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Reduction of the impact of emissivity on high temperature measurements in non-contact thermometric devices

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Non-contact measurements of high temperature, accomplished with the use of infrared cameras and pyrometers, are utilized in many fields of science and industry. However, in order to obtain reliable measurement results from aforementioned devices, one should take account of the emissivity value of a thermal source the temperature of which is being measured. This is due to the necessity of calibration of non-contact thermometric devices in relation to emission characteristics of a blackbody, which is an ideal source with the maximum emissivity value. In order a non-contact temperature measurement was made possible without the necessity of taking into account the emissivity value, an original concept of the measurement method was developed, taking the advantage of thermal radiation laws – Planck's law and Wien displacement law. The basic idea of the accepted method is the departure from amplitude recording (as in "conventional" pyrometry and thermovision) for linking of temperature recording with a maximum position in Planck's curve. This article presents a novel approach that was used in the development of an original algorithm of temperature determination for performance of non-contact measurements of high temperature. The algorithm will enable to perform measurements without the necessity of introducing the emissivity value of a radiation source into a measurement instrument and will limit the impact of radiation absorption via the medium in which a measurement is being performed on the results of measurements. The applied methodology will allow conducting non-contact temperature measurements at a distance without the necessity of calibration the measuring device with regard to a blackbody.

Keywords: emissivity impact, high temperature measurements, non-contact thermometer.

1. Introduction

As a consequence of the first law of thermodynamics any object the temperature of which is above absolute zero emits thermal radiation in the form of electromagnetic waves, in the range of wavelengths from 0.1 to 400 μm.

In order to describe the amount of energy emitted from a unit area surface of a thermal source for one ($\Delta\lambda \to 0$) wavelength (or frequency), in the unit of time, the term of spectral exitance has been introduced as a function of wavelength or frequency as:

$$M_\lambda = \frac{2\varepsilon\pi c^2 h}{\lambda^5}\frac{1}{\exp(kc/\lambda kT) - 1} \tag{1}$$

$$M_v = \frac{2\varepsilon\pi v^3 h}{c^2}\frac{1}{\exp(hv/kT) - 1} \tag{2}$$

where M_λ denotes the spectral exitance in wavelength of a thermal object, M_v – the spectral exitance in frequency of a thermal object, c – light velocity in the vacuum, h – Planck's constant, k – Boltzmann's constant, ε – emissivity of the thermal radiation source, v – frequency of the electromagnetic wave, λ – length of the electromagnetic wave, and T – the absolute temperature.

When considering thermal radiation emission from the real source, its emissivity

$$\varepsilon = M_{RS}/M_{BB} \tag{3}$$

has to be taken into account (where M_{RS} denotes the spectral radiant exitance in wavelength of a surface, M_{BB} – the spectral exitance in wavelength of a blackbody). This parameter describes the amount of energy emitted by the real source the emissivity of which is less than one ($\varepsilon < 1$), in relation to the ideal source (blackbody) the emissivity of which is equal to one ($\varepsilon = 1$). Spectral exitance of the blackbody as a function of wavelength and temperature for two values of the radiation source emissivity is shown in Fig. 1.

Thermal technology also introduces the concept of a grey body with emissivity of less than one ($\varepsilon < 1$) but constant, corresponding to the average value, in the considered range of wavelength.

The higher the absolute (thermodynamic) temperature, the shorter the wavelengths of the maximum of Planck's curve. This dependence (called Wien's displacement law), has been mathematically described by

$$\lambda_{max} T = c_3 \tag{4}$$

where λ_{max} denotes wavelength at maximum emittance, T – temperature, c_3 – Wien's displacement constant.

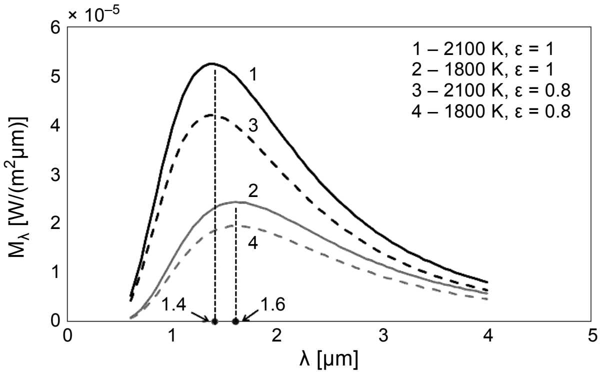

Fig. 1. Spectral exitance as a function of wavelength and temperature for two values of the radiation source emissivity [1].

By integrating the Planck formula (see Eq. (1)) over the whole range of wavelength, which describes the total exitance as a function of the fourth power of temperature, is obtained. This dependence is called the Stefan–Boltzmann law and is expressed as

$$M = \varepsilon\sigma T^4 \tag{5}$$

where σ denotes Stefan–Boltzmann constant.

Thermal radiation laws: Planck's law and Stefan–Boltzmann's law, form the basis of operation of commonly used in science and industry, non-contact thermometric instruments such as pyrometers and thermal cameras. In these devices, the value of the indicated temperature depends on the adopted value of thermal source emissivity [1–3]

2. Influence of the emissivity on the Planck's curve shift

The emissivity of the thermal radiation source, the physical interpretation of which was described in the previous section, depends on many variables such as: wavelength, temperature, measuring angle, the physico-chemical properties of the source surface and also measuring time. Therefore, the determination of the correct emissivity value is difficult and complex but, at the same time also very important for the realization of non-contact temperature measurements and acquisition of reliable results from them. The uncertainty of determination of the emissivity has a significant contribution in the uncertainty of real temperature measurement of an object, carried with the use of "conventional" non-contact thermometric instruments [4–9]. In these instruments, the emissivity of the real thermal radiation source affects the amplitude shifting of Planck's curve in relation to the calibration curve for the blackbody (Fig. 1). Therefore, the measurement signal in infrared cameras and pyrometers recording by the detector has a lower value than the signal recorded for a blackbody radiation source. This implies the necessity of the elaboration a new algorithm for measuring temperature which would be able to significantly reduce or eliminate the effect of this parameter on the measurement result [10–12].

The lower the emissivity value, the smaller the value of the spectral exitance for each wavelength (the amplitude shift of the Planck's curve is shown in Fig. 1). However, the wavelength of the maximum spectral exitance is constant, independent of the radiation source emissivity for the given temperature.

This is one of the basic assumptions adopted in the author's algorithm for determination of the temperature. In addition, when considering the value of the spectral exitance for black and grey body for wavelengths shorter than 1 μm, a slight deviation of the emission curves of the grey body from the black body emission curves occurred.

The analysis of the emissivity impact of the thermal radiation source at 1773 K on the amplitude shift of emission characteristics for the four exemplary values of emissivity and for wavelengths shorter than 0.75 μm is shown in Fig. 2.

The Wien displacement law (Eq. (4)) results from the Planck law (Eqs. (1) and (2)) describing the quantity of emitted energy from the source as a function of temperature

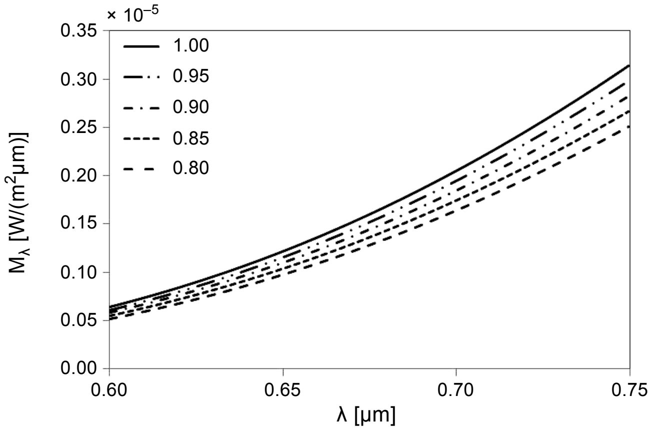

Fig. 2. Emission curves of the thermal source of the temperature of 1773 K for the four values of emissivity.

and wavelength. The mathematical analysis of the impact of the thermal radiation source emissivity on the Wien displacement law is presented below.

The designation introduced:

$$A = \lambda^5 \exp\left(\frac{c_2}{\lambda T} - 1\right) \tag{6a}$$

$$A' = \frac{\mathrm{d}A}{\mathrm{d}\lambda} \tag{6b}$$

$$C_1 = 2\pi hc^2 = 3.74 \times 10^{-16}\ \mathrm{Wm}^2 \tag{6c}$$

$$C_2 = \frac{hc}{\lambda} = 1.4388 \times 10^{-2}\ \mathrm{m{\cdot}K} \tag{6d}$$

and then the derivative of the Planck's formula (Eq. (1)) for the real source relative to the wavelength was calculated

$$\frac{\mathrm{d}M}{\mathrm{d}\lambda} = \frac{\varepsilon(\lambda)c_1A' - c_1[\varepsilon(\lambda)]'A}{A^2} \tag{7}$$

Assuming the radiation emission from the grey source for which $\varepsilon(\lambda)$ = const, the following is obtained:

$$\frac{\mathrm{d}M}{\mathrm{d}\lambda} = \frac{\varepsilon(\lambda)c_1A'}{A^2} \tag{8}$$

and then the extremum of Eq. (8) is calculated as

$$\frac{\varepsilon(\lambda)c_1 A'}{A^2} = 0 \quad \leftrightarrow \quad A' = 0 \tag{9}$$

$$\frac{\mathrm{d}A}{\mathrm{d}\lambda} = 5\lambda^4 \exp\left(\frac{c_2}{\lambda T} - 1\right) + \lambda^5 \exp\left(\frac{c_2}{\lambda T}\right)\left(-\frac{c_2}{\lambda T}\right) = 0 \tag{10}$$

$$5\exp\left(\frac{c_2}{\lambda T} - 1\right) = \frac{c_2}{\lambda T}\exp\left(\frac{c_2}{\lambda T}\right) \tag{11}$$

after substituting $c_2/(\lambda T) = x$, and after transforming the formula (11), the following is obtained:

$$\frac{c_2}{\lambda T} = 4.965 \tag{12}$$

from which the Wien displacement law is derived:

$$T\lambda_{\max} = 2.8976 \times 10^{-3} \text{ m·K} \tag{13}$$

As shown above, the assumption about emission of the thermal radiation from the real source as a grey source, does not affect the mathematical form of Wien's displacement law, which is the basis for determining of the temperature in the developed non-contact temperature determination algorithm.

3. New method for determining the temperature

On the basis of the analysis carried out in the previous section and the conclusions arising there from, the assumption of the grey character of thermal radiation has been adopted for temperature determination. The first stage of the work on the original temperature determination algorithm consisted in defining, with the use of the correlation coefficient r, and determination of the linear dependence between the wavelength and the value of spectral exitance in the wavelength range of 0.6–0.75 μm. The correlation coefficient allows to analytically determine if there is a linear relation between the two parameters. In Table 1, the values of the correlation coefficients for emission curves in the temperature range 973–2273 K are compared. Such a selection of the wavelength range and the temperature results from the operation range of the detector in the measuring device used for the verification of the developed method of measurement.

Based on the obtained value of the correlation coefficient, it has been found that for the emission curves, in the given range of the wavelength and the temperature, a straight line could be matched by the method of linear regression, using the method of least squares (MLS), because in each case $|r| < 1$. The closer the regression coefficient is to 1, the stronger is the linear relationship. Based on the date in Table 1, it can be concluded that together with the temperature increase, the linear dependence of

Table 1. The correlation coefficient for thermal source emission curves with different values of temperature.

Temperature T [K]	Correlation coefficient r
973	0.932
1073	0.947
1173	0.959
1273	0.969
1373	0.976
1473	0.982
1573	0.986
1673	0.990
1773	0.993
1873	0.995
1973	0.996
2073	0.998
2173	0.999
2273	0.999

emission curves becomes stronger and stronger for the range of wavelength and temperature under consideration.

Figure 3 presents the emission curves for the three selected temperatures with straight lines matched to them with determined directional coefficients of straight lines a and coefficients of determination R^2. The determination coefficient is the fundamental parameter describing the quality of the mathematical model matched to measurement data. When the value of the R is closer to 1, the adopted model is better describing the

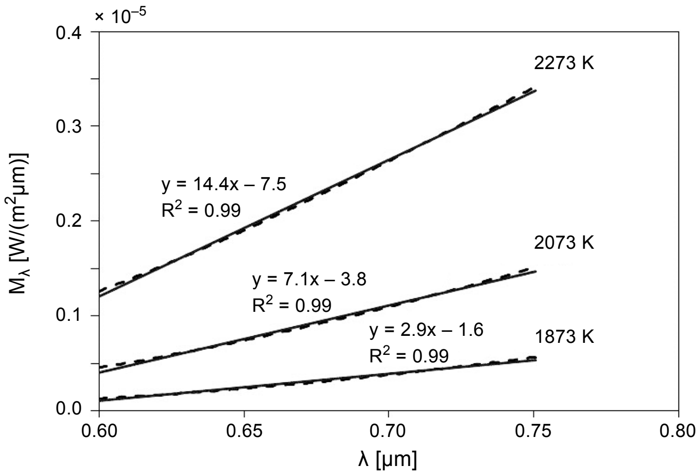

Fig. 3. Dependence of the spectral exitance on the wavelength and temperature matched to straight lines: dashed line – Planck's curve, solid line – the matched straight line.

T a b l e 2. Selected parameters describing the emission characteristics for different temperatures.

Temperature T [K]	λ_{max} [μm]	Coefficient a [W/(m^{2}μm^2)]	R^2
973	2.978	0.000253×10^{-5}	0.869
1073	2.701	0.00161×10^{-5}	0.898
1173	2.470	0.0074×10^{-5}	0.920
1273	2.276	0.0268×10^{-5}	0.938
1373	2.111	0.079×10^{-5}	0.952
1473	1.967	0.201×10^{-5}	0.964
1573	1.842	0.449×10^{-5}	0.973
1673	1.732	0.91×10^{-5}	0.980
1773	1.634	1.67×10^{-5}	0.985
1873	1.547	2.87×10^{-5}	0.990
1973	1.469	4.63×10^{-5}	0.993
2073	1.398	7.08×10^{-5}	0.995
2173	1.334	10.32×10^{-5}	0.997
2273	1.275	14.44×10^{-5}	0.999

relationship between the measured data. In this case, the model of linear dependence has been adopted. The value of the coefficient a, determination coefficient R, and the value of the wavelength in the maximum of spectral exitance λ_{max} for temperature in the range of 973–2273 K are presented in Table 2. It can be noticed that when the determination coefficient is larger, the temperature is higher, then together with the temperature increase, the linear model better describes emission characteristics within the wavelength range under consideration.

The directional coefficient a describes the matched straight lines, which is characteristic for given temperature. Therefore, the coefficient a has been associated with the wavelength in the maximum of the spectral exitance, and the dependence is as follows:

$$\lambda_{max} = -0.15 \ln(a/10^6) + 1.35 \tag{14}$$

The dependence of the wavelength in the maximum of spectral exitance as a function of the directional coefficient of the matched straight line is shown in Fig. 4.

Utilizing the dependence (14) and Wien's displacement law, the following equation has been obtained which constitutes the basis for determining the temperature in the developed measurement method

$$T = \frac{2.8976 \times 10^3}{-0.15 \ln(a/10^6) + 1.35} \tag{15}$$

The temperature in this case is determined indirectly based on the previously determined directional coefficient a of the straight line matched to the recorded measure-

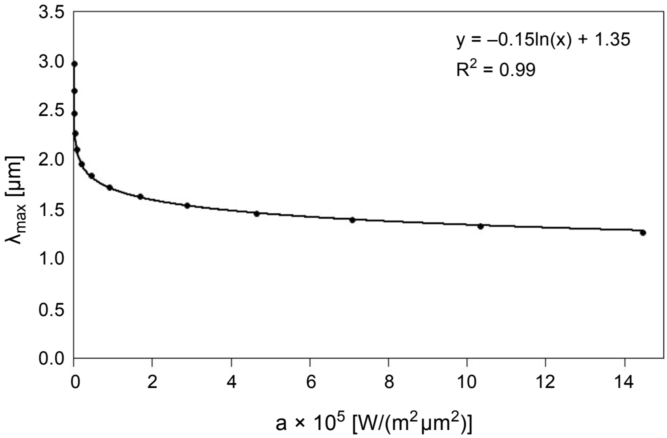

Fig. 4. Dependence of the coefficient of wavelength in the maximum of spectral exitance from directional coefficient of straight line *a*.

ment data (sensor signal as a function of wavelength). In theory, in order to designate a straight line, just two points are needed; therefore, the measurement data for the two wavelengths only need to be registered.

Thus, the developed measurement method consists in what follows:

– registration of measurement points on the left side of the emission curve for the specified temperature of the thermal radiation source,

– matching of a straight line to the registered measurement data and determination of a directional coefficient *a* of the straight line,

– determination of temperature values using the Eq. (15).

4. Conclusions

The developed measurement method, the theoretical principles of which have been presented in this article, enables the elimination or significant reduction of the emissivity of a thermal radiation source in the measurements results being obtained. This has been achieved by associating the temperature of a thermal radiation source with a directional coefficient *a* of a straight line matched to the measurement data (detector's signal as a function of wavelength). The directional coefficient *a* is related to the wavelength in the maximum of emission curve relevant with the Planck's curve and with the value of exitance (or intensity) of thermal radiation. Moreover, the measurements accomplished with the use of the developed measurement method, are "absolute" measurements, *i.e.*, there is no need for calibration of the measuring devices as it was the case with pyrometers and infrared cameras that had to be calibrated in relation to a blackbody. The developed algorithm allows for the realization of non-contact measurements, directly using Wien's displacement law, the validity of which has been confirmed in numerous scientific studies.

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