UDC 536.3

MEASUREMENT OF RADIANT PROPERTIES OF A FLAME BY A RADIOMETER WITHOUT CONDENSING AGENTS

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A radiometer without condensing agents for the measurement of the radiant properties of a flame is described. In contrast with Schmidt's method, the instrument is insensitive to turbulent fluctuations of the flame.

A widely used method of measuring the total radiation and emissivity of flames and gas layers is the Schmidt method [1, 2], in which a total-radiation radiometer is used to measure the radiation (more exactly the radiation intensity) of the flames on the background of a "cold" black body (water-cooled enclosure with a small opening)

$$I_c = I_f = \varepsilon_f \frac{\sigma_0}{\pi} T_f^4. \tag{1}$$

Subsequently, the radiation of the flame is measured on the background of a "hot" black body (an ordinary source of practically black radiation with controlled temperature)

$$I_h = I_c + (1 - a_f) I_0. \tag{2}$$

Using these results and the known value of I_0, one can determine the effective absorptivity of the flame for radiation at the temperature T_0 used during the measurement:

$$a_f = 1 - (I_h - I_c)/I_0. \tag{3}$$

In addition to that, one can determine the effective temperature of the flame

$$T_f = \sqrt[4]{\pi I_c/\varepsilon_f \sigma_0}. \tag{4}$$

The variable ε_f of a selectively emitting flame in a nonequilibrium temperature field cannot be determined exactly. Usually one assumes $\varepsilon_f = a_f$ in equation (4).

The advantage of this method is the metrologically correct determination of two physical characteristics of the flame (I_f and a_f) with no distortion of the flame. However, the advantage cannot be fully utilized with ordinary total-radiation pyrometers due to the selectivity of their optical systems.

Since the flame is always selective, the measurement of its radiation by means of an instrument with selective sensitivity is associated with systematic errors which are difficult to compensate. Additional errors are introduced by the unavoidable contamination of the optical system. The commonly used blackened radiation receiver is nearly gray [3] and, in the absence of condensing or protective elements, would constitute an instrument with practically no selectivity. The scheme of such an instrument is simple and well known [3, 4], but only in one instance has it been used to measure the radiation of a flame [5], in which case the sensitive element was covered by a fluorite plate, thereby eliminating the basic advantage of the method.

In accordance with the above principle an instrument was constructed with circular orifices in a water-cooled casing. Small quantities of dry nitrogen were continuously blown into the casing to prevent the flame gases from entering the instrument. The secondary instrument was a reflecting galvanometer. The radiation sensor was first constructed in the form of a standard thermopile (a battery of miniature thermocouples in which the hot junctions, which receive the external radiation, are collected on a "target" in the center and the cold junctions are on the periphery). Subsequently, to increase the sensitivity of the instrument, there was developed a technique of preparing thermopiles from 0.1 mm wires of bismuth-antimony and bismuth-tin.

In order to be able to make a rational choice of the parameters of a thermopile, one must know its emf. An exact theory of a vacuum thermopile without convective heat transfer at the electrodes has been developed by Fisher [6].

The problem of calculating the emf of a thermopile can be reduced to the determination of its temperature field. Heat transfer in the thermopile takes place in the following manner. The central "target" absorbs external radiation and loses heat by convection, radiation, and conduction along the electrodes. The electrodes exchange heat by radiation with the walls of the enclosure and by convection with the gas filling the enclosure. In the calculations we make the following assumptions, most of which are identical with Fisher's assumptions [6]: the "target" has a constant temperature over its entire surface; the hot junctions fastened to the "target" are at the same temperature; all electrodes have identical properties and identical temperature distributions; the radiant heat transfer between the electrodes and the transverse temperature gradients in the electrodes is negligible; the external heat flux is constant over the surface of the "target," which is a very good approximation for instruments with a visual angle of up to 15°; the cold junctions are at the temperature of the cooling water; the reflection of the external radiation from the blackened walls of the enclosure is negligible; the enclosure is filled with a diathermic medium at the constant temperature T_w; the coefficients of convective heat transfer are constant along the electrodes and over the surface of the "target"; since the temperature gradients in the electrodes and in the enclosure are not large (hundredths of a degree), the radiant heat transfer may be represented by a value α_r = const. According to actual calculations for an electrode diameter of 0.1 mm and a temperature $T_w = 300$°K, the ratio α_r/α_e is of the order of 0.01-0.04, which makes it possible to neglect the radiant heat transfer from the electrodes.

Drawing up the thermal balance of an element of the electrode, we obtain the equation governing the temperature field of the electrode

$$\frac{\lambda_e f}{u\alpha_e}\frac{d^2T}{dx^2} = T - T_w. \tag{5}$$

The solution of this equation, with the boundary condition at the wall of the enclosure $x = 0$, $T = T_w$, $q = q_0$, is

$$T = T_w + \sqrt{\frac{\lambda_e f}{u\alpha_e}}\,\frac{q_0}{\lambda_e}\,\mathrm{sh}\left(x\sqrt{\frac{u\alpha_e}{\lambda_e f}}\right). \tag{6}$$

From the thermal balance of the target we obtain the heat flux through the electrode at $x = l$:

$$q_{x=l} = \frac{\alpha_t F}{nf}\{R[(T_{h.j.}^4 - T_w^4) - p(T_0^4 - T_w^4)] + (T_{h.j.} - T_w)\}. \tag{7}$$

Since $q_{x=l} = -\lambda_e(dT/dx)_{x=l}$, equations (6) and (7) determine the value q_0. Substituting q_0 in (6), we obtain a relation between $T_{h.j.}$ and T_w. We expand the quantity $T_{h.j.}^4 - T_w^4$ in a power series and truncate the series after the term linear in $T_{h.j.} - T_w$. Since $l\sqrt{u\alpha_e/\lambda_e f} = 8-9$, we have $\mathrm{th}\,(l\sqrt{u\alpha_e/\lambda_e f}) \approx 1$. Finally,

$$T_{h.j.} - T_w = \beta\varepsilon_t\sigma_0 F(T_0^4 - T_w^4)/2n\sqrt{\lambda_e u f\alpha_e} \times [1 + (1 + 4RT_w^3)\alpha_t F/n\sqrt{\lambda_e f u\alpha_e}]^{-1}. \tag{8}$$

The emf developed by the battery is given by the equation

$$E = nE_0(T_{h.j.} - T_w). \tag{9}$$

Equation (8) was checked experimentally by several methods. The readings of the instrument were independent of T_w within a narrow range of T_w (Fig. 1), which follows from equation (8) with $T_0 \gg T_w$, since the value of $4RT_w^3$ is of the order 10^{-1} and $\alpha_t F/n\sqrt{\lambda_e u f\alpha_e}$ is of the order of 10^{-2}.

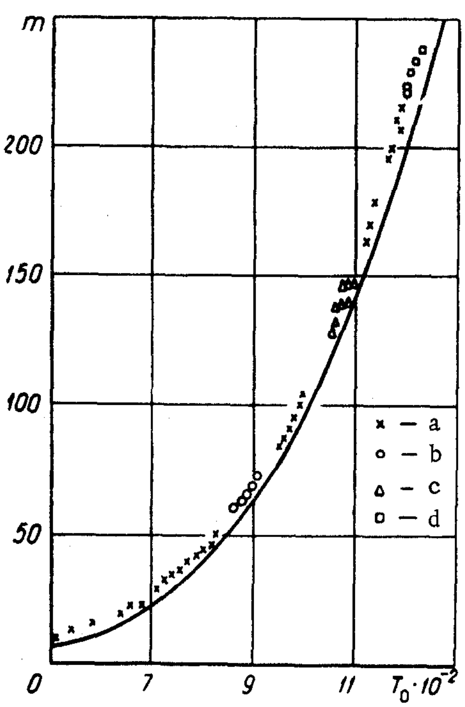

Fig. 1. Comparison of calculated and experimental calibration of the radiometer (T_0 [°K], m [mm]). a) T_w = 13.0°C; b) 14.0°C; c) 17.2-18.2°C; d) 14.5°C.

The experimental results for thermopiles consisting of 1, 12, and 24 junctions were in good agreement with the theoretical curve according to which the emf of a thermopile is practically independent of the number of junctions for n > 10.

The influence of convective heat transfer at the electrodes and at the target was verified by blowing through the radiometer carbon dioxide, the thermal conductivity of which is about one half of that of nitrogen, and comparing the calibration curves.

The discrepancy between the calculated and experimental calibrations of the radiometer by means of a black body was about 5-8 percent (Fig. 1), which allows us to recommend equation (8) for the design and analysis of thermopiles.

The instrument described above was used to measure the radiation from a vertical flame of coke oven gas in a lined combustion chamber. The thickness of the flame was 300 mm. The combustion chamber had openings to which the radiometer and the black bodies were attached by sleeves of vacuum tubing.

Instruments of simple design yielded completely distorted results. The value of a_f varied along the flame in the range 0.5-0.7, which is unrealistically high for a nonluminous gas flame of 300 mm thickness. The flame temperature calculated from (4) was of the order of 400-600°C, which is impossible. In the experiments T_0 varied in the range 1000-1100°C, and the temperature of the core of the flame, as measured by means of a suction thermocouple, was of the order of 1350°C. The measurements yielded in all cases $I_h < I_0$, which in the case when $T_f > T_0$ contradicts the second law of thermodynamics.

The analysis of the experimental data and tests of various modifications of flame configuration and radiometer design led to the hypothesis that the reason for the distorted readings was turbulent pulsations of the flame, which reached the thermopile and increased the values of α_e and α_t.

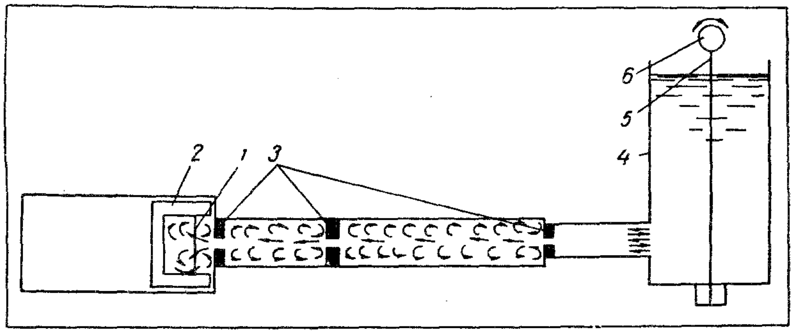

Fig. 2. Scheme of the hydraulic model of the radiometer and eddy currents: 1) thermopile; 2) thermopile casing; 3) orifice plates; 4) water tank; 5) vibrator; 6) load.

To check this hypothesis, we have carried out a qualitative analysis of the motion of nitrogen in the radiometer by means of a hydraulic model. The model of the inner enclosure of the radiometer (Fig. 2) was made of plastic. The analysis was carried out by visual observation of dye flow in water.

The model showed that when the casing of the thermopile is perfectly hermetic and is connected to the outside only through orifice plates, the blowing of nitrogen does not result in a flow around the thermopile and does not affect the readings.

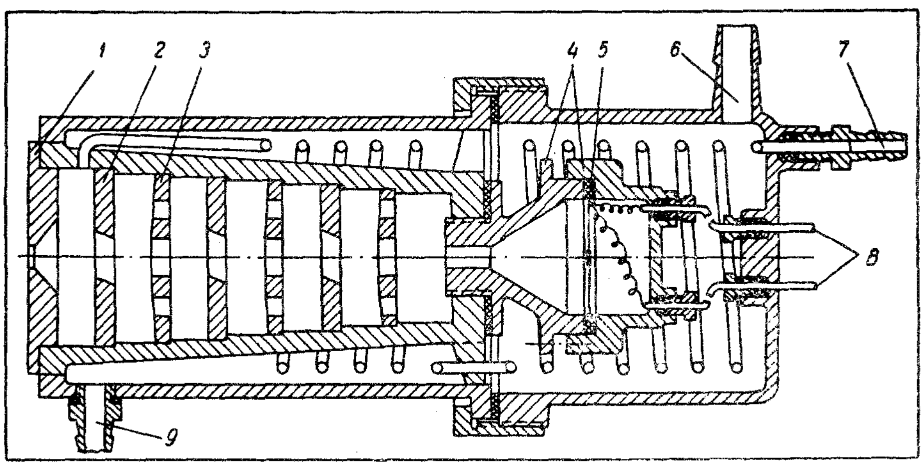

Fig. 3. Scheme of the final design of the radiometer: 1) forward orifice plate; 2) oblique orifice plate; 3) ordinary orifice plate; 4) thermopile casing; 5) thermopile; 6) water outlet; 7) nitrogen inlet; 8) galvanometer leads; 9) water inlet.

The turbulent pulsations of the flame can be regarded as rapid perturbations of pressure and density of the medium which propagate in the form of acoustic waves. Since our modeling was only qualitative, the exact nature of the vibrator, the frequency, and the energy of the vibrations had no significant effect. The use of water was also admissible, as the propagation of sound in a liquid and in a gas is identical [7, 8]. The vibrator (Fig. 2) consisted of a steel plate with a load at the upper end. Pulling and then releasing the plate one could set it in damped oscillatory motion.

The tests showed that the orifice plates of the instrument are sources of intensive motion of the fluid. Each compression wave pushes through the orifice a small volume of liquid, which rapidly turns into a vortex ring. The ring flows away from the orifice and induces a vortex flow. The vortex rings produced by each compression wave follow one another and result in a steady turbulent flow of the fluid in the entire section behind the orifice (Fig. 2). Expansion waves result in an analogous flow in the opposite direction.

The fluid particles undergo an oscillatory motion in the sound wave [8], which should also affect the convective heat transfer at the thermopile. Under conditions of free convection and low-frequency pulsations, the intensification of the heat transfer can reach 100% [9] and in accordance with (8) can result in errors of 25%. Thus the design of a radiometer should guarantee not only the complete absence of eddy flows in the thermopile casing, but also should provide maximum damping of waves produced by flame pulsations.

The model tests showed the following principles of eddy formation: When nitrogen flows through an orifice, no vortex rings are formed, as the stream carries away the fluid volume flowing out from the orifice, but the sound wave does propagate through the orifice. The diameter of the vortex rings, their velocity, and their depth of penetration into the region behind the orifice decrease with increasing orifice diameter and orifice plate thickness. This explains the complete absence of eddy flow in the thermopile casing shown in Fig. 3, with conical forward orifice and thick orifice plates.

Clearly, the eddy flows in the orifices are induced at the expense of the energy of the acoustic wave, and to decrease this energy it is necessary to develop, as far as possible, the eddy flow between the orifice plates. The strongest damping of pulsations is obtained by a combination of ordinary orifice plates and plates with oblique surfaces (Fig. 3). The latter produce a vortex ring which propagates along the orifice axis and is displaced with respect to the optical axis of the radiometer. Thus, this ring cannot contribute to vortex formation at the next orifice. The energy losses of the acoustic wave are highest in this arrangement. The effectiveness of the additional orifices was proved by actual measurements of flame radiation.

Figure 3 shows an instrument designed in accordance with the above considerations, which is insensitive to pulsations. The inner casing of the instrument and the orifice plates were made of copper for better equalization of temperature. For the same reason the orifice plates were soldered into the casing. Both experiment and theory showed that the thermopile casing should have the lowest thermal inertia possible, otherwise the time-variations of the cooling water temperature would lead to nonuniform heating of the casing, and thus would result in a scatter of the readings. Therefore, the copper casing is in direct contact with the cooling water. For better temperature equalization, the nitrogen passes through a coil submerged in the cooling water before it is blown into the orifice section.

The scatter of the readings during calibration by means of a black body was not more than 1%. An elementary error estimate of Schmidt's method in the given modification yields the following maximum possible errors: in I_f – 1.5%, in a_f – 6.5%, and in T_f – 5%. The accuracy actually obtained in practice was less: the scatter of the readings obtained with a flame was 10-15%.

NOTATION

a_f – absorptivity of flame; E – emf of thermopile; E_0 – specific emf of one thermocouple; F – surface area of "target" (one side); f – cross section of electrode; I_c and I_h – results of flame radiation measurement on a background of a "cold" and a "hot" black body, respectively; I_f – radiation intensity of flame; I_0 – radiation intensity of black body at temperature T_0; l – length of electrode from its point of attachment to the casing to the "target"; n – number of junctions in thermopile; $p = \beta\varepsilon_t/(\varepsilon_e + \varepsilon_t)$; q – heat flux in electrode; $R = \sigma_0(\varepsilon_e + \varepsilon_t)/2\alpha_t$; T_f – flame temperature; T_w – cooling water temperature; $T_{h.j.}$ – temperature of hot junctions of thermopile; u – electrode circumference; x – coordinate along electrode; α_r, α_e, and α_t – coefficients of radiant heat transfer in the thermopile enclosure, convective heat transfer at the electrode surface, and convective heat transfer at the "target"; β – shape factor emitter-thermopile; ε_f – emissivity of flame; ε_e and ε_t – emissivity of electrode and "target," respectively; λ_e – thermal conductivity of electrode; σ_0 – Stefan-Boltzmann constant; m – galvanometer reading.

REFERENCES

1. M. R. Kissel, Journeé d'études sur les Flames, Fevier, 1958.
2. A. E. Kadyshevich, Measurement of Flame Temperature [in Russian], Metallurgizdat, 1961.
3. G. Ribo, Optical Pyrometry [in Russian], GTTI, 1934.
4. A. G. Blokh, Fundamentals of Radiative Heat Transfer [in Russian], GEI, 1962.
5. M. A. Styrikovich and E. V. Stashkevich, ZhTF no. 2, 1936.
6. M. S. Zeltser, ZhTF, no. 2, 1936.
7. A. P. Mel'nikov, Fundamentals of Theoretical Aerodynamics [in Russian], 1953.
8. E. Skuchik, Fundamentals of Acoustics [in Russian], IL, 1958.
9. A. S. Shternberg, Teploenergetika, no. 8, 1962.

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