ПРО ПОХИБКУ БЕЗКОНТАКТНОГО ВИМІРЮВАННЯ ТЕМПЕРАТУРИ, ЗУМОВЛЕНУ НЕВІДОМИМ ЗНАЧЕННЯМ КОЕФІЦІЄНТА ЧОРНОТИ

ON ACCURACY OF CONTACTLESS TEMPERATURE MEASUREMENT LIMITED BY UNKNOWN EMISSIVITY FACTOR

Яцишин С. П., д-р техн. наук, проф., Гамула П. Р., канд. техн. наук, доц., Мідик А. В., аспірант,
Національний університет «Львівська політехніка», Україна

Svyatoslav Yatsyshyn, Dr. S., Prof., Pavlo Hamula, PhD, As.-Prof., Andriy Midyk, PhD Student
Lviv Polytechnic National University, Ukraine; e-mail: slav.yat@gmail.com

Chunzhi Wang, Dr. Sc., Prof.
Hubei University of Technology, Wuhan, China

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Анотація. У роботі вивчаються методи безконтактного вимірювання температури, точність яких обмежується багатьма чинниками, головним з яких вважають коефіцієнт чорноти контрольованої поверхні об’єкта. Саме незнання цього фактора визначає методичну складову похибки вимірювання. Вона притаманна не лише пірометричним засобам, але й тепловізійним, які саме тому належать до якісних засобів вимірювання температури. Вони є основними приладами для проведення енергетичного аудиту будівель та споруд, стандартизації та сертифікації теплотехнічних матеріалів. Завдяки дослідженню розробляється метод визначення коефіцієнта випромінювальної здатності матеріалу, що уможливлює високоточне вимірювання теплових потоків. А це, своєю чергою, дає змогу характеризувати з високою достовірністю теплоізоляційні, будівельні матеріали і створити підстави для встановлення придатності будівельних конструкцій та споруд на відповідність державним і міжнародним стандартам. Крім того, завдяки виконаній роботі можна змінити конструкцію технічних пірометрів, а саме пірометрів випромінювання, у сфері високоточних вимірювань температури у промислових та лабораторних умовах, оскільки визначення коефіцієнта випромінювальної здатності сприяє точному вимірюванню теплових потоків.

Результату досягають за рахунок визначення згаданого коефіцієнта речовини за допомогою повторних вимірювань тієї самої поверхні тіла з цільовою зміною температури чутливого елемента засобу вимірювання, використовуючи незалежне джерело тепла. Це дає змогу підвищити точність вимірювань теплового потоку, випромінюваного будь-яким тілом.

Ключові слова: вимірювання температури, коефіцієнт чорноти випромінюваної поверхні, точність вимірювання, пірометр, тепловізор.

Abstract. The major error of temperature measurements of different objects is due to uncertainty of their emissivity factor value. And vice versa, for correct determination of a true temperature, using conventional temperature means (pyrometers, thermal image cameras), one has to know in advance the emissivity factor of the studied object’s surface or better to set its value in place immediately before a measurement. The latter is proposed by authors to significantly increase the accuracy of temperature measurement. Namely, it needs to change previously the temperature of the sensitive element of a measuring mean and carry out measurements. The similar procedure is performed under the unchanged temperature condition. The difference between temperature readings of the same point of the studied surface gives the possibility to compute an emissivity factor. It improves the measurement accuracy. Derived equations allow fulfilling the specified operation at different temperature differences of the sensitive element.

Key words: Temperature measurement, Emissivity factor, Measurement accuracy, Temperature measurement, Pyrometer, Thermal image camera.

Introduction

The thermal energy radiated by the warmed body surface depends on the emissivity factor. Each object, whose temperature to be measured, has its material’s surface with its inherent emissivity factor. Adjustment of the emissivity factor in a pyrometer or thermal image camera is essential in order to measure the actual temperature. It has to be done manually and match the measured object. Pyrometer always fixes the temperature of a measuring point, and a conversion based on the emissivity factor is performed.

However, the value of emissivity factor is unknown or known with a certain uncertainty, and respectively the readouts of pyrometers (thermal image camera) are characterized with uncertainty caused by emissivity factor as well as the set of other factors (for instance, heterogeneity of temperature distribution on a measured surface) [1].

Goal of the work

Aim of the current issue is the creation and development of the method for determining the emissivity factor of a material's surface at the moment immediately preceding the temperature measuring stage. That it can be considered as a prerequisite for the correct contactless temperature measurement of the object. Further, the determination of the emissivity factor allows using the elaborated expression to measure exactly the radiation temperature, and in the next step to compute the thermodynamic temperature of the sample.

Method research

Specifics of the researched method belong to the theory and technique of optical thermometry, heat engineering, audit and certification of heat engineering materials.

Since we study the underpinning pillars of contactless thermometry (pyrometry), let's consider the known method for determining the integral value of the radiant properties of materials. For instance, the basic method is the one, based on the Stefan-Boltzmann law. It is realized [2] on the basis of the dependence: $e = \left(\frac{T_R}{T}\right)^4$, where T_R is the surface radiation temperature of the tested sample; T is the thermodynamic temperature. The thermocouple is applied for measuring temperature of the surface. It rises a significant error of the temperature measurement due to substantial heat withdraw through the thermos electrodes that is strengthening with temperature difference.

So we suggest below the improved method of determining the integral value of the radiation properties of the surface. It is based on the Stefan–Boltzmann law and consists in the measurement of intensity of the radiation heat exchange between the object surface and a sensitive element of the measuring instrument at known temperature of the latter. The exchange is expressed in the radiation temperature attributed to the scale marks of the measuring instrument (e.g., pyrometer) during calibration. At the same time, the calibration of radiation pyrometers is carried out using the blackbody model, for which it is assumed that the emissivity factor is close to 1. Since the real samples of the studied materials are characterized by certain values of factors, different from 1, the significant error of more than 10 % arises in the readouts of pyrometers.

As a result, for one group of radiation pyrometers, it is assumed in advance that they are operated at the same value (0.95) of the emissivity factor of the material under measurement, or at a reduced factor of the thermodynamic system "pyrometer – measuring surface" (it is introduced below). For another group of more complex types of radiation pyrometers this factor can be adjusted manually by a metrologist on the instrument panel within the limits of 0.1 (0.3) ... 1.0.

It is clear that for the first and for the second groups, as a result of neglection of the real value of the emissivity factor of the measured surface, there exists a significant error of method. To a greater extent, the abovementioned applies to thermal image cameras, which, as a result, show only a qualitative picture, for example, of heat loss of a building. In order to avoid the mentioned error, the application of special tables with the emissivity factors for various materials and the degree of surface treatment is recommended [3]. For instance, the emissivity factor of oxidized steel is equal to 0.85 and of polished steel is 0.075. The problem is solved by analyzing the heat exchange peculiarities in the system "pyrometer (thermal image camera) – object with its measured surface".

To understand the essence of the proposed method, let's consider the flow of energy E_0, radiated from the measured surface to the pyrometer (more precisely to its blackened plate, on which the thermopile or bolometer receiver of energy is deployed). According to the Stefan-Boltzmann law, it equals to: $E_0 = s\,T^4;\ E_0 = C_0\left(\frac{T}{100}\right)^4$, where C_0 $=10^8\cdot\sigma$ = 5.7 [W/m^{2}K^4] is the radiation factor of the black body. When the body is not black, but, for example, "gray", the emissivity factor $\varepsilon \le 1$ is implemented. It describes how much radiation of this body is less intense than that of the black body. The radiation heat exchange between two bodies (the measured surface of area S and the complicated construction of the pyrometer with its ε_{pyr} that includes, as the major, the sensitive element of temperature T_{se}) is determined by the difference of 2 flows of effective radiation as:

$$q = e_{se} C_0 S\left[\left(\frac{T_{surf}}{100}\right)^4 - \left(\frac{T_{se}}{100}\right)^4\right], \qquad (1)$$

here the factor:

$$e_{pyr} = \left(\frac{1}{e_{surf}} + \frac{1}{e_{se}} - 1\right)^{-1}, \qquad (2)$$

is adjusted for the two-bodies system (measured object surface with its ε_{surf} and directly sensitive element with its ε_{se}) and depends on the ratio of areas of reciprocally radiating objects.

A certain value of the radiation temperature is assigned for each value of q while calibrating the pyrometer. It is due to a specific structure of each pyrometer with its characteristic coefficient A of converting the energy flux into heating of the sensitive element, as well as further processing of the signal received from the latter. Note that coefficient A should also take into account the value $C_0 S$. Then the calibration is carried out on the blackbody model, trying to achieve the condition $\varepsilon_{se} \to 1$. As a result, one can obtain the equation of the conversion function of the particular pyrometer, expressed in terms of radiation heat exchange between its sensitive element and the measured surface: $T_R = T_R\left(T_{surf}; T_{se}; e_{se}\right)$. There are 2 unknowns in it, such as T_{surf} and ε_{se}. The equation can be solved only by taking that $\varepsilon_{se} \to 1$. However, such a path leads to the significant error of method.

Therefore, in the developed method, conditions are created for the preliminary determination of the reduced emissivity factor ε_r in order to obtain an actual conversion function of the pyrometer in the form of $T_R = T_R\left(T_{surf}\right)\Big|_{T_{se}=Const;\, e_r=Const}$ when the values of temperature and the emissivity factor for the sensing element are known. For this purpose, we consider the system of 2 equations with 2 mentioned unknowns, and here the 2nd equation describes the state of heat exchange between the surfaces of the measured object and sensitive element of the measuring instrument, previously heated up on a few degrees (ΔT):

$$T_{R1} = e_r A\left[\left(\frac{T_{surf}}{100}\right)^4 - \left(\frac{T_{se}}{100}\right)^4\right], \quad (3)$$

$$T_{R2} = e_r A\left[\left(\frac{T_{surf}}{100}\right)^4 - \left(\frac{T_{se}+\Delta T}{100}\right)^4\right] \quad (4)$$

Subtracting equation (4) from (3), we obtain

$$\Delta T_R = e_r A\left[\left(\frac{T_{se}+\Delta T}{100}\right)^4 - \left(\frac{T_{se}}{100}\right)^4\right] \quad (5)$$

Let's take into account that the measuring junctions of the pyrometer's thermopile consist of a number (>100) consistently connected thermocouples. They are preferably located on a platinum lobe covered with platinum black, realizing the condition of achievement the $T_{se} \to 1$. Therefore as it can be seen from (2), the equality takes place: $\varepsilon_r \approx \varepsilon_{surf}$. Then equation (5) is transformed into the following equation:

$$10^8 \Delta T_R = e_{surf} A\Big[4T_{se}^{\,3}\Delta T + 6T_{se}^{\,2}(\Delta T)^2 + $$
$$+ 4T_{se}(\Delta T)^3 + (\Delta T)^4\Big]. \quad (6)$$

For practical calculations, it is enough to use the first two terms of a polynomial, since each next component in a bracket is approximately at 2 orders of magnitude smaller than the previous one:

$$10^8 \Delta T_P = e_{surf} C_0 S\left[4T_{se}^{\,3}\Delta T + 6T_{se}^{\,2}(\Delta T)^2\right]. \quad (7)$$

From here we obtain an expression for calculating the emissivity factor of the measured object's surface:

$$e_{surf} = \frac{10^8 \Delta T_P}{A\left[4T_{se}^{\,3}\Delta T + 6T_{se}^{\,2}(\Delta T)^2\right]}. \quad (8)$$

Implementing the proposed method

Let's assume that in order to ensure efficiency of the method and simplicity of further calculations, an increase in the temperature of the sensitive element ΔT, equal to 1 % from T_{se}, is set. Then the equation (8) is simplified to:

$$e_{surf} = \frac{10^8 \Delta T_P}{0{,}0406 \cdot A \cdot T_{se}^{\,4}} = \frac{\Delta T_P}{0{,}0406 A\left(\frac{T_{se}}{100}\right)^4} \quad (9)$$

When the measuring device together with the sensitive element is hold at 293 K, the simple expression can be obtained for the further calculations:

$$e_{surf} = \frac{2{,}9924}{K^4}\frac{\Delta T_P}{A}, \quad (10)$$

here A [1/K] is the factor of conversion of radiation flow into the pyrometer's readings under the conditions given in the specifications for the device.

The proposed method is implemented by using a pre-calibrated pyrometer (thermal image camera) with a known value of factor A. The measuring device was equipped with an electrical heater of the sensitive element with its power supply. Temperature measuring block was provided with the thermistor switched in the leg of the bridge circuit. It allows set the given temperature increment for the sensitive element, equal to 3 K. In this a way we have checked the emissivity factor of the studied surfaces, by setting its value have eliminated the uncertainty (or more correctly eliminated the methodic error) in pyrometer's readouts and as a consequence have performed the measuring instrument significantly more exact.

This is especially valuable for establishing the state of energy saving of housing and communal services by conducting energy audits of the built and reconstructed houses, especially in connection with the implementation of European standards for energy efficiency [4].

Conclusion

Due to the development of the method for determining the emissivity factor of a heated object, it becomes possible to carry out an accurate measurement of radiation flows. This, in turn, allow determining the heat insulation of building materials and products with high reliability and, thus, create the basis for defining the suitability of building components and structures on compliance with state and international standards.

In addition, the considered work can be used for calibrating the technical pyrometers, namely radiation pyrometers, in the field of exact temperature measurements in industrial or/and laboratory conditions, since the more accurate measurements of radiation flows are guaranteed by following the previous determination of the emissivity factor of studied object.

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