = \varepsilon \cdot L_{ob} + (1 - \varepsilon) \cdot \varepsilon_{bg} \cdot L_{bg},$$

where: ε_{bg} — the emissivity of background objects; L_{bg} — the intensity of the radiation of the background object with temperature T_{bg} ;

The radiation intensity from the object with double reflection of background radiation is defined as:

$$(6) \quad L_{2B} = \varepsilon \cdot L_{ob} + (1 - \varepsilon) \cdot \varepsilon_{bg} \cdot L_{bg} + (1 - \varepsilon) \cdot (1 - \varepsilon_{bg}) \cdot (1 - \varepsilon) \cdot \varepsilon_{bg} \cdot L_{bg}.$$

Therefore, the effective radiation intensity with multi-reflection determined by the formula:

$$(7) \quad L_{ef} = \varepsilon \cdot L_{ob} + \varepsilon_{bg} \cdot L_{bg} \cdot (1 - \varepsilon) \cdot \left(1 + \sum_{n=1}^{\infty} (1 - \varepsilon_{bg})^n (1 - \varepsilon)^n\right),$$

where: n — the number of multi-reflection of radiation.

The formula $1 + \sum_{n=1}^{\infty} (1 - \varepsilon_{bg})^n (1 - \varepsilon)^n$ is an infinite geometric progression of type $1 + m + m^2 + m^3 + \dots$ where: $m < 1$.

The sum of this progression is determined as:

$$(8) \quad \lim_{n \rightarrow \infty} \sum_{m=0}^{\infty} m^n = \frac{1}{1 - m}, \text{ где } m = (1 - \varepsilon_{bg})(1 - \varepsilon).$$

In this case:

$$(9) \quad \lim_{n \rightarrow \infty} \left(1 + \sum_{n=1}^{\infty} (1 - \varepsilon_{bg})^n (1 - \varepsilon)^n\right) = \frac{1}{1 - (1 - \varepsilon_{bg})(1 - \varepsilon)}.$$

Taking into account the reflected background radiation, we propose the following concepts:

1. The coefficient of multiple reflection of radiation in the object - background system:

$$(10) \quad k_{ob-bg} = \frac{1}{1 - (1 - \varepsilon_{bg})(1 - \varepsilon)}.$$

The coefficient k_{ob-bg} shows the effect of multiple reflections on the effective radiation in the object-background system. If there are no multiple reflections of radiation, the coefficient of multiple reflections is equal to $k_{ob-bg} = 1$.

2. The effective coefficient of background radiation in the system object - background:

$$(11) \quad \varepsilon_{ef-bg} = \varepsilon_{bg} \cdot \frac{1}{1 - (1 - \varepsilon_{bg})(1 - \varepsilon)} = \varepsilon_{bg} \cdot k_{ob-bg}.$$

The coefficient ε_{ef-bg} shows the value of background radiation in the object - background system.

The effective radiation intensity of the object:

$$(12) \quad L_{ef} = \varepsilon \cdot L_T + (1 - \varepsilon) \cdot L_{bg} \cdot \varepsilon_{ef-bg}.$$

The condition of neglecting the influence of multiple reflections of background radiation. Based on the dependences (2 and 3), the condition for neglecting multiple reflections for the object-background system is as follows:

$$(13) \quad \lim \frac{1}{1 - (1 - \varepsilon_{bg})(1 - \varepsilon)} \rightarrow 1.$$

According to the previous formulas, we can conclude that reflection can be neglected if the following requirement is satisfied:

$$(14) \quad (1 - \varepsilon) \cdot (1 - \varepsilon_{bg}) \ll 1.$$

The requirement for neglecting the influence of multiple reflections of background radiation.

Based on the dependence (10), the general requirement for neglecting the influence of second reflections ($n=2$) of background radiation in the object-background system is defined by such a formula [10]:

$$(15) \quad \lim k_{ob-bg} \rightarrow 1$$

Namely:

$$(16) \quad \lim \frac{1}{1 - (1 - \varepsilon_{bg})_{(n=2)}(1 - \varepsilon)} \rightarrow 1.$$

From the formula (16), we can conclude that neglecting the second reflection is possible given the equation:

$$(17) \quad (1 - \varepsilon) \cdot (1 - \varepsilon_{bg})_{(n=2)} \ll 1.$$

The requirement for neglecting the influence of multiple reflections of background radiation can be met in the following cases:

1) The reflection coefficients of the object and the background are close to zero, which is possible when their radiation properties are close to the properties of the black body:

$$(18) \quad (1 - \varepsilon) \ll 1 \text{ and } (1 - \varepsilon_{bg}) \ll 1.$$

2) The reflection coefficient of the object is much smaller than the reflection coefficient of the background objects, which is possible when the surface properties of the object are close to the properties of the black body:

$$(19) \quad (1 - \varepsilon) \ll (1 - \varepsilon_{bg}).$$

In this case, the background radiation reflected from the object can be neglected.

3) The reflection coefficient of the background is much smaller than the reflection coefficient of the object.

$$(20) \quad (1 - \varepsilon_{bg}) \ll (1 - \varepsilon).$$

Since the emissivity of real objects is in the range from 0.3 to 0.95, the validity of this ratio requires: the radiation properties of the background should be approached as the radiation properties of the black body, which is possible in the following cases:

- temperature radiation measurements take place in an open space where the background is the cloudy sky with a known temperature;
- the source of background radiation is at a great distance from the area of the object.

Simulation.

Mathematical models of the influence of background radiation on the results of radiation temperature measurements were performed for the following ranges:

- object temperature - from 0°C to 500°C;
- background temperature - 20°C, 200°C, 350°C;
- radiation coefficient – 0.6; 0.7; 0.8; 0.9 1.
- background radiation coefficient – 0.6; 0.7; 0.8; 0.9.

For comparison the radiation intensities of an ideal object (with properties of the black body and the emissivity $\varepsilon = 1$) and a real object, the simulation was conducted.

Using Mathcad Professional, the temperature dependences of the effective radiation intensity at different values of the background temperature and the emissivity are calculated by the formula 21 and presented in Fig. 1.

$$\begin{aligned}
 L_{e\phi}(T, \varepsilon, T_{bg}) &= \varepsilon \cdot b_{ob} + (1 - \varepsilon) \cdot b_{bg} \cdot \varepsilon_{ef-bg} = \\
 (21) \quad &= \varepsilon \cdot \int_{\lambda_1}^{\lambda_2} C_1 \cdot n^{-2} \cdot \lambda^{-5} \cdot \left(e^{\frac{c_2}{n\lambda T}} - 1 \right)^{-1} d\lambda + \\
 &+ \varepsilon_{ef-bg} \cdot (1 - \varepsilon) \cdot \int_{\lambda_1}^{\lambda_2} C_1 \cdot n^{-2} \cdot \lambda^{-5} \cdot \left(e^{\frac{c_2}{n\lambda T_{bg}}} - 1 \right)^{-1} d\lambda
 \end{aligned}$$

Figure 2 shows the temperature dependences of the effective radiation flux at different values of the background radiation temperature. Figure 1 shows the character of the changes of radiation intensity depending on the background radiation compared with the graph of the black body with $\varepsilon = 1$. When the background temperature approaches the temperature of the black body, the graphs intersect.

The following conclusions can be drawn from the compared dependencies in the figure:

- the more the effect of reflected background radiation enhances the effective radiation intensity from the object, the higher the background temperature;
- if the background temperature approaches the temperature of the object, the value of the effective radiation intensity increases and the radiative properties of the object are close to the properties of the black body.

Therefore, if the background temperature approaches the temperature of the object, the value of the methodological error decreases and in some cases may approach zero.

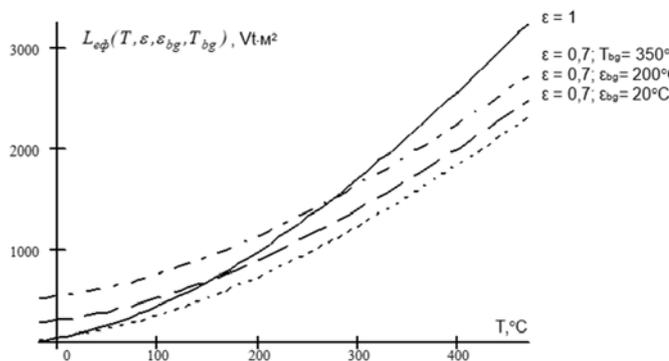


Fig.1. Influence of background radiation on the effective radiation intensity from the surface of the object

The neglect of the reflected background radiation on the effective radiation intensity will lead to errors of temperature measurement. The temperature dependences of errors of

radiation temperature measurement at various values of temperature of the background are calculated and presented in Fig. 2.

The errors from neglecting the multiple reflection of the background radiation are calculated and presented in Fig. 3.

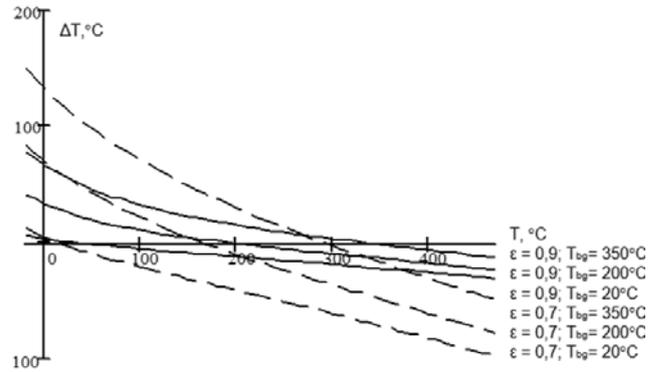


Fig.2. Temperature dependences of the error in measuring the radiation temperature, as a result of disregarding the reflected background radiation.

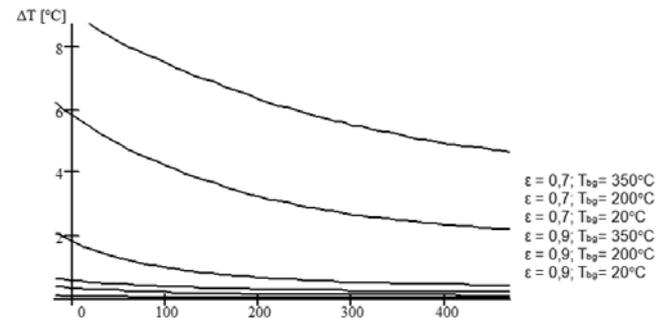


Fig. 3. The errors from neglecting the multiple nature of the reflection of the background radiation

Conclusions.

Ignoring the second and larger number of reflections is possible if the reflected intensity of the background radiation is much less than the intensity of radiation from the object. In this case, we can assume that the most significant contribution to the measurement results is made by the actual radiation of the object and the radiation of surrounding objects only once reflected from the target area.

If one of the conditions (formulas 16-20) is fulfilled, the formula (7) will be simplified as in (5), which means that only a single reflection of the background radiation in the object-background system will be taken into account.

Thus, ignoring multiple reflections requires the condition that at least one of the objects in the background-object system has a value of emissivity close to 1.

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