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NUMERICAL RESULTS OF DIFFUSION COMBUSTION IN A TURBULENT FLOW OF REACTING GASES

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Abstract
In this paper, a numerical solution to the problem of the symmetrical flow of methane with respect to the axis under an infinite satellite flux and diffusion combustion is proposed. To simulate the object, dimensional equations in Mises variables of a turbulent boundary layer of interacting gases were used. The equations for the components of the gas mixture are reduced to one equation by introducing the Schwab-Zeldovich function.

To solve the problem in the Mises coordinates, a two-layer four-point nonlinear scheme for separating boundaries was used, and the second order was given by the longitudinal coordinate. The iterative process was used due to the nonlinearity of the equations of accumulation and displacement of substations. Individual results of the numerical experiment are presented.

Keywords: Turbulent jet, gas mixture, diffusion flame, velocity, total enthalpy, finite differences, computational experiment.

Introduction

Currently, gas is the main source of thermal energy: about 70% of the energy produced and consumed in the world is spent on gas combustion, and 30% comes from water, wind, solar and nuclear fuel.

At the same time, the efficiency of using natural and liquefied gas fuels is very low. In this regard, the processes of flame formation and propagation, methods of effective control of them, enrichment and development of existing mathematical models are studied in depth on the basis of new achievements in the field of turbulence, injection and combustion theory.

Various methods of continuous organization of the combustion process have been developed, the theoretical foundations of which are based on the theory of turbulent shock flows and the theoretical provisions of the kinetics of kinetic reactions. The jet stream theory is based on a simplified version of the Nef-Stokes system of equations based on the turbulent boundary layer approach.

Two methods of organizing the combustion process in a turbulent boundary layer are widely used. In the first of them, the fuel-oxygen mixture is injected separately into the combustion zone, and the method is classified according to the formation of a diffusion flame.

The second method is fuel and oxygen (or an oxygen-air mixture) in the form of a mixture ready to be combined. Different types of these methods have been developed to control the characteristics of the flame (length, width, temperature, or solids). At the same time, the basic requirements are met in the design of the combustion device, for which it is desirable to conduct a theoretical study.

Theoretical work in this area is still ongoing due to the incomplete theoretical basis of chemical exothermic reactions under turbulent flow conditions. In practice, the combustion process can be organized cyclically or in large volumes at low volume and high pressure by continuously injecting reactants and isolating reaction products in the same way [1]. In the second method, chemically interacting agents can be introduced as a separate or final mixture [7]. We can study these methods based on diffusion or uniform combustion models [8].

Models of uniform combustion include the Bunzen burner, Arrhenius' law, and chemical equilibrium models [9]. The mathematical model of diffusion combustion is associated with the names of Burke, Schumann, B. A. Schwab and J. B. Zeldovich, where it is assumed that the burning rate is very high and has a thin flame surface [10]. This model was developed by F. Aliyev and Z. Zhumaev for individual combustion gases and combustible gases. Although it is assumed that the rate of a chemical reaction is infinite, diffusion combustion has a long flame length. As a result, this method is widely used in the manufacture of building materials and the production of mercury in rotary kilns, and helps to create the necessary temperature and content for heat and mass transfer in accordance with process requirements.

A review of the literature [3.7-10] shows that the diffusion combustion of fuel with the main component methane has not been sufficiently studied. Currently, methane is the main component of natural gas produced in Uzbekistan. The main reasons for this are the "aging" of gas fields and the separation of heavy hydrocarbons from natural gas by one- or three-stage low-temperature separation. Taking into account these aspects, the article considers methane dissipation and diffusion combustion.

A physical problem in this matter. Combustion flows through a pipe, the radius of which is gas, and propagates at the speed of an air flow. Each gas mixture separately has its own composition and thermal properties. Fuel gas reacts with oxygen in the air. The rate of combustion is considered to be very high, so that oxygen does not enter the combustion zone of the fuel, and oxygen from the air cannot penetrate through the combustible mixture. Chemically passive gases are capable of convective migration and diffuse with other components.

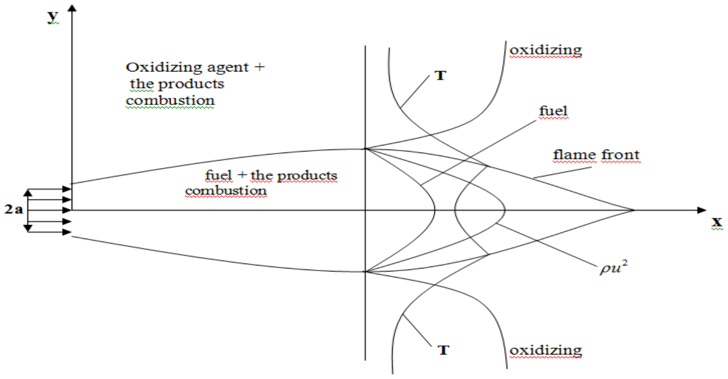


Figure 1. Schematic representation of an immersion jet with a diffusion plume.

The combustion process is modeled as the stoichiometric equation of the irreversible general reaction:

Formulation of a mathematical problem. Heat and Mass Transfer Processes

$$\begin{cases} \rho u\dfrac{\partial u}{\partial x}+\rho\vartheta\dfrac{\partial u}{\partial r}=\dfrac{1}{r}\dfrac{\partial}{\partial r}\left(\rho(\nu+\nu_t)r\dfrac{\partial u}{\partial r}\right), \\ \dfrac{\partial\left(\rho ur\right)}{\partial x}+\dfrac{\partial\left(\rho\vartheta r\right)}{\partial r}=0, \\ \rho u\dfrac{\partial H}{\partial x}+\rho\vartheta\dfrac{\partial H}{\partial r}=\dfrac{1}{\Pr r}\dfrac{\partial}{\partial r}\left(\rho(\nu+\nu_t)r\dfrac{\partial H}{\partial r}\right), \\ \rho u\dfrac{\partial c_2}{\partial x}+\rho\vartheta\dfrac{\partial c_2}{\partial r}=\dfrac{1}{Sc\, r}\dfrac{\partial}{\partial r}\left[\rho\left(\dfrac{1}{\mathrm{Re}}+\nu_t\right)r\dfrac{\partial c_2}{\partial r}\right]+\omega_2, \\ \rho u\dfrac{\partial c_n}{\partial x}+\rho\vartheta\dfrac{\partial c_n}{\partial r}=\dfrac{1}{Sc\, r}\dfrac{\partial}{\partial r}\left[\rho\left(\dfrac{1}{\mathrm{Re}}+\nu_t\right)r\dfrac{\partial c_n}{\partial r}\right]+\omega_n \ \ (n=1,3,4...N). \end{cases} \tag{1}$$

The system of differential equations is supplemented by the algebraic equations of enthalpy and state of the gas mixture, respectively:

$$H=c_pT+c_2h_2^*,\ c_p=\sum_{k=1}^{N}c_{pn}c_n,$$

$$p=\rho\frac{R_0}{m}T=const,\quad m=\left(\sum_{n=1}^{N}m_n/c_n\right)^{-1}, \tag{2}$$

system of equations [3,5,9]. Here are longitudinal and radial velocity regulatorsu, v m/s; - Gas density $\rho, \mathrm{T}\left(\kappa g\ m^{-3}\right)$ and absolute temperature (K); $\Pr, \mathrm{Sc}$ - Prandtl and Schmidt turbulence numbers; c_k - mass concentration of components; ω_k - mass combustion rate $\left(kg\, m^{-3}\ s^{-1}\right)$; ν_t − turbulent viscosity; H - complete enthalpy;

The conditions for access to the flow zone are as follows:

$$\left.\begin{aligned} &x=0:\begin{cases} u=u_2, H=H_2, \overset{\approx}{C}=1,\ k=k_2,\ \varepsilon=\varepsilon_2,\ v=0 \quad 0\le y\le a \\ u=u_1, H=H_1, \overset{\approx}{C}=0,\ k=k_1,\ \varepsilon=\varepsilon_1,\ v=0 \quad a<y\le\infty \end{cases} \\ &x>0:\begin{cases} \dfrac{du}{dy}=v=\dfrac{dH}{dy}=\dfrac{d\overset{''}{C}}{dy}=\dfrac{dk}{dy}=\dfrac{d\varepsilon}{dy}=0, \quad y=0 \\ u\to u_1,\ v\to 0,\ H\to H_1,\ \overset{''}{C}\to 0, k\to k_1,\ \varepsilon\to\varepsilon_1 \qquad y\to y_\infty \end{cases} \end{aligned}\right\} \tag{3}$$

Turbulence modeling. We used the $\boldsymbol{k-\varepsilon}$ model for turbulent exchange [1-3]:

$$\begin{cases} \rho u\dfrac{\partial k}{\partial x}+\rho\vartheta\dfrac{\partial k}{\partial r}=\dfrac{1}{\delta_\varepsilon r}\dfrac{\partial}{\partial r}\left(\rho r\nu_t\dfrac{\partial k}{\partial r}\right)+G_k-\rho\varepsilon, \\ \rho u\dfrac{\partial\varepsilon}{\partial x}+\rho\vartheta\dfrac{\partial\varepsilon}{\partial r}=\dfrac{1}{\delta_\varepsilon r}\dfrac{\partial}{\partial r}\left(\rho r\nu_t\dfrac{\partial\varepsilon}{\partial r}\right)+c_{\varepsilon 1}f_1\dfrac{\varepsilon}{k}G_k-c_{\varepsilon 2}\rho f_2\dfrac{\varepsilon^2}{k}. \end{cases}$$

$$\nu_t = \frac{c_\mu f_\mu k^2}{\varepsilon}, \quad R_R = \frac{\sqrt{k}\, r}{\nu}, \quad f_1 = 1 + \left(\frac{A_1}{f_\mu}\right)^3, \quad f_2 = 1 - e^{-R_t^2}, \tag{4}$$

$$R_t = \frac{k^2}{\nu\varepsilon}, \quad f_\mu = \left(1 - e^{-A_\mu R_R}\right)^2 \left(1 + \frac{A_t}{R_t}\right), \qquad \mathrm{G}_k = 4\rho\nu_t \left(\frac{\partial u}{\partial r}\right)^2, \quad c_{\varepsilon 2} = 1.92, \quad c_\mu = 0.09, \quad \delta_k = 1 \;,$$

$$c_{\varepsilon 1} = 1.44, \quad \delta_\varepsilon = 1.3, \; A_1 = 0.05, \; A_\mu = 0.0165$$

A method for reducing the equations of component retention to a single equation is proposed. The problem of distribution and combustion of gaseous methane in the air flow of a satellite is considered. We believe that methane has equal concentrations in combustible gas. The stoichiometric equation of the process can be written in the form

$$v_2 A + v_1 O_2 \rightarrow v_3 CO_2 + v_4 H_2O + h_2^*,$$

where stoichiometric $\nu_1 = 2.0 \;\; \nu_2 = 1, \;\; \nu_3 = 1.0, \;\; \nu_4 = 2.0$ coefficients , Refer to oxygen, combustibles, carbon monoxide, and water vapor; $h_2^* = 55644$ In addition, the presence of molecular nitrogen N_2, which is considered a chemically passive component, is taken into account. Accordingly, in this case, the number of equations for the retention of the components is , $N = 5$ which are abbreviated as $L(c_k) = \omega_k \qquad (k = 1..5)$.

Here $L(c_k) = \rho u \frac{\partial c_k}{\partial x} + \rho v \frac{\partial c_k}{\partial y} - \frac{1}{Sc\, y} \frac{\partial}{\partial y}\left(\rho \varepsilon y \frac{\partial c_k}{\partial y}\right)$ is a linear and uniform argument - mass concentration k is a component c_k operator , and ω_k is the mass rate of formation (disappearance) k of the number of molecules at a given point of the flame front in one period of time. For the rates of chemical reactions, where it is taken into account, the following relations take place

$$\begin{aligned} &\omega_3 \, \nu_k \, m_k + \omega_k \nu_3 \, m_3 = 0 \quad \text{при} \quad k = 1,2; \\ &\omega_3 \, \nu_k \, m_k - \omega_k \nu_3 \, m_3 = 0 \quad \text{при} \quad k = 4; \\ &\omega_3, \;\; \omega_4 \geq 0 \,. \end{aligned} \tag{5} \quad \omega_1, \;\; \omega_2 \leq 0 ,$$

The dependencies given indicate the way in which the rates of chemical reactions can be excluded from the equations of conservation of components $L(c_k) = \omega_k$.

If you enter Schwab-Zeldovich functions according to,

$$\tilde{C}_k = \begin{cases} c_3 \, \nu_k \, m_k + c_k \nu_3 \, m_3 = 0 \quad \text{при} \quad k = 1,2; \\ c_3 \, \nu_k \, m_k - c_k \nu_3 \, m_3 = 0 \quad \text{при} \quad k = 4, \end{cases} \tag{6}$$

Then the equations for the conservation of components for $k = 1,2$ and 4 take the form that does not contain additives $L(\tilde{C}_k) = 0$.

The equation for the concentration of the inert gas, since $\omega_5 = 0$, is also similar $L(c_5) = 0$. I.e. we have four differential equations for the five concentrations of the components.

Let's draw up boundary conditions for the introduced functions:

$$\begin{aligned}&\left(\tilde{C}_1\right)_1=\left(c_3\right)_1\nu_1 m_1+\left(c_1\right)_1\nu_3 m_3,\ \left(\tilde{C}_1\right)_2=\left(c_3\right)_2\nu_1 m_1,\\ &\left(\tilde{C}_2\right)_1=\left(c_3\right)_1\nu_2 m_2,\ \left(\tilde{C}_2\right)_2=\left(c_3\right)_2\nu_2 m_2+\left(c_2\right)_2\nu_3 m_3,\\ &\left(\tilde{C}_4\right)_1=\left(c_3\right)_1\nu_4 m_4-\left(c_4\right)_1\nu_3 m_3,\ \left(\tilde{C}_4\right)_2=\left(c_3\right)_2\nu_4 m_4-\left(c_4\right)_2\nu_3 m_3.\end{aligned}\qquad(7)$$

Now we will introduce relatively redundant functions relative to $\tilde{C}_k$

$$\overset{\approx}{C}_k=\frac{\tilde{C}_k-\left(\tilde{C}_k\right)_1}{\left(\tilde{C}_k\right)_2-\left(\tilde{C}_k\right)_1}=\frac{c_5-\left(c_5\right)_1}{\left(c_5\right)_2-\left(c_5\right)_1}.\qquad(8)$$

The analysis shows that the equations $L(\overset{\approx}{C}_k)=0$ are mutually equivalent because they have the same coefficients and boundary conditions. This will make it possible to obtain four equations $L(\overset{\approx}{C}_k)=0$ to proceed to one equation $L\left(\overset{\approx}{C}\right)=0$.

In particular, at the inlet to the fuel zone, this function has a value of 1, at the inlet to the oxidizer zone and at the interface of the jet, it has a value of 0. For this function, there is symmetry on the axis of the jet.

With a known value of this function, the concentration of the inert gas is determined simply:

$$C_5=\left(C_5\right)_1+\left[\left(C_5\right)_2-\left(C_5\right)_1\right]\overset{\approx}{C}.\quad \tilde{C}_k=\left(\tilde{C}_k\right)_1+\left[\left(\tilde{C}_k\right)_2-\left(\tilde{C}_k\right)_1\right]\overset{\approx}{C}.$$

Substituting values $\tilde{C}_k$, $\left(\tilde{C}_k\right)_2$, $\left(\tilde{C}_k\right)_1$ in these constraints results in a system of linear equations

$$\begin{cases}c_3\nu_1 m_1+c_1\nu_3 m_3=\left(c_3\right)_1\nu_1 m_1+\left(c_1\right)_1\nu_3 m_3+\\ \qquad+\left[\left(c_3\right)_2\nu_1 m_1-\left(c_3\right)_1\nu_1 m_1-\left(c_1\right)_1\nu_3 m_3\right]\overset{\approx}{C},\\ c_3\nu_2 m_2+c_2\nu_3 m_3=\left(c_3\right)_1\nu_2 m_2+\\ \qquad+\left[\left(c_3\right)_2\nu_2 m_2+\left(c_2\right)_2\nu_3 m_3-\left(c_3\right)_1\nu_2 m_2\right]\overset{\approx}{C},\\ c_3\nu_4 m_4-c_4\nu_3 m_3=\left(c_3\right)_1\nu_4 m_4-\left(c_4\right)_1\nu_3 m_3+\\ \quad+\left[\left(c_3\right)_2\nu_4 m_4-\left(c_4\right)_2\nu_3 m_3-\left(c_3\right)_1\nu_4 m_4+\left(c_4\right)_1\nu_3 m_3\right]\overset{\approx}{C}.\end{cases}\qquad(9)$$

Let's simplify the system:

$$\begin{cases}c_3+c_1\dfrac{\nu_3 m_3}{\nu_1 m_1}=\left(c_3\right)_1+\left(c_1\right)_1\dfrac{\nu_3 m_3}{\nu_1 m_1}+\left[\left(c_3\right)_2-\left(c_3\right)_1-\left(c_1\right)_1\dfrac{\nu_3 m_3}{\nu_1 m_1}\right]\overset{\approx}{C},\\ c_3+c_2\dfrac{\nu_3 m_3}{\nu_2 m_2}=\left(c_3\right)_1+\left[\left(c_3\right)_2-\left(c_3\right)_1+\left(c_2\right)_2\dfrac{\nu_3 m_3}{\nu_2 m_2}\right]\overset{\approx}{C},\\ c_3-c_4\dfrac{\nu_3 m_3}{\nu_4 m_4}=\left(c_3\right)_1-\left(c_4\right)_1\dfrac{\nu_3 m_3}{\nu_4 m_4}+\\ +\left[\left(c_3\right)_2-\left(c_3\right)_1-\left(\left(c_4\right)_2-\left(c_4\right)_1\right)\dfrac{\nu_3 m_3}{\nu_4 m_4}\right]\overset{\approx}{C}.\end{cases}\qquad(10)$$

At the flame flare, the concentration of the reagent is zero. In this case, the value of the relative redundant function corresponding to the flame front is determined from the first two equations of this system:

$\overset{\approx}{C}^{*}=\left[1+\dfrac{(c_2)_2}{(c_1)_1}\dfrac{\nu_1 m_1}{\nu_2 m_2}\right]^{-1}$ when $\overset{\approx}{C}^{*}<\overset{\approx}{C}\le 1$ there is no oxidizer in the fuel zone – $c_1=0$.

$$c_2=\left[(c_2)_2+(c_1)_1\frac{\nu_2 m_2}{\nu_1 m_1}\right]\overset{\approx}{C}-(c_1)_1\frac{\nu_2 m_2}{\nu_1 m_1},\; c_3=(c_3)_1+(c_1)_1\frac{\nu_3 m_3}{\nu_1 m_1}+\left[(c_3)_2-(c_3)_1-(c_1)_1\frac{\nu_3 m_3}{\nu_1 m_1}\right]\overset{\approx}{C},$$

$$c_4=(c_4)_1+(c_1)_1\frac{\nu_4 m_4}{\nu_1 m_1}+\left[(c_4)_2-(c_4)_1-(c_1)_1\frac{\nu_4 m_4}{\nu_1 m_1}\right]\overset{\approx}{C}. \qquad (11)$$

The state $0\le\overset{\approx}{C}<\overset{\approx}{C}^{*}$ of the oxidation zone in which there is no fuel is determined $c_2=0$. The concentrations of other components are determined by the formulas:

$$c_1=(c_1)_1-\left[(c_1)_1+(c_2)_2\frac{\nu_1 m_1}{\nu_2 m_2}\right]\overset{\approx}{C},$$

$$c_3=(c_3)_1+\left[(c_3)_2-(c_3)_1+(c_2)_2\frac{\nu_3 m_3}{\nu_2 m_2}\right]\overset{\approx}{C}, \qquad (12)$$

$$c_4=(c_4)_1+\left[(c_4)_2-(c_4)_1+(c_2)_2\frac{\nu_4 m_4}{\nu_2 m_2}\right]\overset{\approx}{C}.$$

Verification of the resulting formulas for concentrations can be done by calculating the sum of the concentrations. When considering dependencies

$$(c_2)_2+(c_3)_2+(c_4)_2+(c_5)_2=1,$$

$$(c_1)_1+(c_3)_1+(c_4)_1+(c_5)_1=1 \qquad (13)$$

and mass balance according to the stoichiometric reaction equation

$$\nu_1 m_1+\nu_2 m_2=\nu_3 m_3+\nu_4 m_4 \qquad (14)$$

The sum of the concentrations in each zone is unity, although the mass concentrations of the components depend on the variable $\overset{\approx}{C}$.

Thus, depending on the value of the relative redundancy function, $\overset{\approx}{C}$ the position of the flame front and the concentration of components are determined unambiguously. The boundary conditions for this function, as noted above, are

$$\overset{\approx}{C}(0,y)=\begin{cases}1 & 0\le y\le a,\\ 0 & y>a,\end{cases}\quad \frac{\partial\overset{\approx}{C}(x,0)}{\partial x}=0,\quad \overset{\approx}{C}(x,y_\infty)\to 0. \qquad (15)$$

Chemical reaction with finite velocity simulation

The combustion process is modeled in the form of a stoichiometric equation of an irreversible general reaction**:**

$CH_4+2O_2=CO_2+2H_2O+h_2^*$, here h_2^* **is** the amount of heat released as a result of an exothermic reaction. The reaction rate is modeled on the basis of Arrhenius' law [3]. $\omega_2=A_{r1}c_1c_2\rho^2\exp\left(-\frac{A_{r2}}{T}\right)$. Designations are introduced here

$$A_{r1}=-5{,}028\cdot10^{11}\,\frac{a\rho_2}{m_1u_2},\quad A_{r2}=\frac{200010.0}{8{,}31441}\,(K)$$

Tangential disturbance of the common boundary of intermediate flows and the presence of a high-temperature flame front in the heat and mass transfer region indicate flow turbulence in this region. Due to the presence of the main direction of flow, the equations of the turbulent boundary layer can be used in the movement of gases.

Introduction of dimensionless variables and Mises variables. To solve the problem, you went to dimensionless coordinates using the property values $a,u_2,H_2,\ \rho_2$:

$$\bar{x}=\frac{x}{a},\ \bar{r}=\frac{r}{a},\ \bar{u}=\frac{u}{u_2},\ \bar{v}=\frac{v}{u_2},\ \bar{\varepsilon}=\frac{\varepsilon}{au_2},$$

$$\bar{H}=\frac{H}{H_2},\ \bar{\rho}=\frac{\rho}{\rho_2},\ \bar{T}=\frac{T}{T_2},\ \bar{p}=\frac{p}{\rho_2u_2^2},\ \bar{h}_2^*=\frac{h_2^*}{H_2}. \qquad (16)$$

For example, the equation for storing and pumping fuel has the form:

$$\rho_2\bar{\rho}u_2\bar{u}\frac{\partial c_2}{a\partial\bar{x}}+\rho_2\bar{\rho}u_2\bar{v}\frac{\partial c_2}{a\partial\bar{r}}=\frac{1}{\mathrm{Sc}\,a\bar{r}}\frac{\partial}{a\partial\bar{r}}\left[\rho_2\bar{\rho}au_2\left(\frac{1}{\mathrm{Re}}+\bar{v}_t\right)a\bar{r}\frac{\partial c_2}{a\partial\bar{r}}\right]-$$

$$-7\cdot10^8\,\frac{c_1c_2\rho_2^2\bar{\rho}^2}{m_1}\exp\left(-\frac{190300}{8{,}31441T}\right),$$

where the measurement ω_2 was passed to SI and also accounted for $\rho_1=c_1\rho$ and $\rho_2=c_2\rho$.

Now multiply both sides of the equation by $\frac{a}{\rho_2u_2}$, we also get

$$\bar{\rho}\bar{u}\frac{\partial c_2}{\partial\bar{x}}+\bar{\rho}\bar{v}\frac{\partial c_2}{\partial\bar{r}}=\frac{1}{Sc\,\bar{r}}\frac{\partial}{\partial\bar{r}}\left[\bar{\rho}\left(\frac{1}{\mathrm{Re}}+\bar{v}_t\right)\bar{r}\frac{\partial c_2}{\partial\bar{r}}\right]+A_{r1}c_1c_2\bar{\rho}^2\exp\left(-\frac{A_{r2}}{T}\right).$$

$$\begin{cases}
\bar{\rho}\bar{u}\dfrac{\partial\bar{u}}{\partial\bar{x}}+\bar{\rho}\bar{\vartheta}\dfrac{\partial\bar{u}}{\partial\bar{r}}=\dfrac{\partial}{\bar{r}\partial\bar{r}}\left[\bar{\rho}\left(\dfrac{1}{\mathrm{Re}}+\bar{\nu}_t\right)\bar{r}\dfrac{\partial\bar{u}}{\partial\bar{r}}\right],\\
\dfrac{\partial\left(\bar{\rho}\bar{u}\bar{r}\right)}{\partial\bar{x}}+\dfrac{\partial\left(\bar{\rho}\bar{\vartheta}\bar{r}\right)}{\partial\bar{r}}=0,\\
\bar{\rho}\bar{u}\dfrac{\partial\bar{\bar{H}}}{\partial\bar{x}}+\bar{\rho}\bar{\vartheta}\dfrac{\partial\bar{\bar{H}}}{\partial\bar{r}}=\dfrac{1}{\mathrm{Pr}\,\bar{r}}\dfrac{\partial}{\partial\bar{r}}\left[\bar{\rho}\left(\dfrac{1}{\mathrm{Re}}+\bar{\nu}_t\right)\bar{r}\dfrac{\partial\bar{\bar{H}}}{\partial\bar{r}}\right],\\
\bar{\rho}\bar{u}\dfrac{\partial\bar{c}_2}{\partial\bar{x}}+\bar{\rho}\bar{\vartheta}\dfrac{\partial\bar{c}_2}{\partial\bar{r}}=\dfrac{1}{Sc\bar{r}}\dfrac{\partial}{\partial\bar{r}}\left[\bar{\rho}\left(\dfrac{1}{\mathrm{Re}}+\bar{\nu}_t\right)\bar{r}\dfrac{\partial\bar{c}_2}{\partial\bar{r}}\right]+A_{r1}c_1c_2\bar{\rho}^2\exp(-A_{r2}/T),\\
\bar{\rho}\bar{u}\dfrac{\partial\bar{\bar{C}}}{\partial\bar{x}}+\bar{\rho}\bar{\vartheta}\dfrac{\partial\bar{\bar{C}}}{\partial\bar{r}}=\dfrac{1}{Sc\bar{r}}\dfrac{\partial}{\partial\bar{r}}\left[\bar{\rho}\left(\dfrac{1}{\mathrm{Re}}+\bar{\nu}_t\right)\bar{r}\dfrac{\partial\bar{\bar{C}}}{\partial\bar{r}}\right],\\
\bar{\rho}\bar{u}\dfrac{\partial\bar{k}}{\partial\bar{x}}+\bar{\rho}\bar{\vartheta}\dfrac{\partial\bar{k}}{\partial\bar{r}}=\dfrac{1}{\delta_k\bar{r}}\dfrac{\partial}{\partial\bar{r}}\left(\bar{\rho}\bar{\nu}_t\bar{r}\dfrac{\partial\bar{k}}{\partial\bar{r}}\right)+4\bar{\rho}\bar{\nu}_t\left(\dfrac{\partial\bar{u}}{\partial\bar{r}}\right)^2-\bar{\rho}\bar{\varepsilon},\\
\bar{\rho}\bar{u}\dfrac{\partial\bar{\varepsilon}}{\partial\bar{x}}+\bar{\rho}\bar{\vartheta}\dfrac{\partial\bar{\varepsilon}}{\partial\bar{r}}=\dfrac{1}{\delta_\varepsilon\bar{r}}\dfrac{\partial}{\partial\bar{r}}\left(\bar{\rho}\bar{\nu}_t\bar{r}\dfrac{\partial\bar{\varepsilon}}{\partial\bar{r}}\right)+4c_1\left[1+\dfrac{A_1}{f_\mu}\right]^3\bar{\rho}\bar{\nu}_t\dfrac{\bar{\varepsilon}}{\bar{k}}\left(\dfrac{\partial\bar{u}}{\partial\bar{r}}\right)^2-\\
-c_2\left(1-e^{-\frac{\bar{k}^4}{\mathrm{Re}^2\bar{\varepsilon}^2}}\right)\bar{\rho}\dfrac{\bar{\varepsilon}^2}{\bar{k}}.
\end{cases}\qquad(17)$$

The notation is introduced here $f_\mu=\left(1-e^{-A_\mu\mathrm{Re}\sqrt{\bar{k}}r}\right)^2\left(1+A_t\dfrac{\bar{\varepsilon}}{\mathrm{Re}\,\bar{k}^2}\right)$.

$$T=\frac{H_1+\left(H_2-H_1\right)\bar{\bar{H}}-c_2h_2^*}{c_p},\quad \bar{\nu}_t=c_\mu f_\mu\frac{\bar{k}^2}{\bar{\varepsilon}}.\qquad(18)$$

Since direct-flow freely expanding jets are considered, on the basis of data known from theory and practice in the field of flow, the value of static pressure is assumed to be constant: $p=const$ (according to Bai Shi-Yi, for jet streams without combustion, the change in static pressure is no more than 0.5% of the dynamic pressure, and for jets with combustion this fact is confirmed by Spaulding's experimental and theoretical data). As a result, the equation of state of the gas mixture takes the form of

$$\bar{\rho}=\frac{m}{(m)_2\bar{T}}.\qquad(19)$$

The second feature of the problem is that the flow propagates along the x-axis from left to right and there are no boundary conditions in the right side of the flow area, since this does not affect the propagation processes. Accordingly, the process is appropriately described by parabolic equations. So we use Mises coordinates and enter the current function according to the ratios:

$$\rho ur=\psi\frac{\partial\psi}{\partial r},\quad \rho vr=-\psi\frac{\partial\psi}{\partial x}.\qquad(20)$$

The second equation of the system is held unambiguously. The value of the transverse coordinate necessary for the calculation is found by the formula $\frac{r^2}{2}=\int_0^\psi\frac{\psi d\psi}{\rho u}$. In other equations of the system, the transition from coordinates (x,y) to coordinates (ξ,ψ) is carried out according to the formulas:

$$\frac{\partial}{\partial x}=\frac{\partial}{\partial \xi}+\frac{\partial \psi}{\partial x}\frac{\partial}{\partial \psi}=\frac{\partial}{\partial \xi}-\frac{r}{\psi}\rho v\frac{\partial}{\partial \psi}, \qquad (21)$$

$$\frac{\partial}{\partial r}=\frac{\partial \psi}{\partial r}\frac{\partial}{\partial \psi}=\frac{r}{\psi}\rho u\frac{\partial}{\partial \psi}.$$

This converts the right-hand sides of the equations to the form

$$\rho u\frac{\partial}{\partial x}+\rho v\frac{\partial}{\partial r}=$$

$$=\rho u\left[\frac{\partial}{\partial \xi}-\frac{r}{\psi}\rho v\frac{\partial}{\partial \psi}\right]+\rho v\frac{r}{\psi}\rho u\frac{\partial}{\partial \psi}=\rho u\frac{\partial}{\partial \xi}.$$

The left-hand sides of the equations are transformed as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\rho\varepsilon r\frac{\partial}{\partial r}\right)=\frac{1}{r}\frac{r}{\psi}\rho u\frac{\partial}{\partial \psi}\left(\rho\varepsilon r\frac{r}{\psi}\rho u\frac{\partial}{\partial \psi}\right)=$$

$$=\frac{1}{\psi}\rho u\frac{\partial}{\partial \psi}\left(\frac{\rho^2\varepsilon r^2 u}{\psi}\frac{\partial}{\partial \psi}\right).$$

$$\begin{cases}\dfrac{\partial u}{\partial \xi}=\dfrac{1}{\psi}\dfrac{\partial u}{\partial \psi}\left[\dfrac{\rho^2 u\, r^2\left(\nu+\nu_t\right)}{\psi}\dfrac{\partial u}{\partial \psi}\right],\\ \dfrac{\partial H}{\partial \xi}=\dfrac{1}{\Pr\psi}\dfrac{\partial}{\partial \psi}\left[\dfrac{\rho^2 u\, r^2\left(\nu+\nu_t\right)}{\psi}\dfrac{\partial u}{\partial \psi}\right],\\ \dfrac{\partial c_2}{\partial \xi}=\dfrac{1}{\mathrm{Sc}\,\psi}\dfrac{\partial}{\partial \psi}\left[\dfrac{\rho^2 u\, r^2\left(\nu+\nu_t\right)}{\psi}\dfrac{\partial c_2}{\partial \psi}\right]+A_{r1}\dfrac{c_1 c_2\rho^2}{u}\exp(-A_{r2}/T),\\ \dfrac{\partial \bar{\bar{C}}}{\partial \xi}=\dfrac{1}{\mathrm{Sc}\,\psi}\dfrac{\partial}{\partial \psi}\left[\dfrac{\rho^2 u\, r^2\left(\nu+\nu_t\right)}{\psi}\dfrac{\partial \bar{\bar{C}}}{\partial \psi}\right],\\ \dfrac{\partial k}{\partial \xi}=\dfrac{1}{\psi}\dfrac{\partial}{\partial \psi}\left(\dfrac{r^2 u\,\rho^2}{\psi}\dfrac{\nu_t}{\delta_k}\dfrac{\partial k}{\partial \psi}\right)+4\dfrac{\rho^2 r^2 u}{\psi^2}\nu_t\left(\dfrac{\partial u}{\partial \psi}\right)^2-\dfrac{\varepsilon}{u},\\ \dfrac{\partial \varepsilon}{\partial \xi}=\dfrac{1}{\delta_\varepsilon\psi}\dfrac{\partial}{\partial \psi}\left(\dfrac{\rho^2 u r^2}{\psi}\nu_t\dfrac{\partial \varepsilon}{\partial \psi}\right)+\\ +c_1\left[1+\left(A_1/f_\mu\right)^3\right]\dfrac{\varepsilon}{k}4\dfrac{\rho^2 u r^2}{\psi^2}\nu_t\left(\dfrac{\partial u}{\partial \psi}\right)^2-c_2\left(1-e^{-\frac{k^4}{\mathrm{Re}^2\varepsilon^2}}\right)\dfrac{\varepsilon^2}{ku},\end{cases} \qquad (22)$$

SOLUTION

Numerical method of solving the problem. Using the Base Radius a consumption u_2 density ρ_2, and enthalpy H_2, measurements were made in the system and conditions of the equations, and Mises coordinates were introduced (ξ,ψ). The equations of mass displacement and retention of components were reduced to one equation by introducing the Schwab-Zeldovich functions and the relative peak concentration $\tilde{\tilde{C}}$ [3,5]. As a result, the basic equations

$$\left\{\begin{aligned}
&\frac{\partial u}{\partial \xi}=\frac{1}{\psi}\frac{\partial u}{\partial \psi}\left[\frac{\rho^2 u\, r^2\left(\nu+\nu_t\right)}{\psi}\frac{\partial u}{\partial \psi}\right],\\
&\frac{\partial H}{\partial \xi}=\frac{1}{\Pr \psi}\frac{\partial}{\partial \psi}\left[\frac{\rho^2 u\, r^2\left(\nu+\nu_t\right)}{\psi}\frac{\partial u}{\partial \psi}\right],\\
&\frac{\partial c_2}{\partial \xi}=\frac{1}{\mathrm{Sc}\, \psi}\frac{\partial}{\partial \psi}\left[\frac{\rho^2 u r^2\left(\nu+\nu_t\right)}{\psi}\frac{\partial c_2}{\partial \psi}\right]+A_{r1}\frac{\mathrm{c}_1\mathrm{c}_2\,\bar{\rho}^2}{u}\exp(-\mathrm{A}_{r2}/\mathrm{T}),\\
&\frac{\partial \overset{\approx}{C}}{\partial \xi}=\frac{1}{\mathrm{Sc}\, \psi}\frac{\partial}{\partial \psi}\left[\frac{\rho^2 u r^2\left(\nu+\nu_t\right)}{\psi}\frac{\partial \overset{\approx}{C}}{\partial \psi}\right],\\
&\frac{\partial k}{\partial \xi}=\frac{1}{\psi}\frac{\partial}{\partial \psi}\left(\frac{r^2 u\,\rho^2}{\psi}\frac{\nu_t}{\delta_k}\frac{\partial k}{\partial \psi}\right)+4\frac{\rho^2 r^2 u}{\psi^2}\bar{\nu}_t\left(\frac{\partial u}{\partial \psi}\right)^2-\frac{\varepsilon}{u},\\
&\frac{\partial \varepsilon}{\partial \xi}=\frac{1}{\psi}\frac{\partial}{\partial \psi}\left(\frac{\rho^2 r^2 u}{\psi}\frac{\nu_t}{\delta_\varepsilon}\frac{\partial \varepsilon}{\partial \psi}\right)+4\frac{c_1\rho^2 r^2 u}{\psi^2}\bar{\nu}_t\frac{\varepsilon}{k}\times\\
&\times\left[1+A_1\left(1-\mathrm{e}^{A_\mu \mathrm{Re}\sqrt{\bar{k}}\,r}\right)^{-2}\left(1+\frac{A_t\bar{\varepsilon}}{\mathrm{Re}\,\bar{k}^2}\right)^{-1}\right]^3\left(\frac{\partial u}{\partial \psi}\right)^2-c_2\left(1-e^{\frac{-\mathrm{Re}^2\varepsilon^2}{k^4}}\right)\frac{\varepsilon^2}{ku},
\end{aligned}\right. \tag{23}$$

$$T=\frac{H_1+\left(H_2-H_1\right)\bar{\bar{H}}-c_2h_2^*}{c_p},$$

$$\bar{\rho}=\frac{mT_2}{(\mathrm{m})_2 T},\ \bar{\nu}_t=c_\mu f_\mu\frac{\bar{k}^2}{\bar{\varepsilon}}.$$

the corresponding boundary conditions were formed.

$$0\le\bar{\psi}<1:\bar{u}=1,\bar{T}=1,\bar{\bar{C}}=1,\ c_n=\left(c_n\right)_2,k=k_2,\varepsilon=\varepsilon_2.\ 1\le\bar{\psi}<\bar{\psi}_\infty:$$

$$\bar{u}=\bar{u}_1,\bar{T}=\bar{T}_1,\bar{\bar{C}}=0,c_n=\left(c_n\right)_1,k=k_1,\varepsilon=\varepsilon_1.$$

$$\xi>0\ ,\psi=0:\ \frac{\partial\bar{u}}{\partial\bar{\psi}}=0,\frac{\partial\bar{T}}{\partial\bar{\psi}}=0,\ \frac{\partial\bar{\bar{C}}}{\partial\psi}=0,\ \frac{\partial c_2}{\partial\psi}=0,\ \frac{\partial\bar{k}}{\partial\bar{\psi}}=0,\ \frac{\partial\varepsilon}{\partial\psi}=0. \tag{24}$$

$$\psi\to\psi_\infty:\bar{u}=\bar{u}_1,\ \bar{T}=\bar{T}_1,c_2=\left(c_2\right)_1,\bar{\bar{C}}=0,\ k=k_1,\ \varepsilon=\varepsilon_1.$$

The constant approximation scheme was used to solve nonlinear equations in Mises coordinates. [9-11].

$$\frac{\partial U}{\partial\bar{\xi}}=\frac{1}{\delta_U}\frac{\partial}{\bar{\psi}\partial\bar{\psi}}\left(K\lambda h_\psi\frac{\partial U}{\partial\bar{\psi}}\right)+f_U\,. \tag{25}$$

In the first group, where $\lambda=\frac{1}{\mathrm{Re}}+\nu_t$ Log in

$$\begin{aligned}
&U=u:\ \delta_U=1,\ f_U=0;\\
&U=\bar{\bar{H}}:\ \delta_H=\Pr,\ f_H=0;\\
&U=\bar{\bar{C}}:\ \delta_C=Sc,\ f_C=0;
\end{aligned} \tag{26}$$

$$U=c_2:\ \delta_{c2}=Sc,\ f_{c2}=A_{r1}\frac{c_1c_2\bar{\rho}}{\bar{u}}\exp(-A_{r2}/T).$$

In the old group, where $\lambda = \nu_t$, there are two equations:

$$U = k: \quad \delta_U = \delta_k,\; f_k = 4\frac{Kh_\psi}{\overline{\psi}}\lambda\left(\frac{\partial \overline{u}}{\partial \overline{\psi}}\right)^2 - \frac{\overline{\varepsilon}}{\overline{u}} = \overline{\mathrm{E}} - \frac{\overline{\varepsilon}}{\overline{u}},$$
$$U = \varepsilon: \quad \delta_U = \delta_\varepsilon, \quad f_\varepsilon = \overline{E}\frac{\overline{\varepsilon}}{\overline{k}}\left[1 + \left(\frac{A_1}{f_\mu}\right)^3\right] - c_2\left(1 - e^{\frac{-k^4}{\varepsilon^2 \mathrm{Re}^2}}\right)\frac{\overline{\varepsilon}^2}{\overline{k}}. \tag{27}$$

We come to an approximation of the equations. For the first group, we have:

$$\lambda_j = \frac{1}{\mathrm{Re}} + \left(\overline{\nu}_t\right)_{i,j} \;;$$

$$\frac{U_{i,j}^s - U_{i-1,j}}{h_\xi} = \frac{1}{2Sc_u jh_\psi^2} \times \Big[\left(K_{i,j+1}\lambda_{j+1} + K_{i,j}\lambda_j\right)\left(U_{i,j+1}^s - U_{i,j}^s\right) -$$
$$-\left(K_{i,j}\lambda_j + K_{i,j-1}\lambda_{j-1}\right)\left(U_{i,j}^s - U_{i,j-1}^s\right)\Big] + \left(f_u\right)_{i,j}^{s-1},$$

Multiply both sides of the equation by $2Sc_u h_\xi j$ and enter the notation $\sigma = h_\xi / h_\psi^2$. Then we get the

$$\sigma\left(K_{i,j+1}\lambda_{j+1} + K_{i,j}\lambda_j\right)U_{i,j+1}^s -$$
$$-\left[2Sc_u j + \sigma\left(K_{i,j+1}\lambda_{j+1} + K_{i,j}\lambda_j\right) + \sigma\left(K_{i,j}\lambda_j + K_{i,j-1}\lambda_{j-1}\right)\right]U_{i,j}^s +$$
$$+\sigma\left(K_{i,j}\lambda_j + K_{i,j-1}\lambda_{j-1}\right)U_{i,j-1}^s = -2Sc_u j\left(U_{i-1,j} + h_\xi\left(f_u\right)_{i,j}^{s-1}\right).$$

Let's outline

$$a_j^{(\mathrm{U})} = \sigma\left(K_{i,j+1}\lambda_{j+1} + K_{i,j}\lambda_j\right), \;\; c_j^{(\mathrm{U})} = \sigma\left(K_{i,j}\lambda_j + K_{i,j-1}\lambda_{j-1}\right),$$
$$b_j^{(\mathrm{U})} = 2Sc_U j + a_j^{(\mathrm{U})} + c_j^{(\mathrm{U})}, \;\; d_j^{(\mathrm{U})} = -2Sc_U j\left(U_{i-1,j} + h_\xi\left(f_U\right)_{i,j}^{s-1}\right).$$

Then the finite-difference equation takes the form:

$$a_j^{(\mathrm{U})}U_{i,j+1}^s - b_j^{(\mathrm{U})}U_{i,j}^s + c_j^{(\mathrm{U})}U_{i,j-1}^s = d_j^{(\mathrm{U})}. \tag{28}$$

If we believe that

$$U_{i,j-1}^s = \alpha_{j-1}^{(\mathrm{U})}U_{i,j}^s + \beta_{j-1}^{(\mathrm{U})},$$

We then get the fit factor values for the internal nodes:

$$\alpha_j^{(\mathrm{U})} = \frac{a_j^{(\mathrm{U})}}{b_j^{(\mathrm{U})} - \alpha_{j-1}^{(\mathrm{U})}c_j^{(\mathrm{U})}}, \;\; \beta_j^{(\mathrm{U})} = \frac{-d_j^{(\mathrm{U})} + c_j^{(\mathrm{U})}\beta_{j-1}^{(\mathrm{U})}}{b_j^{(\mathrm{U})} - \alpha_{j-1}^{(\mathrm{U})}c_j^{(\mathrm{U})}} \tag{29}$$

The first $S_{\min}$ approach is performed without checking the status of the approach and replacing

$$\begin{array}{l} \overset{\approx}{u}{}_{i,j}^{s-1} = \overset{\approx}{u}{}_{i,j}^{s}, \quad \overset{\approx}{H}{}_{i,j}^{s-1} = \overset{\approx}{H}{}_{i,j}^{s}, \\ \rho_{i,j}^{s-1} = \rho_{i,j}^{s}, \quad \overset{\approx}{C}{}_{i,j}^{s-1} = \overset{\approx}{C}{}_{i,j}^{s} \end{array} . \tag{30}$$

Later $S_{\min}$, the convergence condition is checked $\max_{j\in\left[0;\, N_j\right]}\left|\overset{\approx}{H}{}_{i,j}^{s-1} - \overset{\approx}{H}{}_{i,j}^{s}\right| < \varepsilon_t$.

If the convergence conditions are met, the system moves to the next level at. Otherwise, the s-th approach is adopted

$$\overset{\approx}{u}{}^{s-1}_{i,j} = \overset{\approx}{u}{}^{s}_{i,j}, \quad \overset{\approx}{H}{}^{s-1}_{i,j} = \overset{\approx}{H}{}^{s}_{i,j},$$

$$\rho^{s-1}_{i,j} = \rho^{s}_{i,j}, \quad \overset{\approx}{C}{}^{s-1}_{i,j} = \overset{\approx}{C}{}^{s}_{i,j}$$

and moves on to the next approximation.

If all the requirements for the accuracy of the newly found parameter values are met, if necessary, the values of the integrals of excess momentum, enthalpy, as well as the unburned part of the fuel in this section are calculated.

The upper limit of dimensionless coordinates of the flow curve was assumed to be 20 and new discrete steps were introduced for longitudinal and radial coordinates. The longitudinal coordinate calculation continued until the value of the conservative function on the axis dropped to 0.05.

After performing these steps, the results were saved in three files. The first file contained the axial velocity, enthalpy, turbulence coefficient for the cross-section, radial flame coordinates determined by linear interpolation, boundary layer velocity limitation, $b(x)$ and observational data.

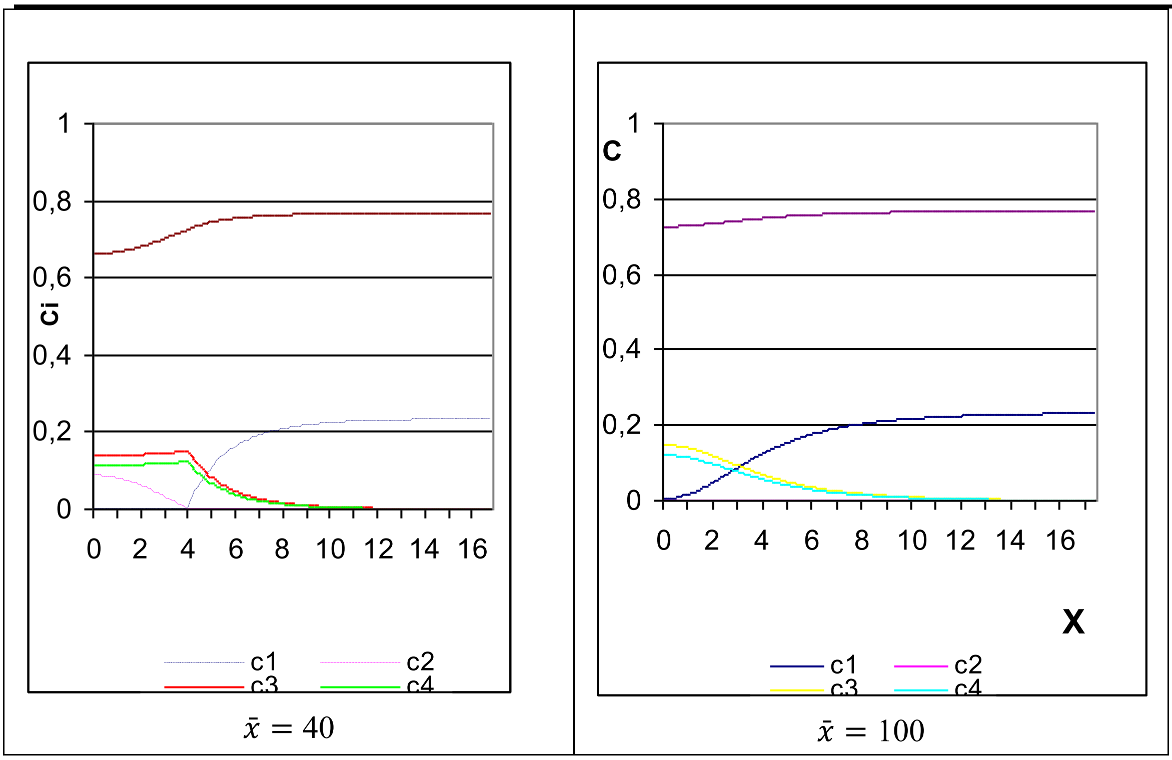
The second file contains information about the changes in the functions of the radial coordinates of velocity, enthalpy, temperature, concentration, and turbulence at certain locations. In this case, a special algorithm was used to switch from the normal step of the flow line function to a dimensionless radial coordinate using the linear interpolation formula in h_y the graphical drawing algorithms.

In the third file, the data needed to construct isothermal curves in the temperature calculation region were stored in unlimited coordinates. Due to the limitations of some of the measurements considered, especially the computational area, the graphics capabilities of Pascal ABS computer graphics were not available. Because of this, the resulting data was processed using Excel software.

Outcomes

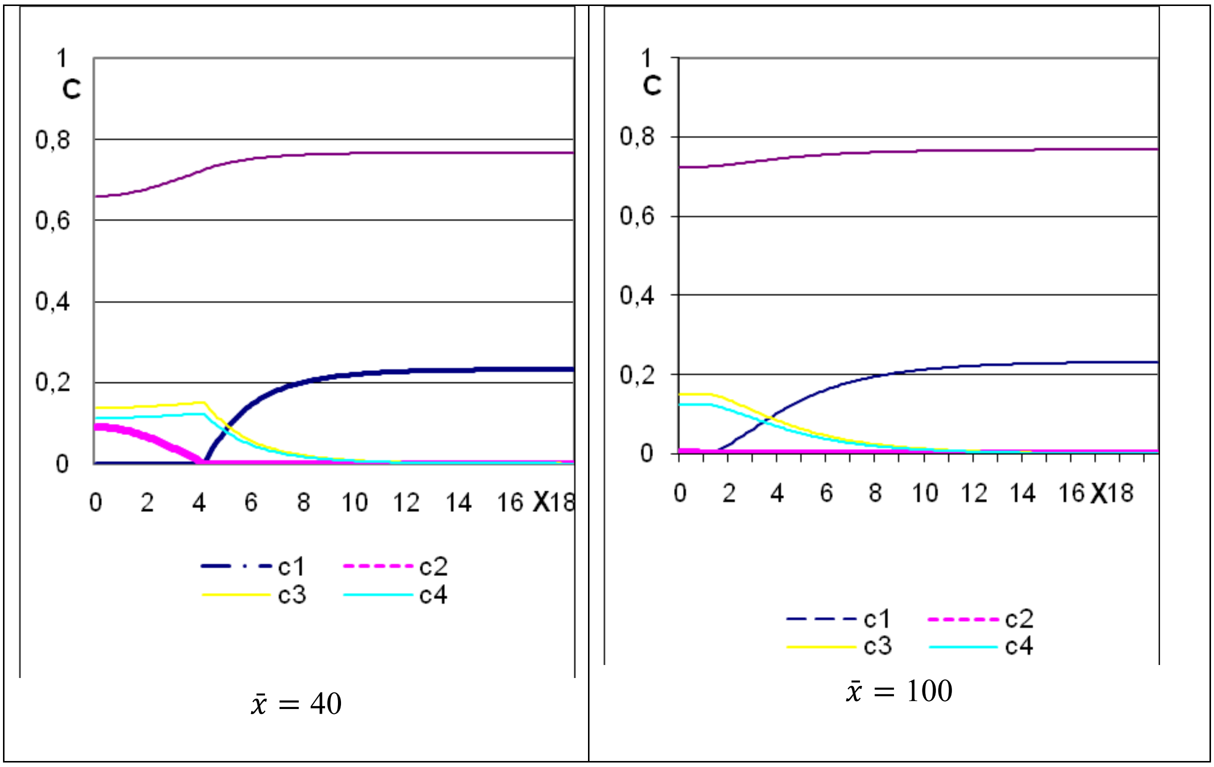
In this article, we will limit ourselves to discussing the effect of the temperature of individual gases on isotherms and concentrations.

The ignition reaction includes methane gas and nitrogen. $(c_1)_1 = 0.232,\ (c_5)_1 = 0.768, (c_2)_2 = 1$ The speed of the main flow is 61 m/s, the speed of the accompanying current is 18.3 m/s. $T_1 = 1000\ K$ From where $T_2 = 293K$ and $T_2 = 400K$ because they $\overline{x} = 40$ and $\overline{x} = 100$ the diagrams show concentration.



$\bar{x} = 40$ $\bar{x} = 100$

Rice. 2. $T_1 = 1000\,K$ and $T_2 = 293\,K$ of concentrations.



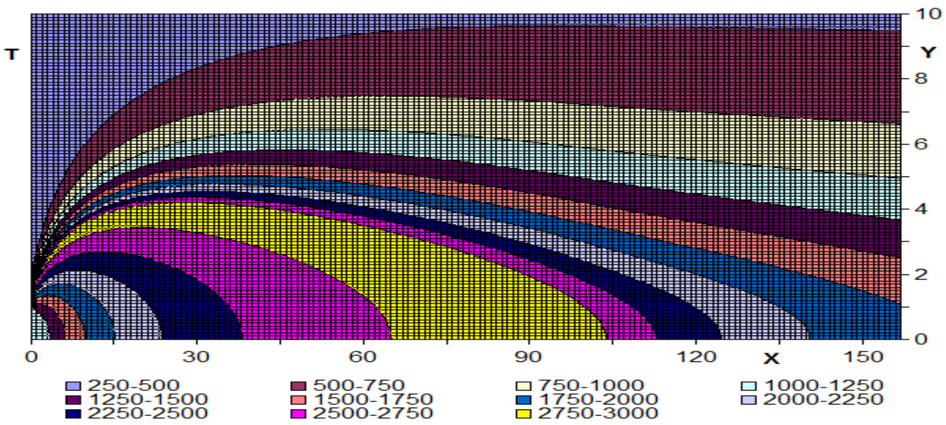
$\bar{x} = 40$ $\bar{x} = 100$

Rice. 3. $T_1 = 1000\,K$ and $T_2 = 400\,K$ of concentrations.

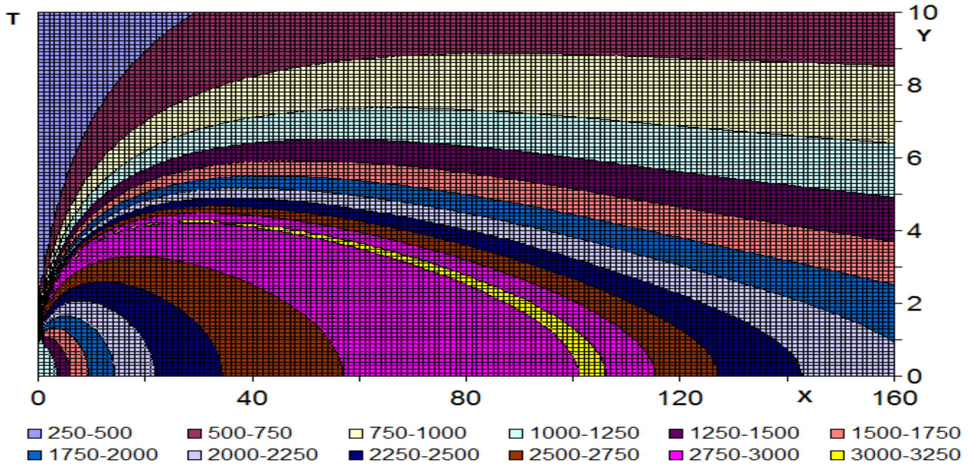
As you can see from this graph, $\bar{x} = 40$ the fuel core is damaged.

View of concentration after flame $T_1 = 1000\,K$ and $T_2 = 293\,K$ as $\bar{x} = 100$ shown in the diagram above. $T_1 = 1000\,K$ From $T_2 = 400\,K$ $\bar{x} = 100$ these results, it can be concluded that the combustion will last longer if the temperature is higher. The same results were obtained for velocity, total enthalpy and intensity, which were much less than the initial length of the flame. The results, based on the same data as in the introduction, showed that the methane flame is short and wide compared to the propane flame. This can be explained by the small pulse of the methane flow.

$T_1 = 1000\ K$ when $T_2 = 293\ K$ and $T_2 = 400K$ here is an example of isotherms that are



Rice. 4. $T_1 = 1000\ K$ and $T_2 = 293\ K$



Rice. 5. $T_1 = 1000\ K$ and $T_1 = 1000\ K$

The maximum temperature in the first case is T=2929K, and in the second case, the $T^* =$values of 3018.84 were calculated.

FINDINGS

As the temperature field expands, the maximum temperature at the end of the flame is on the axis of symmetry. Conversely, an increase in air temperature leads to an increase in the length of the flame. The first is associated with a decrease in fuel gas consumption, and the second is associated with a high oxygen content in the air. Overall, the results show that the temperature and estimated combustion area of methane fuel in the airstream are significantly different from the combustion temperature of propane.

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