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USE OF COMPUTER TOMOGRAPHY FOR DETERMINING THE TRANSVERSE TEMPERATURE AND CONCENTRATION PROFILES IN A JET OF COMBUSTION PRODUCTS

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Temperature and concentration profiles in a jet of combustion products are reconstructed by computer tomography from the measured transverse distributions of brightness in the wing of the 4.3-μm CO_2 band. A comparison with radial distributions of temperature and CO_2 concentration in a flow that are measured by contact methods is performed.

To develop methods of remote diagnostics of heated molecular gas flows such as flames, gas flares of combustion products, etc., very efficient use can be made of the characteristics of their thermal radiation, which are highly informative. However, the association of optical characteristics of the emitting volume with thermodynamic parameters of the flow is not simple by virtue of nonuniformity of the gasdynamic fields and the phenomenon of radiation reabsorption.

There is a class of flows whose gasdynamic structure is similar and is reduced to a universal field in dimensionless coordinates by choosing the corresponding scales. The distribution of physical fields which determine the optical properties of these flows is dependent on some characteristic values of temperature, pressure, and concentration that distinguish a given individual flow from the class of those similar to it.

A procedure for reconstructing the temperature field of a turbulent jet from the measured axial and transverse profiles of the spectral density of the energy brightness of the radiation (SDEB) is presented in [1] for this class of flows. This procedure is based on universal relations that relate SDEB distributions to thermodynamic parameters on a gas channel section (with the nozzle radius R_0, the temperature T_0, and the concentration C_0) [2]. These relations were obtained theoretically and experimentally for a nonreacting subsonic submerged jet, the flow in which is self-similar. However, it is of interest to develop the procedure for reconstructing spatial fields of the temperature and the concentrations of emitting components of heated jets without recourse to a priori information on the gasdynamic structure of a flow.

An algorithm for performing a tomographic analysis of nonuniformly heated gas flows from radiometric measurements in the infrared spectrum was proposed in [3]. Briefly, its essence reduces to the following. The flow is divided into N_r annular zones by concentric circumferences and into N_φ angles by rays originating from the center of the flow (Fig. 1). The flow parameters are considered fixed within one annular zone and one angle. When the flow has axial symmetry the parameters of the flow are considered fixed within each annular zone. In accordance with the principle of computer tomography and for convenience in carry out the solution division into zones is performed so that the boundaries of the annular zones pass midway between successive cross sections in which SDEB is measured and the aspects of measurements are taken at the same angles, equal to $\Delta\varphi = 2\pi/N_\varphi$. To calculate radiation transfer along the beam, use was made of the following approach, which is a generalization of the Curtis-Godson method for highly nonuniform routes [4]. All the lines falling within a chosen spectral interval $\Delta\nu$ are divided into several groups, each containing a prescribed number of spectral lines with the same halfwidth γ and

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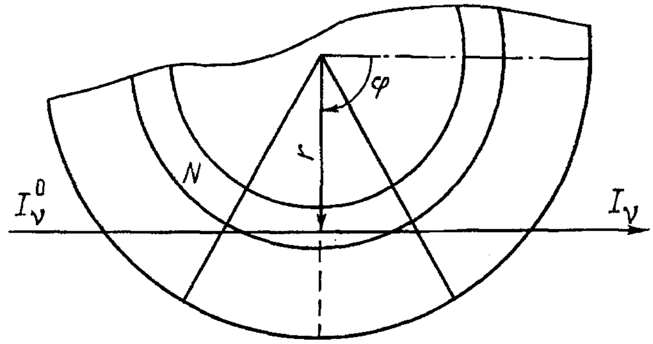

Fig. 1. Scheme of division of the flow.

dependence of the line strength on the temperature. To calculate the SDEB along the beam, we obtain the following expression:

$$I(r, \varphi) = I^0 * R(L) + \int_0^L B^0(x)\, dR(x), \tag{1}$$

where the transmission of the layer $0-X$ is

$$R(x) = \exp\left(-\sum_i \sum_{j=1}^{M} \frac{W_{i,j}}{\sqrt{\left(1 + \frac{1}{4}\frac{(W_{i,j}^2)}{V_{i,j}}\right)}}\right);$$

$$W_{i,j} = \int_0^X AN_{i,j}\, AM_{i,j} \exp\left(-EE_{i,j}/T(x)\right) C_i\, dx; \tag{2}$$

$$V_{i,j} = AN_{i,j} \int_0^X \gamma\, AN_{i,j}\, AM_{i,j} \exp\left(-EE_{i,j}/T(x)\right) C\, dx.$$

Here M is the number of groups; $AN_{i,j}$, $AM_{i,j}$, and $EE_{i,j}$ are group parameters determined, for each gas i and specific selective element, from the prescribed (experimentally or by calculation) dependence of the spectral coefficient of absorption on the temperature and the absorbing mass.

The inverse problem of determining the temperature and concentration fields reduces to the solution of integral equation (1) and (2).

First we consider the solution to problem (1) and (2) for an axisymmetric flow. The value of the SDEB measured in the first beam $I_{1,\nu}$ which passes through the extreme annular zone of the flow is determined by the concentrations of the emitting components i in the first zone C_1^i and the temperature in the first zone T_1:

$$I_{1,\nu} = F_{1,\nu}(C_1^i, T_1). \tag{3}$$

Correspondingly, for the cross section that passes through the N-th annular zone we can write:

$$I_{N,\nu} = F_{N,\nu}(C_1^i, T_1, C_1^i, T_2, \ldots, C_N^i, T_N). \tag{4}$$

Equation (3) contains $(i + 1)$ unknowns, and therefore at least $(i + 1)$ equations are required for a solution to exist. This corresponds to measuring the SDEB at $K \geq (i+1)$ wavelengths. For determining the parameters C_1^i and T_1 in the first zone, we obtain a system of K nonlinear equations. By solving the system of equations (3) and substituting the parameters found into system of equations (4) we find successively the parameters in the N-th zone, where N runs through the values from 2 to N_r. After this values of the parameters C_i and T are determined

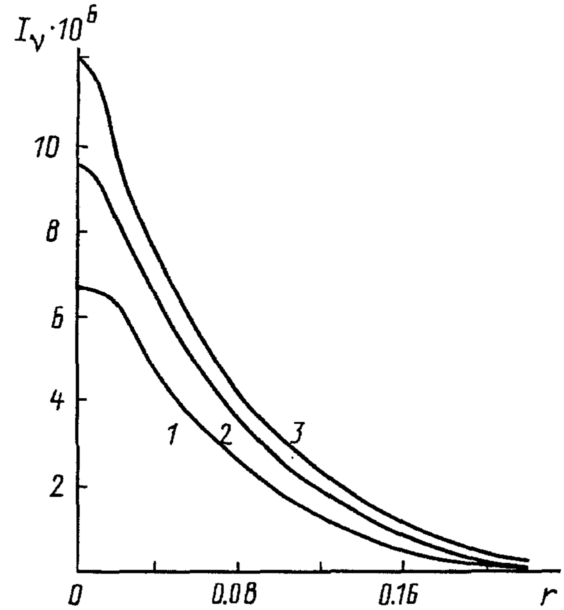

Fig. 2. Transverse SDEB profiles for a jet with $T_0 = 675$ K at $\nu = 2248$ (1), 2264 (2), and 2288 cm^{-1} (3). $I_{n,\nu}$, W/(cm^2·cm^{-1}·sr); r, m.

in all the annular zones. If the flow does not have axial symmetry the SDEB is measured for all cross sections at different aspects. In this case we add the systems of equations for all the aspects to systems of equations (3) and (4) for each zone. We determine the flow parameters in each annular zone within each angle φ by successive solution of the systems of equations for all the aspects for all the zones. In numerical realization of the algorithm described we use a generalized Newton method and SVD-factorization to solve systems of nonlinear equations (3) and (4).

The proposed procedure was used to determine transverse temperature and CO_2 concentration profiles in a submerged axisymmetric isobaric jet of combustion products of hydrocarbon fuels in a model gas-turbine installation [5]. To determine the transverse SDEB profiles, use was made of an IR-spectrometer based on an IKS-21 mounted on a carriage, which made it possible to move the spectrometer in both the horizontal and vertical planes. The measurements were performed in a cross section 7 diameters from the nozzle section in the longwave wing of the 4.3-μm main band of CO_2. The instrument function of the receiver had a triangular shape with a width at a level of 0.5 equal to 80 cm^{-1}. The choice of this wide slit was governed by the wide range of SDEB variation on the edges and at the center of the jet. However, this strongly depletes the obtained, spectral information, which increases the error in determining the emitting component concentrations. To improve the reliability of the reconstruction, we had to decrease the number of independent parameters to be reconstructed. For this purpose use was made of the proportionality of the excess temperature and concentration profiles, which corresponds to the assumption of the absence of the burning-down process in the jet and to the equality of the Prandtl and Schmidt numbers:

$$\frac{T_r - T_{atm}}{T_0 - T_{atm}} = \frac{C_r - C_{atm}}{C_0 - C_{atm}}, \tag{5}$$

where T_r and C_r are the temperature and CO_2 concentration at the point with radius r; T_0, C_0, and T_{atm}, C_{atm} are the temperature and concentration at the nozzle section and in the atmosphere, respectively.

Figure 2 gives measured transverse profiles of the SDEB at three wavelengths (2248, 2264, and 2288 cm^{-1}). The measurements were performed at 0.02-m intervals from the axis of the jet to its boundary. The atmosphere layer in the experiment was 3.85 m. These profiles were used to reconstruct the temperature and CO_2 concentration fields of a jet in a program compiled according to the above algorithm.

The basic difficulties in solving the inverse problem of reconstruction are associated with a possible instability in the solution obtained [6]. To investigate the influence of the disturbing effect of the error in

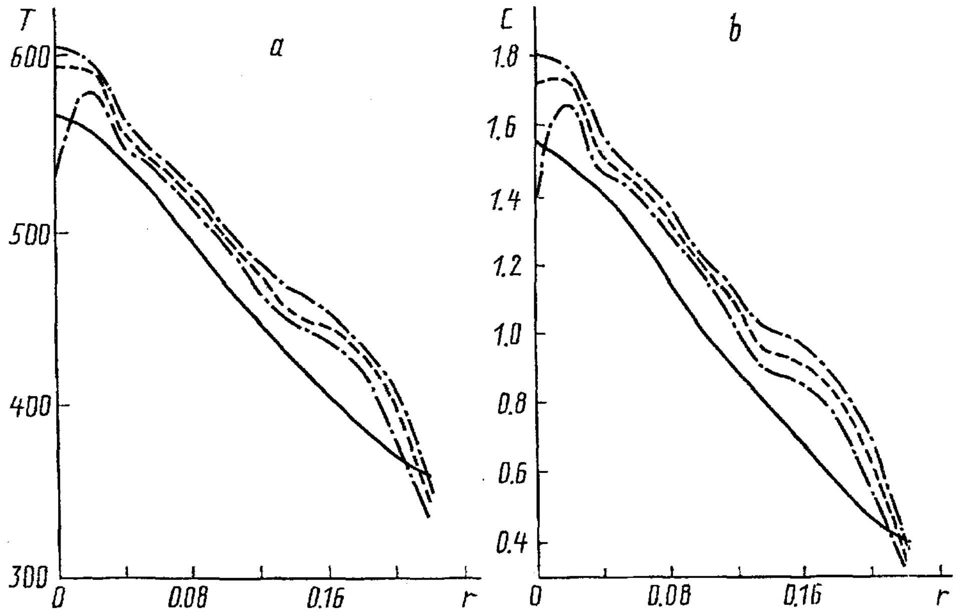

Fig. 3. Comparison of measured (solid curves) and reconstructed (dashed curves) radial distributions of: a) temperature; b) CO_2 concentration; the dot-dash lines show the confidence interval. T, K; C, %.

determining the experimental SDEB profiles on the restored temperature and CO_2 concentration profiles in a jet, use was made of mathematical modeling. On the experimentally obtained SDEB values we superimpose a disturbance that is distributed according to a normal law with the root mean square error $\delta_{n,\nu}$:

$$\delta_{n,\nu} = \varepsilon_1 * I_{n,\nu} + \varepsilon_2 * I_\nu^0 , \tag{6}$$

where I_ν^0 is the background SDEB; ε_1 and ε_2 are the errors in determining the SDEB, which are proportional to the SDEB values of the jet and the background, respectively. In accordance with the experimental error we chose the following values for ε:$\varepsilon_1 = 0.15$ and $\varepsilon_2 = 0.50$. The transverse SDEB profiles distorted in this manner are used to solve the tomographic problem. Fields of arithmetical means of C_i and T and mean square deviations are determined from a random selection of variants of the solutions.

To check the accuracy of the reconstructed temperature profiles we determined the temperature profiles simultaneously with measurements of the SDEB by a suction Chromel-Copel thermocouple with an error of 0.5%. The CO_2 concentration in the jet was monitored using a "CO_2-tester" IR-gas analyzer with a maximum error of 5% [7]. As a comparison of the measured and reconstructed transverse profiles of temperatures and CO_2 concentrations shows, the values of T and C found exceed those measured in the jet (Fig. 3). On the edge of the jet these discrepancies are beyond the errors of the experiment and the confidence interval estimated by the method of mathematical modeling. This makes it possible to assume that the observed difference accounts for the influence of turbulent pulsations on the radiation [8, 9]. It is obvious that when performing measurements of the transverse SDEB profiles in this spectral range, where the influence of pulsations on the radiation is quite weak (for example, 6.3 μm of H_2O), it is possible to reconstruct the radial temperature, which is close to the thermodynamic one. On the other hand, the turbulence of the flow can be inferred from the temperature and concentration branching obtained.

The comparison performed shows the applicability of the proposed method for reconstructing the temperature and the concentrations of emitting components in actual technological installations. It is to be expected that with the spectral ranges and parameters of the recording equipment purposefully chosen using the method of mathematical modeling according to the scheme proposed in [5], we can improve the accuracy and reliability of the obtained results substantially.

NOTATION

r, impact parameter; φ, aspect; ν, frequency; $I_\nu(r, \varphi)$, spectral density of the energy brightness; I_ν^0, radiation of the background; C_i and χ_i, concentration and spectral absorption coefficient of component i; B_ν^0, Planck function; T, temperature; $T(\nu)$, instrument function of the receiver; $R(x)$, transmission of the layer 0-X; $AN_{i,j}$, $AM_{i,j}$, and $EE_{i,j}$, parameters of group j for component i; γ, line halfwidth; N_r, number of annular zones; N_φ, number of aspects; $F_{N,n}$, functional of concentrations and temperatures in each of the N zones; K, number of filters; $\delta_{n,\nu}$, root mean square error.

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