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INFLUENCE OF TURBULENCE ON THE THERMAL RADIATION TRANSFER IN DIFFUSION HYDROGEN FLAMES

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The effect of the turbulent fluctuations of the temperature and concentrations in a diffusion hydrogen flame on its thermal radiation has been quantitatively estimated. The numerical investigations were carried out using the data on the laser probing of this flame. The coefficients of the radiation-transfer equation were determined by averaging instantaneous temperatures and concentrations, which made it possible to eliminate the errors introduced by model distribution functions. It is shown that the effect of the turbulence of a flame on its radiation determines, to a large extent, the formation of the thermal radiation fields of the flame.

The thermal radiation field of a gaseous fuel flame is supposedly formed due to the combined effect of the turbulent mixing, combustion, and radiation-transfer processes occurring in it. In practice, it is very important to know the effect of the turbulence of a flame on its radiation because the thermal balance of many high-temperature energy plants is mainly determined by the radiative heat exchange in them. Numerous efforts have been made to correctly simulate this effect: however, many aspects of the indicated problem still remain to be solved. The quantitative estimates of the effect of turbulent fluctuations of a flame on its radiation are also very contradictory.

Recently, a successive simulation of the radiation of a turbulent flame has been carried out using the method of Lagrangian probability density functions [1, 2]. It has been shown, in part, that the effect of the turbulence of a gaseous hydrocarbon fuel flame on its radiation can increase the resulting radiation flux by 1.5 times or more. Since this practically important result is insufficiently supported by experimental and theoretical data, it makes sense to carry out additional investigations with the use of independent methods.

In the present work, we investigated the effect of the turbulence of a diffusion hydrogen flame on its radiation with the use of the Sandia H_2/He Flame data file [3]. This file includes measured scalar characteristics of diffusion flames of H_2 and mixtures of H_2 and He in air, namely, the temperature and concentrations of the basic gases (O_2, N_2, H_2, H_2O) and the mass concentrations of the minor components — OH and NO. The experimental procedure and measurement results are described in detail in [4, 5]. The Sandia H_2/He Flame file was developed first of all for verification of the numerical simulation data on the formation of nitric oxides (NO_x) in hydrogen flames. This data file can also be used for investigating the effect of the turbulence of a flame on the thermal IR radiation transfer in it. The Sandia H_2/He Flame file includes data on the temperature and concentrations of the above-indicated gases at a number of space points covering the high-temperature flame regions, making a determining contribution to the output thermal radiation. For each indicated point 500–1000 simultaneously measured temperatures and concentrations are presented in this file, which makes it possible to approximate the probability density function of a corresponding quantity with a high degree of accuracy. In the present work, we restricted our consideration to the case of a purely hydrogen flame having the following gasdynamic characteristics: rate of flame flow $u = 296$ m/sec; initial diameter of the flame $D = 3.75$ mm; Reynolds number $\mathrm{Re} = Du/\nu = 10{,}000$; linear dimension of the visible (high-temperature) region of the flame $L_{\mathrm{vis}} = 180D$. For such a flame, the Sandia H_2/He Flame file contains temperatures and concentrations in the seven cross sections normal to the axis of the flame: x/L_{vis} = 1/8, 1/4, 3/8, 1/2, 5/8, 3/4, and 1.

Flames are optically fine due to their small geometric dimensions. As numerical estimates show, the transverse optical thickness of a flame (the product of the absorption coefficient of the flame and its diameter) $\tau \sim 0.1$ at the center of the 2.7-μm band, i.e., the free path of a quantum, significantly exceeds the external scale of turbulence, which is approximately equal to a tenth of the transverse size of the flame. In this case, the characteristics of the ther-

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mal radiation can be calculated using the approximation of optically fine pulsations. The spectral concentration of the radiance of a flame averaged over its turbulent fluctuations is defined within the limits of this approximation as

$$\langle I_\nu \rangle = \int_0^L \langle B_\nu k_\nu \rangle \exp\left(- \int_0^x \langle k_\nu \rangle \, dy \right) dx \,. \tag{1}$$

Here, 0 and L are the boundaries of the radiating volume and the terms in angle brackets stand for quantities averaged over an ensemble of temperatures and concentrations.

In [6], the approximation of optically fine pulsations was used for calculating the selective radiation in definite spectral intervals of vibrational-rotational bands of molecular gases. For this purpose, the known Curtis–Godson method [7], developed for calculating the radiation of nonisothermal molecular gases, was generalized within the limits of the approximation of optically fine pulsations to the case of a turbulent medium:

$$\begin{gathered} \langle I_\nu \rangle = \int_0^L \left\langle B_\nu \frac{s}{d} \rho \right\rangle \left(1 + \frac{2a^3}{b^2} \frac{\gamma}{d} \right) \left(1 + \frac{a^2}{b} \right)^{-3/2} \tau dl \,, \\ a = \int_l^L \left\langle \frac{s}{d} \rho \right\rangle dl' \,, \quad b = 4 \int_l^L \left\langle \frac{s}{d} \rho \right\rangle \left\langle \frac{\gamma}{d} \rho \right\rangle dl' , \end{gathered} \tag{2}$$

where the transmission τ is determined from the expression

$$\tau = \exp\left[- a \left(1 + \frac{a^2}{b} \right)^{-1/2} \right] .$$

In practice, the averaging $\langle ... \rangle$ is usually performed on the basis of the probability density functions of the temperature and concentrations in a flame. However, since the Sandia H_2/He Flame data file contains experimentally measured temperatures and concentrations, the averaging can be reduced to the trivial calculation of the arithmetical means of the corresponding quantities:

$$\langle f(T, C) \rangle = \frac{1}{N} \sum_{i=1}^{N} f(T_i, C_i) \,. \tag{3}$$

In calculating $\langle I_\nu \rangle$, the temperature- and concentration-dependent functions $\left(\frac{s}{d} \rho \right)$, $\left(\frac{\gamma}{d} \right)$, and $\left(B_\nu \frac{s}{d} \rho \right)$ are averaged in the same way. The advantage of this method is the absence of errors arising in the case where model probability density functions are used.

In what follows, we will calculate the 1.4–12-μm radiation because the major portion of the radiant energy of a flame falls in this spectral range. In the indicated range, the radiating component is H_2O. The radiation of the nitric oxides can be neglected because their concentration is small. The spectral concentration of the flame radiance averaged over the temperature and concentration fluctuations will be calculated by formulas (2) and (3). The contribution of the turbulent fluctuations to the radiation will be estimated by the ratio

$$\delta_\nu = \langle I_\nu \rangle / \tilde{I}_\nu \,. \tag{4}$$

The effect of the turbulence of a flame on its radiation will be investigated within the limits of the two-dimensional model of radiative energy transfer in the cross section normal to the axis of the flame. The spectral concentration of the flame radiance will be calculated along the parallel rays passing at a distance Δ from the flame axis.

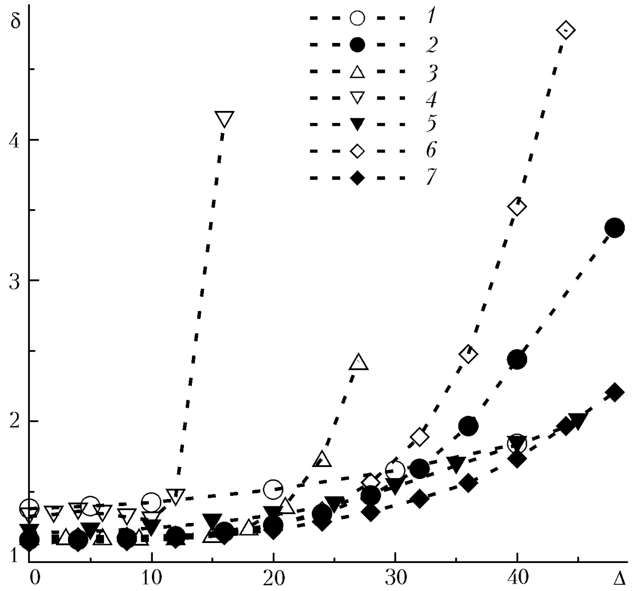

Fig. 1. Dependence of the ratio δ on the distance between the observation ray and the axis of a hydrogen flame in its different cross sections: x/L_{vis} = 1 (1), 1/2 (2), 1/4 (3), 1/8 (4), 3/4 (5), 3/8 (6), and 5/8 (7). Δ, mm.

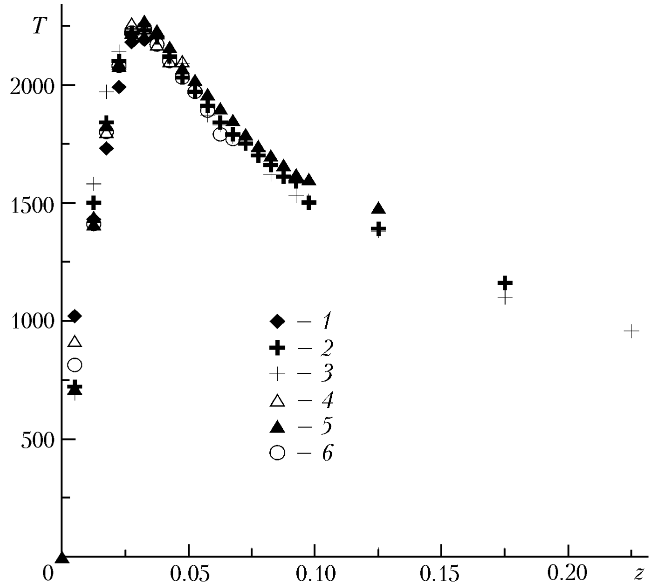

Fig. 2. Dependence of the temperature on the passive impurity concentration in different cross sections of the flame: x/L_{vis} = 1 (1), 1/4 (2), 1/8 (3), 3/4 (4), 3/8 (5), and 5/8 (6). T, K.

Figure 1 shows the dependences of the quantity δ on Δ ($\delta = \langle I\rangle/\tilde{I}$, where $\langle I\rangle = \int_{\lambda_1}^{\lambda_2} d\lambda\, \langle I_\nu\rangle$ and $\tilde{I} = \int_{\lambda_1}^{\lambda_2} d\lambda\, \tilde{I}_\nu$ are the spectral concentrations of the radiance of a hydrogen flame, integrated over the spectral range 1.4–12 μm in seven of its cross sections). It is seen that the turbulence effect increases markedly as the flame edge approaches. The relative contribution of the fluctuations $(\delta - 1)$ along the rays passing through the center of the flame comprises 20–40%, while the contribution of the fluctuations along the rays passing through its peripheral zones is an order of magnitude or more smaller.

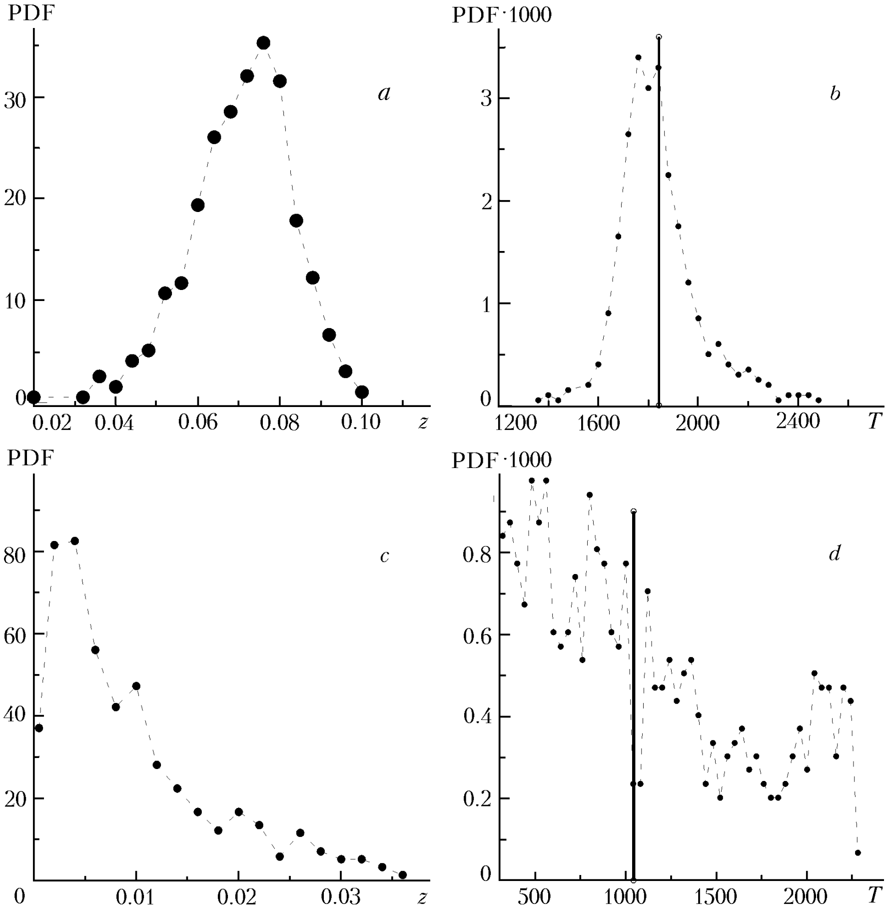

Fig. 3. Probability density function (PDF) of the passive impurity concentration (a and c) and the temperature (b and d) in the flame, $x = 3/8L_{\text{vis}}$, $r = 0$ (a and b) and $r = 40$ (c and d). The vertical lines correspond to the mean values of the temperature. T, K.

The above-described spatial dependence is explained by the features of the effect of the turbulence of diffusion flames on the combustion. The flame considered is among the chemically reactive flows in which the time scale of the chemical reaction t_c is much smaller that the time scale of the molecular mixing t_m, i.e., the Damköhler number $\text{Da} = t_m/t_c >> 1$. In this case, the thermochemical state of the reactive mixture is completely determined by the concentration of the passive impurity (mixed fraction) z [8]:

$$Y_i = Y_i^e(z)\,, \quad T = T^e(z)\,. \tag{5}$$

Relations (5) are illustrated by the dependences of the temperature of a purely hydrogen flame on the concentration of the passive impurity of six in its cross sections, presented in Fig. 2. These dependences represent approximation curves constructed by the instantaneous temperatures and concentrations z, taken from the Sandia H_2/He Flame data file.

Figure 3a shows the probability density function of the passive impurity concentration z, obtained on the basis of processing of experimental data, for $x = 3/8L_{\text{vis}}$ and $r = 0$. It is seen that the probability density function of z is close to a normal one in this case and z changes monotonically (sloping portion of the curve $T(z)$ (in Fig. 2). Because of this, the probability density function of the temperature is also close to a normal one, and the amplitude of the fluctuations (dispersion) is small as compared to the mean temperature (Fig. 3b). This probability density function of the temperature is responsible for the small (20–40%) relative contribution of the turbulent pulsations to the radiation of the flame region considered.

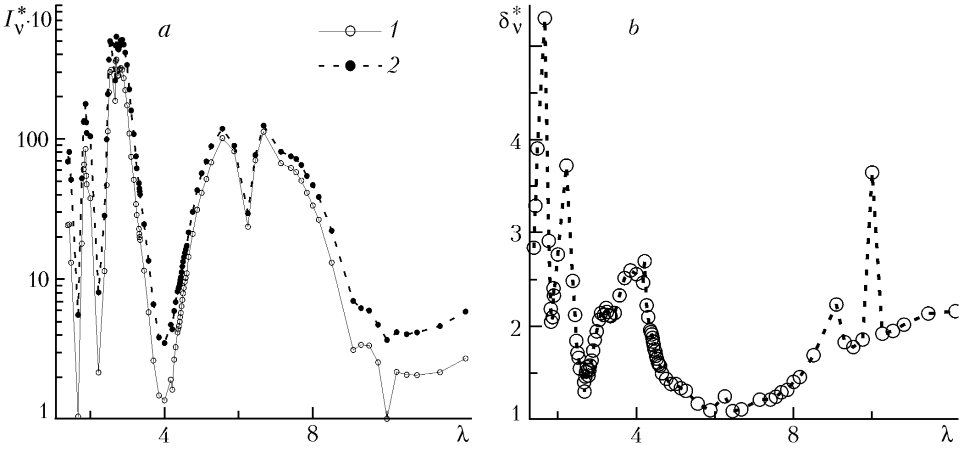

Fig. 4. Spectral dependences of the spectral concentrations of the radiance (SCR) of the flame, integrated over its cross section (a) and calculated with (1) and without (2) account for the turbulent fluctuations, and of the ratio between these SCRs δ^*_ν (b) for $x = L_{\text{vis}}$. I^*_ν, W·m^{-2}·sr^{-1}; λ, μm.

TABLE 1. Relative Contribution of Turbulent Fluctuations to the Radiation Integrated over the Spectrum and the Cross Section of the Flame

x/L_{vis}	1/8	1/4	3/8	1/2	5/8	3/4	1
$(\delta^* - 1)\cdot 100\%$	42	24	31	31	26	35	49

At the same time, at the periphery of this cross section (r = 40 mm) the probability density function of z is very asymmetric and differs markedly from the normal one (Fig. 3c). Moreover, z changes nonlinearly at this point of the flame (nonlinear portion of the curve $T(z)$ (in Fig. 2)). Because of this, the probability density function of the temperature differs even more markedly from the normal one. It is seen from Fig. 3d that, in this case, the probability that the temperature will substantially exceed its mean value is fairly high. Physically this means that, as a result of the turbulent mixing, local sites of combustion arise at the periphery of the flame; these sites are mainly responsible for the radiation of these flame regions.

Figure 4 shows the spectral dependences of the quantities $\langle I_\nu \rangle$, $\tilde{I}_\nu$, and $\delta^*_\nu = \langle I^*_\nu \rangle / \tilde{I}^*_\nu$, where $\langle I^*_\nu \rangle$ and $\tilde{I}^*_\nu$ are the spectral concentrations of the radiance of the flame integrated over its cross section:

$$\langle I_\nu \rangle^* = 2 \int_0^R d\Delta \, \langle I_\nu (\Delta) \rangle \, , \quad \tilde{I}^*_\nu = 2 \int_0^R d\Delta \tilde{I}_\nu (\Delta) \, .$$

The maximum values of δ^*_ν are close to two in the majority of cross sections of the flame studied, and they can reach a value of five or larger only at the boundary of the visible region of the flame ($x = L_{\text{vis}}$). In these regions of the flame there evidently occur effects analogous to the effects considered above for the periphery of its individual cross sections, i.e., against the background of the dying flame there arise local combustion sites that make a determining contribution to the thermal radiation of the flame. The maximum values of δ^*_ν corresponds to the edges of the main absorption bands of the H_2O vapor with centers at 1.8, 2.7, and 6.3 μm, where the radiation intensity is low. At the same time, at the centers of these bands, predominantly at the center of the 6.3-μm band, the contribution of the turbulent fluctuations is fairly small. However, the contribution of the turbulent fluctuations to the radiation integral over the spectrum and the cross section of the flame remains significant. The contribution of the turbulent fluctuations to the flame radiation is conveniently characterized by the quantity $(\delta^* - 1)\cdot 100\%$, where $\delta^* = \langle I^* \rangle / \tilde{I}^*$ and $\langle I^* \rangle$ and $\tilde{I}^*$ are the spectral concentrations of the radiance of the flame integrated over its spectrum and cross section, respectively. As is seen from the table, this quantity is equal to 30–40% for the majority of cross sections of the flame studied, and the analogosuly determined relative contribution of the turbulent fluctuations to the radiation of the whole visible region of the flame is 32%. Thus, the results obtained allow the conclusion that the effect of the turbulence of diffusion hydrogen flames on their radiation determines, to a large extent, the formation of their thermal radiation fields.

NOTATION

B_ν, Planck function, $W \cdot m^{-3} \cdot sr^{-1}$; C, volume concentration; D, diameter of the initial cross section of the flame, m; Da, Damköhler number; I_ν, spectral concentration of a radiance (SCR), $W \cdot m^{-3} \cdot sr^{-1}$; I, SCR integrated over the spectrum of the flame, $W \cdot m^{-2} \cdot sr^{-1}$; I_ν^*, SCR integrated over the cross section of the flame, $W \cdot m^{-2} \cdot sr^{-1}$; $\tilde{I}_\nu$, SCR calculated by the mean thermodynamic parameters, $W \cdot m^{-3} \cdot sr^{-1}$; L, length of a beam, m; L_{vis}, linear dimension of the visible (high-temperature) region of the flame, m; R, radial coordinate of the boundary of the flame cross section, m; T, temperature, K; Re, Reynolds number; Y_i, mass concentration of the ith component; d, mean distance between the spectral lines, m; k_ν, absorption coefficient, m^{-1}; l, l', and y, integration variables; r, radial coordinate, m; s, mean intensity of a spectral line, m^3/kg; t, time scale of the process, sec; u, rate of the flame flow, m/sec; x, axial coordinate, m; z, mass concentration of the passive impurity; Δ, distance from the observation ray to the axis of the flame, m; γ, halfwidth of a spectral line, m; δ, ratio between the SCRs calculated with and without account for the turbulent fluctuations; λ, wavelength, m; ν, kinematic viscosity, m^2/sec; ρ, density, kg/m^3; τ, transmission; $\langle ... \rangle$, averaging over the turbulent fluctuations. Subscripts: c, chemical; e, equilibrium; m, mixing; vis, visible; ν, frequency; 0, initial value.

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