NUMERICAL STUDY OF FLOWS OF A VISCOUS COMPRESSIBLE GAS AND OF AN EQUILIBRIUM GAS MIXTURE IN A FLAT NOZZLE IN THE PRESENCE OF STRONG BLOWING

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The problem of the interaction of a viscous supersonic stream in a flat nozzle with a transverse gas jet of the same composition blown through a slot in one wall of the nozzle is examined. The complete Navier–Stokes equations are used as the initial equations. The statement of the problem in the case of the absence of blowing coincides with [1]. The conditions at the blowing cut are obtained on the assumption that the flow of the blown jet up to the blowing cut is described by one-dimensional equations of ideal gasdynamics. The proposed model of the interaction is generalized to the case of flow of a multicomponent gas mixture in chemical equilibrium. The exact solutions found in [2] are used as the boundary conditions at the entrance to the section of the nozzle under consideration. The results of numerical calculations of the flows of a homogeneous nonreacting gas and of an equilibrium mixture of gases consisting of four components (H_2, H_2O, CO, CO_2) are given for different values of the parameters of the main stream and of the blown jet. In the latter case it is assumed that the effect of thermo- and barodiffusion can be neglected.

1. Much attention has been devoted to the problem of the interaction of a supersonic stream with a transverse gas jet blowing on it. This can be explained by the importance of the practical problems which are modeled to one degree or another within the framework of this interaction.

The considerable number of applications together with the wide range of variation of the characteristics of the interacting streams have given rise to a number of approaches to the study of this problem. These studies have had an experimental nature and have been directed at obtaining similarity laws [3], flow patterns [4], and approximate methods of solution [5-8].

Let us examine the flow of a viscous multicomponent mixture of gases in a flat expanding channel (Fig. 1). It is assumed that the velocity at the line of symmetry in the initial cross section ab is supersonic. The strong blowing of a mixture of gases consisting of the same components as in the main stream is produced through the slot dd_1. The coefficients of viscosity and diffusion and the Prandtl number of the gas mixture are assumed to depend on the composition of the mixture and the thermodynamic parameters of the flow.

The system of equations describing the two-dimensional flows of an m-component mixture of gases consisting of ν chemical elements has the following dimensionless form [2]:

the continuity equation

$$\nabla (\rho \mathbf{V}) = 0 \tag{1.1}$$

the equations of conservation of momentum

$$\rho (\mathbf{V}\nabla) \mathbf{V} = -\frac{1}{\varkappa M^2} \nabla p + \frac{1}{\mathrm{Re}} \left[\frac{1}{3} \nabla (\mu \nabla \mathbf{V}) + \mu \Delta \mathbf{V} + \nabla (\nabla \mu \mathbf{V}) - \mathbf{V} \Delta \mu - \nabla \times (\nabla \mu \times \mathbf{V})\right] \tag{1.2}$$

the equation of conservation of energy

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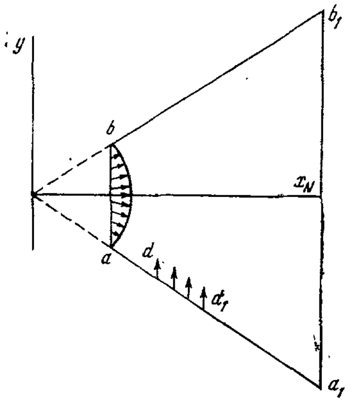

Fig. 1

$$\frac{1}{(\varkappa-1)M^2}\,\rho(\mathbf{V}\nabla)\sum_{\alpha=1}^{m} c_\alpha h_\alpha = \frac{1}{\varkappa M^2}\mathbf{V}\nabla p$$
$$+\frac{1}{\mathrm{Re\,Pr}}\frac{1}{(\varkappa-1)M^2}\,\nabla(\lambda\nabla T)+\frac{1}{\mathrm{Re}}\Big[-\frac{4}{3}\mu(\nabla\mathbf{V})^2+$$
$$+\mu\Delta(\mathbf{V}^2)-2\mu\mathbf{V}\nabla(\nabla\mathbf{V})+2\mu\mathbf{V}(\nabla\times(\nabla\times\mathbf{V}))$$
$$-\mu(\nabla\times\mathbf{V})^2\Big]-\frac{1}{\mathrm{Re\,Sm}}\frac{1}{(\varkappa-1)M^2}\sum_{\alpha=1}^{m}\nabla(\mathbf{J}_\alpha h_\alpha) \qquad (1.3)$$

the equations of diffusion of the chemical elements

$$\sum_{\alpha=1}^{m} n_{\beta\alpha}\nabla(\rho c_\alpha\mathbf{V}+\mathbf{J}_\alpha)=0$$
$$\beta=1,2,\ldots,\nu-1 \qquad (1.4)$$
$$\sum_{\alpha=1}^{m} c_\alpha = 1$$

the equations of chemical equilibrium

$$K_{p\beta}=p^a\prod_{\alpha=1}^{m}\bar{c}_\alpha{}^b,\quad \beta=1,2,\ldots,m-\nu \qquad (1.5)$$
$$b=\nu_{\alpha\beta}''-\nu_{\alpha\beta}',\quad a=\sum_{\alpha=1}^{m} b$$

The Stefan – Maxwell equations

$$\sum_{\alpha=1,\ \alpha\neq\beta}^{m}\frac{\bar{c}_\alpha\bar{c}_\beta}{\rho D_{\alpha\beta}}\left(\frac{\mathbf{J}_\alpha}{c_\alpha}-\frac{\mathbf{J}_\beta}{c_\beta}\right)=\left(\sum_{\alpha=1}^{m}\bar{c}_\alpha\right)^2\nabla\sum_{\alpha=1}^{m}\frac{\bar{c}_\beta}{\bar{c}_\alpha}\quad \beta=1,2,\ldots,m-1 \qquad (1.6)$$
$$\sum_{\alpha=1}^{m}\mathbf{J}_\alpha=0$$

the equation of state

$$p=\rho T\sum_{\alpha=1}^{m}\bar{c}_\alpha \qquad (1.7)$$

where $\mathbf{V}$, ρ, p, T, μ, and λ denote the velocity vector, density, pressure, temperature, and coefficients of viscosity and thermal conductivity of the gas mixture, respectively; c_α, h_α, $D_{\alpha,\beta}$, and $\mathbf{J}_\alpha$ are the concentration, specific enthalpy, coefficients of binary diffusion, and vector of the diffusional flux density of the component α; $n_{\beta\alpha}$ is the number of atoms of element β in component α; $\nu_{\alpha\beta}'$ ($\nu_{\alpha\beta}''$) are the stoichiometric coefficients of component α in the β-th direct (reverse) reaction; $K_{p\beta}$ is the equilibrium constant of the β-th reaction; ∇ is the Hamilton operator , $\Delta=\nabla^2$; Re, Pr, and Sm are the Reynolds, Prandtl, and Schmidt numbers; $\varkappa$ is the adiabatic index

$$\bar{c}_\alpha = c_\alpha / M_\alpha,\quad \bar{\mathbf{J}}_\alpha=\mathbf{J}_\alpha / M_\alpha$$

M_α is the molecular weight of component α.

In converting to dimensionless variables the characteristic values were taken as x_1, $u_1 = V_{x_1}$, ρ_1, T_1, μ_1, λ_1, c_{p_1}, $p_1=\rho_1 RT_1$, and $D_{\alpha\beta_1}$, equal to the corresponding values at the line of symmetry in the initial cross section of the channel (R is the universal gas constant, x_1 is the abscissa of the initial cross section and V_x is the component of the velocity vector along the x axis).

The dependences $K_{p\beta}(T)$, $h_\alpha(T)$, $c_{p\alpha}(T)$, $\mu(T)$, $\lambda(T)$, $D_{\alpha\beta}(p, T)$ close to the system of equations (1.1)-(1.7).

In the case of the flow of a homogeneous chemically nonreacting gas the appropriate system of equations can be obtained from (1.1)-(1.3), (1.7) if the latter one sets

$$\sum_{\alpha=1}^{m} c_\alpha h_\alpha = h,\quad \mathbf{J}_\alpha\equiv 0,\quad \sum_{\alpha=1}^{m}\bar{c}_\alpha=1$$

2. An important moment in the statement of the problem of the interaction of two gas streams under consideration is the formulation of the boundary conditions at the ends of the nozzle section being examined and at the blowing out.

Let us consider the case of the interaction of two homogeneous chemically nonreacting gas streams. Following [1], as the conditions at the entrance to the nozzle (cross section ab) we will use the exact solution [9, 10]

$$u = u^* (z), \quad v = v^*(z), \quad T = T^*(z), \quad p = p^* (z) \tag{2.1}$$

($z = y/x_1$; u and v are the components of the velocity vector along the x and y axes) corresponding to the flow of a viscous compressible gas in a flat nozzle without heat or mass supply and with given values of the half-angle of the nozzle aperture and the numbers M and Be.

At the exit from the nozzle section under consideration (cross section a_1b_1) one can assign the conditions of self-similarity of the flow

$$\partial u/\partial r = \partial T/\partial r = v = 0 \tag{2.2}$$

where $r = (x^2 + y^2)^{1/2}$.

The conditions (2.2), as the numerical calculations of [1] showed, are very "strict" from a computational point of view since they necessitate an increase in the length of the nozzle section under consideration with an increase in Re. In the proposed statement of the problem "milder" conditions of the type

$$\partial^3 u/\partial x^3 = \partial^3 T/\partial x^3 = \partial^3 v/\partial x^3 = 0 \tag{2.3}$$

are used instead of (2.2).

At the walls of the nozzle (except for the blowing out) we assign the conditions of adhesion and nonpenetration

$$u = v = 0 \tag{2.4}$$

and the condition of the absence of heat exchange through the wall

$$\partial T/\partial n = 0 \tag{2.5}$$

(n is the normal to the nozzle wall).

In the formulation of the boundary conditions at the blowing cut (cross section dd_1) we will assume that the flow of the blown jet up to the nozzle cut inclusively is adiabatic and is described by one-dimensional equations of gasdynamics of a nonviscous ideal gas. Then the parameters of the jet at the blowing cut satisfy the equations

$$\begin{aligned} M_S^2 &= M^2 v_S^2 / T_S \\ T_S^* &= \left(1 + \frac{\varkappa - 1}{2} M_S^2\right) T_S \\ p_S^* &= \left(1 + \frac{\varkappa - 1}{2} M_S^2\right)^{\varkappa/(\varkappa-1)} p_S \\ p_S &= \rho_S R T_S \end{aligned} \tag{2.6}$$

The subscript S corresponds to the parameters of the jet at the blowing cut; p^*_S adn T^*_S are the stagnation pressure and temperature of the jet; M is the characteristic Mach number of the main stream. Assuming that the velocity component u of the main stream at the blowing cut is zero, we obtain from the stationary continuity equation

$$(\rho v)_S = (\rho v)_0 \tag{2.7}$$

(the subscript 0 pertains to the parameters of the main stream at the blowing cut).

Equations (2.6) and (2.7) with the assigned values of p^*_S and T^*_S make it possible to determine all the characteristics of the jet, v_S, T_S, and ρ_S, i.e., the necessary boundary conditions at the blowing cut, as functions of the parameter $(\rho v)_0$. Thus, within the framework of the proposed model $(\rho v)_0$ is the determining parameter of the interaction of the main stream and the blowing jet. The value of this parameter is chosen from the condition of satisfying the equation of conservation of momentum along the y axis at each point of the blowing cut. Here is is assumed that in the vicinity of the blowing cut one can neglect the effect of viscous forces.

3. In setting up the boundary conditions in the case of the interaction of two chemically reacting gas streams we willstartfrom the model of the interaction of nonreacting homogeneous gas streams.

At the entrance to the nozzle the profiles $u^*(z)$, $T^*(z)$, $\rho^*(z)$, $c^*_\alpha(z)$, are given corresponding to the exact solution of [2] for fixed values of the nozzle aperture angle, the numbers M and Re, the concentrations of the chemical elements, and the temperature at the line of symmetry in the initial cross section. The conditions (2.4) are carried over to this case without change.

In the case of noncatalytic, thermally insulated nozzle walls one can write the conditions

$$\partial T / \partial n = \partial c_\alpha^{\cdot} / \partial n = 0, \quad \alpha = 1, 2, \ldots, m$$

At the exit from the nozzle one must add the conditions for the concentrations

$$\partial c_\alpha / \partial r = 0, \quad \alpha = 1, 2, \ldots, m$$

or

$$\partial^3 c_\alpha / \partial x^3 = 0, \quad \alpha = 1, 2, \ldots, m$$

to the conditions (2.2) or (2.3).

To obtain the conditions at the blowing cut we assume as before that the blowing is accomplished along the normal to the plane of symmetry of the nozzle and that the flow of the blown equilibrium gas mixture from infinity up to the blowing cut is isentropic and is described by one-dimensional equations of gasdynamics of a nonviscous ideal gas with allowance for the equilibrium chemical reactions. The latter can be represented in the form

$$\begin{gathered}
\sum_{\alpha=1}^{m} c_{\alpha q} h_{\alpha q} + \frac{v_q^2}{2} = \sum_{\alpha=1}^{m} c_{\alpha q0} h_{\alpha q0} \\
(\rho v)_q = (\rho v)_0 \\
s_q \equiv \sum_{\alpha=1}^{m} \frac{1}{M_\alpha} \left[s_{\alpha q} - R \lg \left(\bar{c}_{\alpha q} \Big/ \sum_{\alpha=1}^{m} \bar{c}_{\alpha q} \right) \right] = s_{q0} \\
p_q = \rho_q R T_q \sum_{\alpha=1}^{m} \bar{c}_{\alpha q} \\
\sum_{\alpha=1}^{m} n_{\beta\alpha} \bar{c}_{\alpha q} = \sum_{\alpha=1}^{m} n_{\beta\alpha} \bar{c}_{\alpha q0}, \quad \beta = 1, 2, \ldots, \nu - 1 \\
\sum_{\alpha=1}^{m} c_{\alpha q} = 1 \\
K_{p\beta} = p_q^{\,a} \prod_{\alpha=1}^{m} \bar{c}_{\alpha q}^{\,b} \\
b = \nu''_{\alpha\beta} - \nu'_{\alpha\beta}, \quad a = \sum_{\alpha=1}^{m} b
\end{gathered} \tag{3.1}$$

($s_{\alpha q}$ is the entropy of the component α at $p = 1$ atm, the subscript q corresponds to the parameters of the jet at the blowing cut, the subscript q0 corresponds to the stagnation parameters of the jet, and the subscript 0 corresponds to the parameters of the main stream at the blowing cut).

The system of equations (3.1) with assigned values of the stagnation parameters of the jet is monoparametric. Its solution, i.e., the values of v_q, ρ_q, T_q, p_q, $c_{\alpha q}$ ($\alpha = 1, 2, \ldots, m$), is uniquely determined if the flow rate of the jet $(\rho v)_0$ is known. The latter, as in Sec. 2, is found from the equation of conservation of momentum (1.2) in projection onto the normal to the plane of symmetry of the nozzle.

4. For the numerical solution of the stated problem we used the explicit method of determination [11] with certain modifications [12, 13] making it possible to decrease the determination time and to weaken the condition of stability, reducing it to the well-known Courant–Friedrichs–Levi condition [14].

In [1] it was noted that the difference system of [11] loses stability in the case when a density disturbance occurs in regions of low stream velocities. The vicinity of the blowing cut is such a region in the problem under consideration. Calculations of flows with blowing conducted with the use of the standard system [11] have confirmed the correctness of this observation. To assume the stablilty of the difference system in a wide range of variation of the parameter $(\rho v)_0$ an additional "viscous" term of the type

$$C \left(|u_{ij}^n| \frac{\rho_{i+1j}^n - 2\rho_{ij}^n + \rho_{i-1j}^n}{h_1^2} + |v_{ij}^n| \frac{\rho_{ij+1}^n - 2\rho_{ij}^n + \rho_{ij-1}^n}{h_2^2} \right) \tag{4.1}$$

was introduced into the difference equation approximating the continuity equation, where C is a constant, $\rho_{ij}^n = \rho(n\tau, ih_1, jh_2)$; $h_1 = \Delta x$, $h_2 = \Delta y$, and $\tau = \Delta t$ are the steps of the space–time grid.

The choice of $C = O(h^2)$ ($h = \min(h_1, h_2)$) proved to be sufficient to obtain monotonic density profiles in the blowing zone.

As a result of the methodical calculations conducted it was established that one can make a stable calculation with $\tau = O(h)$ if one assumes that the stagnation parameters of the blown jet are brought to the required values through the linear law

$$\varphi_{q0}^* = t\varphi_{q0} + (1 - t)\,\varphi_0^*, \quad 0 \leqslant t \leqslant 1 \tag{4.2}$$

where φ^*_{q0} is the current value of the retardation parameter of the jet, φ_{q0} is the required value of this parameter, and φ^*_0 is the value of the corresponding parameters of the main stream at points of the blocking cut in the absence of blowing.

If one is limited to the consideration of equimolecular reactions then a = 0 in Eqs. (1.5). In this case for the solution of the equations of the diffusional part of the problem [Eqs. (1.3)-(1.5)] one can use the procedure of [15], consisting in the following. We differentiate Eq. (1.5) logarithmically with respect to time

$$\frac{d\ln K_{p\beta}}{dT}\frac{\partial T}{\partial t} = \sum_{\alpha=1}^{m}\frac{b}{\bar{c}_\alpha}\frac{\partial \bar{c}_\alpha}{\partial t} \qquad \beta = 1, 2, \ldots, m - \nu \tag{4.3}$$

Then we write Eq. (1.4), introducing the nonstationary term and differentiating the latter equation with respect to time, in the form

$$\begin{gathered}\sum_{\alpha=1}^{m} n_{\beta\alpha}\frac{\partial \rho c_\alpha}{\partial t} = \sum_{\alpha=1}^{m} n_{\beta\alpha}\,\nabla(\rho c_\alpha \mathbf{V} + \mathbf{J}_\alpha) \\ \beta = 1, 2, \ldots, \nu - 1 \\ \sum_{\alpha=1}^{m} M_\alpha\frac{\partial \bar{c}_\alpha}{\partial t} = 0\end{gathered} \tag{4.4}$$

The system of equations (1.3) (with the addition of the nonstationary term), (4.3), (4.4) is linear relative to the derivatives $\partial T/\partial t$, $\partial c_\alpha/\partial t$ ($\alpha = 1, 2, \ldots, m$) and permits the determination of these derivatives at each point of the region of flow under consideration.

A similar procedure can be used to calculate the parameters of the blown jet at the blowing cut. With allowance for (4.2) the system of equations obtained from (3.1) by formal differentiation with respect to time makes it possible to find the derivatives $\partial c_{\alpha q}/\partial t$, $\partial T_q/\partial t$, $\partial \rho_q/\partial t$, $\partial p_q/\partial t$, and $\partial v_q/\partial t$ as functions of $\partial(\rho v)_0/\partial t$. The latter value is found from the nonstationary equation of conservation of momentum along y.

The density ot the walls of the nozzle (except for the blowing cut) is determined from the nonstationary continuity equation described at the boundary points with a second-order approximation with respect to the spatial variables. The difference equations, approximating with second order the corresponding differential conditions of the noncatalytic and thermally nonconducting nature of the nozzle walls, permit the determination of the temperature and concentration of the components at the nozzle wall.

The conditions (2.3) in the difference representation have the form

$$f_{Nj}^{n+1} = f_{N-3j}^{n} - 3\,(f_{N-2j}^{n} - f_{N-1j}^{n})$$

(i = N corresponds to the exit cross section of the nozzle).

The functions $u^*(z)$, $v^*(z)$, $T^*(z)$, $p^*(z)\,x^{-1}$, and $c^*_\alpha(z)$ corresponding to the exact solution of [9, 10] (a chemically nonreacting stream) or to the exact solution of [2] (with allowance for equilibrium chemical reactions) are taken as the initial conditions.

In order to test the correctness of the formulation of the boundary conditions and the accuracy of the calculations on a grid with $h_1 = h_2 = 0.1$ control calculations were conducted for the case of M = 1.5, Re = 400, $\varkappa = 1.22$. At t = 6 the maximum deviation of the stream parameters from the values corresponding to an exact solution was observed at the nozzle walls and was 2% for the density and 1% for the other values. An estimate of the effect of the boundary conditions at the exit from the nozzle was obtained from a comparison of the results of calculations for a short ($x_N = 2.9$) and a long ($x_N = 3.6$) nozzle with M = 2, Re = 100, and $p^*_s/p_l = 1.1$ (p_l is the pressure at the line of symmetry of the nozzle at x = 1.9). The blowing was carried out through a slit at $1.9 \le x \le 2.1$. The initial cross section corresponded to x = 1. The

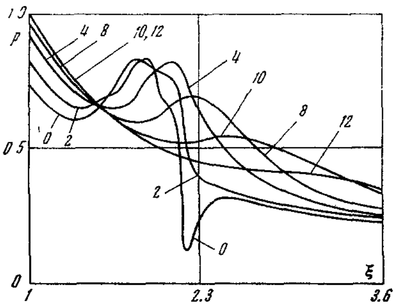

Fig. 2

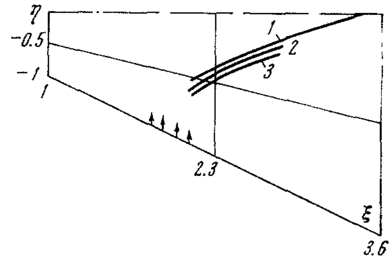

Fig. 3

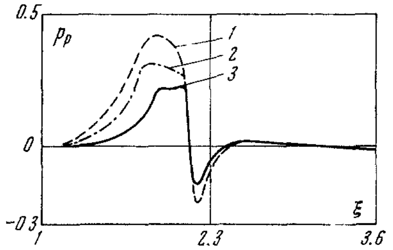

Fig. 4

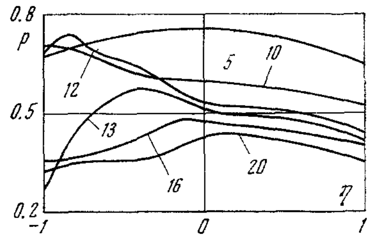

Fig. 5

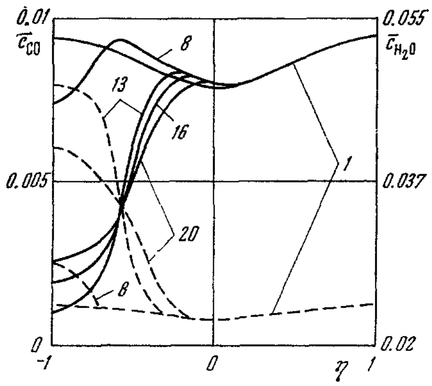

Fig. 6

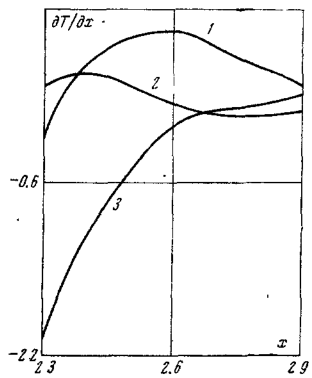

Fig. 7

comparison showed that the maximum difference in the parameters occurs at x = 2.9 and does not exceed 1% at the walls of the nozzle and 0.5% at the line of symmetry.

A test of how the laws of conservation are satisfied, conducted for the variant corresponding to the greatest blowing intensity (M = 3, Re = 135, $p_S{}^*/p_l$ = 1.62) showed that the error does not exceed 3%.

5. Some results of the numerical calculations are presented in Figs. 2-7. Figure 2 illustrates the pressure distribution along the length of the nozzle at different cross sections y = const (the numbers of the curves correspond to the cross sections $y_j = j\Delta y - y_W$, $y_W = x\ \mathrm{tg}\theta_W$) for the case of M = 3, Re = 135, $p_S{}^*/p_l$ = 1.62, θ_W = 24°6', and the absence of chemical reactions.

The positions of the shock waves developing during the interaction of nonreacting streams are shown in Fig. 3 for the case of M = 3, Re = 135, and different values of the parameter $p_S{}^*/p_l$. Curve 1 corresponds to $p_S{}^*/p_l$ = 1.62, curve 2 to $p_S{}^*/p_l$ = 1.32, and curve 3 to $p_S{}^*/p_l$ = 1.125.

Distributions of the parameter $p_p = p_S - p_0$ (p_S is the pressure at the nozzle wall during the blowing of a chemically nonreacting jet and p_0 is the same value in a flow without blowing) are presented in Fig. 4 for the case of M = 3, Re = 135, and different values of $p_S{}^*/p_l$. The respective curve numbers and values of this parameter are the same as in Fig. 3.

Some results of numerical calculations of the interaction of two streams of equilibrium gas mixtures consisting of four components, H_2O, H_2, CO, and CO_2, are presented in Figs. 5-7. It was assumed that equilibrium chemical reactions take place in the mixture which are described by the following total reaction:

$$H_2 + CO_2 \rightleftarrows CO + H_2O$$

the equilibrium constant of which is connected with the concentrations of the reacting components by the equation

$$K_p = (\bar{c}_1\bar{c}_2) / (\bar{c}_3\bar{c}_4)$$
$$(\bar{c}_1 = \bar{c}_{H_2O},\ \bar{c}_2 = \bar{c}_{CO},\ \bar{c}_3 = \bar{c}_{CO_2},\ \bar{c}_4 = \bar{c}_{H_2})$$

The characteristic Schmidt number at the line of symmetry of the nozzle was taken as unity. The coefficient of viscosity of the gas mixture was calculated from the equation of [16] and the Prandtl number of the mixture from the equation

$$\mathrm{Pr} = c_p / (1.204c_p + 1.47)$$

The thermodynamic parameters of the mixture were found with the use of the equations of [17].

Profiles of the pressure at different cross sections x = const are shown in Fig. 5 (the numbers of the curves correspond to the cross sections $x_i = i\Delta x + 1$) for the case of M = 2, Re = 100, $T_S = 1700°$ K, $c_4 = 0.0066$, $\overline{c_1} = 0.0235$, $\overline{c_2} = 0.0078$ (the concentrations of the components at the initial cross section of the nozzle) and the blowing of a gas mixture with a large water vapor content ($c_1 = 0.9$). In this case the stagnation parameters of the jet are $\mathbf{c}_0 = 0.05229$, $\mathbf{c}_C = 0.00229$, $\mathbf{c}_H = 0.112$ ($\mathbf{c}_O$, $\mathbf{c}_C$, $\mathbf{c}_H$ are the reduced concentrations of the corresponding chemical elements), $T_{q0} = 1.33$, $p_{q0}/p_l = 1.36$, and $H_\Sigma = -13.161$ (H_Σ is the enthalpy of the mixture).

Distributions of the concentrations c_2 (solid lines) and c_1 (dashed lines) at different cross sections x = const are presented in Fig. 6 (the respective curve numbers and cross sections are the same as in Fig. 5) for the same values of the parameters of the main stream and for values of the parameters of the blown jet equal to $c_2 = 0.88$, $\mathbf{c}_0 = 0.0367$, $\mathbf{c}_C = 0.003319$, $\mathbf{c}_H = 0.00722$, $T_{q0} = 1.33$, $p_{q0}/p_l = 1.24$, $H_\Sigma = -4.87$.

The calorific effect of the chemical reactions can be followed in Fig. 7, where the profiles of $\partial T/\partial x$ at the blowing cut are presented. Curve 1 corresponds to the case of the blowing of a gas mixture with $c_2 = 0.88$ and $p_{q0}/p_l = 1.24$; curve 2 corresponds to blowing with $c_1 = 0.9$ and $p_{q0}/p_l = 1.34$; curve 3 corresponds to blowing with $p_S^*/p_l = 1.3$ (without chemical reactions).

It is seen that the blowing of a mixture with an enthalpy greater than the enthalpy of the main stream causes an additional temperature increase because of the chemical reactions. In blowing a mixture with a large (in absolute value) negative enthalpy the temperature in the stream first drops because of the endothermic reactions and then increases beacuse the dissipative effect becomes dominant downstream.

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