A TEMPERATURE DISTRIBUTION STUDY IN CROSS SECTIONS OF AXIALLY SYMMETRIC FLAMES

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A technique for determining temperature profiles and emissivities of combustion products in the cross section of a flame from experimentally measured spectral radiation intensities is considered. The optical electronic system used to investigate temperature fields is described, and results on the temperature distribution and emissivity of combustion products in the flame cross section obtained by the concentric zone method are given.

A substantial number of real industrial flames are characterized by large temperature gradients of the combustion products over the flame cross section and length due to nonuniformity of the fuel and oxidizer distribution in the flame volume, the temperature of combustion products depending on coordinates and time.

In studies of the combustion process, calculation of heat fluxes produced by combustion products and solution of other problems, temperature distributions over the cross section, and individual zones of the flame should be known. The thermocouple method is often inapplicable or too labor-consuming. In this case, optical methods are preferable for temperature measurements of combustion products.

At present, there are quite a few optical electronic scanning systems for temperature measurement [1] which carry out control, measurement, and visualization of temperature fields and perform digital information processing. However, these systems are not able to measure real temperatures when emissivity of combustion products is unknown or varying. The use of polychromatic holographic interferometry [2] or spectral tomographic diagnostics [3] in real industrial flames is practically impossible because of the lack of appropriate experimental equipment capable of working in field conditions.

As early as 1954, O. N. Dubrovskaya [4, 5] suggested two methods which were intended for prediction of approximate true temperature distribution in a flame from experimentally measured true or brightness temperatures averaged along the chords. They are the method of concentric zones and the trial and error method. In order to find the cross-sectional temperature distribution of the axisymmetric flames, we used the method of concentric zones. The principle of the method is that the flame cross section is partitioned into several concentric zones and in each zone the temperature of combustion products is assumed constant; it changes discontinuously from one concentric zone to another. A similar condition is imposed on the absorption coefficient of combustion products.

Radiation and absorption in each concentric zone under thermodynamic equilibrium are determined by the temperature and emissivity of combustion products. The scheme of partition of the a flame cross section into concentric zones is given in Fig. 1.

With dissipation neglected, the equation for radiation transfer along the various chords (see Fig. 1) may be written in the form

$$\begin{gathered}
I_{\lambda \mathrm{h}} = I_{0\lambda}(T_4)\alpha_4 l_{\mathrm{h}},\\
I_{\lambda \mathrm{g}} = I_{0\lambda}(T_4)\alpha_4 l_{\mathrm{g}4}[1 + (1-\alpha_4 l_{\mathrm{g}4})(1-\alpha_3 l_{\mathrm{g}3})] + I_{0\lambda}(T_3)\alpha_3 l_{\mathrm{g}3}(1-\alpha_4 l_{\mathrm{g}4}),\\
I_{\lambda \mathrm{f}} = I_{0\lambda}(T_4)\alpha_4 l_{\mathrm{f}4}[1 + (1-\alpha_4 l_{\mathrm{f}4})(1-\alpha_3 l_{\mathrm{f}3})] + I_{0\lambda}(T_3)\alpha_3 l_{\mathrm{f}3}(1-\alpha_4 l_{\mathrm{f}4}),\\
\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots
\end{gathered} \tag{1}$$

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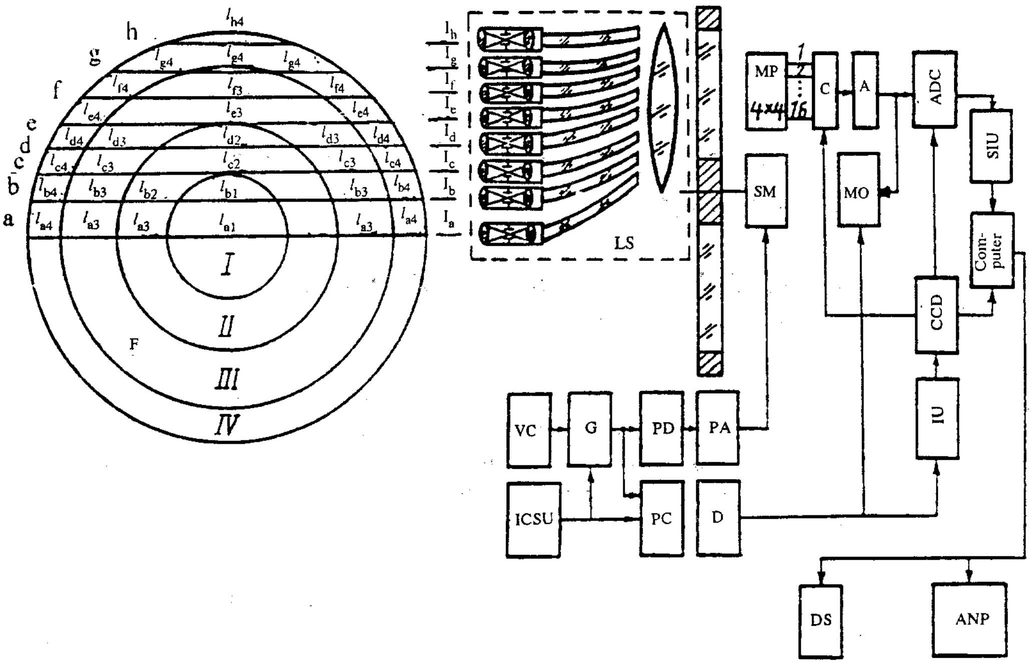

Fig. 1. The scheme of concentric zones of the flame cross section and optical electronic system used to investigate the temperature fields: F) flame; I, II, III, IV) numbers of concentric zones; a, b, c ... h) chords along which the spectral radiation intensities I_a, I_b ... I_h are measured; LS) lens; MP) mosaic photodetector; C) commutator; A) amplifier; ADC) analog-to-digital converter; SM) stepping motor with a cassette containing accessory light filters; VC) voltage control; ICSU) initial cassette setting unit; G) generator; PD) pulse distributor; PC) pulse counter; PA) power amplifier; D) decoder; SIU) standard interface unit; CCD) central control device; IU) interface unit; ACP) automatic character printer; DS) display; MO) mirror galvanometer oscillograph.

$$\begin{aligned} I_{\lambda a} = {} & I_{0\lambda}(T_4)\alpha_4 l_{a4}[1+(1-\alpha_4 l_{a4})(1-\alpha_3 l_{a3})^2(1-\alpha_2 l_{a2})^2 \times \\ & \times(1-\alpha_1 l_{a1})] + I_{0\lambda}(T_3)\alpha_3 l_{a3}(1-\alpha_4 l_{a4})[1+(1-\alpha_3 l_{a3})(1-\alpha_2 l_{a2})^2 \times \\ & \times(1-\alpha_1 l_{a1})] + I_{0\lambda}(T_2)\alpha_2 l_{a2}(1-\alpha_4 l_{a4})(1-\alpha_3 l_{a3})[1+(1-\alpha_2 l_{a2}) \times \\ & \times(1-\alpha_1 l_{a1})] + I_{0\lambda}(T_1)\alpha_1 l_{a1}(1-\alpha_4 l_{a4})(1-\alpha_3 l_{a3})(1-\alpha_2 l_{a2}), \end{aligned}$$

where $I_{0\lambda}(T_i)$ is the spectral intensity of the black-body radiation at temperature T_i equal to the temperature of combustion products in the i-th flame zone; $\alpha_{\cdot i}$ is the spectral absorption coefficient for combustion products in the i-th zone; $a_{ji} = \alpha_i l_{ji}$ is the absorptivity of combustion products in the i-th zone along chord section l_{ji} (under thermodynamic equilibrium $a_{ji} = \epsilon_{ij}$; ϵ is the emissivity); l_{ji} is the length of the j-th chord section (j → a, b, ... h) in the respective flame zone; I_{xj} is the spectral intensity of radiation outflow from the flame along the j-th chord.

The set (1) has eight unknown quantities α_i and T_i and consists of eight independent equations.

For solution of the set (1) the iterative method of successive relaxation is used. The essence of the method is that, first, a certain initial (zero) approximation $\alpha^{(0)}_4$, $\alpha^{(0)}_3$, $T^{(0)}_3$ is preset, then from the second equation of the set $\alpha^{(1)}_4$ is determined by successive approximations, then from the third, $\alpha^{(1)}_3$, from the fourth, $T^{(1)}_3$. From the first equation $T^{(1)}_4$ is determined. At the next step $\alpha^{(1)}_4$, $\alpha^{(1)}_3$, $T^{(1)}_3$ are used as initial values and $\alpha^{(2)}_4$, $\alpha^{(2)}_3$, and $T^{(2)}_3$ are determined, etc. That the difference between α and T in the n-th and (n − 1)-th steps was not more than 1% of their values at the n-th step was taken as a convergence condition.

The scheme of the optical electronic system (OES) used to investigate the temperature fields is shown in Fig. 1. OES is developed on the basis of a 16-component radiant energy detector of the Okun type, an optical fiber unit, and an Élektronika-60 microcomputer [6]. It allows the spectral energy of the flame surface radiation to be measured simultaneously at 16 arbitrary points selected by the researcher.

The system lens provides the object image on the surface of the mosaic radiation detector sensors. The fiber lightguide incorporated in the lens allows the radiation detector, commutator, and amplifier to be located in the zone protected from unfavorable effects from the object of study.

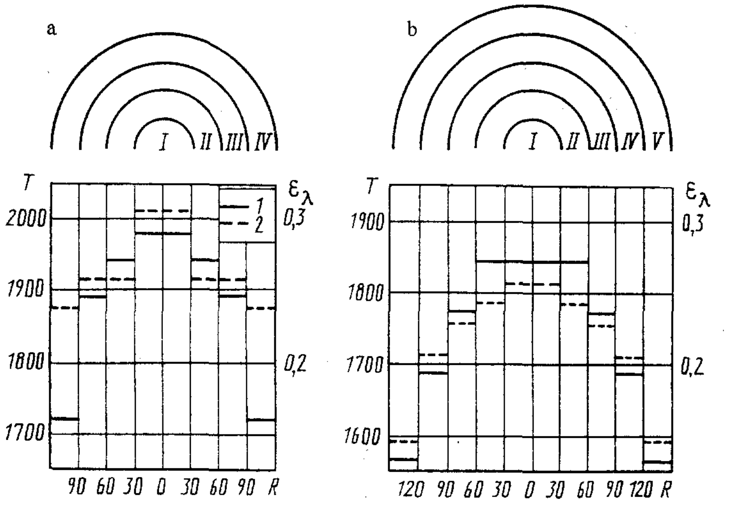

Fig. 2. Temperature and emissivity distributions in the flame cross sections at distances of 300 mm (a) and 600 mm (b) from the nozzle exit section of the combustion chamber: 1) T; 2) ϵ_λ. R, mm; T, K.

The mosaic radiant energy detector of the Okun type consists of 16 sensors arranged in four rows, four sensors in each. The spectral effective range of the detector wavelengths is within 0.5 to 1.1 μm, the sensor detecting area is 1.5 × 1.5 mm. The radiant flux from the object studied is transferred to the detector through light filters placed in the cassette rotating in front of the detector. The light filters transmit the radiation in a step-by-step manner to narrow spectral intervals $\lambda \pm \Delta\lambda$ ($\Delta\lambda$ = 30-50 nm) of the operating wavelengths of the radiation detector. The mosaic detector signals are transferred through the electronic commutator and amplifier to the analog-to-digital converter, at the output of which a six-bit binary code is formed whose value is determined by the output signal level. A standard interface unit forms from four six-bit words of a three-byte group which are transferred in sequence through the immediate access channel into the on-line memory of the computer. The speed of the commutator, amplifier, and analog-to-digital converter provides the inquiry of all sixteen sensors for the time taken by a light filter to pass the radiation detector. A cassette containing the light filters is mounted on the shaft of the stepping motor.

Application of the stepping motor allows the cassette position to be determined without feedback introduction and shooting and information read-out processes to be controlled. The scheme operates as follows. Using the initial cassette setting unit, the first filter is placed in front of the lens and the pulse counter is reset. Then the generator is started by a signal. The voltage regulator increases the generator frequency linearly from 0 to 1330 Hz for 5 sec.

The generator pulses come to the pulse distributor, then they are amplified and transferred to the windings of the stepping motor which rotates the filter cassette.

After the generator has started to operate, each of its pulses is transferred to the counter with a scaling factor which is a multiple of the number of light filters used. The decoder provides information about the cassette position, which allows shooting to be started, and about the operating wavelength of the light filter, which is located in front of the lens at a given time.

One or two minutes after the cassette is set in motion with the operating frequency of filter replacement, transient processes of the motor drive die down, and shooting may be started. In order to control the electronic commutator and to set the periodicity of the signal input to ADC, a central control device (CCD) is used, which controls consistency between the points of the image and of the object shot.

Control of the CCD operation is realized by the decoder of the stepping motor system through the interface unit IU.

Before measurements are started, the whole system is calibrated with a standard emitter (a black-body model); this information is stored by the computer and used as a reference standard.

Figure 2 shows the determined temperatures and emissivities of the combustion products in two flame cross sections located at distances of 300 and 600 mm from the nozzle exit section of the working medium generator. The first flame cross section was partitioned into four concentric zones and the second into five zones, since the flame diameter increased with the nozzle exit section. The spectral emissivities ϵ_λ presented in Fig. 2 are obtained for the wavelength $\lambda = 0.69\ \mu m$.

Mathematical experiments showed that the calculation technique can be used to restore reliably various distributions of real temperatures and emissivities of combustion products in the flame cross section with the use of initial experimental data (spectral intensity of combustion products) measured with an error of not more than 3%. The optical electronic system employed in this study ensures measurements with a preset accuracy. Comparison of the calculated temperatures for the central zone of the flame with thermodynamic calculations showed satisfactory agreement.

NOTATION

T, temperature, I_λ, spectral intensity of radiation; λ, radiation wavelength; α, absorption coefficient; a, absorptivity; ϵ, emissivity; l, length; R, radius.

LITERATURE CITED

1. A. A. Poskachei and E. P. Chubarev, Optical Electronic Temperature Measuring Systems [in Russian], Moscow (1988).
2. A. G. Zhiglinskii, G. G. Kund, A. O. Morozov, and A. N. Samokhin, Feasibility of polychromatic holographic plasma interferometry. XI All-Union Conf. on Low-Temperature Plasma Generators. Abstracts, Pt. 2, Novosibirsk (1989), pp. 171-172.
3. P. P. Kulik, V. V. Ivanov, L. I. Poplevina, and I. M. Tokmulin, Spectral tomographic diagnosis of plasma flows of complex configuration. XI All-Union Conf. on Low-Temperature Plasma Generators. Abstracts, Pt. 2, Novosibirsk (1989), pp. 185-186.
4. O. N. Dubrovskaya, Temperature Measurements in Flames [in Russian], Moscow (1954).
5. O. N. Dubrovskaya, Temperature Measurements in Flames and Gas Flows. Trans. Pyrometry Commission at All-Union Res. Inst. Metrol., Leningrad (1958), pp. 30-40.
6. V. Ya. Klabukov, L. G. Grebenshchikov, V. I. Smirnov, and V. A. Shutov, An Optical electronic system for studying temperature fields of emitting objects. V All-Union Conf. on Radiant Heat Transfer, Abstracts, Stavropol (1982), pp. 49-50.