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Limitation of temperature measurement validity for doublespectral systems of middle infrared range

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Doublespectral method for remote temperature measurement determines temperature of the tested object on the basis of the ratio between two radiometric signals measured in two spectral bands. The method can be treated as valid when the ratio does not depend on the object emissivity, and there exists one-to-one correspondence between the ratio and the object temperature. So far, it has been believed that when neither spectral band is contained totally within the other, the method is valid. In this paper, it has been shown that for the systems of spectral bands located in middle infrared range, the method can be invalid additionally for the non-overlapping, or partially overlapping spectral band case, if the influence of the radiation emitted by the optics and the filters on the measured ratio is not corrected.

1. Introduction

One of the commonly used methods for remote temperature measurement determines temperature of the tested object on the basis of the ratio between two radiometric signals, received from the tested object, measured in two spectral bands. It is believed that the ratio does not depend on the object emissivity (when the emissivity is the same in the two spectral bands). Because the doublespectral method does not require knowledge about the emissivity, the method is convenient for the users. At present, the doublespectral systems (mostly doublespectral pyrometers) are used frequently in industry and science. The system usually measure radiation into two spectral bands located in visible or near infrared range [1]–[4]. However, to lower the temperature measurement range, due to signal-to-noiase ratio consideration, systems working in the middle infrared range are being introduced [5], [6].

It has been shown that the validity of the doublespectral method (there exists one-to-one correspondence between the ratio and the greybody temperature; and the ratio does not depend on the object emissivity) is evident when the spectral bands are infinitesimally narrow [7], or – for a more general case – when neither spectral band is contained totally within the other [8]. However, in papers [6], [7], it has been assumed that the radiation incident onto the detector comes only from the tested object. Providing that the detector spectral band is totally contained within the visible or near infrared range, the assumption can be treated as fully satisfied. However, when the detector is sensitive at longer wavelengths, the influence of the radiation emitted by the optics and the filters of the system that also comes to the detector cannot be treated as negligible. In this paper, an analysis of measurement process of the doublespectral systems has been made. The analysis has been limited to the doublespectral pyreometers without any correction of the influence of the radiation emitted by the optics and the filters on the measured signal, as typical of the visible and near infrared ones. This case is interesting because in contrast to expensive radiometers or imaging systems with such correction mechanism that can correct, although not completely, this influence, such pyrometers could be relatively simple and low cost. A formula that enables determination of the ratio of the two radiometric signals, for any location of the spectral bands and the type of the detector, has been found. On the basis of the developed formula, an investigation of dependence of the ratio on the object temperature and emissivity, and the pyrometer parameters has been carried out. The results have shown that the influence of the radiation emitted by the optics and filters, if not corrected, can radically change the measurement ratio and cause significant errors of the temperature measurement, or even limit validity of the method.

2. General theory

The doublespectral pyrometers measure temperature on the basis of the ratio between radiometric signals measured in two different spectral bands. It is believed [8] that the ratio does not depend on the emissivity of the tested object (for greybody objects) and, with the exception of the totally contained spectral band case, there exists one-to-one correspondence between the ratio and the object temperature. Therefore, the doublespectral systems are used mostly in the applications when the emissivity is unknown, or varies.

The ratio measured for the object of the temperature T_{ob} under real measurement conditions should be the same as the ratio measured for the reference source of the same temperature during calibration process, and one value of the temperature should correspond to the one value of the ratio. It happens when two basic conditions are fulfilled. First, there exists one-to-one correspondence between the ratio and the temperature. Second, the ratio does not depend on the object emissivity. As reported in the literature [1]–[4], the systems of visible and near infrared range work properly, and, therefore, we can assume that they fulfil these conditions. Now, we are going to find out if the doublespectral pyrometers of middle infrared range also fulfil these conditions.

In this section, the basic principles involved in determining the ratio during calibration and measurement process are briefly reviewed. For this purpose, several assumptions for the systems and the measurement conditions have been made. First, let us assume that the pyrometer is calibrated and works under laboratory conditions: the distance between the object and the system is short, and the temperature of the background is low. When this assumption is fulfilled we can consider the influences of the limited transmittance of the atmosphere and of the radiation reflected by the object as negligible. This means that only the radiation emitted by the object and the radiation emitted by the optics and filters come to the IR detector. Second, it has been assumed that the absolute radiation present on the pyrometer's detector is measured. Third, it has been assumed that the tested objects are greybodies. The last three assumptions deal with the problems of internal design of the pyrometer. The doublespectral MIR pyrometers can be designed in many different ways. However, in general, they can be divided into two groups. The first group consists of the systems of two completely different optical-electronic channels that measure continuously two radiometric signals in two different spectral bands. The selection of proper spectral bands is achieved using optical filters, or detectors of different spectral bands. The second group comprises the systems with a single optical-electronic channel (common optics, detector, electronics) that measure with some repetition the two signals. To simplify further analysis, let us make a few additional assumptions. Fourth, let us assume that, for the pyrometers of two optical-electronics channels, the transmittance and F-numbers of the optics, the transmittance of the filters, and sensitivity of the detectors in both optical channels of the system are the same. Fifth, it has been assumed that the optics and the filters can be treated as a single block of transmittance equal to the product of the transmittance of the optics and the filters. Sixth, the selection of proper spectral bands is achieved using optical filters of square bands.

When these six assumptions are fulfiled, the signal measured at the output of the detector of the first channel (or, for the systems from the second group, for the first spectral band) during measurement process can be written as

$$S_1(T_{ob}) = k\left[\int_{\lambda_{1\min}}^{\lambda_{1\max}} \varepsilon M(T_{ob},\lambda)\tau_0(\lambda)\tau_F(\lambda)s(\lambda)dt \right. \\ \left. + \int_{\lambda_{1\min}}^{\lambda_{1\max}} M(T_{opt},\lambda)[1-\tau_0(\lambda)\tau_F(\lambda)]s(\lambda)dt\right] \tag{1}$$

where T_{ob} and ε are the temperature and the emissivity of the object, T_{opt} is the temperature of the optics, $s(\lambda)$ is the detector relative spectral sensitivity, $\tau_0(\lambda)$ is the transmittance of the channel optics, τ_F is the transmittance of the filters, k is the constant of the signal transformation by the optics and the detector, and $M(T_{ob},\lambda)$ is the spectral emittance at the temperature T_{ob} and wavelength λ. The analogous formula can be easily found for the signal measured in the second channel.

Using the Planck formula we have a new form of Eq. (1) as

$$S_1(T_{ob}) = kc_1\left\{\int_{\lambda_{1\min}}^{\lambda_{1\max}} \varepsilon\frac{\tau_0(\lambda)\tau_F(\lambda)s(\lambda)}{\lambda^5[\exp(c_2/\lambda T_{ob})-1]}d\lambda + \int_{\lambda_{1\min}}^{\lambda_{1\max}} \frac{[1-\tau_0(\lambda)\tau_F(\lambda)]s(\lambda)}{\lambda^5[\exp(c_2/\lambda T_{opt})-1]}d\lambda\right\} \tag{2}$$

where c_1 and c_2 are the radiation constants.

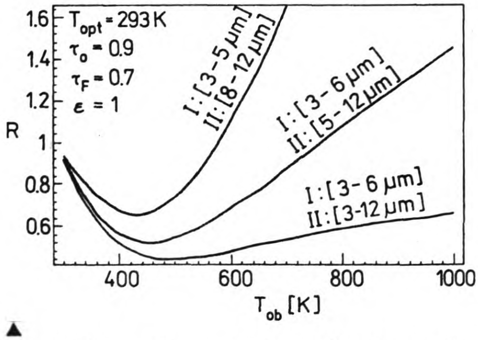
Finally, we have the formula for the ratio between the two signals measured during measurement process as

$$R(T_{ob}) = \frac{\varepsilon \int\limits_{\lambda_{1min}}^{\lambda_{1max}} \frac{\tau_0(\lambda)\tau_F(\lambda)s(\lambda)}{\lambda^5[\exp(c_2/\lambda T_{ob})-1]}d\lambda + \int\limits_{\lambda_{1min}}^{\lambda_{1max}} \frac{[1-\tau_0(\lambda)\tau_F(\lambda)]s(\lambda)}{\lambda^5[\exp(c_2/\lambda T_{opt})-1]}d\lambda}{\varepsilon \int\limits_{\lambda_{2min}}^{\lambda_{2max}} \varepsilon\frac{\tau_0(\lambda)\tau_F(\lambda)s(\lambda)}{\lambda^5[\exp(c_2/\lambda T_{ob})-1]}d\lambda + \int\limits_{\lambda_{2min}}^{\lambda_{2max}} \frac{[1-\tau_0(\lambda)\tau_F(\lambda)]s(\lambda)}{\lambda^5[\exp(c_2/\lambda T_{opt})-1]}d\lambda}. \tag{3}$$

The analogue formula for the ratio under the calibration conditions can be easily received by eliminating the object emissivity ε, as it is equal to one for the blackbodies used during the calibration process, from Eq. (3).

3. Simulation

Classical doublespectral systems of the visible and near infrared range, due to signal-to-noise problems, measure temperature over the level of about 1000 K. The aim of the introduction of the pyrometers of spectral bands located in middle infrared range 3 – 15 μm is to lower the measurement range, to achieve similar range to the singlespectral systems. The latter ones can typically measure temperature (when the emissivity of the object is known), at least, as low as 300 K. Therefore, we are going to limit the analysis to the objects of temperature within the range of 300 – 1000 K. The emissivity of the tested object can, in general, vary from several hundredths to almost one. However, the objects of very low emissivity are rather limited to polished metals and we are going to limit the analysis to the object of emissivity within the range from 0.1 to 1. The pyrometers can be designed using different types of IR detectors. However, the latter ones can be divided into two groups: the non-selective detectors of spectrally non-dependent sensitivity (usually thermal, or pyroelectric detectors) and the selective detectors (photon detectors) whose sensitivity depends on wavelength. Therefore, we are going to limit the analysis to three types of the pyrometers: those equipped with non-selective detectors and the two others equipped with selective detectors.



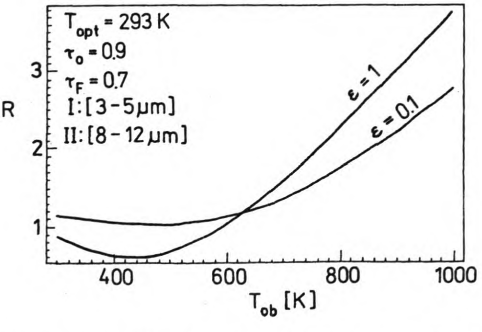


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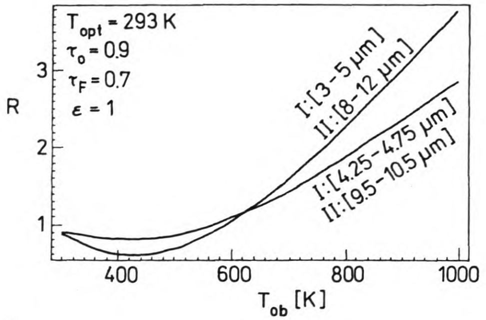
Fig. 1. Dependence of the ratio R on the object temperature T_{ob} for non-selective systems of non-overlapping, partially overlapping and totally contained spectral band cases

Fig. 2. Dependence of the ratio R on the object temperature T_{ob} for two objects of different emissivity



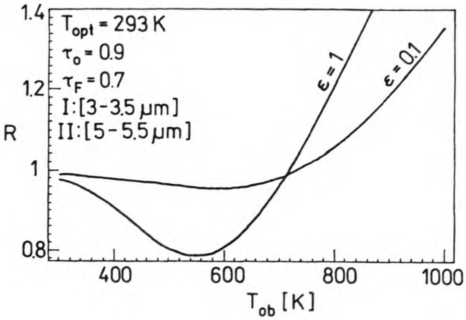


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Fig. 3. Example of the influence of narrowing the width of the spectral bands on the measured ratio R

Fig. 4. Dependence of the ratio R on the object temperature T_{ob} for systems of spectral bands located within the "atmospheric window" 3–5.5 μm for two objects of different emissivity

Now, let us find out what is the behaviour of the MIR doublespectral pyrometers that measure the absolute radiation present on the detector and have no correction of the influence of the radiation emitted by the optics and the filters. As we can see in Fig. 1 for the non-selective pyrometers, we have the phenomena of the ratio ambiguity, as we have a dip in the ratio *vs.* temperature plot. The temperature range where the ratio ambiguity exists is relatively small (300–580 K) for the non-overlapping spectral band case. However, it is not possible to measure the temperature correctly because of significant influence of the object emissivity on the ratio (Fig. 2). Change of the width of the spectral bands has small influence on the location and the width of the ambiguity ratio range (Fig. 3). Similarly, the change of location of the spectral bands to the "atmospheric window" of 3–5 μm does not improve the situation. The ratio still strongly depends on the emissivity (Fig. 4). In general, we can say that for the non-selective systems, either one temperature corresponds to two values of the ratio, or the ratio depends on the object emissivity.

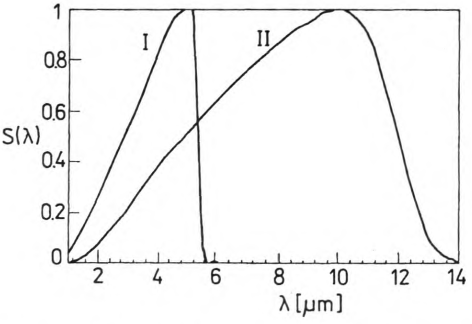
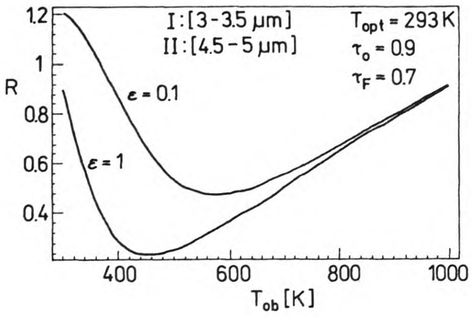


Fig. 5. Detector relative sensitivity functions $s(\lambda)$ as used in the calculations (curve I – the detector of optimal response in 3–5 μm "window"; curve II – the detector of optimal response in 8–12 μm "window")



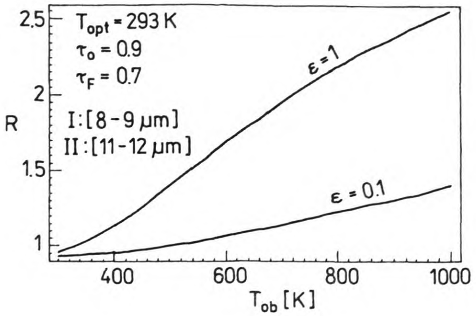


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Fig. 6. Dependence of the ratio R on the object temperature T_{ob} for system using the detector optimized for the "atmospheric window" 3 – 5 μm and the spectral band located within it for two objects of different emissivity

Fig. 7. Dependence of the measured ratio R on the object temperature T_{ob} for system using an IR detector optimized for the "atmospheric window" 8 – 12 μm and spectral bands located within it for two objects of different emissivity

Selective infrared detectors of middle infrared range are usually optimized for one of the "atmospheric windows" 3 – 5 μm or 8 – 12 μm. Therefore, for the purpose of the calculations, the detector relative spectral sensitivity functions $s(\lambda)$ of two such detectors, as presented in Fig. 5, have been used. As we can see from Figs. 6 and 7, we have a completely different situation for the two pyrometers of spectral bands located in these "windows". For the case of the system of spectral bands located in 3 – 5 μm "window", we have a large, practically in the whole analysed area, ratio ambiguity range (the double-value region), Fig. 6. The ambiguity problem does not exist for the system of spectral bands located in the 8 – 12 μm (Fig. 7). However, the strong dependence of the ratio R on the object emissivity ε practically eliminates any practical applications of such systems. We cannot say the same about the systems of spectral bands located in the 3 – 5 μm "window". It is not possible to use such systems successfully in the whole analysed temperature range due to ambiguity problems and the dependence of the ratio on the object emissivity. However, it seems that these pyrometers can measure correctly temperature over the level of about 600 K.

4. Conclusions

The investigation has established that there are much wider areas, where the doublespectral method can be invalid, than it has been commonly believed. On the basis of the results of the investigation four main conclusions have been formulated. First, the doublespectral method, for systems of the middle infrared range, can be invalid not only for the totally contained spectral band case but also for partially, or even non-overlapping case. Second, the method is invalid for the whole class of the non-selective systems of bands located in the middle infrared range. For such systems, even for the non-overlapping case, the condition of one-to-one correspondence between the temperature and the ratio is not fulfilled in the whole analysed temperature range. Additionally, which is even more important, the ratio between the two radiometric signals strongly depends on the objects emissivity. Third, the method can be treated as partially valid for the case of the selective systems. For the systems of spectral bands located in the 8–12 μm range, we have one-to-one correspondence between the temperature and the ratio. However, the method is invalid for these systems due to strong dependence of the ratio on the object emissivity. For the systems of 3–5 μm range, the influence of the object emissivity on the ratio can be treated as negligible for the temperature only over the level of about 650 K. For temperature over that level, we have no ratio ambiguity and the method can be treated as fully valid.

The conclusions presented earlier have significant practical relevancy. However, we have to remember that they are limited to the systems and measurement conditions that fulfil the assumptions which have been made. This means that, in general, they are limited to the systems with no correction of the influence of the optics and the filters radiation on the measured ratio. If this influence is corrected, then the limitations, presented earlier, of the doublespectral method for the MIR systems can be removed.

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