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INVESTIGATION OF ATMOSPHERIC ABSORPTION OF THE RADIATION FROM A WEAKLY HEATED BLACK BODY

A. A. Buznikov and B. P. Kozyrev

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The authors describe the method, apparatus, and results of an investigation of the absorption of the radiation from a weakly heated black body by a horizontal layer of the atmosphere. The investigation was carried out under field conditions over distances up to 2000 m. A black body with a radiating-area diameter of 500 mm was used as the emitter. The temperature of the black body was 310-580°K (0.7-40 μ wavelength).

The development of radiation pyrometry, the analysis of the thermal balance of the surface of the earth, and many other problems require that data be available on the absorption of longwave radiation by a layer of the atmosphere.

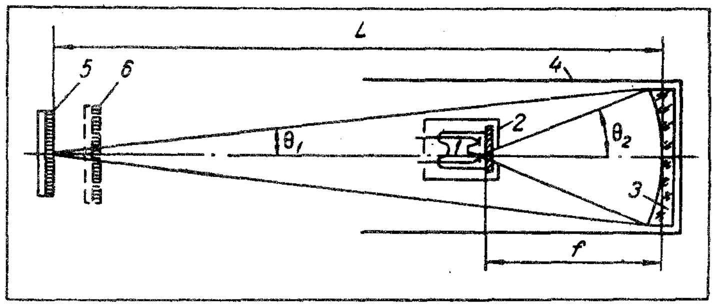

Fig. 1. Scheme for measuring the total transmittance of the atmosphere: 1) RTE; 2) screen; 3) focusing mirror; 4) body of pyrometer; 5) multiple-chamber black body; 6) screen.

This paper presents the results of an investigation of atmospheric absorption of the radiation from a black body over distances up to 2000 m under field conditions. The scheme of the experiment is shown in Fig. 1. The emitter, a multiple-chamber black body with an emitting surface 500 mm in diameter, was described in detail in previous papers [1, 2]. The radiation detector was a vacuum-type compensated radiation thermoelement (RTE) with a forward window of KRS-5 crystal. The detecting plates of the RTE were 1 mm in diameter and blackened on one side by a method developed at the Leningrad Electrotechnical Institute. One of the detecting plates of the thermoelement was located at the focus of the optical system. The image of the multiple-chamber black body was focused on this plate. The other detecting plate was covered by a metal screen.

When the image of the observed object completely covers the detecting plate of the thermoelement, the background radiation has no direct influence on the detector.

In the experiments at distances up to 125 m we used a short-focus optical system. The focusing mirror was coated with aluminum and had a diameter of 280 mm and a focal length F = 500 mm. In order to ensure that the detecting plate of the RTE was covered by the image of the multiple-chamber black body, whenever the distance exceeded 125 m we used a long-focus optical system (F = 6.4 m, diameter 170 mm). At 125 m both systems were used.

The experimental setup constituted a thermal system consisting of emitter, background, detector, optical system, and gas. These elements were in a state of steady radiative interaction. Therefore, the analysis of the fundamental relations of radiation pyrometry can be based on equations of thermal balance written with respect to each of the elements. This analysis was made in detail in [3, 4], where it was shown that the problem of radiation pyrometry of weakly heated bodies in the inverse formulation affords the possibility of formulating a method of investigating the transmission of radiation by the atmosphere.

The total transmission function, or transmittance, P of a layer of the atmosphere for a parallel beam of rays can be defined as the ratio of the intensity of the radiation that passes through the absorbing layer to the intensity of the incident radiation. When a radiation detector is used, we define the total transmittance P as the ratio of the radiative power W incident upon the detecting plate of the RTE in the presence of absorption in the air layer investigated to the radiative power W_0 that would have reached the detector in the absence of absorption

$$P = W/W_0. \quad (1)$$

The value of W was determined experimentally and the value W_0 was calculated assuming that emitter and detector were separated by a vacuum.

The front surface of the active junction of the thermoelement receives the thermal radiation emitted by the part of the surface of the object within the field of view of the detector and the background radiation reflected by that surface. In addition, the front surface of the RTE receives radiation from the focusing mirror, from the body of the pyrometer, from the forward window, and from the screen of the thermoelement. The back surface of the detector receives only the radiation from the inner walls of the body of the pyrometer.

The losses are determined by the true emission of the front and back surfaces of the detecting plates and by the conduction of heat along the wires.

Equating the inflow of energy with the losses, we obtain the equation of thermal balance for the active junction of the vacuum thermoelement:

$$\begin{aligned} &\varepsilon_t' C_s S_1 \sin^2\vartheta_1 [p_{T_0} \varepsilon_0 T^4 + p_{T_b}(1-\varepsilon_0) T_b^4] \frac{S_2}{S_0} + p_f''' \varepsilon_t' C_s \varepsilon_m S_2 T_m^4 \sin^2\vartheta_2 + \\ &+ p_f''' \varepsilon_t' C_s \varepsilon_{sp} T_{sp}^4 (1-\sin^2\vartheta_2) S_2 + \varepsilon_t' C_s \varepsilon_s T_s^4 S_2 (1-\sin^2\vartheta_2) + \\ &+ \varepsilon_t' C_s S_2 \sin^2\vartheta_2 (\varepsilon_f' T_f^4 + r_f T_s^4) + \varepsilon_t'' C_s \varepsilon_s T_s^4 S_2 = \\ &= (\varepsilon_t' + \varepsilon_t'') C_s T_{t_1}^4 S_2 + (\lambda_1 + \lambda_2) \frac{q}{l} (T_{t_1} - T_s). \end{aligned} \tag{2}$$

When the black body is covered by the screen, the detector receives the radiation emitted by the screen and the background radiation reflected by it. In this case the equation of thermal balance is

$$\begin{aligned} &\varepsilon_t' C_s S_1 \sin^2\vartheta_1 [p_{T_z} \varepsilon_z T_z^4 + p_{T_b}(1-\varepsilon_z) T_b^4] \frac{S_2}{S_0} + p_f''' \varepsilon_t' C_s \varepsilon_m S_2 T_m^4 \sin^2\vartheta_2 + \\ &+ p_f''' \varepsilon_t' C_s \varepsilon_{sp} T_{sp}^4 (1-\sin^2\vartheta_2) S_2 + \varepsilon_t' C_s \varepsilon_s T_s^4 S_2 (1-\sin^2\vartheta_2) + \\ &+ \varepsilon_t' C_s S_2 \sin^2\vartheta_2 (\varepsilon_f' T_f^4 + r_f T_s^4) + \varepsilon_t'' C_s \varepsilon_s T_s^4 S_2 = \\ &= (\varepsilon_t' + \varepsilon_t'') C_s T_{t_2}^4 S_2 + (\lambda_1 + \lambda_2) \frac{q}{l} (T_{t_2} - T_s). \end{aligned} \tag{3}$$

The left-hand sides of (2) and (3) differ only in their first terms. The time interval during which the radiation of the black body is replaced by the radiation of the screen is very short, of the order of a few seconds. Assuming that a steady thermal state has been reached, the temperatures of the focusing mirror T_m, the body of the pyrometer T_{sp}, the forward window T_f, and the RTE screen T_s will not change during this short time. Consequently, the power emitted by these elements and received by the detecting plate of the active junction of the RTE will not change.

Subtracting (3) from (2), we obtain

$$\begin{aligned} &\varepsilon_t' C_s S_1 \sin^2\vartheta_1 [p_{T_0} \varepsilon_0 T^4 + p_{T_b}(1-\varepsilon_0) T_b^4 - p_{T_z} \varepsilon_z' T_z^4 - p_{T_b}(1-\varepsilon_z) T_b^4] \frac{S_2}{S_0} = \\ &= (\varepsilon_t' + \varepsilon_t'') 4 C_s T_{t_2}^3 S_2 \tau + (\lambda_1 + \lambda_2) \frac{q\,\tau}{l}, \end{aligned} \tag{4}$$

where

$$\tau = T_{t_1} - T_{t_2}, \quad T_{t_1}^4 - T_{t_2}^4 = 4 T_{t_2}^3 \tau.$$

Defining the sensitivity of the vacuum thermoelement by

$$\varepsilon' = \varepsilon_t' B / 4 T_{t_2}^3 C_s (\varepsilon_t' + \varepsilon_t'') S_2 + (\lambda_1 + \lambda_2) \frac{q}{l},$$

we can rewrite (4) in the form

$$\begin{aligned} &C_s S_1 \sin^2\vartheta_1 [p_{T_0} \varepsilon_0 T^4 + p_{T_b}(1-\varepsilon_0) T_b^4 - p_{T_z} \varepsilon_z T_z^4 - p_{T_b}(1-\varepsilon_z) T_b^4] \frac{S_2}{S_0} = \\ &= B\tau/\varepsilon' = \Delta U/\varepsilon'. \end{aligned} \tag{5}$$

As mentioned above, the emitter had the form of a heated multiple-chamber black body, while the screen used to cover the heated body was also in the form of a multiple-chamber black body. In this case $\varepsilon_0 = \varepsilon_z = 1$ and Eq. (5) becomes

$$C_sS_1\sin^2\vartheta_1(p_{T_0}T^4 - p_{T_z}T_z^4)\frac{S_2}{S_0} = \frac{\Delta U}{\varepsilon'}. \tag{6}$$

Separating p_{T_0} and p_{T_Z} into factors

$$p_{T_0} = p'_a R'_m, \quad p_{T_z} = p''_a R''_m$$

and, taking into account that for two black bodies whose temperatures are not too different $p'_a = p''_a = P$, $R'_m = R''_m = R$, we obtain

$$C_sS_1\sin^2\vartheta_1 PR(T^4 - T_z^4)\frac{S_2}{S_0} = \frac{\Delta U}{\varepsilon'}. \tag{7}$$

For large distances L

$$\sin\vartheta_1 = D/2L. \tag{8}$$

The area of the image S_0 of the object S_1 in the focal plane of the mirror is given by

$$\frac{S_1}{S_0} = (L/f)^2, \quad S_0 = S_1(f/L)^2. \tag{9}$$

Substituting (8) and (9) into (7), we obtain

$$P\frac{C_s(T^4 - T_z^4)}{4}\left(\frac{D}{f}\right)^2 S_2R = \frac{\Delta U}{\varepsilon'}. \tag{10}$$

Hence

$$P = \frac{\Delta U/\varepsilon'}{\dfrac{C_s(T^4 - T_z^4)}{4}\left(\dfrac{D}{f}\right)^2 S_2R} = \frac{W}{W_0}. \tag{11}$$

Expression (11) determines the total transmittance of the atmosphere P.

T, T_Z, and ΔU are measured in the course of the experiment and the quantities D, f, R, S_2, and ε' are known from the design data of the setup.

In the case of the short-focus system (F = 500 mm, D = 280 mm), the signal from the RTE was fed directly to a galvanometer. In the long-focus system the signal was preamplified by means of photoelectrooptical amplifiers, whose sensitivity was calibrated before each measurement by a signal from a standard potentiometer.

The RTE was calibrated by means of a perfectly black body in the laboratory, at 293°K ambient temperature. Therefore, in measurements carried out under field conditions a correction was used to account for the change of sensitivity of the thermoelement with changing ambient temperature.

The black body was mounted on an automobile trailer in a plywood housing, in order to prevent direct exposure to wind. The heating current for the emitter was taken from a generator in the automobile to which the trailer was attached. After steady state was reached, the temperature of the black body was held constant to within ±1°.

Due to the use of an automobile, it was possible to obtain 12-13 experimental points at distances from 25 to 2000 m in 50 min to 1 hr and 20 min.

The atmospheric conditions were continuously measured. For each curve we indicate the ambient temperature t°C, the barometric pressure H, the relative humidity, and the thickness of the condensed water layer w.

The experimental results are shown in the form of graphs $P = f(L)$ at T = const and $P = f(T)$ at L = const (Figs. 2, 3).

The total transmittance decays quite rapidly with increasing layer thickness (Fig. 2). The temperature dependence for five distances is shown in Fig. 3. During the experiment the black body was positioned at one of these distances and its temperature was changed stepwise. One cycle of measurements, consisting of about 25 experimental points from 320 to 570°K, took 1.5-2.5 hr. When curves 1, 2, 3, and 4 (Fig. 3) were taken, the atmospheric conditions were practically constant during this period of time. Curve 5 is based on data measured on different days.

The graphs show that in the temperature range considered the transmittance of a horizontal layer of the atmosphere is practically independent of the temperature of the emitter, although a small increase in transmittance with increasing emitter temperature can be observed in all the curves (Fig. 3). For example, at a distance of 1000 m an increase of the emitter temperature from 350 to 565°K resulted in an increase in P by 12%, and at a distance of 75 m by only 5%.

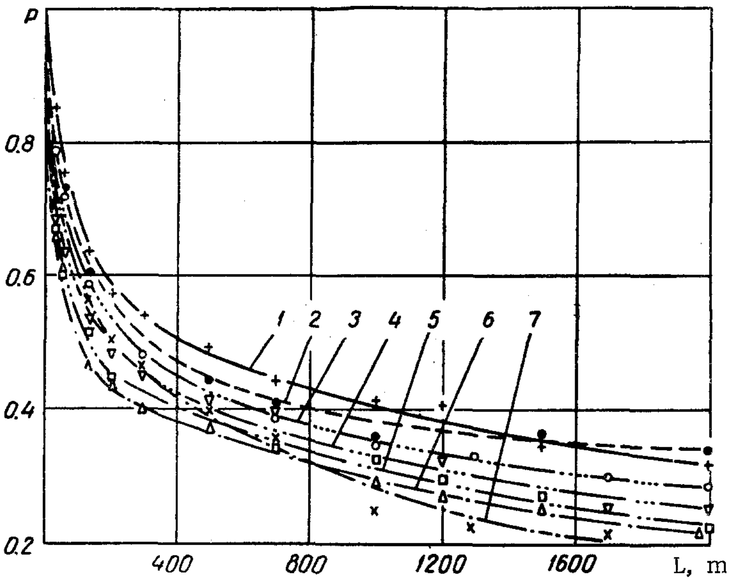

Fig. 2. Transmittance of the atmosphere as a function of distance for T = const: 1) T = = 426°K; t = −5°C; H = 101924.6 N/m²; humidity 95%; ω = 3.1 · 10^{-3} mm/m (night); 2) 542; 10.7; 102924; 67; 6.25 · 10^{-3}, 3) 356; −1; 101991; 92; 4.14 · 10^{-3}; 4) 535; 31.8; 102524; 41; 13.7 · 10^{-3}; 5) 426; 28.0; 102791; 41; 11.25 · 10^{-3}; 6) 350; 21; 102434.6; 42; 7.75 · 10^{-3}; 7) 425; 5; 103124; 5; 91; 6.25 · 10^{-3}.

A change in the temperature of the black body from 323 to 580°K resulted in a shift of the spectral maximum of the radiation toward shorter wavelengths, from 9 to 5 μ. The black body has a broad emission spectrum. For example, 95% of the energy emitted by a perfectly black body at the temperature 323°K falls in the wavelength range from 2 to

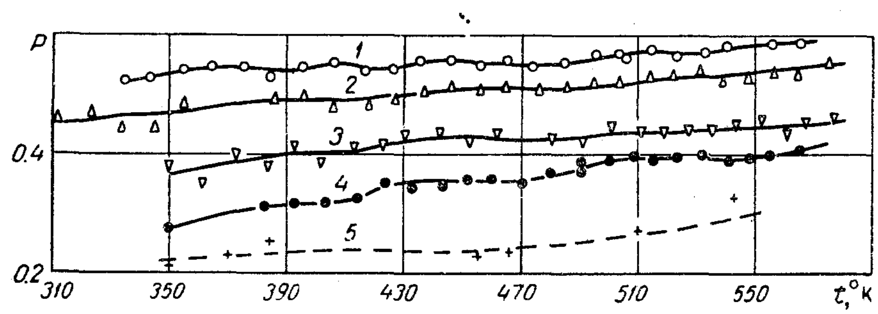

Fig. 3. Transmittance of the atmosphere as a function of emitter temperature for L = const: 1) L = = 75 m; t = 23°C; H = 102177.9 N/m²; humidity 53%; ω = 10.87 · 10^{-3} mm/m; 2) 200; 19.8; 102763.4; 38; 9.02 · 10^{-3}; 4) 1000; 6.4; 101524.7; 80; 9.02 · 10^{-3}; 4) 1000; 6.4; 101524.7; 80; 5.94 · 10^{-3}, 5) 2000; 2-19.3; 102258–102924; 49–90; 5.2 · 10^{-3} –8.2 · 10^{-3}.

40 μ. Therefore, with changing emitter temperature the weights of the separate absorption bands of water vapor and carbon dioxide in the atmosphere change with respect to their contribution to the total absorptivity. This explains the weak dependence of the transmittance P on the emitter temperature (Fig. 3).

The effect of atmospheric conditions on the transmission of black-body radiation through a horizontal layer of air is seen in curves 1, 5, and 7 (Fig. 2), obtained for identical emitter temperature under different weather conditions.

When the temperature of a distant object is measured by means of a radiation pyrometer, it is sometimes impossible to determine exactly the atmospheric conditions. When there are no specific atmospheric disturbances (fog, smoke), the experimental curves P = f(L) (Fig. 2) lie close together in a relatively narrow band. Consequently, in the range of black-body temperatures 350-542°K, ambient temperatures in the range from −5 to +31.8°C, and condensed water layer thicknesses in the range $3.1 \cdot 10^{-3}$ –$13.7 \cdot 10^{-3}$ mm/m, all the experimental curves (Fig. 2) can be replaced by an average $P_{av} = f(L)$ with a scatter $\Delta P = \pm 0.09$.

However, in order to obtain exact values of the total transmittance of the atmosphere P it is necessary to know the atmospheric conditions and, at least, the approximate value of the temperature of the emitter.

NOTATION

T, S_1, ε_0, p_{T_0} – temperature, area, and emissivity of emitting object, and transmittance of all media between emitter and detector; T_Z, ε_Z, p_{T_Z} – corresponding values for screen covering black body; T_t, T_s, T_f, T_m, T_{sp} – temperatures of detecting plate of RTE, RTE screen, forward window, mirror, and pyrometer body; ε_f, ε_s, ε_t', ε_t'', ε_m, ε_{sp} – emissivities of forward window, RTE screen, front and back surfaces of detecting plate of RTE, mirror, and pyrometer body; S_2 – area of detecting plate of RTE; D, f – diameter and focal length of mirror; r_f – total reflectivity of forward window with respect to radiation emitted by screen of RTE; p_a', p_a'' – total transmittances of atmosphere with respect to radiation emitted by hot object and by screen; R_w', R_w'' – total reflectivities of mirror with respect to radiation emitted by hot object and by screen; λ_1, λ_2 – thermal conductivity of wires of RTE; q, l – cross section and length of wires of RTE; B – specific thermal emf of elements of thermocouple of RTE; ΔU – emf at terminals of RTE measured by measuring system.

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Ul'yanov-Lenin Electrotechnical Institute,
Leningrad