Correction factor in temperature measurements by optoelectronic systems

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Abstract. It is often necessary to investigate high temperature fast moving microobjects. If you want to measure their temperature, use optoelectronic measuring systems. Optoelectronic systems are always calibrated over a stationary absolutely black body. One of the problems of pyrometry is that you can not use this calibration to measure the temperature of moving objects. Two solutions are proposed in [1]. This article outlines the first results of validation [2]. An experimentally justified coefficient that allows one to take into account the influence of its motion on the decrease in the video signal of the photosensor in the regime of charge accumulation. The study was partially supported by RFBR in the framework of a research project № 15-42-00106

1. Introduction
Currently, the study of fast high-temperature processes is impossible without the use of optoelectronic systems (OES). With the help of OES successfully measure the temperature and speed of fast processes. The accuracy of the results is influenced by the noise and distortion. Global shutter in such systems significantly increases the measurement accuracy. However, apart from noise on the accuracy of measurement is affected by methodological error. All of the ECO calibrated at a fixed standard black body [2]. The present work raises the problem of imperfection of the methods of measuring the temperature of moving self-luminous objects with the aid of ECO. One of the most promising non-contact methods for measuring temperature is undoubtedly the method of spectral pyrometry. It allows to determine the temperature from macro to nano-objects with unknown emissivity. However, spectral pyrometry is used to determine the average temperature of a certain surface, in the diagnosis of mainly stationary processes. Brightness pyrometry is good for nonstationary processes, but emissivity must be known. The combination of spectral and brightness pyrometry is complementary [3-4]. However, here again it is necessary to take into account the superposition of the radiation of the detected particles in their spatial displacement.

2. The proposed hypothesis
Let it be necessary to measure the temperature of a moving hot microparticle. The energy of radiation of a particle during the accumulation time of a photodetector:

\[ \Delta E = \int_0^\infty \Omega(t)dt. \]

The input optical signal of the photodetector is converted into an electrical signal described by \( I(x, y) \) is a bivariate continuous function discrete spatial arguments \( x, y \).
Conversion of the input signal optical system and the image formation on the sensing site of the photodetector can be represented as follows:
\[ I_{\Omega} = \int g(x, y) \cdot I(x, y) \, dx \, dy, \]

Where \( g(x, y) \) is the weight function. The image on the monitor is in the form of an area, the brightness of the pixels that are above the background. After calibrating the ECO over an absolutely black body, certain values of the brightness of the image pixels correspond to the brightness temperature.

\[ \bar{I} = \frac{1}{n \cdot m} \sum_{i,j} I_{ij}. \]

The entire image is represented as a temperature map. If the radiating object (particle) is stationary, the charge accumulation in the photosensitive cell occurs all the time of exposure, illuminating the same cells. During the accumulation of charge in the photosensitive region of the sensor, the flying luminous particles move by a distance depending on their velocities. The track of a moving particle with velocities of 100 - 1140 m/s is less bright. Calibration on a fixed black body can not be used. To overcome the problem, two approaches are possible. The following assumptions are accepted:

- radiation of a particle uniformly from its entire surface. The brightness of the radiating particle surface is assumed to be equal to the average value of the amplitude of the signal of the photosensitive cells of the illuminated region (the brightness of the pixels of the particle image).
- during the exposure time, the radiation intensity of the particle remains unchanged. This means that the amplitude of the signal of the photosensitive cells of the illuminated region remains constant.
- the particle speed does not change during the exposure time.
- "image" of a spherical fixed particle of radius \( r \) in the image is a square with side \( n = 2r \), a moving particle illuminates a region of size \( n \times m \).

The first approach takes into account the decrease in charge accumulation time by photosensitive sensors due to the decrease in charge accumulation time. This means that the temperature measurement is carried out only by those photosensitive cells that would be illuminated by the same light source if its velocity were zero. So you can apply calibration on a motionless black body. This approach can be used at relatively low speeds of a moving light source. For example, registration of a radiating object (\( T > 2000^\circ C \), \( v \) of the order of 100 m/s) can be performed at microsecond exposures. In this case, the brightness of the study is sufficient to form an image. If the speeds are very high, of the order of 1000 m/s, then the track is a long, but very small brightness. In this case, you can not switch to a smaller exposure. The emitter can not be considered stationary. Calibration on a fixed black body can not be used. In this case, it is necessary to apply the second approach.

The second approach is based on the principle of superposition of the charge accumulated during the exposure time. At the length of track \( m/n \) such particles fit. Therefore, taking into account the superposition principle, the integral brightness, according to which one should judge the temperature of a moving particle in a discrete representation:

\[ I' = \frac{m}{n} \bar{I} = k \cdot \bar{I}, \]

Where \( \bar{I} \) - is the average luminance value in the track, \( k \geq 1 \). Thus, despite the seeming similarity, the correct use of approaches makes it possible to significantly expand the measurement limits for optoelectronic systems.

3. Technique and procedure of the experiment

It consists of: a mini-oven «JC Small Melting», a standard optical diaphragm (1 mm); Electric drill, video camera SOOCO S70. Carrying out experiments with a high-speed camera Video Sprint (1000 fps, exposure 20 ns-20 \( \mu \)s) is difficult due to the lack of a test object with the necessary characteristics. The tube furnace is heated to one of the temperatures of 600-800°C, maintained during video shooting. In the clamp of an electric drill instead of a drill, an optical diaphragm was attached. The electric drill was rigidly mounted so that when the diaphragm rotated through the hole, the bottom of the tubular
furnace could be seen. The diaphragm is parallel to the bottom of the tubular furnace and to the lens. The distance from the aperture to the video camera $l >> 1$ mm. The video was taken at a fixed temperature of the tube furnace (120 frames per second, the accumulation time is constant).

**Figure 1.** Experimental setup.

This was an example of the figure. The moment of interest corresponds to the same spatial position of the diaphragm between the lens and the tubular stove. Through the opening of the diaphragm, the thermal radiation of the heated bottom of the tube furnace was observed. The movement of the hole simulated the motion of a self-luminous particle. The purpose of the experiments is to compare the brightness of the image of the aperture of the fixed diaphragm and the brightness of the track "of the moving particle and to reveal the connection of the brightness of the track from its area. The resulting video files were analyzed in ImageJ. An example of the received frames can be seen in Figure 2 (in conventional colors). In the program ImageJ, we outlined the tracks, measuring their area and brightness.

**Figure 2.** The sequence of frames at different temperatures of the mini-Oven (in conventional colors).

The area of tracks strongly depends on the quality of contouring. At low temperatures, the contrast is small, the dispersion of areas is large, if the contours are searched automatically. The values of the track area, normalized by the area of the fixed hole, were plotted along the abscissa axis.
The scatter of the areas and brightness of the tracks with the automatic selection of the contours can be seen in Figure 3. Therefore, before the binarization to the duplicate video file, the technological methods of image processing were applied: "unsharp masking" and "subtract background", etc.

![Figure 3](image.png)

**Figure 3.** The automatic selection of tracks on the images $T=600^\circ C$, $T=650^\circ C$, $T=700^\circ C$, $T=750^\circ C$.

The average values of the areas of the images were taken as true ("fixed"). For each temperature of the furnace, a hole/track of "fixed" values was found. To find a mathematical model describing the change in the brightness of the image of the hole as it moves, the experimental data were approximated by a linear function. Figure 4 shows the results for some temperatures.

![Figure 4](image.png)

**Figure 4.** Linear approximation of the data.
Despite the imperfections of the installation used, all straight lines have practically the same angle of inclination. This confirms the correctness of the results, because the accumulation time is constant. For any two points belonging to the same straight line in the coordinates \((S; I)\):

\[
\frac{I - I_0}{S} = -\tan \alpha = \text{const}
\]

To keep points on a straight line, it is necessary that the enlargement of the image area of the hole when moving the diaphragm is the same as reducing its brightness. With sufficient accuracy this requirement is satisfied by the experiment:

at 750°C the ratio \(S_n/S = 0.74\), \(I_n/I_0 = 0.84\);

at 800°C the ratio \(S_n/S = 0.74\), \(I_n/I_0 = 0.87\);

Thus, for temperatures \(T > 650°C\), possible to obtain contrast images experimentally shown to increase image area by the same factor, how much the brightness is reduced. Therefore, the second approach, based on the principle of superposition of the accumulated charge during the exposure, is correct.

4. Main results and conclusions
The purpose of the experiment was to test the validity of introducing a correction factor in the method of measuring the temperature of a moving object. The introduction of the correction factor \(k\) allows one to take into account the influence of the speed of motion on the reduction of the video signal of the photosensor (in the charge accumulation mode). The proposed technique allows to use optoelectronic measuring systems as a micro-pyrometer of static objects and an anemometer micro-pyrometer for two-phase flows with particles \(d_{\text{min}} = 33\,\mu\text{m}\) moving at a speed of 100 m/s and having a temperature of not less than 1500 K.

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