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CALCULATION OF A COMBUSTION PROBLEM OF A METHANE-AIR MIXTURE IN A SLOT BURNER WITH A NONREACTIVE INNER INSERT IN A TWO-DIMENSIONAL APPROACH

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The authors solved the burning problem of a methane-air mixture in a narrow slot burner with an internal partition wall in a two-dimensional approximation. The solution was made by means of the Ansys Fluent package for equations taking into account the effect of heat expansion, heat and mass transfer and chemical reaction kinetics of the first order. The study was performed in two stages. At the first stage a cold gas steady flow was calculated; at the second stage, problem of ignition and stable combustion mode setting was solved. The paper shows an example of a stable combustion mode setting for the process having started by the heated inner wall. The obtained results were compared with the results of calculations for one-dimensional model. The experimenters showed qualitative consistency between the results of numerical investigation of the problem in the one-dimensional formulation and simulation results using the Ansys Fluent package.

Keywords: a methane-air mixture, heat and mass transfer, combustion stability, Ansys Fluent, heat recovery.

Introduction

The problem of gas mixture combustion in the miniature burner devices is one of the urgent tasks of modern research. Solving such problems is dictated by the demand for miniaturization of power supplies. One of the lines in the research of gas mixtures combustion in miniature burners is constructing burners with heat recirculation. Heat losses from the side surface to the environment keep the miniature burner from stable combustion of gaseous mixtures. Combustion with heat recycling makes it possible to sustain steady-state combustion by hot recycling due to heating the incoming cold gas by hot reaction products. Heating is carried out owing to heat exchange through the partition wall or inner wall of the burner.

Among heat recovery devices helical burners (Swiss-rolls), countercurrent heat exchangers and U-shaped channels [1] can be distinguished. Burners with heat recovery make it possible to sustain steady combustion of lean gas mixtures [2, 3], as well as combustion in narrow channels and slots [4]. Earlier, in [3-5] the possibility to ignite and sustain combustion of methane-air mixture in a narrow channel with preheated internal partition was shown. In [3] the authors proposed a dimensionless formulation of a gas combustion problem in a narrow channel of rectangular section and identified areas of the oscillatory and stable high temperature combustion modes of lean methane-air mixture. In [4] the mathematical statement from [3] was supplemented by the equations of continuity and the ideal gas law; it showed the effect of heat expansion on the stability of the gas mixture combustion. In [5], based on mathematical formulations of problems from [3-4], the combustion of 6% methane-air mixture in the slot burner with a nonreactive inner insert was calculated. The mathematical formulation of the problem in [5] was determined in dimensional variables and took into account the dependence of the coefficients of diffusion, of thermal conductivity and of heat capacity on the temperature.

The results of the work showed high sensitivity of the stabilizing combustion mode to gas feed rate at the burner inlet. A small increase in the gas mixture feed rate led to burn-out and displacement of the flame front from the burner. Based on mathematical formulations of [3-5], this paper considers the problem of 6% methane-air mixture combustion in the slot burner with a nonreactive inner insert in a two-dimensional approximation. The task research was performed using the Ansys Fluent application program package.

1. Problem statement

A cold methane-air mixture at u_{vh} rate, T_{vh} temperature, a_v concentration of combustible components is fed into a narrow slot burner with an inner insert (Fig. 1). The problem is considered in a two-dimensional mathematical formulation; the width of the burner pass is greater than the thickness of the nonreactive insert, $d > d_1$. The mixture enters the burner from the side $x = 0$, $y \in (d_{1t}, d_t)$, (area I, Fig. 1). In the area of the turning section of the burner, $x \in (L_1, L)$, $y \in (d_t, d_b)$, the gas changes the direction of its movement (area II, Fig. 1). On the boundary $x = 0$, $y \in (d_{1b}, d_b)$ the gas issues (area III, Fig. 1b). The nonreactive insert in Fig. 1 is marked by the IV index and is determined by the area $x \in (0, L_1)$, $y \in (d_{1b}, d_{1t})$. The inner insert is supposed to be previously uniformly heated to T_{1v} temperature. The boundary between the inner insert and the gas is supposed a perfect contact and the conjugate problem of heat transfer is solved there.

In formulating the problem the following assumptions are made:

- the burner external walls are thermally insulated;
- the laminar flow of an incompressible viscous gas is considered;
- D diffusion coefficient, and λ gas thermal conductivity, as well as density and gas flow rate – they all depend on the temperature [5-7];
- the chemical process is supposed to be determined by a one-stage irreversible chemical reaction:

$$\nu_{CH4}\, CH_4 + \nu_{O2}\, O_2 + \nu_{N2}\, N_2 = \nu_{CO2}\, CO_2 + \nu_{H2O}\, H_2O. \tag{1}$$

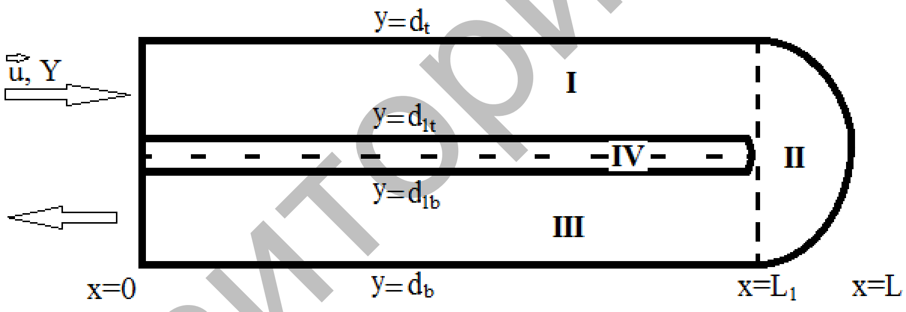


Fig.1. The slot burner scheme: I – the inlet; II – the turning area; III – the outlet; IV – the inner insert

For the accepted assumptions the mathematical formulation of the problem is as follows:

The energy equation for the reaction mixture:

$$\frac{\partial}{\partial t}(\rho E)+\nabla\cdot\left(\vec{u}(\rho E+p)\right)=\nabla\cdot(\lambda\nabla T)-\sum_{j=1}^{5}h_j^0 R_j\,,\ \ x, y\in \mathrm{I, II, III}. \tag{2}$$

The energy equation for the insert:

$$\frac{\partial}{\partial t}(\rho_1 E_1)=\lambda_1\nabla^2 T_1\,,\ \ x,\ y\in \mathrm{IV}. \tag{3}$$

The equation for the mass fraction of the component:

$$\frac{\partial(\rho Y_i)}{\partial t}+\nabla\cdot\left(\rho\,\vec{u}Y_i-\tilde{D}_m(T)\,\nabla Y_{CH4}\right)=R_i,\ i=1..4,\ x,y\in\text{I},\text{II},\text{III}. \tag{4}$$

The continuity equation:

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\vec{u})=0\,. \tag{5}$$

The momentum conservation equation:

$$\frac{\partial(\rho\,\vec{u})}{\partial t}+\nabla\cdot(\rho\,\vec{u}\,\vec{u})+\nabla p=\nabla\cdot\boldsymbol{\tau}\,. \tag{6}$$

The equation of state:

$$p=\rho RT\sum_{j=1}^{5}\frac{Y_i}{M_i}\,. \tag{7}$$

Here $\boldsymbol{\tau}=\mu\left(\nabla\vec{u}+\nabla\vec{u}^T\right)$ is a stress tensor, $E=\sum_{j=1}^{5}Y_j h_j+\frac{\vec{u}^2}{2}$ is the total energy of the gas, where $h_j=c\,(T-T_{vh})$ is the enthalpy of the j-th component formation, $E_1=c_1(T_1-T_{1,vh})$ is the enthalpy for the nonreactive insert. The thermal conductivity and diffusion coefficients depend on the temperature, as $\lambda=\lambda_{st}\left(\frac{T}{T_{vh}}\right)^s$, $\tilde{D}_m(T)=D_{st}\rho_{st}\left(\frac{T}{T_{vh}}\right)^s$ [6].

In the equations (2), (4) the rate of each component formation is determined by the formula

$$R_i=\frac{\nu_i M_i}{\nu_{CH4}M_{CH4}}k_0\rho_{\text{см}}Y_{CH4}\exp\left(-\frac{E}{RT}\right),$$

where for the i values the following components correspond: $i=1$ –CH_4, $i=2$ – O_2, $i=3$ – CO_2, $i=4$ – H_2O, $i=5$ – N_2.

The agreed notations mean: t – time; x – the longitudinal coordinate; y – the transverse coordinate; Y_{CH4} – the mass fraction of methane in the mixture; E_a – the activation energy; R – the universal gas constant; ρ – the density; p – the pressure; u – the flow rate of the mixture; μ – the kinematic viscosity coefficient of the gas, d – the height of the tip cross-section of the slot burner, d_1 – the width of the insert; L – the length of the insert, M_i – the molar mass of the mixture component, ν_i – the stoichiometric coefficients of the equation (1).

In equation (2) the parameters of the inner insert are marked by index 1, the parameters at the inlet of the burner are marked by the index *vh* . The indices *b* (bottom) and *t* (top) indicate the lower and upper boundaries of the inner insert and of the burner. The parameter values at T=300 K are marked by the index *st*.

The following values of thermophysical and kinetic parameters were chosen [5]: E=239 *kJ/mol*, c=1065 *J/(kg·K)*, s=2/3, λ_{st}=0.025*W/(m·K)*, R=8.31 *J/(mol·K)*, ρ_{st}=1.179 kg/m^3, D_{st}=1,992·$10^{-5}m^2/s$, μ=1.7·$10^{-5}m^2/s$.

The slot burner characteristics: the slot size d_t=d_b=6$10^{-3}m$, the insert thickness d_{1t}=d_{1b}=2·10^{-4} m, the channel length L=5·$10^{-2}m$, the length of the nonreactive insert L_1=4.4·$10^{-2}m$.

The thermophysical parameters of the burner wall material were accepted equal to $c_1=687\,J/(kg\cdot K)$, $\lambda_1=30\,W/(m\cdot K)$, $\rho_1=7500\ kg/m^3$ (heat-resistant steel).

The values of stoichiometric coefficients, the specific enthalpy of formation, as well as the molar masses of the mixture components met the generally accepted ones: $\nu_{CH4}=1$, $\nu_{O2}=2$, $\nu_{CO2}=1$, $\nu_{H20}=2$; $M_{CH4}=16{,}043\cdot 10^{-3}\ kg/mol$, $M_{O2}=32\cdot 10^{-3} kg/mol$, $M_{CO2}=44\cdot 10^{-3}\ kg/mol$, $M_{H2O}=18\cdot 10^{-3}\ kg/mol$; $h_{CH4}=-74.81\cdot 10^{-3}\ kJ/mol$, $h_{O2}=0\ kJ/mol$, $h_{CO2}=393.51\cdot 10^{-3} kJ/mol$, $h_{H2O}=-241.82\cdot 10^{-3} kJ/mol$.

2. Results and discussion

The calculations were performed using SIMPLE method of the second-order accuracy. The time step was chosen equal to 10^{-5} sec, the effect of the boundary layer was taken into account by mesh refinement near the wall, and the maximum pitch in space was 10-5 m. At the first stage of the calculation it was assumed that there were no chemical reactions, and into the cold burner a 6% methane-air mixture was let in. Once the flow of gas in the tube reached completely steady state, the calculation of the first stage was finished.

It was supposed that the flow became stable if discrepancies for the continuity and momentum conservation equations were of the order of 10^{-3}; for the energy equation the discrepancy was 10^{-6}. When the flow reached the steady state, the temperature of the nonreactive insert was purposely increased to high values. After that calculation of chemical reactions started. It was supposed that there were three-dimensional chemical reactions, the speed of which was determined by the Arrhenius law.

At the entrance boundary the gas temperature equal to $T_{vh}=300\ K$ was set, the relative mass concentration of the methane $a_{vh,CH4}=0.035$, the relative mass concentration of oxygen in the mixture $a_{vh,O}=0.23$, the relative mass concentration of the reaction products $a_{vh,CO2}=0$, $a_{vh,H2O}=0$. On the outer walls of the slot burner gas impermeability conditions for the gas, as well as zero heat flow were set, which corresponded to adiabatic outer walls. On the surface of the inner insert, the conjugate problem of heat exchange was solved that corresponded to the boundary conditions of form IV. At the outlet of the slot burner free issue of gas mixture was provided; it was supposed that outside the burner the ambient temperature was $T_S=300K$, the relative mass concentration of reagents and reaction products was assumed to be zero, $a_{S,CH4}=a_{S,O2}=a_{S,CO2}=a_{S,\,H2O}=0$.

The feed rate of the reaction mixture at the inlet varied over a wide range to determine the maximum value at which a high-temperature combustion mode could be set. At the first stage of calculations it was assumed that at the inlet the transverse component of the flow rate was zero, $u_y=0$, the longitudinal component of the rate was set equal to $u_x=0.19$ m/s. For the given values of the components the flow rate of the cold unresponsive mixture was calculated. The example of steady flow is shown in Fig. 2.

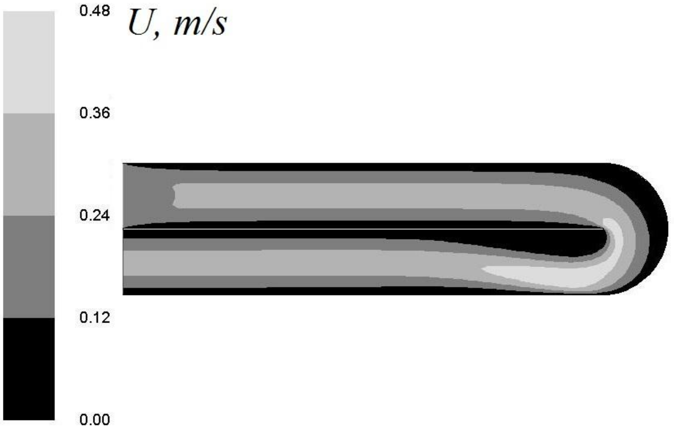
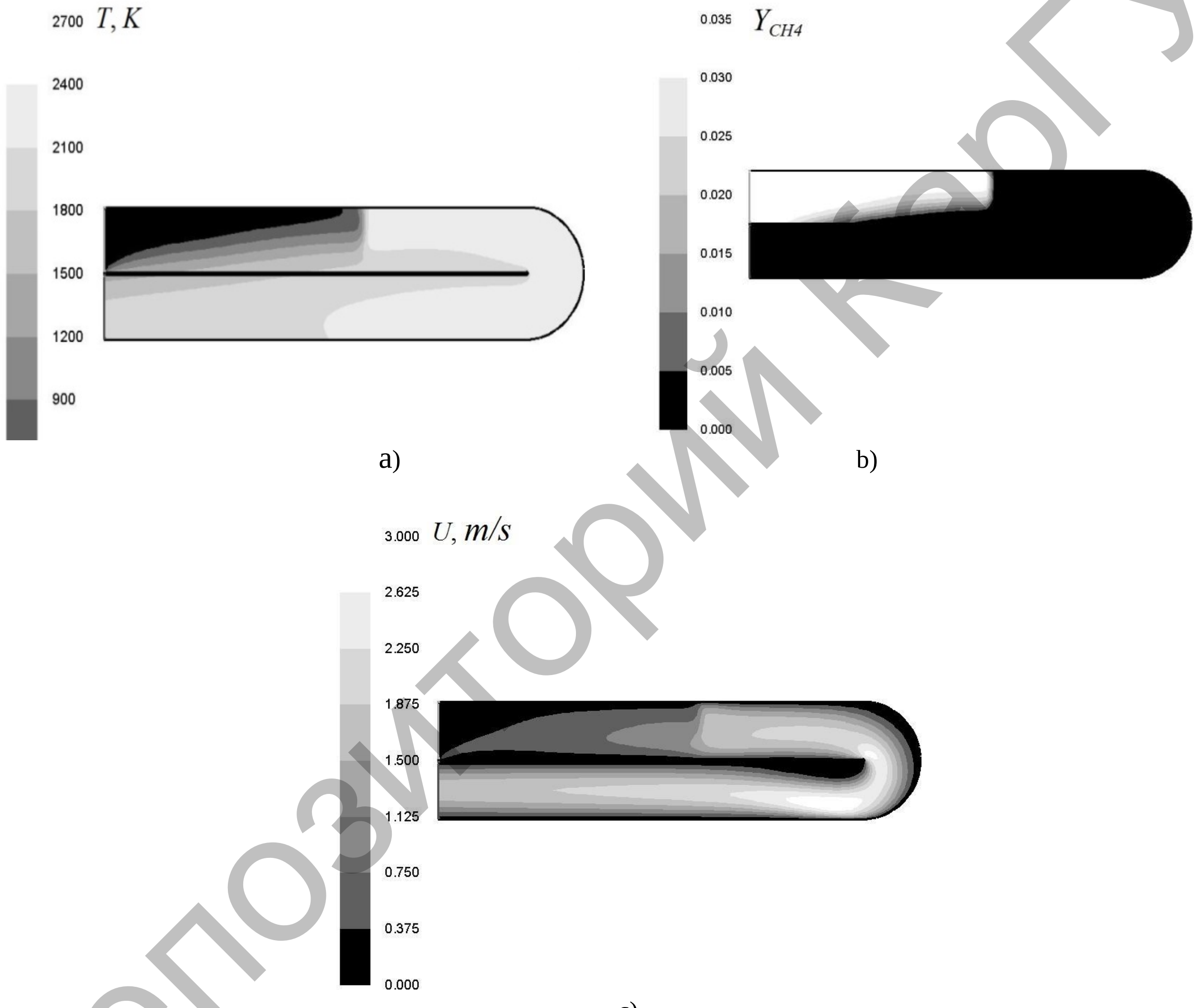


Fig. 2. The stabilized field of the cold gas flow for $u_x=0.19$ m/s

After the stabilization of the flow rate of the cold gas the insert temperature increased to T_{1v}=1500 K. The cold gas mixture flowing through a slot burner was heated owing to heat exchange with the hot surface of the nonreactive insert and ignited in the outlet tube (area II, Fig. 1). Further, the flame front moved against the flow and set in the top of the slot burner (area I, Fig. 1). An example of a steady high temperature combustion mode is shown in Fig. 3.

Fig. 3a represents the distribution of the gas temperature in the burner space. The maximum temperature set in the burner is approximately equal to T_{max}=2400 K. Fig. 3b shows the distribution of the relative mass concentration of methane after the setting of the combustion mode.



a) b)

c)

Fig. 3. The stabilized distribution of the gas temperature (a), of the methane concentration (b) and of the mixture flow rate (c) for T_{1v}=1500K, u_x=0.19 m/s

Fig.3c presents a field of gas flow rate. The maximum flow rate was u_{max} = 3m/s. According to Fig. 3 the flame front set in the upper part of the burner corresponding with the results of [3-5].

For the one-dimensional formulation of the problem [5] authors determined the boundaries of a steady high-temperature combustion mode depending on the values of the initial temperature of the nonreactive insert and the gas feed rate at the inlet of the burner. The main results of the calculation are shown in Fig. 4. According to Fig. 4 for the initial insert temperature T_{1v} = 1500K the high-temperature combustion mode is possible for the gas feed rate of the at the inlet u_v < 0.25 m/s, which agree with the results of this work.

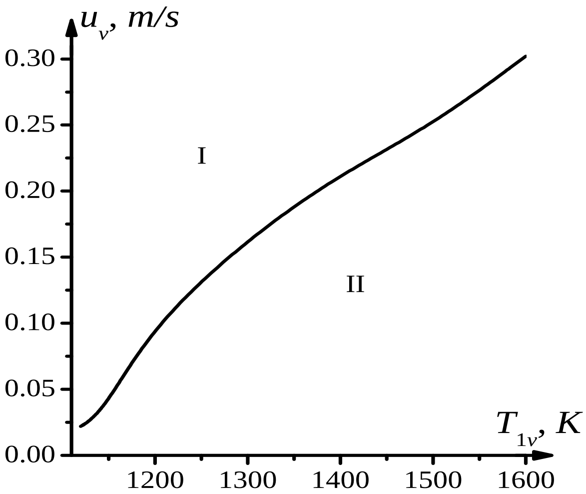


Fig. 4. The areas of stabilized combustion modes of the methane-air mixture in the slot burner:
I – the area with no ignition, II – the area of ignition and combustion

Conclusion

As a result of the calculations the characteristic distribution of the gas mixture parameters after the setting of a steady combustion mode was determined. The authors found a qualitative conformity of the calculation results for a two-dimensional model with the results of calculations for one-dimensional model. The next stage of research problem of the methane-air mixture combustion in the slot burner with a non-reactive insert in a two-dimensional approximation is to clarify the stability boundary of the gas mixture combustion depending on the gas feed flow rate at the inlet of the burner.

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