Usage of dual-channel radiation thermometers in dusty environment

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Abstract. The article presents the simulation results of noncontact temperature measurements uncertainty (in the measurement range of 350...750 ºС), which were performed using dual-channel radiation thermometers through a cloud of clinker dust in the cases of different dust concentrations. It is shown that the use of dual-channel spectral ratio radiation thermometers is more efficient compared to single-channel measuring instruments. According to the simulation study the best results in terms of the uncertainty level of dual-channel radiation thermometer were obtained by the using in its design the couple of a wide-band and a narrow-band measuring sensors. It is proven that in order to cover the entire temperature range of 350...750ºС with an acceptable level of uncertainty, it is advisable to utilize the dual-channel radiation thermometer in the combined single-channel and dual-channel mode of operation.

1. Introduction
Non-contact temperature measurement methods are convenient (and, sometimes, irreplaceable) methods for monitoring thermal processes in industry [1]. However, currently existing radiation thermometers and thermal imagers are not always able to provide the necessary accuracy of measurements, especially in cases of significant influence of unaccounted external factors on the measurement process [2]. One of such factors is the dust cloud that can be exist in the transmission area between a target and a radiation thermometer. In this case, the main problem is related to the instability of the optical properties of the dusty environment.

A previous study [3] showed that a single-channel radiation thermometer (a partial radiation pyrometer) can measure with acceptable accuracy in dusty conditions only by using an external correction on the base of a reliable value of the correction factor. However, the correction factor should be introduced by the operator, and it is often impossible to estimate its value in real industrial environment due to the fact that the dust cloud is usually a non-stationary system with constantly changing parameters. As an alternative, we propose to consider the possibility of usage of dual-channel radiation thermometers (with the focus on spectral ratio radiation thermometers) in dusty conditions. The classic spectral ratio thermometers have proved their effectiveness in the area of noncontact monitoring of the high-temperature objects with an unknown emissivity [4].

The continuous improvement of manufacture technologies of sensitive elements (including the reduction of its self-noise level) is of particular interest for research, because it has become possible to use broadband radiation detectors as a part of a dual-channel radiation thermometer systems. This feature can increase the signal-to-noise ratio and extend the temperature range of measurements of such systems.
2. The statement of the problem

The main objective of the paper is the experimental and simulation study of the measurement uncertainty of the dual-channel radiation thermometers, which can be constructed using modern electronic components for taking measurements in the temperature range of 350...750°C.

Initially, we have to select several sensitive elements with different spectral sensitivity characteristics that can be useful in the construction of measuring instruments for the particular temperature range. These selected detectors (taking into account their self-noise characteristics) will be considered as part of single-channel and two-channel radiation thermometers under identical environment (temperature measurement through a cloud of clinker dust). So, this will make it possible to compare the quality of measurements of two types radiation thermometers (thermometers of partial radiation and dual-channel thermometers of the spectral ratio), and also it will allow to select the best detectors couple for taking measurements in the selected temperature range through a cloud of dust.

The study consists of three stages:

1) experimental determination of the influence of a non-stationary dust cloud on the infrared radiation passing through it;
2) simulation modeling of noncontact temperature measurement uncertainty of the single-channel radiation thermometers in the range of 350...750°C in dusty environment in the case of a variable medium transmittance ($\tau=0.5...1$);
3) simulation modeling of the temperature measurement uncertainty of the two-channel radiation thermometers different types under similar conditions.

For the experimental part of the study we use the real clinker powder taken from the actual industrial cement plant.

3. The theory

It is known, that the modern radiation thermometers of spectral relation are mainly used for the measurement of high temperatures (metallurgy, measurement of the temperature of a gas flame, gas discharge plasma) and their design usually includes narrow-band sensors [5]. This feature reduces the quality of temperature measurement below 1000°C due to infrared radiation energy decrease at low temperatures (the signal level drops significantly in relation to the intrinsic noise of the detectors). At the same time, the possibility of using of broadband sensors, which is providing a higher signal-to-noise level, as a sensitive elements has been investigated not well yet.

As a rule, the sensors used for non-contact temperature measurements in the range of 200 ... 1000°C have a spectral sensitivity range within the limits of 2 ... 5 μm [6]. This is due to the fact that this spectral range provides the minimum level of absorption of infrared radiation by the main atmospheric gases. From this point of view, at the preliminary stage we have selected five up-to-date radiation detectors (photovoltaic sensors based on lead selenide): two of these sensors are broadband ($\lambda_1=2.6...4.5 \mu m$; $\lambda_2=1.6...3.6 \mu m$), and three detectors are relatively narrow-band ($\lambda_3=2.9...3.05 \mu m$; $\lambda_4=3.51...3.65 \mu m$; $\lambda_5=4.19...4.4 \mu m$).

On the base of the selected sensing elements five measuring channels should be constructed and investigated. Each of these channels can be considered as a separate single-channel radiation thermometer and a combination of two channels can be used in the construction of a dual-channel radiation thermometer. The principle of operation of a dual-channel spectral ratio radiation thermometer is shown in Figure 1 (where $s_1$ and $s_2$ are signals received from radiation receivers; $T$ – temperature value measured by the device). The intrinsic noise level of each sensor can be described in arbitrary units as follows: $N_1=0.34$; $N_2=4.5$; $N_3=6.4$; $N_4=3.1$; $N_5=13$ [7].
4. The result of the study

4.1. The first stage
The first stage of the study was devoted to the experimental research carried out on the basis of a specially constructed multi-channel radiation thermometer setup described in [3, 7]. This experimental setup consists of five measurement channels described above. The research revealed the features of influence of a non-stationary cloud of cement dust on the infrared radiation passing through it from the point of view of radiation thermometry. The study was conducted in the range of measuring temperatures of 300 ... 750 °C, while the concentration of dust varied over a wide range.

Figure 2 shows the relation between the mean-square deviation of the transmittance fluctuations and the average value of the transmittance \( \tau \) of the dust cloud (this parameter could be considered as an inversely proportional estimate of dust concentration). This relation was determined by a series of experiments performed in different measurement conditions (the gray dots in Figure 2). The resulting spread of values can be approximated by the specific curve (shown in Figure 2 as a black line). In other words, the dust level increase leads to non-linear rising of the random component of dust fluctuations.

In addition, the results showed that the cloud of real clinker powder affects the readings of measuring channels with different spectral sensitivity characteristics (in the wavelength range of 1.6 ... 4.5 \( \mu \text{m} \)) in the same way.
4.2. The second stage

At the second stage of the study, each measuring channel was considered as a specific single-channel radiation thermometer, the spectral sensitivity characteristic of which is unique.

Based on the experimental data of the first stage, the simulation modeling of the expanded uncertainty (with the coverage probability of \( P = 0.95 \)) of the single-channel radiation thermometers was carried out. Figure 3 describes the relationship between the expanded measurement uncertainty of all five channels and the estimated temperature of an object in the range of 350 ... 750 °C upon condition of constant \( \tau = 0.9 \). Figure 4 represents the relationship between the expanded uncertainty and the environmental transmittance value (\( \tau = 0.5 \) ... 1) in the case of constant temperature \( T = 550 ^\circ C \). In the simulation, the external correction mechanism of single-channel radiation thermometer was not intentionally used, so, the value of correction factor was equal to 1. The numerals (1...5) in Figure 3 and Figure 4 correspond to the numbers of the measuring channels.

![Figure 3](image3.png)  
**Figure 3.** The relationship between the measurement uncertainty of the channels and the estimated temperature.

![Figure 4](image4.png)  
**Figure 4.** The relationship between the measurement uncertainty of the channels and the dust cloud transmittance.

On the base of the obtained simulation data it was established:

a) when measuring in a dusty condition, the level of intrinsic noise of a sensitive element does not have a primary effect on the quality of the measurement result, since the level of dustiness is of primary importance in this case;

b) without applied the external correction, the uncertainty of the best version of a single-channel radiation thermometer (detector №1) in the case of an insignificant dust level (\( \tau=0.9\ldots1 \)) does not exceed 16 °C in the range of 350...500 °C; does not exceed 22 °C in the sub-range of 500...650 °C; and 28 °C in the sub-range of 650...750 °C.

c) the measurement uncertainty of the best single-channel radiation thermometer rises significantly along with increasing of the dust level: it reaches 50 ... 90 °C in the case of a moderate dust level (\( \tau=0.7\ldots0.9 \)) and exceeds 70...100°C in the presence of a medium dust level (\( \tau=0.5\ldots0.7 \)).

4.3. The third stage

It was established that on the basis of five mentioned channels it is possible to construct a seven different versions of double-channel radiation thermometers (with the couple combination of channels - 1 and 4; 1 and 5; 2 and 4; 2 and 5; 3 and 4; 3 and 5; 4 and 5). The usage of three remaining couple combinations leads to an inadmissible shape of radiation thermometer conversion characteristic.

Based on the experimental data of the first stage, the simulation modeling of the expanded measurement uncertainty ( \( P = 0.95 \)) of the double-channel radiation thermometers (operating in the spectral ratio mode) was carried out for the cases of \( \tau = 0.7 \) (Figure 5) and \( \tau = 0.9 \) (Figure 6). These
graphs reveal that the uncertainty of all considered double-channel radiation thermometers has the maximum at a temperature of 350 °C (the uncertainty reaches 40...71 °C for the best version of the thermometer) and tends to fall significantly with an increase of target temperature (it is about 9...13 °C at 750 °C for the best version). It should also be noted that the combination of broadband sensor №1 and narrowband sensor №4 (i.e. channels 1 and 4) exhibits the best results in terms of the level of uncertainty, most likely because the signal-to-noise ratios of corresponding channels are the highest.

Figure 5. The relationship between the measurement uncertainty of the dual-channel radiation thermometers and the estimated temperature in the case of $\tau = 0.7$.

Figure 6. The relationship between the measurement uncertainty of the dual-channel radiation thermometers and the estimated temperature in the case of $\tau = 0.9$.

Figure 7 reveals the relationship between the expanded uncertainty of the best dual-channel radiation thermometer version (with channels 1 and 4) and the measured temperature in range of 350...750°C for different values of the medium transmittance ($\tau = 1; 0.9; 0.7; 0.5$).

As it was mentioned, this version of a dual-channel radiation thermometer showed the least uncertainty level in the whole range of conditions considered: the uncertainty is near 9..40°C with an insignificant dust level; 10...52 °C with a moderate dust level; and 13...71°C in the presence of a medium dust level.

The next phase of this simulation stage was dedicated to the detailed comparison of the measurement quality of the best single-channel radiation thermometer (based on channel 1) and the
best version of dual-channel one (based on channels 1 and 4). Figure 8-11 reveals the expanded measurement uncertainty of these radiation thermometers in the case of transmittance changing ($\tau = 0.5 \ldots 1$) at several temperature points.

The usage of all considered dual-channel radiation thermometers operating in the spectral ratio mode is inefficient for measuring the temperatures below 500ºС. Even in a case of insignificant dustiness ($\tau=0.9\ldots1$), the uncertainty level of a single-channel radiation thermometer is noticeably lower than any dual-channel one (even without applying the external correction). On the other hand, the usage of dual-channel radiation thermometers is effective for measuring temperatures above 500ºС: the simulated uncertainty of the best variant of a dual-channel radiation thermometer does not exceed 15ºС in the case of an insignificant dust level ($\tau=0.9\ldots1$); does not exceeds 20 ºС in the presence of moderate dustiness ($\tau=0.7\ldots0.9$); and does not exceed 25ºС in the case of a medium level of dust ($\tau=0.7\ldots0.9$). In addition, the uncertainty of single-channel measuring systems rapidly increases along with the rising of temperature of the target.

**Figure 8.** The uncertainty comparison between the best versions of single-channel (1) and double-channel (1:4) thermometers at $T=380ºС$.

**Figure 9.** The uncertainty comparison between the best versions of single-channel (1) and double-channel (1:4) thermometers at $T=500ºС$.

**Figure 10.** The uncertainty comparison between the best versions of single-channel (1) and double-channel (1:4) thermometers at $T=600ºС$.

**Figure 11.** The uncertainty comparison between the best versions of single-channel (1) and double-channel (1:4) thermometers at $T=700ºС$. 
According to the results of the study, the authors of the paper propose to consider the possibility of using the best version of a dual-channel radiation thermometer in a combined mode of operation as it described in [8].

This suggestion will presumably minimize the level of uncertainty in the entire temperature range (350 ... 750 °C). The central idea of this method based on the continuous estimation and averaging the transmittance value in the dual-channel mode of operation. This mean estimate of transmittance is used as the correction factor for a wideband measuring channel operating as a single-channel radiation thermometer.

The simulated uncertainty of the best double-channel radiation thermometer operating in such mode is presented in Figure 12. For this simulation it was assumed that the dust level was remaining approximately constant for 2 seconds, that is quite consistent to real industrial conditions. In Figure 12 it can be seen that the measurement uncertainty is in the range of 6.5...22°C even in the case of a medium dust level (τ = 0.5 ... 0.7).

5. Conclusions
During the experimental stage of the study, the empirical relationship between the standard deviation level of the environmental transmittance fluctuations (clouds of cement dust) and the average value of the transmittance (describing the degree of dustiness) was obtained.

The stage of simulation of the temperature measurement process by a single-channel radiation thermometer made it possible to determine the best variant of its design (by using the detector №1 with sensitivity region λ₁=2.6...4.5 μm) and estimate extended uncertainty, which rises with an increase of dustiness and target's temperature. According to the simulation study the best results in terms of the uncertainty level of dual-channel radiation thermometer were obtained by the using in its design the couple of a wide-band (λ₁=2.6...4.5 μm) and a narrow-band (λ₄=3.51...3.65 μm) measuring sensors. It is established, that the increasing of target's temperature measured by the double-channel radiation thermometers (in the spectral ratio mode) leads to the decrease in the measurement uncertainty. Wherein the level of intrinsic noise of sensitive elements is of great importance.

According to the results of the research, it should be concluded that the usage of dual-channel radiation thermometers (in the spectral ratio mode) to measure temperatures above 550°C in the case of unknown environmental dustiness can be unambiguously effective in contrast with the single-channel devices. However, it is suggested that in order to cover the entire temperature range of 350...750°C with an acceptable level of uncertainty (no more than 20 °C), it is advisable to utilize the best variant of dual-channel radiation thermometer in the combined single-channel and dual-channel mode of operation.
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