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GASDYNAMIC STIMULATION OF COMBUSTION OF LEAN FUEL MIXTURES. 2. EVALUATION OF THERMODYNAMIC PARAMETERS AND THE MAGNITUDE OF HEAT LOSSES

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Various gasdynamic regimes of combustion of a lean fuel mixture of propane with air, including combustion of the mixture at rest, combustion with annular twisting of the gas, and combustion stimulated by jets of a burning gas injected into the combustion chamber (PJC) were analyzed from the viewpoint of the magnitude of heat losses. The advantage of PJC over other combustion regimes is shown. We suggest a simple method to evaluate the pressure increase by calculating the magnitude of the energy release with allowance for heat losses to the combustion-chamber walls.

The preceding part of the work was devoted to experimental investigation of various gasdynamic regimes of combustion of lean fuel mixtures [1]. We showed that the gasdynamic structure of the flow in the combustion chamber exerted a most direct effect on the process of energy release, thereby determining the time of combustion, the magnitude of heat losses and, consequently, the pressure increase, and the final temperature of the combustion products.

It should be noted that the thermodynamic parameters for fuel combustion in a closed constant volume with a complex surface of the flame front can be calculated using various relatively accessible algorithms [2-4]. And moreover, correspondence between the calculated and measured values of the pressure in the combustion chamber can be attained only when the volume fraction of the burnted gas can be accurately taken into account in the calculations. In this connection we made an attempt to analyze the thermal efficiency of the previously experimentally investigated combustion regimes based on a simplified technique of calculation of heat losses and to evaluate the pressure increase in the combustion chamber. However, we did not consider the process in dynamics, but instead at each instant of time we analyzed the equilibrium thermodynamic parameters behind the combustion-wavefront for a given volume fraction of the burned gas and a known area of contact of the combustion products with the wall.

It is evident that the magnitude of the maximum increase in pressure in the chamber depends first of all on the duration of the combustion process. The faster the combustion, the smaller the heat losses and, consequently, the higher the increase in pressure. Moreover, the thermodynamic parameters of the combustion products and the magnitude of the heat losses may also depend on the structure of the gasdynamic flow in the combustion chamber, which determines the duration and area of the contact of the combustion products with the wall. As an example, Fig. 1 presents oscillograms of the pressure change in the combustion chamber for different techniques of ignition of the fuel mixture. The initial pressure in the chamber was 0.18 MPa, and the combustion was initiated in a premixed gas mixture of propane with air, with the excess-fuel coefficient being 0.7. The time of combustion was defined as the time interval between the instants of ignition and attainment of maximum pressure in the combustion chamber. As follows from the given oscillograms, the minimum time

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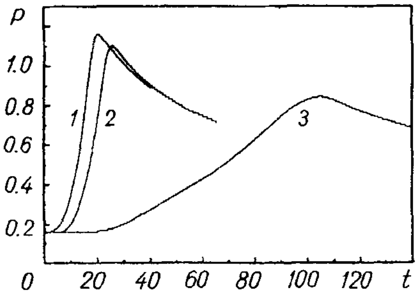

Fig. 1. Typical oscillograms of the pressure in the combustion chamber for different regimes: 1) initiation of combustion by burning-gas jets (PJC); 2) spark initiation in annular twisting of the gas; 3) laminar combustion initiated by spark ignition. P, MPa; t, msec.

for complete combustion and, correspondingly, the maximum increase in pressure were recorded in the PJC regime. Here, the higher thermodynamic parameters are due to lower heat losses because of the accelerated course of the process itself, i.e., the shorter contact of the hot combustion products with the cold walls, and also to the smaller surface of their contact, especially in the initial stages of development of the process. The latter is associated with the presence of a gas heat-insulating interlayer between the hot combustion products and the wall, which favors a decrease in the removal of heat from the zone of combustion.

To analyze the efficiency of various regimes of combustion, we evaluated the increase in pressure and the heat losses in regimes of laminar combustion, gas twisting, and PJC initiation. Calculations were carried out for regimes of combustion of a propane–air mixture with a coefficient of excess fuel of 0.7 and an initial pressure of 0.2 MPa. The scheme of calculation presupposed the following stages: adiabatic approximation in evaluating the heating and the rise in pressure due to the chemical energy evolved in combustion, evaluation of heat losses, reduction of the energy release by the magnitude of the heat losses, and refinement of the thermodynamic parameters in the combustion chamber.

The increase in pressure in the combustion chamber in an adiabatic approximation was calculated based on the equations of mass and energy balance between the initial and final products with allowance for the equation of state and the thermal effect of the reaction:

$$\Sigma\, [m_{\mathrm{c}}\, (\Delta E_{\mathrm{c}})_{T_{\mathrm{i}}}] = \Sigma\, [m_{\mathrm{e}}\, (E^{T_{\mathrm{c}}} - E^{T_{\mathrm{i}}})]\ ; \tag{1}$$

$$\Sigma\, m_{\mathrm{e}} = \Sigma\, m_{\mathrm{i}}\ ; \tag{2}$$

$$P_{\mathrm{e}} = P_{\mathrm{i}}\, (T_{\mathrm{e}}/T_{\mathrm{i}})\, (\Sigma\, m_{\mathrm{e}}/\Sigma\, m_{\mathrm{i}})\ . \tag{3}$$

Here m_{c} is the number of moles of burned gases; m_i, m_{e} and $E^{T_{\mathrm{i}}}$, $E^{T_{\mathrm{c}}}$ are the total number of moles and the amounts of the internal energy of the corresponding components before and after combustion. The technique of calculation of the temperature and pressure is described in detail in [5].

The calculation results for the pressure in the combustion chamber in an adiabatic approximation for the various regimes and their comparison with experimental data are presented in Fig. 2. At each instant of time the calculation was performed with account for the fraction of the mixture burned, which was determined from a frame-by-frame display of the process. It is evident that the adiabatic approximation gives a maximum pressure overestimated by 23–60% depending on the regime of combustion. Thus, corrections for the nonadiabaticity of the process and allowance for heat losses are necessary in carrying out an appraising calculation of the thermodynamic parameters in the combustion chamber.

The magnitude of the heat losses was calculated assuming constancy of the difference between the temperatures of the flame front and the wall, with allowance for the fraction of the burned gas and the known

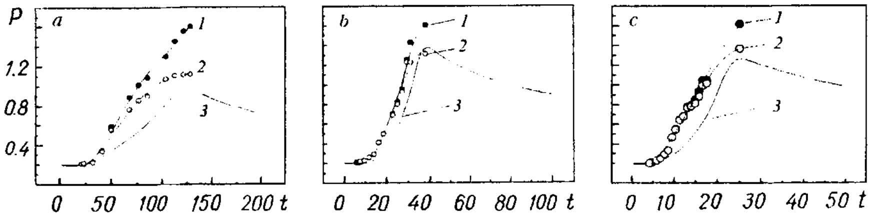

Fig. 2. Comparison of experimental and calculated curves of pressure in the combustion chamber for laminar combustion of the mixture (a), combustion with annular twisting of the gas (b), and initiation of combustion by burning jets (c): 1) pressure calculated in an adiabatic approximation; 2) pressure calculated with allowance for the heat losses to the chamber walls; 3) measured pressure.

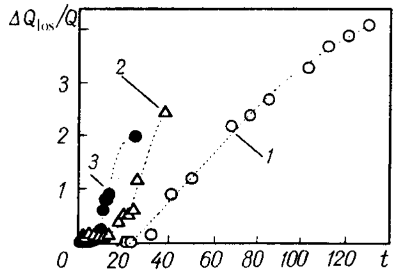

Fig. 3. Relative magnitude of the heat losses (%) to the combustion-chamber walls in different regimes: 1) laminar combustion; 2) combustion with annular twisting of the gas; 3) PJC. The magnitude of the heat losses is normalized to the magnitude of the total energy release in combustion of the mixture.

area of contact of the combustion products with the wall, which were determined based on the results of frame-by-frame photography. The calculations were performed for the regimes of laminar combustion and combustion in the presence of gas flow twisting and PJC. According to [6], the heat losses of the combustion products through the surface S of their contact with the wall are determined by the expression

$$Q_{los} = 2\,(\lambda c_p\,\rho/\pi)^{1/2}\,(T_e - T_w)\,S t^{1/2}\,, \tag{4}$$

where t is the time of contact. To calculate Q_{los}, the value of S for each instant of time was determined based on the frame-by-frame displays of the process.

To calculate the thermodynamic parameters with allowance for heat losses, Eq. (1) of system (1)-(3) was modified with Eq. (4) taken into account:

$$\Sigma\,[m_c\,(\Delta E_c)_{T_i}] - Q_{los} = \Sigma\,[m_e\,(E^{T_e} - E^{T_i})]\,. \tag{5}$$

Results of a refined calculation of the pressure are also given in Fig. 2, whence it follows that allowance for the heat losses to the wall makes it possible to assess sufficiently accurately the minimum increase in pressure under the condition that the time of combustion and the geometry of the working chamber are known. The discrepancy between the calculated and experimental curves for the pressure indicates an insufficient degree of accuracy in determining the volume of the gases burned and the surface area of their contact with the wall in different stages of development of combustion. Nevertheless, good agreement between the calculated and measured maximum pressures testifies to the validity of using this method for calculating the pressure change in the combustion chamber. Since heat removal by heat conduction alone was taken into consideration in the evaluation of heat losses, the agreement between the calculated and measured maximum values of P allows us to consider this kind of heat loss to be predominant for the combustion regimes considered.

Of particular interest is analysis of the relative heat losses to the wall in laminar combustion, combustion with twisting of the gas, and PJC (Fig. 3). The magnitude of the losses was referred here to the value of the total energy released in the combustion of the mixture. It is seen that the relative losses in laminar combustion may attain more than 40%. They do not exceed 25% in the regime with gas twisting and 20% with PJC, which is half the losses in laminar combustion and a quarter smaller than in combustion with annular twisting of the fuel mixture. We note that in all the regimes a substantial increase in losses is observed at the instant of the start of contact of the combustion products with the walls of the working chamber.

The data presented in Fig. 3 make it possible to evaluate the gasdynamic efficiency of the combustion regime from the viewpoint of minimization of heat losses. We introduce the parameter $\tau = t_{\rm los}/T$. Then, the regime of laminar combustion will be characterized by values $\tau \approx 0.25$, the regime with twisting by $\tau \approx 0.34$–0.39, and that with PJC by $\tau \approx 0.32$–0.4. It is easily seen that the gasdynamic structure of the flow in the last two regimes provides minimum time of contact of the hot combustion products with the wall.

In conclusion we note that the performed analysis of the magnitude of the heat losses made it possible to show the advantages of combustion regimes in vortex gas flows that provide minimum time and surface of contact of the hot combustion products with the wall. The maximum increase in pressure can easily be evaluated here based on the considered simplified model of the process on the assumption that the heat flux to the wall of the combustion chamber is the main channel of heat losses. Consequently, use of gasdynamic techniques of thermal insulation of hot combustion products with a view to increasing their thermodynamic parameters is rather efficient, and optimization of the gasdynamic structure of the flow allows one not only to control the rate of combustion but also to minimize the heat losses.

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NOTATION

τ, dimensionless time parameter; $t_{\rm los}$, time during which the heat losses do not exceed several per cent of the total energy release, sec; T, total time of combustion of the mixture, sec; t, current time, sec; λ, thermal conductivity coefficient, W/(m·K); c_p, specific heat, J/(mole·K); ρ, density, kg/m^3; $T_{\rm e}$, temperature of the mixture burned, K; $T_{\rm c}$, temperature of the products of the reaction of combustion, K; $T_{\rm w}$, temperature of the combustion chamber wall, K; S, area of contact of the combustion products with the wall, m^2; $Q_{\rm los}$, magnitude of the heat losses, J; Q, total energy release, J; $\Delta E_{\rm c}$, thermal effect of the reaction, J; $E^{T_{\rm i}}$, $E^{T_{\rm c}}$, internal energy before and after combustion, J; m, number of moles of the corresponding component or the total number of moles; P, pressure, Pa. Subscripts: i, initial mixture; e, burned mixture; c, products of the reaction of combustion; w, wall.

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