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Pyrometer for temperature measurement of selective objects of unknown and variable emissivity

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Abstract:

An active multiband pyrometer for non-contact temperature measurement of objects of unknown and spectrally-dependent emissivity was developed. It enables temperature measurement of the objects of temperature within 500°C-1200°C range with a speed up to 200 Hz. The pyrometer consists of a source of infrared radiation that emits radiation on the object under measurement and a receiver that measures radiation reflected and emitted by the object into four narrow spectral bands. Tests show that the developed pyrometer enables temperature measurement of real selective objects with the standard uncertainty equal to 1 % of the output temperature in its temperature measurement range.

1 Introduction

According to the number of spectral bands of the detection system the radiation thermometers can be divided into single-, dual- and multiband systems. The same systems according to criterion of presence of an additional radiation source can be divided into active systems that represent a radiation source co-operating with a receiver and passive systems that consist of only a receiver. Practically only passive single- and dualband systems are available commercially so far. Incomplete knowledge about emissivity of selective objects is often a source of significant errors of temperature measurement with these systems. Indications of passive multiband systems do not depend theoretically on object emissivity even when the latter depends significantly on wavelength and changes during technological process. There can be noticed a significant interest in passive multiband systems and have been published reports about designs of a few passive multiband pyrometers or thermal cameras [1-6]. However, there are also studies that suggest distinct disadvantages of passive multiband systems and the conclusion that these systems should not be capable of producing accurate results in most practical applications [7,8].

Active sigle-, dualband or multiband thermometers represent another possible solution to ensure better temperature measurement accuracy. Active singleband pyrometers (a classical passive singleband pyrometer integrated with a radiation source, for example- a laser) are available nowadays commercially [9]. However, in many cases their accuracy degrades significantly when the angle between the object surface and line the measurement point – the pyrometer is not normal. There was published a report about achieving a very good accuracy of temperature measurement of selective objects with a system that can be called an active multiband pyrometer and consists of a commercially available source of infrared radiation and a spectroradiometer [10]. However, due to high costs of its components, low measurement speed, laboratory character and complicated measurement procedure this active multiband pyrometer cannot be used in most industrial applications. A low cost mobile active fourband AMP 2000B pyrometer developed for high-speed non-contact temperature measurement in industrial applications of objects with unknown and wavelength-dependent emissivity has been developed and is presented in this paper.

2 Basic concept

It is well-known that due to problems with estimation of emissivity of the tested objects, the errors of temperature measurement with classical passive singleband (mono-color) systems are often significant. In spite of this fact, the systems of this type clearly dominate on

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the market because of their relative low cost and that, so far, there are no alternative systems of significantly better accuracy in industrial conditions.

Manufactures of passive dualband (dual-color) systems sometimes advertise that indications of these systems do not depend on object emissivity and atmospheric conditions. However, it can be shown that it is true only in case of grey body type objects and when atmospheric transmittance is the same in the two system spectral bands [11].

The passive multiband systems apparently differ from the single- or dualband systems only because of the higher number of system's spectral bands. However, the differences are much more significant. Passive single- or dualband systems usually use their calibration chart or a single analytical formula for temperature determination. Passive multiband systems determine object temperature by solving a set of *n* equations with *m* unknowns, as presented below:

$$\begin{aligned} S_1 &= f\,(T_{ob}, \varepsilon(\lambda_1)), \\ S_2 &= f\,(T_{ob}, \varepsilon(\lambda_2)), \\ & \\ S_n &= f\,(T_{ob}, \varepsilon(\lambda_{\mathrm{n}})), \end{aligned} \tag{1}$$

where n is the number of detection bands, S_n is the signal measured at n band, T_{ob} is the real object's temperature, $\varepsilon(\lambda)$ is the object emissivity at wavelength λ.

If the number of system's spectral bands n is higher than the number of the unknowns m of the theoretical model, then it is possible to solve the set of equations (1) and to determine the object temperature T_{ob}. The different values of the object emissivity for different spectral bands is the main obstacle to obtain the number of system spectral bands equal to the number of the unknowns. The system closure can be achieved by setting equal emissivities in certain pairs of spectral bands, by the so called balancing of intermediation observation or curve fitting of spectral emissivity. In order to approximate well a curve of object emissivity that depends lightly wavelength using any of these methods it is necessary to input to the set of equations (1) at least three unknown parameters representing object emissivity; in case of the strong variations of object emissivity on wavelength the minimal number of these parameters must be significantly higher. It was shown in Ref. [12] that high number of unknown parameters representing object emissivity in the set of equations (1) makes the indications of passive multiband systems very sensitive to any disturbances in the measurement channel. Therefore, in spite of theoretical potential to measure accurately temperature of objects of unknown and wavelength-dependent emissivity, accuracy of practical such systems can be comparable to accuracy of typical passive singleband systems [12].

Active sigleband systems consists of a classical passive singleband system working as a receiver integrated with an emitter of optical radiation. These systems use generally two-phase measurement procedure. Object emissivity is determined during the first phase on the basis of the measured power of radiation emitted by the emitter and reflected by the tested object. Object temperature is determined during the second phase on the basis of the measured power of the radiation emitted by the object and the calculated earlier value of the object emissivity. However, reflectance of typical objects of reflective-diffusive surfaces significantly depends on the angle of incident radiation. Therefore, accuracy of determination of object emissivity significantly degrades when the angle between the object surface and line the measurement point – the pyrometer is not normal.

To summarise the presented above discussion we can say that accuracy of passive singleband systems can be low in so called difficult cases like objects of unknown and wavelength-dependent emissivity. However, alternative solutions to these classical systems such as passive dualband systems, passive multiband systems and active singleband systems so far failed to show high accuracy of mearement of temperature of such objects, too.

High accuracy of temperature measurement of objects of unknown and wavelength-dependent emissivity was achived using a system that can be called an active multiband system [10]. The system consists of a commercially available source of infrared radiation and a IR spectroradiometer [10]. Object temperature is determined on the basic of measured three spectrums: $S_0(\lambda)$ – the spectrum of radiation emitted by the co-operating source, $S_{\mathrm{l}}(\lambda)$

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– the spectrum of radiation emitted by the tested object, and $S_{II}(\lambda)$ – the spectrum of sum of radiation emitted by the co-operating source and reflected by the object and the spectrum of radiation emitted by the tested object by solving a set of equations of two unknowns: object temperature and an additional constant that depends on geometry of the set: the co-operating source, the system and the tested object.

Due to high costs of its components, low measurement speed, laboratory character and measurement procedure requiring direct measurement of spectrum of radiation emitted by the co-operating source, this active multiband pyrometer cannot be used in most industrial applications.

The system presented in this paper can be also classified as an active multiband pyrometer like the system presented above. However, its design and measurement procedure was significantly simplified. First, instead of using a sophisticated and expensive spectroradiometer, a much simple four-band receiver is used. Second, the measurement procedure was modified to enable determination of object temperature when the mentioned above spectrums are measured at only a few spectral bands. What is also important in many applications the speed of measurements was significantly increased enabling temperature measurement of objects of rapidly changing temperature.

3 Measurement method

A following algorithm is used to determine temperature of the tested object.

First step, the output electrical signals caused by modulated radiation emitted by the source and reflected by the object in all system spectral bands S_{1r},S_{2r}, S_{3r}, S_{4r} are measured.

Second step, the output electrical signals caused by radiation emitted by the tested object S_1,S_2, S_3, S_4 are measured.

Third step, calculation of the relative reflectance of the tested object ρ_n in all spectral bands

$$\rho_n = S_{nr}/S_{n0r} \tag{2}$$

where ρ_n is relative object reflectance in n spectral band, S_{nr} is the signal due to reflected radiation by the tested object in n spectral band, and S_{n0r} is the signal caused by reflected radiation by the standard object of very high reflectance close to 1 in n spectral band.

Step fourth, solving numerically the following set of equations

$$\begin{aligned} S_1 &= [1 - k \times \rho_1] \times S_{bb1}(T_{out}) \\ S_2 &= [1 - k \times \rho_2] \times S_{bb2}(T_{out}) \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ S_4 &= [1 - k \times \rho_4] \times S_{bb2}(T_{out}) \end{aligned} \tag{3}$$

where S_1,S_2, S_3, S_4 are the output electrical signals caused by radiation emitted by the tested object in n pyrometer spectral bands, k is an unknown constant, and $S_{bbn}(T_{out})$ are output signals caused by radiation emitted by a blackbody of temperature T_{out}.

The latter signals is calculated using this formula

$$S_{bb(n)} = \frac{a_n}{\lambda_{ef(n)}{}^5 \left[e^{\frac{c_2}{\lambda_{ef(n)} T}} - 1 \right]}, \tag{4}$$

where a_n is a design constant for n spectral channel, and $\lambda_{ef(n)}$ is effective wavelength of n spectral band. Both parameters are determined experimentally during calibration of the pyrometer.

The set of equations (2) is solved and the unknowns T_{out} and k are determined using the least squares method by finding the global minimum of the function $min(T_{out}, k)$

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$$\min(T_{out},k)=\sum_{i=1}^{4}\left\{S_i-k\left[1-\rho_i\right]S_{bbi}(T_{out})\right\}. \tag{5}$$

However, any other numerical method can be used to find the unknowns parameters T_{out} and *k.*

4 Pyrometer design

The AMP 2000B pyrometer consists of three basic blocks: the IR emitter that irradiates the tested object, the receiver that registers the radiation emitted and reflected by the tested objects in four separate spectral bands, and a PC computer that is used to calculating the object temperature and for storage of the measurement results. The basic diagrams of the first two blocks are presented in Figure 1.

A high temperature small body is used as a source of infrared radiation in the emitter block. The image of the source is projected onto the surface of the tested object using a multi-lens optical system shown in Figure 1. The optical system of the emitter is characterised by a low F-number is order to increase power of radiation emitted by the source that comes to the tested object. Special care was also taken to assure uniformity of irradiation of the tested object.

The radiation emitted by the source on its way from the source to the tested object is modulated using a mechanical chopper. Rotation of the chopper plate is assured by a high speed DC motor of optimised and stabilised speed of rotation.

An infrared radiation from the tested object is focused on a photo-voltaic infrared detector of the InGaAs type using BK 7 glass – silica achromat. The optical system was optimised to have the aberration blur smaller than the diameter of the detector. Moreover, the optical system is characterised by a small F-number that enables to obtain a high signal-to-noise ratio.

The signal from the tested object is modulated by a rotary plate on which four optical filters are fitted. Spectral bands of most of the filters are located within the range 1-2.2 μm and they were chosen to minimise an influence of atmospheric absorption on a signal from the object to the detector.

A photo-voltaic InGaAs infrared detector of an extended spectral band 1-2.2 μm was chosen for application in the pyrometer due to several factors. First, it was noticed from the simulations 1-2.2 μm is an optimum spectral band for the required temperature measurement range. Second, this type of detectors is characterised by very high temperature stability that enables to achieve high measurement accuracy at different environment conditions.

The temperature of the detector is decreased using a thermoelectrical cooler stabilised in order to increase detectivity.

An preamplifier is used to amplify very small signals at the output of the detector. The preamplifier is characterised by a low noise and ultra low input current. Total gain of the preamplifier can be set as high as 10^5 V/A. The preamplifier has typical gain–bandwidth products from DC to 10 kHz.

The signal from the output of the preamplifier is sent to the lock-in amplifier in the main measurement channel. The amplified analogue signals from the amplifier is next converted to a digital by a 16-bit word A/D converter. The signals after digitisation are registered in a computer memory. The temperature of the tested object is calculated on the basis of the signal recorded in the four spectral bands using the calculation method described in Section 3. The most important functional parameters of the developed pyrometer are shown in Tabele.1.

5 Test results

The AMP 2000B pyrometer was developed with aim of to use it in applications requiring high speed temperature measurements of selective objects of unknown and variable emissivity.

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In order to estimate the intrinsic uncertainty of the pyrometer there were made comparisons of its readings with readings of a contact thermometer during low speed measurements. The intrinsic uncertainty of the contact thermometer was estimated by the manufactures as equal to 0.2% of the output temperature and can be treated as negligible in comparison to uncertainties of the pyrometer. The tests were carried out during temperature measurements of a ceramic IR heater slowly heated from 500C up to 1000C. The results indicate that the standard uncertainty of the AMP 2000B pyrometer during such measurements is equal to 1% of the output temperature in Kelvins. We can estimate that the uncertainty of the pyrometer should be the same during high speed measurement, too.

It would be desirable to test pyrometer accuracy during high speed measurement with frequencies up to 200Hz. However, it was not possible to determine accurately true errors of temperature measurement of rapidly heated objects with this pyrometer as no method of better accuracy was available for comparisons. Typical contact methods that enable very accurate temperature measurement are too slow and additionally the sensors cannot be used as they change mechanical properties of the heated material.

6 Conclusions

A mobile active four-band AMP 2000B pyrometer that enables high speed non-contact temperature measurement of rapidly heated objects of unknown and wavelength-dependent emissivity was developed. The tests show that it enables temperature measurement of such objects with the standard uncertainty equal to 1% of the output temperature. It can be considered as a significant improvement as typical passive singleband pyrometers can offer similar accuracy only in case of blackbodies or objects of exactly known emissivity.

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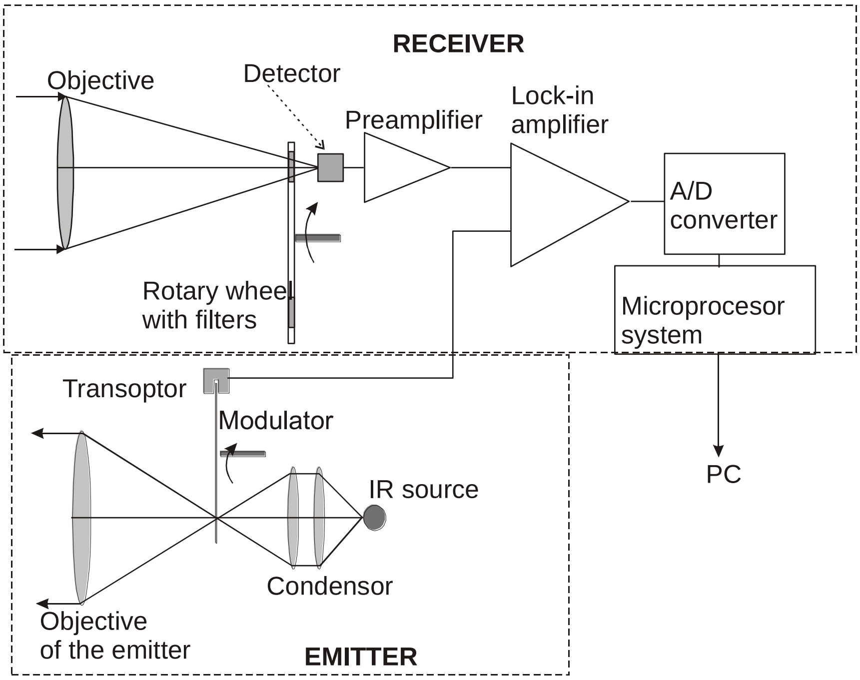

Figure 1. Basic diagram of the pyrometer AMP 2000B

a) b)

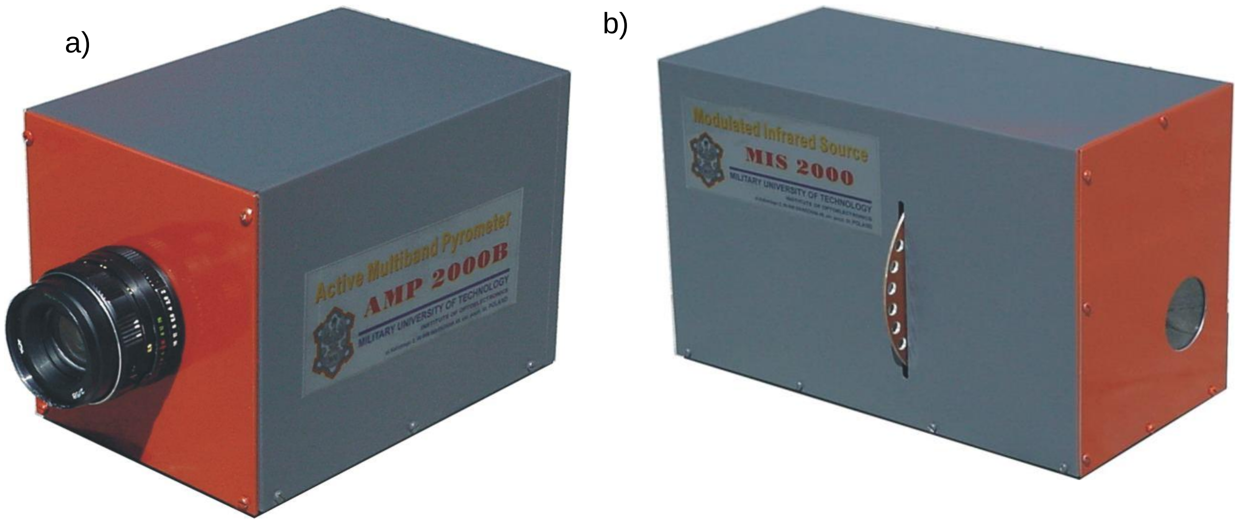

Figure 2. View of the pyrometer AMP 2000B a)receiver b) emitter

Tabele.1 Functional features of the developed pyrometer AMP 2000B

Parameter	Value
measurement temperature range	500-1200 C
measurement frequency	up to 200 Hz
measurement distance range	1-30 m
spatial resolution	5 mrad (standard optics)
field of view for distance 1 m	5×5 mm
range of operation temperatures	5°C-30°C (can be extended)
dimensions	200/110/200mm – receiver 200/150/300mm - emitter
mass	2 kg – receiver 3 kg - emitter