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MEASUREMENT OF GAS-FLOW TEMPERATURES BY TWO THERMOCOUPLES

V. I. Men'shikov

UDC 536.532:533.6.011

A method for determination of the true temperature of a gas flow by two thermocouples is proposed. Results of an experimental verification are presented.

To reduce errors in measurement of gas-flow temperatures, either a thermocouple with very fine conductors (0.05 mm) or several thermocouples with conductors of different diameter are used [1]. Below, we offer a more accurate method of measurement with two thermocouples.

Let the hot junction of the thermocouple have the shape of a sphere with diameter d and with a conductor diameter equal to 2r. The two metals or alloys forming the thermocouple junction have coefficients of thermal conductivity λ_1 and λ_2, respectively. We assume that the conductors are located in an insulating medium of thickness δ, with coefficient of thermal conductivity λ_3.

Upon placement of the thermocouple junction in a high-temperature gas flow it will be heated by convective heat transfer. At the same time, the junction will be cooled by loss of heat through radiation and thermal conductivity of the free ends of the thermocouple. Obviously, for the steady state

$$P_c = P_r + P_t, \tag{1}$$

where P_c is the power conveyed to the junction by convective heat transfer; P_r is the power lost by the junction through radiation; and P_t is the power lost through thermal conductivity.

The power supplied by convective heat transfer is determined by Newton's formula

$$P_c = \alpha_1 (T_g - T_1) S, \tag{2}$$

where α_1 is the coefficient of convective heat liberation; T_g is the temperature of the gas flow, °K; T_1 is the junction temperature, according to its calibration, °K; and S, is the area of the heat-exchange surface, πd^2.

Institute of Geochemistry, Siberian Branch, Academy of Sciences of the USSR, Irkutsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 31, No. 5, pp. 794-799, November, 1976. Original article submitted October 28, 1975.

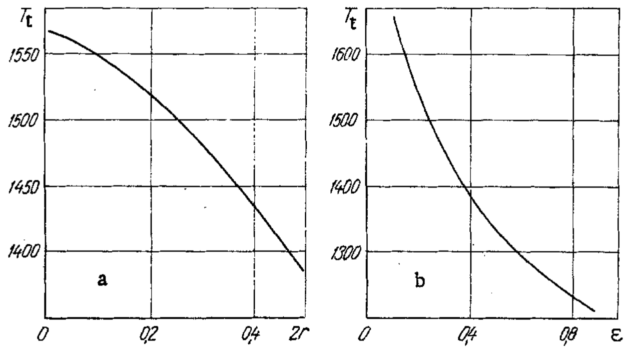

Fig. 1. Thermocouple-junction temperature versus: a) diameter of thermocouple conductor (ε = 0.21 = const; T_g = 2065°K; α = 143 W/m^2 · deg; d = 3 mm); b) integral emissivity of junction material (d = 3 mm; 2r = 0.2 mm; T_g = 2065°K; α = 143 W/m^2 · deg.

The power radiated by the junction for gases which are transparent in the visible range of the spectrum can be given in the form

$$P_r = \varepsilon_1 C_0 \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_m}{100} \right)^4 \right] S, \tag{3}$$

where ε_1 is the integral emissivity of the junction material; C_0 is a constant equal to 5.69 W · m^{-2} · deg^{-4}; and T_m is the temperature of the surrounding medium, °K.

The power lost by the junction through thermal conductivity will be proportional to the difference between temperatures T_1 and T_m:

$$P_t = \Lambda (T_1 - T_m), \tag{4}$$

where Λ is the generalized thermal conductivity with consideration of heat loss from the junction by thermal conductivity of the metallic conductors and insulators through convective cooling of the thermocouple ends. We have taken the expression for Λ in the case of conductors with identical diameters in the form [2]

$$\Lambda = \pi (\sqrt{\lambda_1} + \sqrt{\lambda_2})\, r \sqrt{\frac{2r}{\frac{1}{\alpha_3} + \frac{\delta}{\lambda_3}}}, \tag{5}$$

where α_3 is the coefficient of convective heat liberation for cooling of the free ends of the thermocouple.

Substituting Eqs. (2), (3), and (4) into Eq. (1) and solving for T_g, we have

$$T_g = T_1 + \frac{\varepsilon_1 C_0}{\alpha_1} \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_m}{100} \right)^4 \right] + \frac{\Lambda}{\alpha_1 \pi d^2} (T_1 - T_m). \tag{6}$$

It follows from Eq. (6) that the gas temperature is higher than the temperature indicated by the thermocouple. It also follows that to produce a minimum error in the determination of T_g, i.e., to reach a maximum in T_1 (with consideration of the calibration range of the thermocouple) it is necessary not only to reduce r, but also to choose a type of thermocouple with the lowest value of ε. If we assume that the greatest error in gas-temperature determination will be produced by the third term of the right side of Eq. (6), then it is also desirable to increase the diameter of the junction. Obviously, upon increase in d it is necessary to fulfill the condition

$$P_c \ll P_g,$$

where P_g is the power of the gas flow.

With the exception of α_1, the parameters appearing in Eq. (6) may be taken from the literature. The coefficient of convective heat liberation α_1 for heating of a thermocouple junction by a gas flow depends on the geometric dimensions of the junction, the velocity of the gas flow, and also on the thermal conductivity

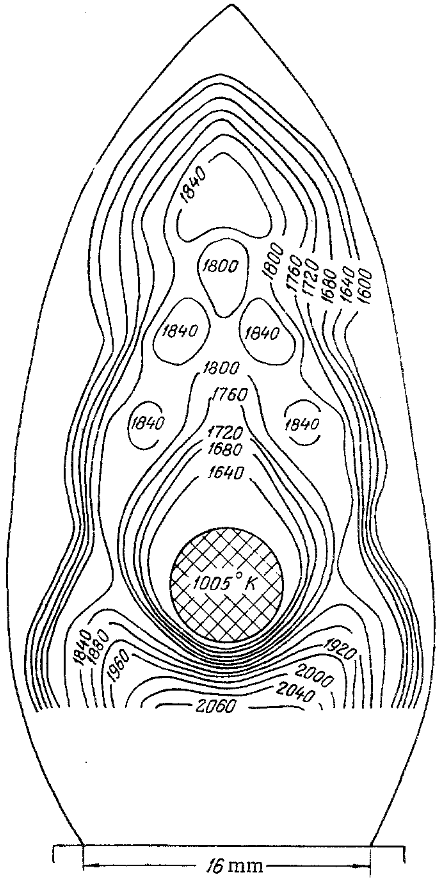

Fig. 2. Temperature field of propane–air flame for flow over a carbon cylinder.

and viscosity of the gas in the flow. The gas composition is not always known, and moreover, the physical properties of the gas must be determined at a temperature that is unknown to us.

We will place a second thermocouple, with one parameter changed, at the same point of the gas flow. We maintain unchanged the geometric dimensions and type of the thermocouple, but change the integral emissivity of the thermocouple junction. Then for the second thermocouple, in analogy to Eq. (6), we may write

$$T_g = T_2 + \frac{\varepsilon_2 C_0}{\alpha_2}\left[\left(\frac{T_2}{100}\right)^4 - \left(\frac{T_m}{100}\right)^4\right] + \frac{\Lambda}{\alpha_2 \pi d^2}(T_2 - T_m), \tag{7}$$

where T_2 is the junction temperature of the second thermocouple, °K; α_2 is the coefficient of heat liberation for convective heating of the second thermocouple.

For identical heating geometry and identical processing of the heated bodies, with no change in gas-flow parameters, we may assume that $\alpha_1 = \alpha_2 = \alpha$. If $\varepsilon_2 > \varepsilon_1$, then subtracting Eq. (7) from Eq. (6) and solving for α, we obtain

$$\alpha = \left\{\varepsilon_2 C_0\left[\left(\frac{T_2}{100}\right)^4 - \left(\frac{T_m}{100}\right)^4\right] - \varepsilon_1 C_0\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_m}{100}\right)^4\right] + \frac{\Lambda}{S}(T_2 - T_1)\right\}\{T_1 - T_2\}^{-1}. \tag{8}$$

Calculating α from Eq. (8) and substituting its value into Eq. (6) or Eq. (7), we find the gas temperature T_g. Obviously, the proposed approach is convenient for relatively low junction temperatures, at which the value of ε is stable, and for pure flows, where radiative heat exchange between junction and flow may be neglected.

The proposed method was verified experimentally by determining the temperature of a propane–air flame. Two type PP platinum–rhodium/platinum thermocouples were used, with identical conductor diameter 2r, equal to 0.5 mm. For one thermocouple the junction of diameter 3 mm was produced by melting the conductors in an electric arc. The junction thus obtained was brought to a polished surface. The junction of the second thermocouple (1 mm) was covered by a polished sphere of diameter 3 mm, prepared from chromium–nickel stainless steel, with a hole drilled to a depth of 1.5 mm. The conductors of both thermocouples were covered by porcelain tube insulators with wall thickness 1 mm and internal diameter 0.6 mm. Thermo-emf was measured by type PP potentiometers. Thermocouple calibration was checked by comparison of thermo-emf indications with those of a reference thermocouple during simultaneous measurements of the temperature of a massive heated body. The coefficients of thermal conductivity for platinum, platinum–rhodium (10% Rh), and porcelain were taken from [3] as 71, 36, and 0.22 $W \cdot m^{-1} \cdot deg^{-1}$. The temperature of the surrounding medium was 300°K.

The coefficient of heat liberation α_3 for air draft over the thermocouple ends was calculated from the formula [4]

$$\mathrm{Nu}_f = 0.8\sqrt{\mathrm{Re}_f},$$

where Nu_f is the Nusselt number; Re_f is the Reynolds number.

At an air-draft rate of 0.6 m/sec, the coefficient α_3 was equal to 29.5 $W \cdot m^{-2} \cdot deg^{-1}$.

The emissivity of the stainless steel for multiple oxidation at 920°C and the same junction temperature was taken as 0.70 [5]. For the platinum–rhodium junction at a temperature of 1110°C the emissivity was 0.21 [5]. It should be noted that upon oxidation of the steel sphere a change in emissivity is clearly noticeable. Thus, upon placing the unoxidized sphere and thermocouple in the flame, the initial temperature indications were ~1040°C. After two or three periods of oxidation in air, the indications stabilized at a value 120° lower than the original. This fact may be used to check the change in emissivity of the thermocouple junctions.

The temperature of the propane–air flame calculated from Eqs. (5), (6), and (8) for the stoichiometric regime was 2065°K. Measurements were performed at a height of 10 mm above the flame-forming grid. Thermocouple-junction temperatures were 1198 and 1383°K. Thus, the gas temperature T_g for $\varepsilon = 0.21$ was composed of the terms $T_g = 1383 + 308 + 374 = 2065$°K. Reproducibility of results for one and the same point at the center of the flame was characterized by a variation coefficient not exceeding 0.5%. For the stoichiometric regime in this flame the following calculated temperature values are available: 2384°K to an accuracy of 2–4° [6] and 2080°K [7].

It should be noted that the coefficient of convective heat liberation in the propane–air flame found experimentally from Eq. (8) and equal to 143 $W \cdot m^{-2} \cdot deg^{-1}$ agrees with the calculated value of 158. The latter value of α was obtained with the criterial equation obtained in [8] for flow over cylinders of stainless steel and nickel of a propane–oxygen flame. This equation was verified in [8] for Reynolds numbers Re_f = 30-800. Since at temperatures of ~2100°K dissociation of combustion products is insignificant [6], we took this equation in the form

$$\mathrm{Nu}_f = 0.5\,\mathrm{Re}_f^{0.5}\,\mathrm{Pr}_f^{0.37}\,(T_f/T_\omega)^{-0.0133}, \tag{9}$$

where Pr_f is the Prandtl number.

Solving this equation for α, we have

$$\alpha = \frac{0.5\lambda\left(\frac{\omega d}{\nu}\right)^{0.5}\left(\frac{\nu}{a}\right)^{0.37}(T_f/T_\omega)^{-0.0133}}{d}, \tag{10}$$

where ω is the gas-flow velocity; λ is the coefficient of thermal conductivity of the gas; ν is the coefficient of kinematic viscosity; a is the coefficient of thermal diffusivity; T_f is the gas temperature, °K; and T_ω is the body temperature, °K.

Since the combustion products of a propane–air flame, like air itself, consist of 78% nitrogen, to evaluate α the gas parameters were calculated for air.

For T_f = 2065°K the following values were obtained: $\lambda = 0.50$ W/m · deg; $\nu = 3.75 \cdot 10^{-4}$ m²/sec; and $a = 2.51 \cdot 10^{-3}$ m²/sec.

Gas-flow velocity was equal to 2 m/sec. In our case $\mathrm{Re}_f = 16$.

Optimization of thermocouple parameters for gas-flow-temperature measurement is of great interest. If Eq. (6) is solved for thermocouple temperature T_t, we obtain an equation relating the thermocouple-junction temperature to the thermocouple parameters:

$$\frac{\varepsilon C_0}{100^4}T_t^4 + \left(\frac{\Lambda}{\pi d^2} + \alpha\right)T_t = \alpha T_g + \varepsilon C_0\left(\frac{T_m}{100}\right)^4 + \frac{\Lambda}{\pi d^2}T_m. \tag{11}$$

A numerical solution of this equation for a flame with a temperature of 2065°K is shown in Fig. 1a, b.

As follows from Fig. 1a, it is desirable to reduce the conductor diameter to about 0.1 mm; further reduction in diameter does not give a large increment in junction temperature and produces technological difficulties.

The thermocouple temperature depends most strongly on the emissivity of the junction material (Fig. 1b). It is obvious that under given conditions it is desirable to cover the junction with materials having a suitable emissivity. For example, at lower temperatures a gold coating may be used.

As an example of the actual use of the method, Fig. 2 presents the temperature field of a propane–air flame for flow over a carbon cylinder, as constructed from measurements by the method described above. Measurements were performed simultaneously by two thermocouples located at different sections of the flame, but at one and the same point of the plane of intersection of the extended flame with the rectangular flame-forming grid (16×110 mm). The carbon bar heated by an electric current acts an an evaporator for solid test specimens in the flame atmosphere (a furnace-flame atomizer), as used in atomic absorption analysis. As is evident from Fig. 2, at low temperatures the bar forms a "cold" region in the "tail" of the flame, which has a negative effect on dissociation of the compounds of the specimen to be analyzed. The data of Fig. 2 permit the conclusion that this geometry for flame flow over the evaporator is not optimum. The complex character of the temperature isolines indicate the turbulent nature of gas flow in the "tail."

We note that the coefficient α determined experimentally for the carbon cylinder ($d = 6$ mm) under the condition $P_c = P_r$ proved to be 2.3 times smaller than the value calculated from Eq. (10), which is evidently connected with the high absorption capability of the material and the formation of a thermally insulating gaseous film.

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