COMBUSTION OF HYDROGEN JETS SYSTEM IN A SUPERSONIC STREAM

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There are given the data of calculated theoretical research of diffusive combustion of flat supersonic hydrogen jets in a supersonic stream, received by Navier-Stock's parabolic equations, closed by one-parameter $(k - l_\omega)$–model of turbulence and multistage mechanism of hydrogen oxidation. The regularities of combustion, depending on the operating parameters, are discussing. The influences of air stream structure and the ways of fuel feed to the length of inflammation delay and to the quantity of hydrogen burnout level have been defined.

Introduction. The research of hydrogen combustion in supersonic flows presents great difficulties both in theoretical and experimental plan. Theoretical research is complicated by the fact that the regularities of combustion at supersonic speeds are defined by the intensities of turbulent exchange processes, chemical reaction velocities in a stream and by the influence of gas dynamic effects accompanying heat release. Thus, each from the listed factors may essentially influenced on combustion process. It's almost impossible to carry out full-scale experiments in laboratory conditions for Mach numbers of a stream $M > 5$.

There are some experimental and calculated theoretical researches of combustion in supersonic jet streams ($M < 3$) [1–8]. They show the multistage of chain reactions [1,2], inflammation delay of hydrogen-air mixture [3-5], necessity of the account of pulsation concentration to the velocity of chemical transformations [4,5] and gas-dynamic mechanism influence on combustion [6,8].

The detailed experimental data on a turbulent structure of supersonic shift streams have allowed to study the regularities of turbulent mixing [9] and to evaluate the use of modern models of turbulence for their description. In particular, a less expressed anisotropy character of turbulence in the mixing area of two supersonic streams has been revealed [9]. In accordance with experimental data [9], the conducted calculated theoretical analysis of different isotropic models of turbulence allowed to reveal that one–parameter $(k - l_\omega)$-model of turbulence satisfactorily describes main regularities of mixing area of two supersonic streams [10].

Supersonic combustion with shocks has been investigated in [10,11] and the influence of shock waves on inflammation and mixing processes has been found out. As experimental data show [3,8], hydrogen jet mixing with air co-flow is one of the most important factors to organize hydrogen combustion. In this connection, discovering of mixing mechanism depending on various dynamic, thermal, kinetic and geometric conditions has a great importance for practice.

In experimental researches of diffusion hydrogen combustion in non-calculated supersonic jet of high-enthalpy air there has been revealed the alternation of the areas of intensive combustion with the areas of combustion delay, caused by gas-dynamic flow structure [8]. In particular, the influence of different ways of fuel feed to the length of inflammation delay of hydrogen has been pointed out. The registration of OH radical radiation by flare length has allowed to evaluate combustion intensity and completeness [8]. The alternation of a zone of intensive combustion with a zone of delayed combustion may influence on the working process efficiency during the organization of supersonic hydrogen combustion in combustion chambers and needs detailed study.

In this connection, the authors of the given paper aimed to show that the attraction of PUNS system in combination with approved models of hydrogen oxidation turbulence and kinetics may give more full notion on the regularities of supersonic hydrogen jet system combustion in co-flow supersonic air stream.

The results of calculated theoretical researches of diffusive combustion of supersonic plane hydrogen jet system in co-flow supersonic stream are given below.

Mathematical model of a stream. There is considered the supersonic combustion in the field of turbulent mixing of supersonic plane hydrogen jets system with supersonic air stream. Hydrogen jet is running out in parallel or under a small angle α into supersonic air stream from flat slots with the height d_1, disposed at the distance d_2 from each other. The axis OX is directed along a plane of stream symmetry and the axis OY is perpendicular to it. The strip with the width H, limited by planes of symmetry, may be isolated as the system of flat jets is periodically repeated, and the solution of the problem in this field may be considered by substituting of rejected part with conditions of symmetry along boundary planes.

The stream in a whole field is supposed to be supersonic, the gas is considered to be viscous, heat conducted, chemically reacting and stream condition – to be turbulent.

The system of parabolic equations of energy, continuity, substance and angular momentum equation written in a matrix form can be used to describe an averaged stream. Turbulent two-dimensional motion of gas mixture is described by the system of parabolic time-average Navier-Stock's equations

$$\frac{\partial \vec{F}}{\partial x} + \frac{\partial \vec{G}}{\partial y} = \frac{\partial}{\partial y}\left(\vec{S} + \vec{H}\right) + \vec{W} \qquad (1)$$

where $\vec{F} = \vec{F}\left[\rho u, \rho u^2 + p, \rho uv, (\rho E + p)u, \rho u C_i\right]$,

$$\vec{G} = \vec{G}\left[\rho v, \rho uv, \rho v^2 + p, (\rho E + p)v, \rho v C_i\right],$$

$$\vec{W} = \vec{W}\left[0,0,0,0,\dot{W}_i\right],$$

$$\vec{S} = \vec{S}\left[0, \mu_t \frac{\partial u}{\partial y}, \frac{4}{3}\mu_t \frac{\partial v}{\partial y}, \gamma \frac{\mu_t}{Pr_t}\frac{\partial e}{\partial y} + \mu_t\left(\frac{1}{2}\frac{\partial u^2}{\partial y} + \frac{2}{3}\frac{\partial v^2}{\partial y}\right), \frac{\mu_t}{Sc_t}\frac{\partial C_i}{\partial y}\right],$$

$$\vec{H} = \vec{H}\left[0,0,0,\frac{\mu_t}{Sc_t}\left(\sum_i h_i \frac{\partial C_i}{\partial y}\right),0\right].$$

here are considered next symbols: u, v - longitudinal and transversal components of velocity, p - pressure, ρ - density, e-specific internal energy, C_i-concentration of substance in a mixture, h_i - specific enthalpy of i-component of a mixture, μ_t - coefficient of turbulent dynamic viscosity, Pr_t, Sc_t - turbulent analogues of Prandtle and Schmidt numbers, which are $Pr_t, Sc_t = 0{,}9$.

The equation of ideal gas state is written in the next form:

$$p = \rho R T, \qquad (2)$$

where $R = R_o \sum_i \frac{C_i}{m_i}$, m_i is a molecular mass of i– component of mixture, R_0 – an universal gas constant.

Complete energy is the next:

$$E = \sum_i C_i \int_{T_0}^{T} c_{vi} dT + \frac{u^2 + v^2}{2} + \sum_i h_i^0 C_i \qquad (3)$$

where h_i^0, c_{vi} - are, accordingly, heat of formation and thermal capacity per unit volume of i – component of mixture.

Wilke formula [12] is used to calculate thermal physical properties of hydrogen air mixture. Dependence of a thermal capacity coefficient on temperature is taken as a polynomial of the forth degree [12].

The coefficient of turbulent dynamic viscosity μ_t is determined by one-parameter $(k - l_\omega)$-model of turbulence.

$$\mu_t = C_\omega \rho l_\omega \sqrt{k} \tag{4}$$

The kinetic energy of turbulence k is determined by the equation:

$$\rho u \frac{\partial k}{\partial x} + \rho v \frac{\partial k}{\partial y} = \frac{\partial}{\partial y}\left(\mu_t \frac{\partial k}{\partial y}\right) + \mu_t \left(\frac{\partial u}{\partial y}\right)^2 + \frac{\mu_t}{\rho Sc_t}\frac{\partial \rho}{\partial y}\frac{\partial k}{\partial y} - \frac{C_d \rho k^{\frac{3}{2}}}{l_\omega} \tag{5}$$

The constants of model take the meanings: $C_\omega = 0.07, C_d = 0.13$.

All the quantities, formed the system of equations (1) – (5), are dimensionless. Coordinates x, y are referred to d_1, components of velocity u and v are referred to U_1, density ρ to ρ_1, pressure p to $\rho_1 U_1^2$, specific internal energy e to U_1^2, the coefficient of turbulent viscosity μ_t to $\rho_1 U_1 d_1$, kinetic energy of turbulence k - to U_1^2.

There has been found out the expression to determine l_ω, conformed to the experimental data [13].

$$l_\omega = \frac{u_{max} - u_{min}}{\left(\frac{\partial u}{\partial y}\right)_{max}}, \tag{6}$$

where u_{max}, u_{min} are, accordingly, maximum and minimum meaning of longitudinal velocity, and $\left(\frac{\partial u}{\partial y}\right)_{max}$ – maximum meaning of partial derivative of longitudinal velocity in the given section.

The velocity of hydrogen combustion in the air is described by multiply staged mechanism, enclosed 9 reversible chemical reactions, where 6 active substances H, O, OH, H_2O, O_2, H_2 [14] participate:

$$\begin{array}{lll} H+O_2 \rightleftarrows OH+O, & O+H_2 \rightleftarrows OH+H, & H_2+OH \rightleftarrows H+H_2O \\ H+OH \rightleftarrows O+H_2O, & H_2+M \rightleftarrows H+H+M, & H_2O+M \rightleftarrows OH+H+M \\ OH+M \rightleftarrows O+H+M, & O_2+M \rightleftarrows 2O+M, & H_2+O_2 \rightleftarrows 2OH \end{array} \tag{7}$$

The influence of alternation effects on the quantity of averaged velocities of elementary chemical reactions has been taken into account with the help of modified model of Spigler's immiscibility [15,16], which approximately determines a dampening influence of concentration pulsation on the velocity of chemical reactions. The determination of reaction velocities, considering immiscibility, reduces to substitution of constants of velocities of j reactions in forward (k_f^j) and return (k_b^j) directions to $k_f^j\left(1 - U_f^j\right)$, $k_b^j\left(1 - U_b^j\right)$ where the levels of immiscibility U_f^j and U_b^j are expressed through averaged concentration meanings of components and their root – mean –square pulsations [16]

$$U_f^j = U_j(j=1,2),\ U_f^j = min\{U_1 + U_2, 1\}, (j=3,...,9),$$
$$U_b^j = U_f^j,\ U_j = max\left\{\frac{\xi_j^2 - 0{,}233 Z_j^2}{\xi_j^2 + Z_j^2}, 0\right\}, (j=1,2), \tag{8}$$
$$\xi_j^2 = \frac{1}{c_\omega Sc_t}\left(l_\omega \frac{\partial Z_j}{\partial y}\right)^2$$

where $Z_j\,(j=1,2)$ is, accordingly, the concentration of chemical elements H and O.

Though this model is considered to be the most simplified, however, its using brings to the best agreement of calculation results and results of experiments [15,16].

Boundary conditions of equations' system (1) –(8) in initial section at $x=0$ has the following form:

a) in jets $u_1 = cos\alpha,\ v_1 = sin\alpha$

or $u_1 = cos\alpha,\ v_1 = -sin\alpha$,

$$\rho = 1,\ e = \frac{C_{v1}}{M_1^2 R_1 \gamma},\ k = C_k u_1^2,\ C_i = C_{i1}; \tag{9}$$

b) in stream

$$u_2 = \frac{M_2}{M_1}\sqrt{\frac{R_2 T_2}{R_1 T_1}},\ v_2 = 0,\ \rho = \frac{T_1 R_1}{n T_2 R_2},\ e = \frac{C_{v2} T_2}{M_1^2 T_1 R_1 \gamma},\ k = C_k u_2^2,\ C_i = C_{i2}.$$

In the planes of symmetry $y=0,\ y=H$ the next symmetry conditions are given

$$\frac{\partial u}{\partial y} = \frac{\partial \rho}{\partial y} = \frac{\partial e}{\partial y} = \frac{\partial C_i}{\partial y} = \frac{\partial k}{\partial y} = 0, v = 0. \tag{10}$$

The system of equations (1) – (8) together with the boundary conditions (9), (10) is solving by numerical method. Finite–difference expressions of the convective terms and terms with pressure gradients in a longitudinal direction have been got with left-hand differences because of positive own meanings of Jacobian matrix $A = \partial F/\partial U$, and in a transverse direction – with differences "against stream", considering the sign of own meanings of Jacobian matrix $B = \partial G/\partial U$ by the scheme of splitting of stream vectors [17, 18]. The terms, describing viscous voltages of a shift and heat stream, have been received by central differences. The difference analogues of the equation of mass conservation, angular momentum equation and energy are solving jointly by the method of matrix pass [19]. The approbation of numerical calculation method of the system of gas dynamic equation is given in [10]. Solution of the equation of concentration of active substances' transformation in general iterative process is separately from the main system. Recommendations [2] have been taken into account during integration of chemical kinetics equation.

Discussion of calculation results. The main operating parameters of the stream are non-calculation degree $n = p_1/p_2$, Mach's number of the jet M_1 and the stream M_2, jet temperature T_1 and stream temperature T_2, coefficient of excess air - θ , angle of jet outflow α . The effect of operating parameters to mechanisms of ignition and combustion has been investigated in the numerical experiment. Calculation conditions are given in the table 1.

Calculation data corresponding to the regime 1 (see table 1), are given in the figure 1, 2. Calculation results of diffusive combustion of the system of plane supersonic hydrogen jets in a supersonic stream show cellular distributions of dynamic, heat and concentration characteristics in the stream field.

Таблица 1

	M_1	M_2	T_1, K	T_2, K	θ	n	$C^0_{H_2}$	$C^0_{O_2}$	C^0_{OH}	$C^0_{H_2O}$	$C^0_{N_2}$
Режим 1	2.0	3.5	300	1270	4.18	0.7	1.0	0.256	0.0007	0.191	0.5523
Режим 2	2.0	3.5	300	1270	4.19	0.7	1.0	0.256	-	0.191	0.553

As it is shown at the fig. 1b, the ignition delay brings to the fact that a hydrogen jet mixes with air flow, forming a homogeneous reacting mixture, which doesn't burn because of a little jet temperature. It is easy to notice that ignition begins in the layer of jet and stream mixing at the distance $x = 20$ gauges in compression zone, where necessary kinetic conditions are supplied. There is appeared the hydroxyl OH concentration, indicating the beginning of chain reactions. The flame front has a complicated form. Its internal part is distributing on a homogeneous mixture and is closed because of complete oxygen combustion in this zone. But its external part is spreading on mixing layer (fig. 1,c). The combustion heightens the temperature and the pressure, generates heat Mach waves, which form a wavy structure of the stream by interacting with gas-dynamic waves, caused by non-calculation of jet outflow (fig. 1,a).

Inhomogeneous field of the pressure causes the convective overflows (fig. 2,b) and give rise to large-scale viscous formation (fig. 2,c), determining the mixing of the system of plane hydrogen jets in a supersonic stream. The pressure and the temperature are increasing, chain reactions are strengthening and hydroxyl OH concentration is increasing in compression zones. And in rarefaction zones, contrary, the pressure and the temperature are decreasing, the velocity of chain reactions is decelerating (fig. 1,a). Received isolines distribution of hydroxyl concentration is in correlation with a wavy structure of gas-dynamic area (fig. 1,b).

It should be noticed that received calculation data are in a qualitative agreement with the results of experiments on diffusive hydrogen combustion in non-calculated regimes of supersonic jet outflow [8]. During experiments there are observed cellular distributions of hydroxyl concentration, connected with gas-dynamic structure of the motion and characterized, accordingly, the fields of combustion strengthening and inhibition [8].

Calculated results of supersonic hydrogen jet combustion in supersonic airy stream, corresponding to the regime 2 (see table 1), are given in the figure 3. It is easy to notice that the ignition of hydrogen airy mixture begins at the distance $x / d_1 = 180$ gauges from the beginning of jet outflow. As it is shown in the figure 3, the ignition delay brings to the fact that a hydrogen jet mixes with an airy flow, forming a homogeneous reacting mixture, which doesn't burn because of a small hydrogen jet. As the result of cool jet mixing with hot flow the temperature of the mixture increases to T=900K and, thereby, necessary kinetic conditions for chemical reactions are provided and there is happened combustion.

The distribution pattern of hydroxyl OH concentration shows the formation of diffusion flame front (fig. 3,b) that is also well shown from the pattern of the temperature distribution (fig. 3,c).

Sharp increasing of the temperature in flame front brings to the pressure increasing and formation of shock waves. (fig. 3,a). The zone of increased pressure brings to an initiation and distribution of Mach waves. Mach waves, spreading from the flame front, reflect from the flow boundary and, interacting between themselves, form a wavy structure with the zones of compression and rarefaction, separated by oblique shock waves (fig. 3,a). In rarefaction zones the mixture is increasing and in the compression zones, contrary, it is decreasing. And a diffusive flame front has a cellular structure in accordance with a wavy stream structure. It is evident from the pattern of the distribution of hydroxyl OH concentration (fig. 3,b) and the temperature (fig. 3,c). The diffusive flame front has a final thickness, the zone of chain reactions has a volumetric character and it is not located in the thin surface. OH hydroxyl concentration has a maximum meaning at the flame front (fig. 3,b).

Calculated theoretical results of the researches allow to conclude the following:

1. Diffusive combustion of the system of plane supersonic hydrogen jets in supersonic stream is occurring in cellular structures with alternation of the zones of intensive chemical reactions with the zones of their inhibition.
2. Gas-dynamic and heat Mach waves cause a large–scale viscous formations, intensifying fuel mixing with oxidizer.
3. The presence of active particles in the stream composition initiates the ignition of hydrogen–airy mixture, provides intensive running of chemical reactions and shortens the length of ignition delay.

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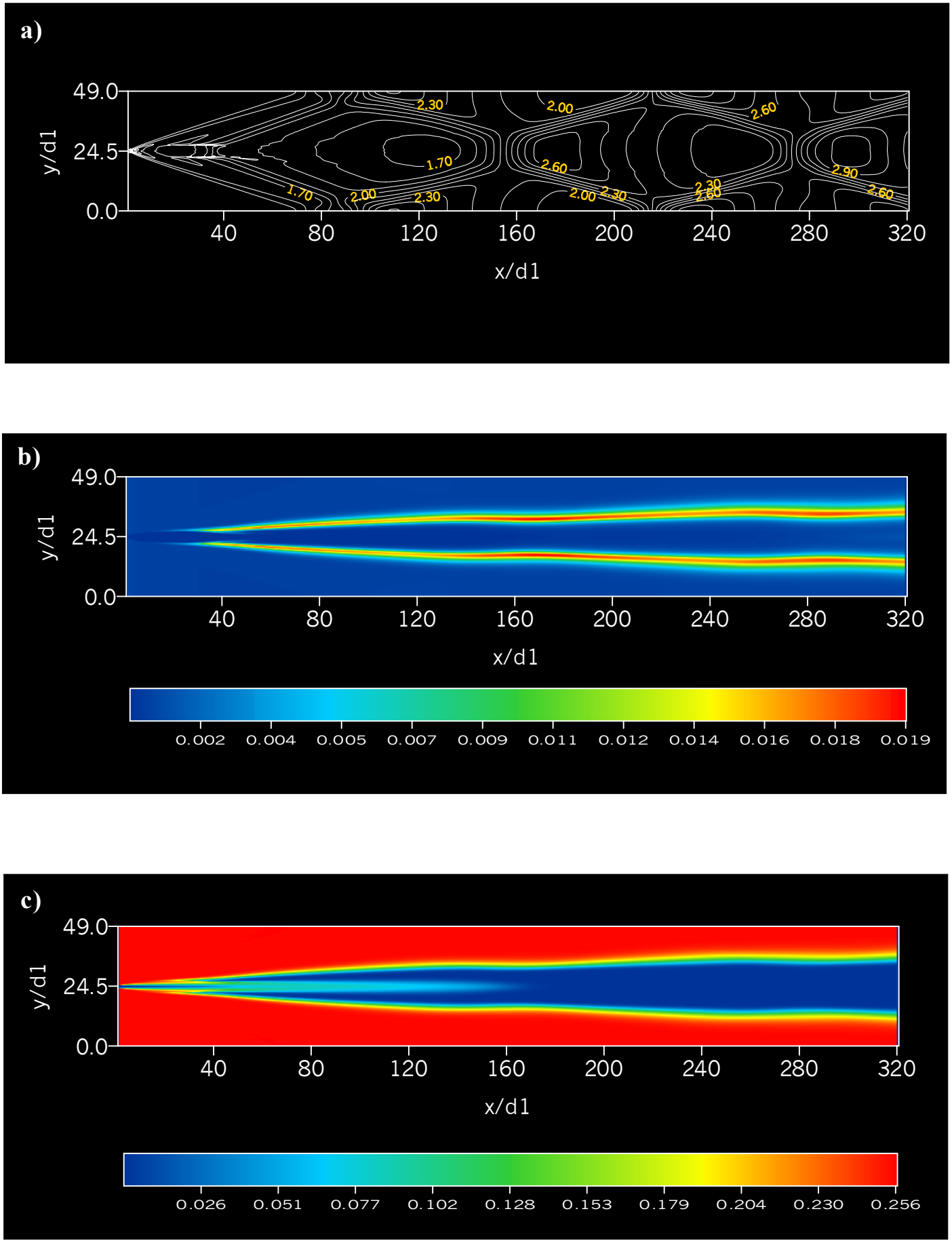

Fig.1. a) isobars; b) OH concentration fields; c) O_2 concentration field

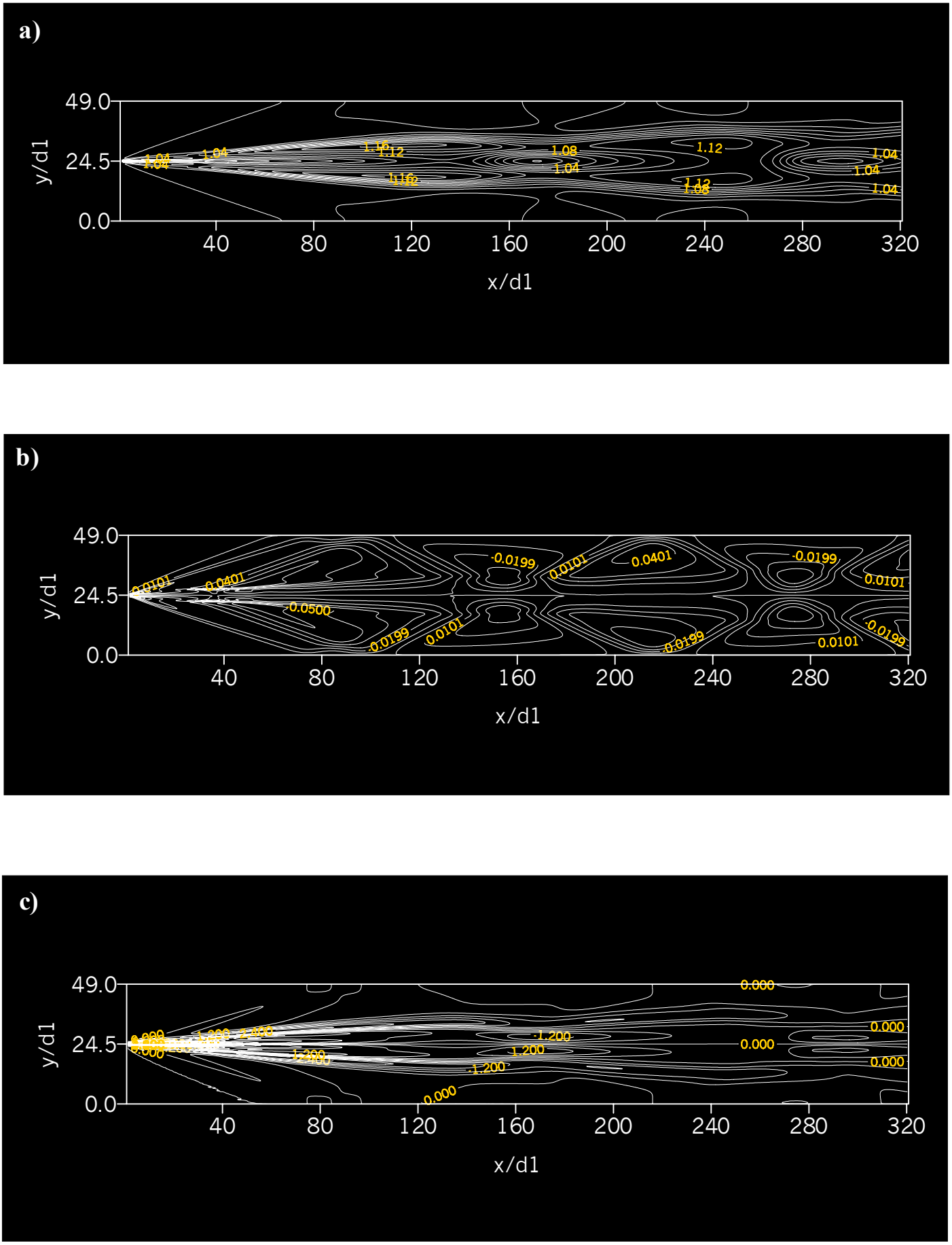

Fig.2 a) field of longitudinal rate; b) field of transverse rate; c) field of vorticity

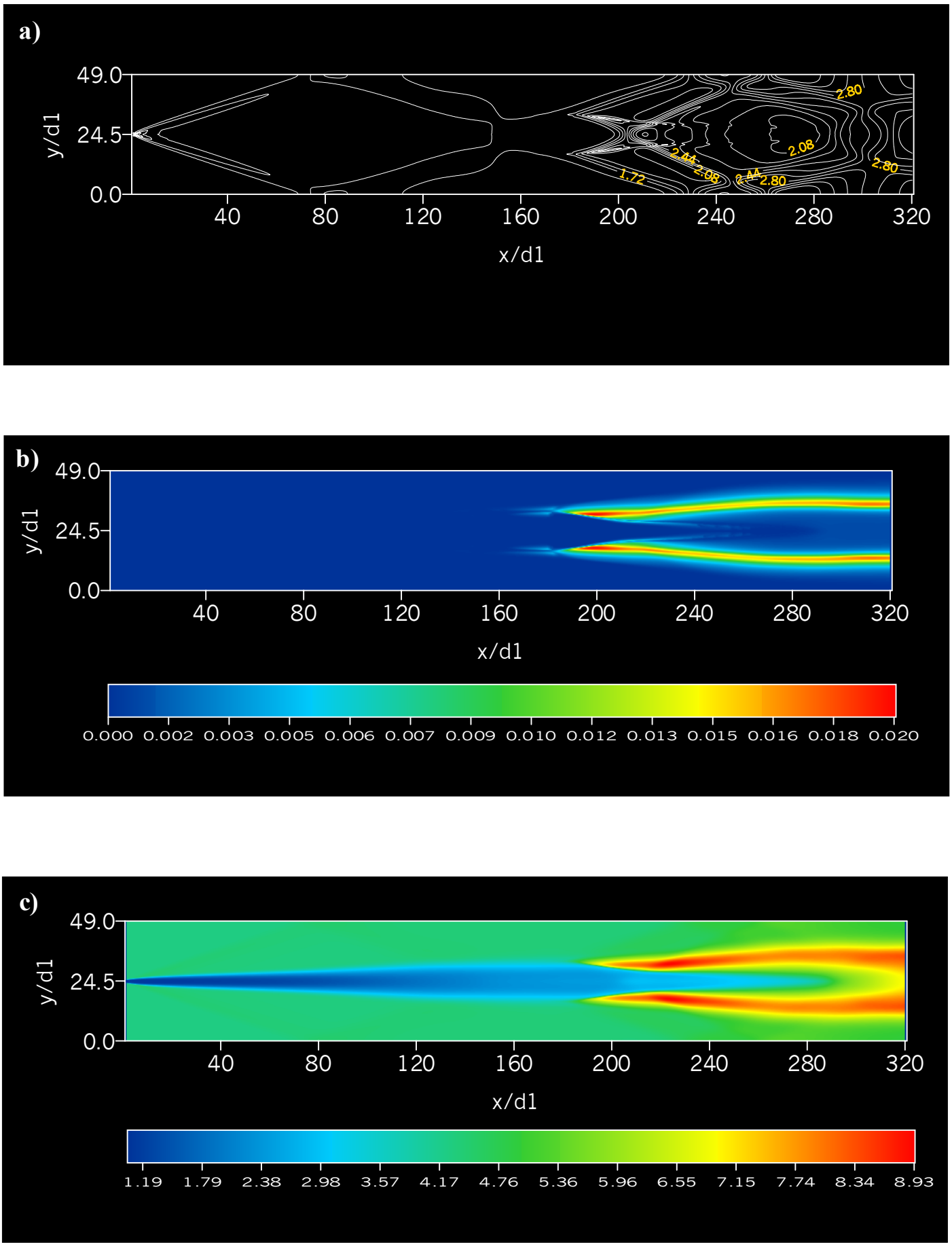

Fig.3. a) isobars; b) *OH* concentration fields; c) temperature field