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GASDYNAMIC STIMULATION OF COMBUSTION OF LEAN FUEL MIXTURES. 1. EXPERIMENTAL STUDY

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We studied combustion modes experimentally for a lean fuel mixture of propane–air, including combustion of a quiescent mixture, combustion with annular gas swirling, and combustion stimulated by the jets of a burning gas that are injected into the combustion chamber (pulsed jet combustion – PJC). It is shown that, in providing a maximum combustion rate, the PJC mode has an obvious advantage in initiation of combustion of extremely lean fuel mixtures over other gasdynamic combustion modes.

Gasdynamic methods of monitoring and controlling of combustion processes (gasdynamic combustion control – GCC) are of interest from the standpoint of regulation of spatial liberation of chemical energy and the velocity and direction of propagation of the combustion wave front. Some results of gasdynamic control of combustion that is based on its formation in a shear laminar flow are presented in [1]. In a number of studies, use is made of acoustic action on the medium to control the formation of vortices and monitor their dimensions. A modification of the flame structure in [2] by means of the turbulence that develops downstream permitted an increase of up to 75% in the spatial energy liberation. Vortex breakdown was controlled by using additional lateral jets. Investigations of gasdynamic stabilization of combustion via gas swirling in tangential injection of the fuel mixture into a cylindrical combustion chamber [3] revealed a relation between the local energy liberation and the gasdynamic flow structure. In [4, 5], an effect of the intensity of turbulent pulsations on the velocity of flame propagation was demonstrated and it was shown that combustion can be accelerated both due to large-scale distortion of the flame front and as a result of the change of local combustion zones during small-scale velocity fluctuations. In [6], combustion was intensified by gasdynamic action of burning-gas jets on the medium (PJC), which facilitated mixture ignition and at the same time formed gasdynamic disturbances in the combustible medium that stimulated combustion.

We performed a comparative analysis of various gasdynamic methods of combustion acceleration, including annular gas swirling in the combustion chamber and generation of vortex flows with pulsed injection of burning-gas jets into the chamber. The efficiency of these methods was considered for extremely lean fuel-air mixtures taken as a case in point.

Experimental Setup and Recording Methods. Experiments were carried out on a model cylindrical combustion chamber (Fig. 1). The chamber was 80 mm in diameter and 22 mm in width (110.5 ml). On the ends it was closed by 8-mm-thick quartz windows. As the fuel gas we used a propane–air mixture with an excess-fuel coefficient $\varphi = 0.7$. Consideration was given to combustion of both a quiescent mixture and a mixture with vortex swirling in the combustion chamber. To induce an annular flow, the fuel mixture was injected tangentially through an opening 0.5 mm in diameter in the side wall of the chamber. At a pressure in the injector forechamber of 0.5 MPa, the injection lasted about 2 sec, which produced a static gas pressure of 0.2 MPa after the admission was completed. Then, the mixture was ignited with the aid of a standard automobile spark plug.

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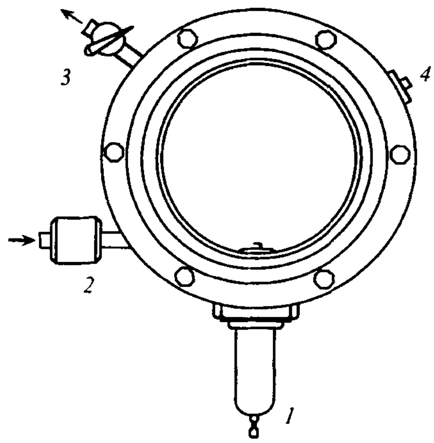

Fig. 1. Combustion chamber: 1) ignition system; 2) injector for setting up annular gas swirling; 3) cock for evacuation of the combustion chamber; 4) pressure gauge.

Combustion of the quiescent gas in the combustion chamber was initiated by either a spark or burning-gas jets (PJC). When PJC was used, additional brief injection (of length 10 msec) of a propane–air mixture with $\varphi = 1.2$ was carried out through a channel in a modified automobile spark plug. The critical cross section for this auxiliary flow was 0.2 mm in diameter. A typical pressure in the PJC forechamber was 0.5 MPa. The PJC jet was oriented perpendicular to the wall of the combustion chamber, along its axis of symmetry. Spark ignition of the fuel mixture in the cavity of the device described was effected with a 10 msec delay after the PJC injection was completed.

The combustion was studied using a shadow scheme of visualization of the flame front with simultaneous pressure recording by a Kistler 601 A piezoelectric gauge. Frame-by-frame recording of the process was executed by a drum camera or a Kodak Ektapro HS Motion Analyzer 4540 camera.

The gasdynamic flow pattern in the combustion chamber was investigated by the method of laser-Doppler velocity measurement (LDV) using equipment of the DANTEC firm. To produce an LDV signal, the chamber was filled with a mixture of oil particles of size 3–5 μm with air. The illumination was effected by an argon laser. Some experiments drew on the method of track stroboscopic photography of particles of size $\sim 0.1 \times 0.1$ mm, which were produced by grinding a 5-μm-thick lavsan film and were injected into the chamber along with the gas.

In the present work, we studied experimentally the modes of propagation of the flame front under different gasdynamic conditions: in an undisturbed medium, in the presence of annular gas swirling in the combustion chamber, and with formation of several large-scale vortex flows in the combustible medium.

Propagation of the Flame Front in an Undisturbed Medium with Spark Initiation. Under conditions of laminar combustion of a lean propane–air mixture with $\varphi = 0.7$ with an initial pressure of 0.2 MPa, the velocity of propagation of the flame front was determined based on frame-by-frame photography of the process (see Fig. 2a). As follows from Fig. 2b, it ranges from 0.4 to 1.5 m/sec depending on the combustion phase. Acceleration or deceleration of the propagation of the flame front becomes understandable from a comparison of these data with the change in the area of the combustion front (see Fig. 2c). At the initial instant of process development, the flame front has a hemispherical shape. In this stage, its area increases rapidly, and the power of energy liberation is maximum with minimum contact of burnt hot gases with the walls. Under these conditions, the velocity of flame propagation is at a maximum 1.5 m/sec. Subsequently, the front becomes two-dimensional convex, and its area diminishes, which is equivalent to a decrease in the power of energy liberation. Simultaneously, the heat loss to the wall increases. As a result, the flame velocity falls to ~ 0.4 m/sec. Thus, the front velocity reaches a steady-state value as a result of dynamic equilibrium of the liberation of chemical energy in it and the heat loss of energy that accumulated in the combustion products. The nearly fourfold increase in the velocity attests to the dominant influence, on the process rate, of the heat

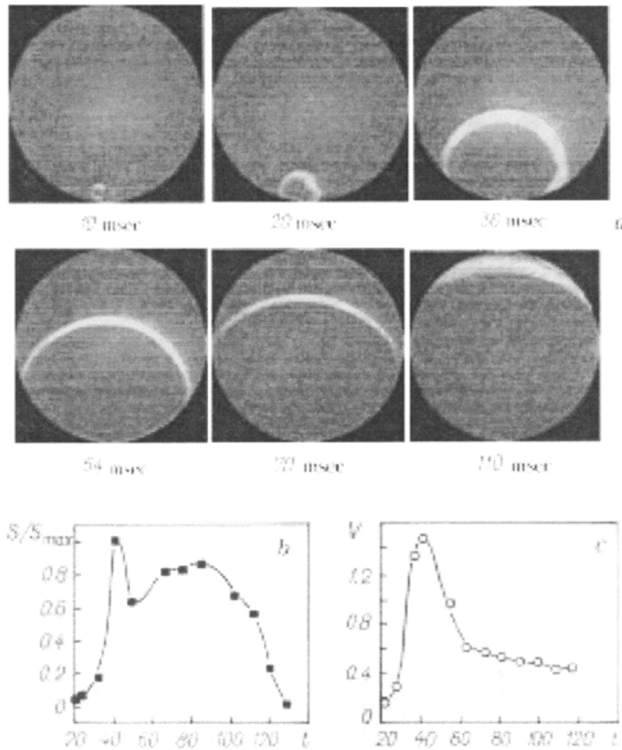

Fig. 2. Frame-by-frame display of laminar combustion in the combustion chamber (a) and change in the surface area of the flame S/S_{max} (b) and in the velocity of propagation of its front (c) during the process. V, m/sec; t, msec.

loss that, under conditions of laminar combustion of the mixture in a closed volume, is associated with significant heat fluxes to the walls of the combustion chamber as a consequence of a sizeable area of contact of hot combustion products with it.

Combustion with Annular Gas Swirling. The heat loss to the wall can be reduced by setting up, between it and the burnt gases, a heat-insulating gas interlayer that impedes their contact for the longest time possible. The required flow structure can be realized via initial tangential gas swirling in the combustion chamber.

Figure 3a presents a gasdynamic flow structure with annular gas swirling at the instant of time preceding ignition with a static pressure of 0.2 MPa. In this case, the flow field was visualized by the method of track stroboscopic photography of particles that were injected into the combustion chamber along with the flow of the fuel mixture. The reconstructed flow pattern is fairly intricate: against the background of the annular gas flow, a "fine" flow structure is observed that consists of a great many small-scale vortices localized at the center of the vortex chamber. The spread in the gas velocities is fairly great: from 8.4 m/sec in the injection zone to 7 m/sec in the wall region behind the ignition system and then to 5 m/sec at the wall that is opposite the spark initiator. Noteworthy is the presence of gas flows directed from the periphery to the center of the chamber, where a great number of vortices are concentrated, in which the gas velocity ranges from 3.5 to 6.3 m/sec. This indicates that it is possible to realize combustion modes such that the zone of energy liberation is localized at the chamber center in the presence of an interlayer of yet unburnt gas in the wall regions. The gasdynamic flow structure described should facilitate a decrease in the time of contact of hot gases with the cold walls, a reduction in the heat loss, and, therefore, attainment of higher thermodynamic parameters in the combustion chamber.

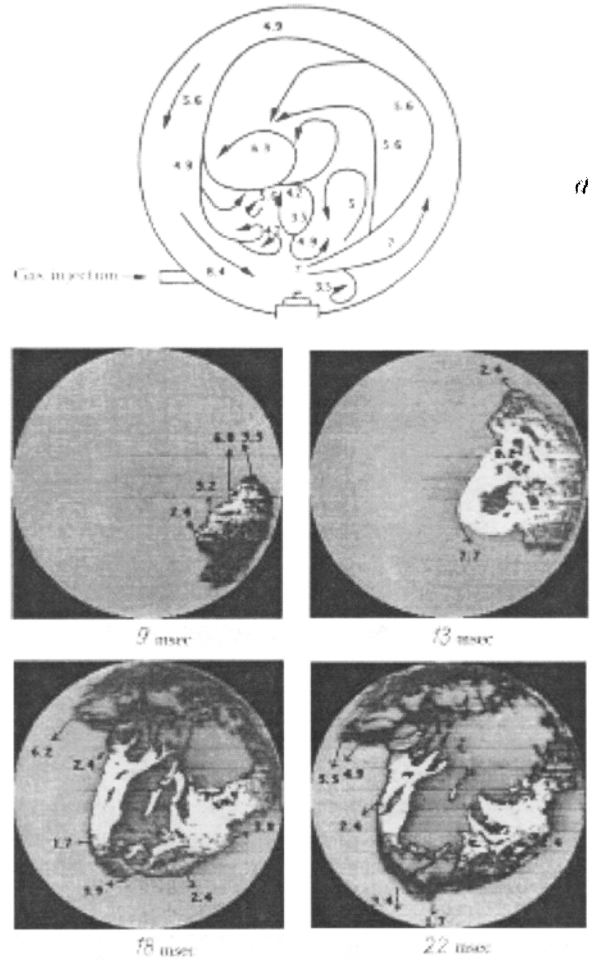

Fig. 3. Velocity field (a) and frame-by-frame display of combustion (b) with annular gas swirling. The numerals indicate the velocity in m/sec.

Since the velocity of the tangential gas swirling (5–7 m/sec) is severalfold higher than the velocity of the flame propagation in the undisturbed medium (~0.4 m/sec), the flow structure realized offers more rapid transfer of the flame front over the chamber volume and shortening of the combustion time.

The shadow photographs of the propagation of the flame front with the tangential gas swirling that are presented in Fig. 3b indicate the dominant influence of the gasdynamic-flow structure on the combustion. It is not difficult to notice that the main combustion zone develops in the central part of the combustion chamber. Clearly visible are layers of cold gas near the side wall that isolate hot combustion products from contact with it.

Based on a frame-by-frame display of the process, the velocity and direction of propagation of the flame front were determined at different combustion stages. The corresponding velocity vectors and their magnitudes are presented in the shadow pictures. A comparison of the velocities of flame propagation with the previously reconstructed velocity field that is realized in the combustion chamber with no combustion of the fuel mixture shows that these magnitudes are close. Thus, the gas swirling does not exert a strong influence on the velocity of the flame propagation relative to the gas medium. The combustion duration is approximately equal to the time of a single gas turnover, and the higher parameters of the combustion products in this case result from a reduction in the heat loss to the wall.

Combustion Initiation by Flame Jets (PJC). One of the most efficient ways of igniting lean fuel mixtures is the PJC method, proposed by T. Oppenheim [6], which is based on preliminary initiation of combustion of a mixture (with an excess-fuel coefficient $\varphi \geq 1$) in a small intermediate cavity followed by injection

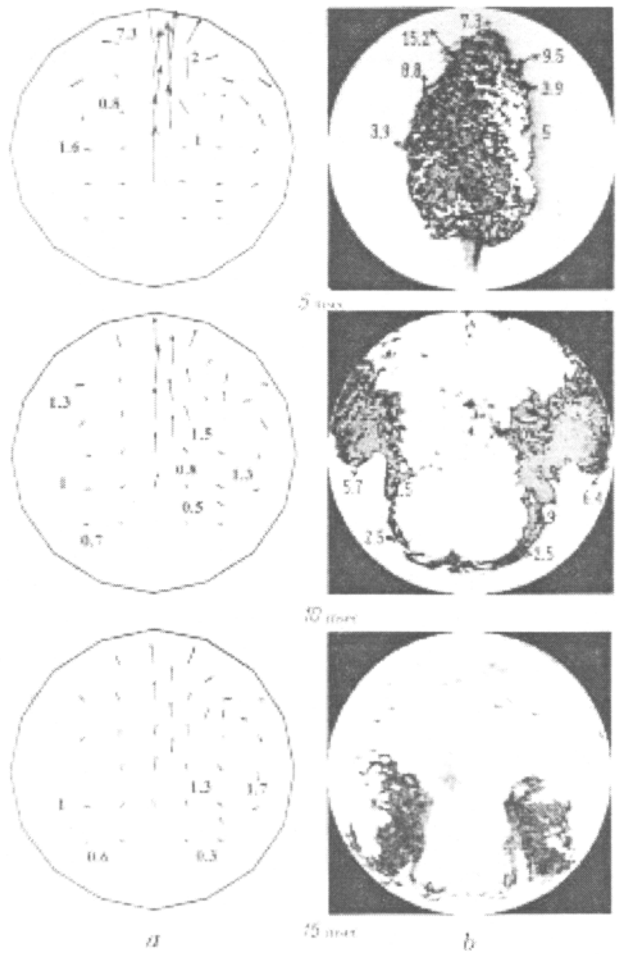

Fig. 4. Velocity field in the combustion chamber (a) and frame-by-frame shadow display of the process in PJC injection (b) at different instants of time from the start of initiation. The numerals indicate the velocity in m/sec.

of jets of the burning mixture into the main volume. Owing to the large surface of interaction of the flame jets with the lean fuel mixture, its ignition is facilitated noticeably, especially in the case of ignition of extremely lean fuel mixtures. Another feature of PJC is intense gasdynamic action on the gas medium in the combustion chamber. The latter consists in the fact that pulsed injection of high-velocity jets of burning gas, on the one hand, promotes turbulization of the fuel gas in the main volume, which accelerates flame propagation, and, on the other hand, forms large-scale annular flows that foster transfer of combustion zones with the gas flows and rapid ignition of the mixture over the entire volume.

Figure 4 presents frame-by-frame shadow photographs of PJC ignition of a mixture with $\varphi = 0.7$ along with results of measurements, by the LDV method, of the velocity field in the combustion chamber for this gasdynamic mode. The static pressure of the gas in the chamber was 0.2 MPa. In the LDV experiments, the parameters in the PJC forechamber corresponded to values of them that are typical of the combustion mode (the excess-fuel coefficient in the air mixture was $\varphi = 1.2$, the pressure was 0.5 MPa, the duration of the PJC injection was 10 msec, the mixture ignition in the PJC cavity was carried out with a delay of 10 msec after the injection was completed). The data obtained (Fig. 4a) show that, as a result of PJC injection directed along the axis of symmetry of the combustion chamber, two large-scale symmetric vortex flows are formed in its cavity. The gas moves at maximum velocity along the axis of injection and gradually decelerates as it approaches the point of turn on the opposite wall. The highest measured flow velocity at the chamber center was about 10–12 m/sec. The tangential velocity at the point of turn was also high, about 7 m/sec.

Figure 4b presents measurement results for the velocity of flame propagation with PJC ignition that were obtained from the recording of the displacement of the flame front in frame-by-frame shadow photographs. In the PJC forechamber, the parameters of the injected flow complied with the conditions for measurement of the velocity field by the LDV method. The combustion chamber was filled with a propane-air mixture with $\varphi = 0.7$ with an initial pressure of 0.2 MPa. A comparison of the combustion for the cases of annular gas swirling and PJC shows the advantage of the latter: the velocity of the flame propagation relative to the medium in the PJC mode is higher than the corresponding value for the case of combustion intensification by the annular gas swirling. This advantage is most noticeable in the initial stages of combustion and is related primarily to the high level of turbulization of the medium with the PJC injection. As the results of the LDV measurements show, turbulent pulsations of the velocity can reach 10–15 m/sec. Thus, PJC is much more capable of intensifying the combustion than ordinary annular gas swirling.

Shadow displays of the process revealed that, at the initial instant of time, the velocity of the flame front that is produced by the PJC jet reaches 28 m/sec. At the opposite wall it decreases to 15–18 m/sec (see Fig. 4b), which is much in excess of the velocity of the flame propagation for the mode with the annular gas swirling. This is caused by the higher initial velocity of the flame jet that is injected in PJC and by generation, by it, of intense turbulent pulsations that promote acceleration of turbulent combustion. Owing to this, ignition by the PJC jets provides more rapid combustion of the mixture in comparison with the other investigated gas-dynamic modes. An important asset of ignition using a PJC jet is also the absence of contact of the flame front with the walls of the combustion chamber up to the instant of collision of the burning jet with the opposite wall. This should cause a low level of heat loss, especially in the initial stage of combustion.

In conclusion it should be noted that the advantage of PJC modes is linked not just with maximum stimulation of combustion at a low level of heat loss. In operation with extremely lean fuel mixtures, the problem of their ignition becomes fairly urgent. In our experiments spark ignition triggered combustion of a propane–air mixture with an excess-fuel coefficient $\varphi = 0.7$ in only approximately half the cases. At the same time, PJC provided absolutely reliable initiation for compositions that are close to the ignition threshold. Thus, reliable ignition of lean fuel mixtures with subsequent maximum stimulation of their combustion by high-velocity jets of hot gases makes it possible to regard PJC modesas very attractive from the standpoint of their use in a new generation of highly efficient and economical internal combustion engines..

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NOTATION

φ, excess-fuel coefficient; V, velocity, m/sec; S, surface, m^2; t, time, msec.

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