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A COMPENSATION-TYPE PYROMETER

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The operating principles and engineering solutions for constructing compensation-type pyrometers with nonlinear negative feedback and a built-in calibrator are considered.

Keywords: *pyrometer, compensation, calibrator, emittance.*

Compensation-type pyrometers are a class of measuring instruments with compensation. These instruments have higher stability and accuracy than direct-conversion instruments.

We will consider a pyrometer in which information on the nonlinearity of the conversion of the temperature into the output signal is introduced into the negative-feedback channel [1]. In this case, the effect of instability of the transfer constants of the amplification and conversion of the intermediate sections of the pyrometer is reduced, the nonlinearity of the conversion of the temperature into the output signal is reduced (the transmission characteristic is linearized) and the dynamic range of the measurements is expanded.

The Compensation Pyrometer. A block diagram of this pyrometer with a photodiode radiation receiver is shown in Fig. 1. The pyrometer consists of the photodiode *3*, the cathode of which is connected to the input *I* of a differential amplifier *4*, while the anode is connected to the zero busbar and a voltage source *1*, connected to one lead of resistor *2* with regulated resistance, the second lead of which is connected to the cathode of the photodiode *3* and the input *I* of differential amplifier. The input *II* of differential amplifier *4* is connected to the zero busbar, and its output, which is the analog output of the pyrometer, is also connected to the input of the analog-to-digital converter (ADC) *5*, connected to a computer *6*. The computer is connected to the regulated resistor *2*, which is a component of the negative feedback circuit. The output of ADC *5* is the digital output of the pyrometer.

The pyrometer operates as follows. When the photodiode is illuminated with a radiant flux Φ from the heated surface it generates a current I_F, which is converted into a voltage by the amplifier. By the Stefan–Boltzmann law, the flux Φ is proportional to the temperature of the heated surface:

$$\Phi = \sigma A \varepsilon T^4, \tag{1}$$

where T is the temperature of the radiating surface, $\sigma = (5.6697 \pm 0.0029)\cdot 10^{-12}$ W/(m$^2\cdot$K^4) is the Stefan–Boltzmann constant, and ε and A is the blackness coefficient and the area of the heated surface.

Hence, the photocurrent I_F, generated by the photodiode, which operates in the short-circuit photogalvanic connection mode, will correspond to the expression

$$I_F = k_F \Phi, \tag{2}$$

where k_F is the conversion coefficient of the radiant flux into photocurrent.

The output voltage of the amplifier is applied to the input of the analog-to-digital converter, where it is converted into a digital code N, which is fed to the computer. Here it is scaled and raised to the fourth power (in practice the power is determined after the transmission characteristic is approximated when calibrating the pyrometer) and is then fed to a resistor.

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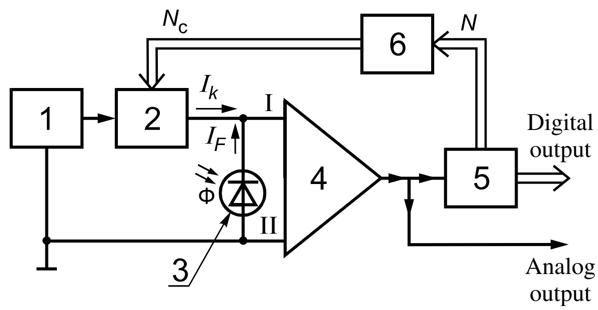

Fig. 1. Block diagram of the compensation pyrometer: *1*) voltage source; *2*) resistor; *3*) photodiode; *4*) differential amplifier; *5*) ADC; *6*) computer.

The digital code N is proportional to the output voltage U_{out} of the amplifier:

$$N = k_{\text{ADC}} U_{\text{out}}, \tag{3}$$

where k_{ADC} is the conversion coefficient of the analog-to-digital converter.

The digital code N_{C}, which is fed to the regulated resistor, is proportional to U_{out} of the amplifier:

$$N_{\text{C}} = k_{\text{CC}} k_{\text{ADC}} U_{\text{out}}^4, \tag{4}$$

where k_{CC} is the computer conversion coefficient.

Under the action of this code, the regulated resistor changes the compensating current I_{K}, fed from the voltage source to input *II* of the differential amplifier, which is proportional to N_{C}:

$$I_{\text{K}} = k_0 N_{\text{C}}, \tag{5}$$

where k_0 is the conversion coefficient of the regulated resistor.

As a result of the action of the negative feedback, due to the high gain of the differential amplifier, the photocurrent of the photodiode and the compensating current of the voltage source flowing through the regulated resistance are equalized:

$$I_{\text{K}} = I_F. \tag{6}$$

Substituting the values of the currents into (6), taking (1)–(5) into account, we obtain:

$$k_0 k_{\text{CC}} k_{\text{ADC}} U_{\text{out}}^4 = k_F \sigma A \varepsilon T^4. \tag{7}$$

It follows from (7) that a voltage, proportional to the temperature of the radiating surface and the fourth root of the coefficients, which participate in the conversion of the radiation into an electric signal, is generated at the amplifier output:

$$U_{\text{out}} = T\sqrt[4]{k_F \sigma A \varepsilon /(k_0 k_{\text{CC}})} / k_{\text{ADC}},$$

where, at the output of ADC, a digital code N is generated, proportional to the output voltage U_{out} of the amplifier

$$N = T\sqrt[4]{k_F \sigma A \varepsilon /(k_0 k_{\text{CC}})}.$$

Extracting the fourth-root considerably reduces the error in the dependence of the output voltage on the measured temperature, connected with the changes in the coefficient ε of the heated surface during measurements and the other con-

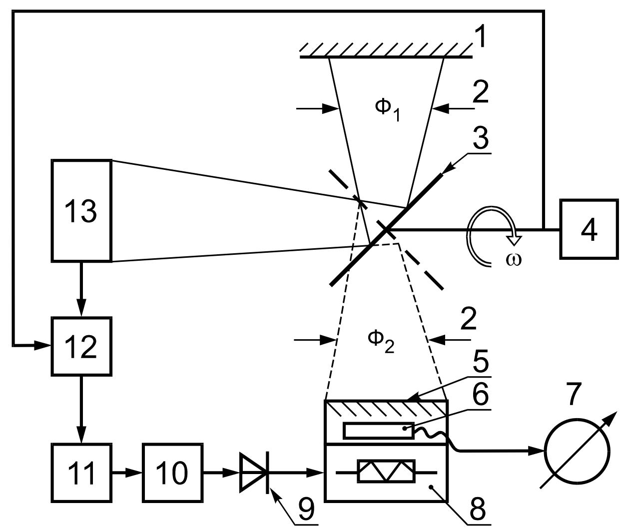

Fig. 2. Block diagram of the pyrometer with the calibrator: *1*) radiation source (the control object); *2*) iris; *3*) rotating mirror; *4*) motor; *5*) changeable radiating surface; *6*) contact thermometer; *7*) measuring instrument; *8*) additional autonomous source of thermal radiation; *9*) diode; *10*) integrator; *11*) amplifier; *12*) synchronous switch; *13*) radiation receiver.

version coefficients of the device. Hence, the use of a computer enables us to increase the accuracy of a measurement of the temperature of heated surfaces as a result of the operation of extracting the fourth root, which leads to a reduction in the numerical values of ε and the conversion coefficients, exact values of which are not known in advance and can be changed during the measurements.

One of the main problems in pyrometry is measuring the actual temperature for an unknown and variable emittance of the control surface.

The use of technical compensation solutions with a built-in calibrator enables the uncertainty to be eliminated in pyrometer measurements of temperature, resulting from changes in the coefficients ε. This problem is solved by using, in the electrical circuit of the pyrometer, a compensation circuit with slave balancing [2], in which the radiation receiver is a means for the successive recording of two radiant fluxes: one from a source with a measured radiation temperature (the control object) and the second from a source with a radiation surface identical with the radiation surface of the control object (the calibrator). The equalization current in the negative feedback circuit heats the radiation surface of the calibrator to the temperature at which the radiant fluxes from the controlled surface and the calibrator become equal. Thus equality of the temperatures from the radiation of the surfaces of the control object and the calibrator is achieved.

A Pyrometer with a Built-In Calibrator. A block diagram of this pyrometer is shown in Fig. 2. It operates as follows. An image of the radiation source (the object being monitored) *1* is incident, via an iris *2* and a rotating mirror *3*, attached at an angle of 45° to the sighting axis, on to a radiation receiver *13*. At the instant when the mirror is sighted on to the radiating surface of the additional source of thermal radiation *5*, the flux issuing from this surface is also recorded by receiver *13*. Hence, at the output of the integrator, an electrical signal is generated, which produces a current through the heating element of the source *8* from the surface *5*, identical to the surface of the object being monitored. As a result, a flux Φ_1 from the radiation source (the object being monitored) *1*, and then a flux Φ_2 from the radiating surface *5* of the source *8*, are incident alternately on the receiver *13*. If these fluxes are not equal, an alternating component of the photocurrent occurs at the output of the operating amplifier *11* due to the synchronous switching of its inverting and noninverting inputs using the switch *12*, connected to the motor *4* which rotates the mirror *3*. Its average value is proportional to the difference in the illuminations of the receiver by both surfaces. A source *8* with changeable samples of fragments of the radiation surfaces *5* is connected to the out-

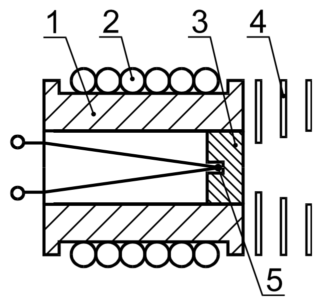

Fig. 3. Construction of the source of calibrated radiation: *1*) heat-conducting body; *2*) heater; *3*) fragment of the surface; *4*) blind; *5*) contact thermometer.

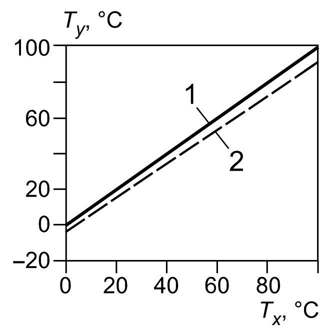

Fig. 4. Characteristics of the compensation pyrometer: *1*, *2*) ideal and actual characteristics; T_x and T_y are the temperatures of the monitored surface and the result of modeling of the pyrometer circuit.

put of the amplifier through an integrator *10* and a diode *9*. Hence, the current in the circuit of the additional source *8*, and consequently, the temperature of the emitting surface *5* will change so long as the fluxes Φ_1 and Φ_2 recorded by the receiver are not comparable and the mean value of the current at the integrator output does not vanish. Then, using the Stefan–Boltzmann approximation we can write $\sigma A\varepsilon_1 T_1^4 = \sigma A\varepsilon_2 T_2^4$, whence

$$T_1 = T_2 \sqrt[4]{\varepsilon_2 / \varepsilon_1} = T_2$$

(the subscripts 1 and 2 relate to the object being monitored and the replaceable sample, respectively).

Hence, the temperature of the radiating surface of the object being monitored is uniquely equal to the temperature of the replaceable sample of the fragment of the emitting surface of the additional autonomous source of thermal radiation, since the coefficients ε_1 and ε_2 are equal and cancel out. The temperature of the replaceable sample is measured by the contact thermometer *6*.

The block diagram of the pyrometer with the built-in calibrator (see Fig. 2) was modeled in the LabVIEW software. In Fig. 3, we show the results of modeling for specified different blackness coefficients of the object being monitored and of the calibrator at a level of 0.01 and for an error in comparing the fluxes of 0.1%, where T_x is the temperature of the monitored surface, and T_y is the result of modeling of the pyrometer circuit, expressed in temperature units.

The Source of Calibrated Radiation. The additional autonomous source of thermal radiation (Fig. 4) consists of the following: a heat-conducting body *1*, a heater *2*, a replaceable fragment of the surface of the calibrated radiation, identical to the surface of the object being monitored *3*, a blind *4*, to eliminate rereflection, and a contact thermometer *5*, for example, a thermocouple.

Conclusions. The use of nonlinear feedback in pyrometers, determined by the conversion function of the temperature of the radiating surface into an electric signal of the radiation receiver, linearizes the transfer characteristic of the pyrometer, leading to a reduction in the error of its output signal, due to the uncertainty of the blackness coefficient of the radiating surface.

By ensuring 100% negative feedback in the pyrometer with the calibrator, one can eliminate the uncertainty due to the change in the blackness coefficient of the radiating surface and compensation of the errors in converting all the elements, encompassed by the feedback, including the most unstable one – the radiation receiver, so that the error is reduced to the error in measuring the temperature by the contact thermometer.

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