GASDYNAMIC STRUCTURE OF A HEATED SUBMERGED SUBSONIC JET

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Measurements are made of the radial and axial distributions of the concentration of a small impurity and the temperature and velocity of a nonisothermal turbulent jet. Comparison of experimental and theoretical data shows that they agree well.

To develop and refine methods of calculating the optical characteristics of radiation from subsonic submerged turbulent jets, it is necessary to know the laws of distribution of the gasdynamic parameters over the flow field. Concentration and temperature fields of isobaric jets have been extensively studied [1-5]. At the same time, there has not been sufficient study of the structure of jets characterized by the degree of heating $\theta = T_a/T_e \geqq 2$. The investigations [6, 7] examined jets with an initial temperature up to 1500 K and established that the degree of heating of the working gas of the jet is manifest both in a change in the distributions of the mean values of relative velocity and excess temperature and in the nonmonotonic behavior of the fluctuation components of these parameters. However, the authors did not investigate the distribution laws for the concentration of a small impurity.

The goal of the present study is to experimentally investigate the fields of velocity, temperature, and impurity concentration for heated jets and examine the feasibility of describing them within the framework of a numerical calculation on the basis of boundary layer approximation.

Measurements were made on a model unit which allowed us to obtain an axisymmetric submerged subsonic isobaric jet. Jets heated to different degrees were produced on the unit, which was described in detail in [8]. Jets having a chemical composition typical of jets of combustion products of hydrocarbon fuels were directed into a stationary air space through a nozzle of radius R_a = 100 mm. The molecular weights of the combustion products and air were similar. Table 1 shows the initial parameters of the jet in the investigated regimes. The velocity field of the jet was measured to within 10% by a pitot tube, while the temperature field was measured by a suction-type Chromel–Copel thermocouple with a large time constant. This allowed us to smooth pulsations and to determine the mean temperatures to within 1%.

The CO_2 concentration was determined with a modernized infrared gas analyzer which measures the absorption of infrared radiation by the test gas. The IR radiation is selected by a combination infrared filter, while a nonselective pyroelectric transducer serves as the radiation detector. The gas concentration is determined by comparing the signals appearing at the output of the detector. These signals are related to the degree of absorption of radiation by the test gas in the working cuvette and the reference cuvette.

Figure 1 shows an optical block diagram of the gas analyzer. The radiation source 1 is a Nichrome wire 0.3 mm in diameter wound about a ceramic rod and heated to the temperature 1073 K. The lens 2 (diameter 30 mm, f = 60 mm), the focus of which includes the source, forms a parallel beam of radiation and directs it to the reference 3 and working 4 cuvettes. The latter take the form of cylinders 10 mm long and 15 mm in diameter. They are equipped with pipes 5 for admission and escape of the gas. The reference container is filled with nitrogen, which does not absorb the infrared radiation. The ends of the containers are closed by windows made of BaF_2. The radiation was modulated at a frequency of 150 Hz with a chopper 6. The lamps 7 and photodiodes 8 form synchronizing pulses needed to control the electronic equipment. The lens 10 (diameter 30 mm, f = 25 mm) receives the radiation from the cuvettes and IR filters 9 and directs it to the sensitive element of the detector 11,

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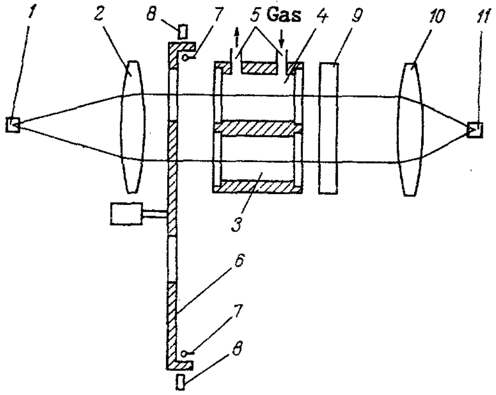

Fig. 1. Optical block diagram of the gas analyzer.

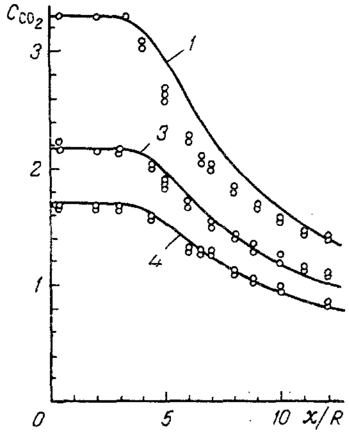

Fig. 2. Comparison of calculated (curves) and measured (points) distribution of CO_2 concentration along the jet axis for regimes 1, 3, and 4. C_{CO_2}, vol. %.

which is an MG-30 pyroelectric transducer. The infrared filter has the following parameters: center of the passband 4.3 μm, half-width 0.15 μm, transmittance at the maximum 45%.

Samples were taken with a copper tube having an inside diameter of 4 mm. The tube was fixed at a certain point in space to within ±1 mm. A PR-7 sampling aspirator was used for continuous removal of gas at the rate 0.3 liters/min. The samples passed through a settling tank with paper filters and the working cuvette. The filter removed carbon particles and other mechanical impurities from the gas and condensed the water vapor.

The working cuvette was cleaned out with nitrogen before the experiment. The analyzer was calibrated with standard gas mixtures with different concentrations of CO_2 in nitrogen: 0.52; 1.3; 2.07; 3.2; 4.1; 4.92 vol. %. The upper measurement limit was established in accordance with the requirements of the experiment. In our case, the range of CO_2 concentration was 0-5 vol. %. The desired concentration was determined from the calibration curve to within 5% of the upper limit.

The values of initial CO_2 concentration determined at the nozzle edge by the "CO_2-tester" agree well with the values calculated from the regime parameters with the assumption of complete fuel combustion. The distributions of the gasdynamic quantities of the jet were measured in cross sections in the initial, transitional, and main sections and along the jet axis. The reliability of the test results was evaluated by comparing the fluxes of excess enthalpy, momentum, and mass of CO_2 in different sections of the jet against the values at the nozzle edge. Their ratios ranged within 0.75-1 along the jet. Such a change is typical of experiments with nonreactive jets [1] and is evidence of the sufficient reliability of the measured concentration, temperature, and velocity fields.

The distributions were calculated by a method based on the solution of gasdynamic equations in a two-dimensional axisymmetric boundary-layer approximation. In the calculation, we

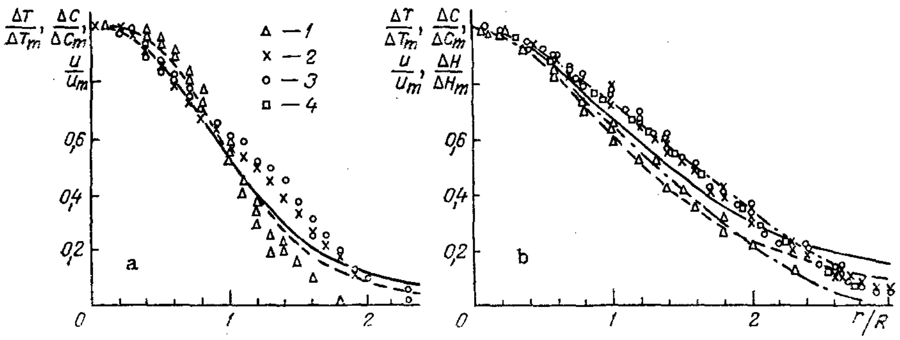

Fig. 3. Measured radial profiles of relative velocity (1), excess temperature (2), CO_2 concentration (3), and enthalpy (4) on the transitional (x/R_a = 4.4) (a) and main (x/R_a = 8.8) (b) sections of the jet with T_a = 600 K; the dashed and solid curves respectively show results of calculation of u/u_m and $\Delta C/\Delta C_m$ by the "new" Prandtl theory; the dot-dash curves show the Schlichting profile.

TABLE 1. Regime Parameters

No. of regime	T_a, K	u_a,m/sec	C_a, vo.%		$Re\cdot 10^{-4}$
			calc.	expt.	
1	850	43	3,2	3,3	8,7
2	750	37	2,5	2,5	9,4
3	675	34	2,2	2,15	10,0
4	600	29	1,55	1,6	11,0
5	500	25	1,2	1,15	12,5

used a model of eddy viscosity based on the "new" Prandtl theory. The method of calculation was described in detail in [9], where it was shown that at Pr = 0.66 there is good agreement between theoretical and experimental distributions of velocity and in absolute units for the investigated jets. We also took a value of 0.66 for the Schmidt number in the calculations. It can be seen from Fig. 2 that the theoretical distributions of CO_2 concentration along the jet axis agree satisfactorily with the distributions obtained with the "CO_2-tester" for all test regimes with edge temperatures from 600 to 850 K.

It can be seen from Fig. 3 that the fields of relative excess concentration, temperature, and enthalpy are identical within the limits of the measurement accuracy. Examining the radial distributions of the parameters on the transitional section of the jet, we note that the profiles of excess velocity, concentration, and temperature intersect.

On the main section of the jet, the radial distributions of the gasdynamic parameters are described well by the self-similar Schmidt profile:

$$\frac{u}{u_m} = \left[1 - \left(\frac{r}{b_u}\right)^{3/2}\right]^2, \tag{1}$$

$$\frac{\Delta T}{\Delta T_m} = \frac{\Delta H}{\Delta H_m} = \frac{\Delta C}{\Delta C_m} = \left[1 - \left(\frac{r}{b_T}\right)^{3/2}\right]^2, \tag{2}$$

where $2b_u$ is the width of the dynamic mixing zone; $2b_T$ is the width of the thermal mixing zone. These widths are determined from the relation: $b_u = 2.27 r_{u=0.5u_m}$; $b_T = 2.27 r_{T=0.5(T_m+T_e)}$. The mutual location of the profiles is characterized by the extension coefficient $B_{uT} = r_{u=0.5u_m}/r_{T=0.5(T_m+T_e)}$. The value of this coefficient in our case is 0.75-0.90, which agrees well with the data in [1].

Comparison of the measured transverse realtive velocities and the excess CO_2 concentrations against the values calculated by the "new" Prandtl theory showed that the theory somewhat less accurately describes the experimental results close to the edge of the jet. This shows that the theoretical radial profiles differ in form from the empirical profiles. However, the difference is not large and amounts to about 10%. This difference may be connected with the constancy of the eddy viscosity coefficient across the section.

The measurements of the axial distributions of the gasdynamic parameters showed that the length of the initial section in the investigated range of edge temperatures is about $3.5R_a$. This is evidence of the high degree of initial turbulence of the jet [10]. Figure 4 shows the

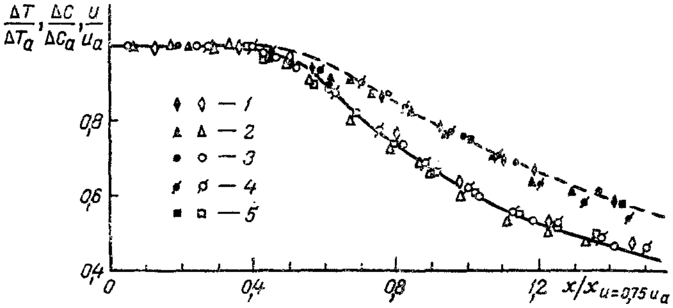

Fig. 4. Change in u/u_a (dark points) and $\Delta T/\Delta T_a$, $\Delta C/\Delta C_a$ (clear points) along the jet axis with different initial jet parameters: dashed and solid curves – calculations of u/u_a and $\Delta C/\Delta C_a$ by the "new" Prandtl theory for regime 1, respectively. The numbers of the points correspond to the numbers of the regimes in Table 1.

distribution of the gasdynamic parameters along the jet axis. The distributions were constructed in relative coordinates, in accordance with the recommendations of M. Ya. Yudelovich. As the unit of length we took the value of the longitudinal coordinate at which axial velocity is $0.75u_a$. It can be seen from the figure that the profiles of the excess parameters identically depend on the relative longitudinal coordinate for jets heated to different degrees. The use of such coordinate smakes it possible to demonstrate the gasdynamic similitude of low-temperature jets with different initial parameters and to significantly simplify the theoretical description of these jets. The calculated axial profiles of excess CO_2 concentration and velocity in relative coordinates agree well with the experimental data.

NOTATION

x, linear coordinate along the jet axis, reckoned from the nozzle edge; r, linear coordinate perpendicular to the jet axis and reckoned from it; R_a, nozzle radius; b, half the width of the mixing zone; u, velocity; T, temperature; C, concentration of CO_2; H, enthalpy; Pr, turbulent Prandtl number; Re, Reynolds number; $\Delta T = T - T_e$, $\Delta C = C - C_e$, $\Delta H = H - H_e$, excess temperature, concentration, and enthalpy. Indices: a, m, e, values of the parameters on the edge, on the axis, and outside the jet.

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