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Continuous Spin Detonation in Annular Combustors

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An acetylene–oxygen mixture is burned in two annular chambers 100 mm in diameter in the spin detonation regime with supercritical and subcritical differences of oxygen pressure in the annular slot. By varying the flow rates of components of the mixture, width of the slot for oxidizer injection, point of fuel injection, and initial ambient pressure, the regions of existence and the structure of transverse detonation waves are studied, and the limits of existence of continuous detonation in terms of pressure in the chamber are determined. The losses of the total pressure in the flow in oxygen-injection slots and in fuel-injector orifices are estimated.

Key words: fuel, continuous detonation, subsonic flow, combustor, transverse detonation waves, flow structure.

INTRODUCTION

Turbulent combustion is widely used in today's engine combustors. High-frequency instability that can arise there is extremely undesirable and has to be eliminated. In detonation-combustion chambers, high-frequency instability manifested in the form of transverse detonation waves (TDW) [1] dominates in the course of burning. Therefore, the chamber structure and the method of fuel injection should be chosen in a manner that amplifies the TDWs. The combustor should have a closed annular geometry, and the injectors uniformly distributed along the annular channel should provide rapid mixing in the vicinity of the injectors [2]. As fuel burning occurs in the region of TDW front propagation, the axial size of the combustors are minimum in the case of continuous detonation. Particular requirements to high-quality mixing of components in a narrow region in the chamber for formation of a detonation-capable layer of the mixture lead to an increase in the pressure ratio in the injectors $\pi_{\rm m,ch} = P_{\rm m}/P_{\rm ch}$, where $P_{\rm m}$ is the static pressure in the manifold and $P_{\rm ch}$ is the static pressure in the chamber in the vicinity of injectors. Thus, in annular cylindrical combustors of liquid-propellant rocket motors (LRM) [3], where the propellant components are injected through a system of orifices in the end-face wall of the combustor, stable TDWs arise at $\pi_{\rm m,ch} = 2$–4. The higher the pressure ratio $\pi_{\rm m,ch}$, the better the mixing, the smaller the effect of the elevated pressure of products in the region of the TDW front on the injection system, and the more stable the detonation. In this case, however, the losses of the total pressure of the flux of components in the injectors are higher. By the example of continuous detonation of an acetylene–oxygen mixture in an expanding channel, it was found [4] that it is possible to ensure detonation in a subsonic flow of the mixture occupying the entire cross section of the chamber almost without total pressure losses by providing a constant flow rate of the oxidizer owing, to a supercritical pressure ratio in the annular slot.

The present paper is a continuation of [4]. Its goal is to study detonation regimes of fuel combustion at supercritical and subcritical pressure ratio in the annular slot for oxidizer injection. This is reached by changing the oxidizer-injection slot width and the chamber geometry. In practical aspects, it is of interest to know the total pressure losses to the oxidizer-injection slots and the range of detonation existence in terms of various parameters, as well as to study the effects that accompany continuous detonation modes of fuel combustion.

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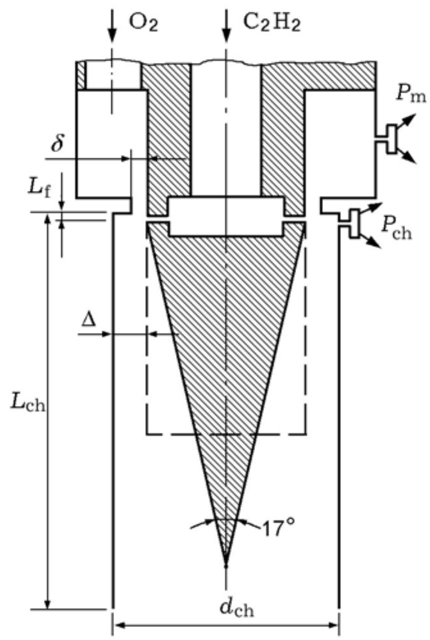

Fig. 1. Layouts of a combustor: chamber A with an expanding cross section of the annular channel (mark out by solid lines) and chamber B with a constant cross section (mark out by dashed lines).

EXPERIMENTS

The experiments were performed in combustors of two types whose layouts are shown in Fig. 1: chamber with an expanding cross section of the annular channel (chamber A) and chamber with a constant cross section of the annular channel (chamber B). Chamber A had the following geometric parameters: diameter $d_{\rm ch} = 100$ mm, initial width of the channel at the end face of the chamber $\Delta = 5$ mm, channel length $L_{\rm ch} = 300$ mm, angle of expansion in the downstream direction $\theta = 8.5°$, distance from the end of the chamber to the acetylene injector $L_{\rm f} = 1$ mm (in some experiments, $L_{\rm f} = 50$ mm; in this case, an annular cylindrical channel of width $\Delta = 5$ mm was placed up to the fuel-injection point), oxygen-injection slot width $\delta = 0.275$–2.5 mm, cross-sectional area of oxygen injection from the annular manifold with a cross-sectional area of 200 mm^2 to the annular channel $S_{\rm ox} = 77.7$–708 mm^2, and cross-sectional area of the acetylene injector $S_{\rm f} = 40.4$ mm^2. Chamber B had a channel with a constant cross section $\Delta = 5$ mm ($S_{\rm ox} = 1490$ mm^2) and length $L_{\rm ch} = 100$ mm; the remaining parameters were the same as those of chamber A.

The layout of the experimental setup is similar to that described in [4]. The detonation products exhausted from the chamber to a 0.43-m^3 tank with an initial ambient pressure $P_{\rm a,0} = (0.06$–$1.0) \cdot 10^5$ Pa. In the course of injection, the pressure in this tank gradually increased. In some experiments, exhaustion into the atmosphere with a constant pressure $P_{\rm a} = 1.01 \cdot 10^5$ Pa occurred. The time of the process was set by a control system and was varied within the interval $\tau_d = 0.23$–0.47 sec. The entire process was recorded onto a photographic film through a longitudinal window 8 mm wide and 100 mm high with the help of a photorecorder with a falling drum [5]. The computer system registered signals from pressure gauges (in receivers, manifolds, chamber, and tank for exhaust products).

The flow rates of propellant components during the experiment decreased as the gases exhausted from the receivers. Their values were calculated by the technique described in [4]. The volumes of the receivers were 3.3 liters (oxygen) and 1.82 liters (acetylene). In the case of oxygen injection through a slot of width $\delta = 0.275$ mm, the initial flow rate $G_{\rm ox,0}$ counted from the moment of the maximum pressure increase in the manifold (≈25 msec after the beginning of exhaustion from the receiver) was 75.6 g/sec for the initial pressure in the receiver $P_{\rm ox,0} = 6 \cdot 10^5$ Pa. The initial flow rate of acetylene $G_{\rm f,0}$ after the maximum increase in pressure in the manifold was 24.2 g/sec for the initial pressure in the receiver $P_{\rm f,0} = 3.5 \cdot 10^5$ Pa. The ratio of the components was close to a stoichiometric value. During the process ($\tau_d = 0.41$ sec), the flow rate of oxygen decreased to $G_{\rm ox} = 16.3$ g/sec, the flow rate of acetylene decreased to $G_{\rm f} = 6.2$ g/sec, and the fuel-to-air equivalence ratio Φ increased to 1.18. As the width of the annular slot increased from 0.5 to 2.5 mm, the initial flow rate of oxygen increased to $G_{\rm ox,0} = 85$ g/sec, because the main factor governing the oxygen flow rate became the cross-sectional area of the valve orifice ($S = 113$ mm^2). For the tank pressures used, the initial flow rates mentioned above remained substantially unchanged. A noticeable decrease in flow rates was observed at the end of exhaustion if the products were exhausted into the atmosphere, with a subsonic flow formed in the slot for oxygen injection and in the orifices of fuel injectors.

TEST RESULTS

Under certain conditions, detonation combustion of a C_2H_2–O_2 mixture in stable spin TDWs was ensured in the above-described combustors. Figure 2 shows the fragments of typical photographic records of transverse detonation waves, which were taken by the method of velocity compensation [6], in the case of exhaustion into a medium with an initial ambient pressure

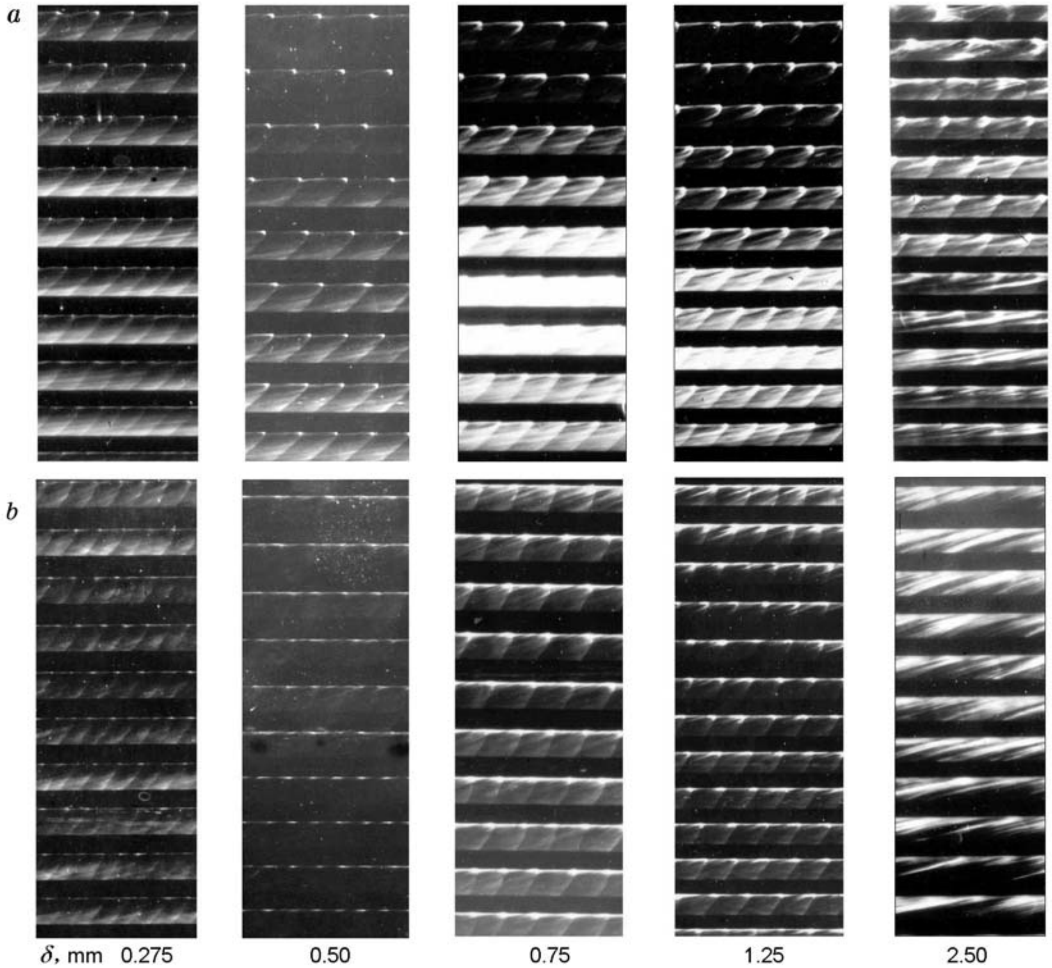

Fig. 2. Photographic records of TDWs in chambers A (a) and B (b).

$P_{a,0} = 0.2 \cdot 10^5$ Pa. The duration of each fragment is ≈0.2 msec, and each subsequent line in the fragments is shifted in time by 12.5 msec. As the oxidizer-injection slot width increases from $\delta = 0.275$ mm to 2.5 mm, other initial conditions being identical, the transverse detonation waves persist in chamber A and are attenuated in chamber B. At $\delta = 2.5$ mm, the waves propagating over the products of turbulent combustion in chamber B degenerate into transonic waves. The TDW structure in chamber A with an expanding channel has no principal distinctions from the TDW structure in chamber B and is similar to that described in [4].

The TDW velocity was determined by the formula

$$D = \pi \langle d_{\rm ch} \rangle v_{\rm dr} / (\Delta l n), \quad (1)$$

where $\langle d_{\rm ch} \rangle = (d_{\rm ch} + d'_{\rm ch})/2$ is the mean diameter of the annular channel ($d_{\rm ch}$ and $d'_{\rm ch}$ are the outer and inner diameters of the channel), Δl is the distance between the neighboring TDWs in the photograph, n is the number of TDWs along the chamber circumference, and $v_{\rm dr}$ is the linear velocity of the drum of the photorecorder. In the present experiments, we had $v_{\rm dr} = 100$ m/sec. Based on the photographs obtained by the method of velocity compensation, the number of TDWs cannot be determined exactly, except for cases where the choice was made between one, two, or even three transverse detonation waves. In the general case, the criterion for choosing the number of waves was the velocity of the ideal Chapman–Jouguet detonation $D_{\rm CJ} = 2424$ m/sec (at a temperature of 273 K and atmospheric pressure) for detonation of well-mixed components of the $C_2H_2 + 2.5O_2$ mixture. In the case of continuous spin detonation, the inequality $D_{\rm CJ} > D$ is valid because of incomplete mixing of the components, their partial burnout ahead of the TDW, and losses of momentum due to detonation-front curvature [7–9]. Therefore, this inequality should be satisfied in choosing the number of

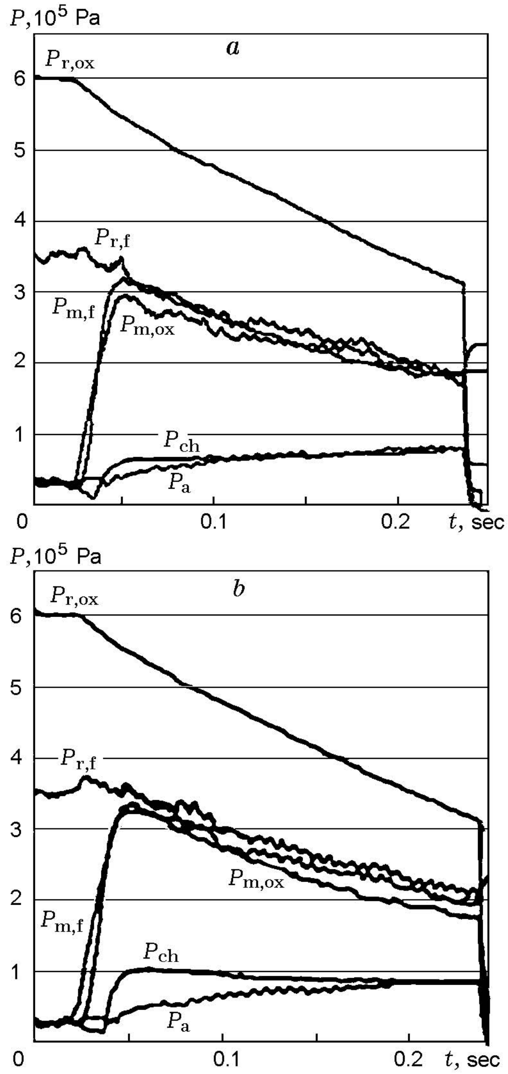

Fig. 3. Pressure oscillograms recorded in chamber A (a) and in chamber B (b): $P_{\rm r,ox}$ and $P_{\rm r,f}$ are the pressures in the oxygen and acetylene receivers, $P_{\rm m,ox}$ and $P_{\rm m,f}$ are the pressures in the oxygen and acetylene manifolds, $P_{\rm ch}$ is the pressure in the chamber, and $P_{\rm a}$ is the ambient pressure in the tank for collecting detonation products; $\delta = 0.275$ mm, $G_{\rm ox,0} = 75.6$ g/sec, $G_{\rm f,0} = 24.2$ g/sec, and $P_{\rm a,0} = 0.2 \cdot 10^5$ Pa.

transverse detonation waves. If weak transonic waves are formed in the chamber, they can be clearly distinguished from TDWs by the absence of a typical structure and a forward-going tail. In this case, the tail is a weak transonic wave with combustion over its entire length rather than a shock wave.

To exactly determine the velocity and the number of transverse detonation waves, we performed test experiments using the method of scanning of glowing objects moving through a transverse slot 8 mm wide mounted perpendicular to the window in the region of TDW front propagation. The TDW velocity was estimated as $D' = k \tan \beta v_{\rm dr}$, where k is the zoom-out coefficient and β is the slope of scanning. The number of waves was determined by rounding the ratio nD/D', whose nominator was found by Eq. (1), to an integer; after that, the same formula was used to determine the exact value of the continuous detonation velocity D.

It was found that the most stable detonation modes are observed in the case of sonic exhaustion of oxygen through an annular slot of width $\delta = 0.275$ and 0.5 mm. Note that Fig. 2b recorded for $\delta = 0.5$ mm shows the photographic records with TDWs rotating in the opposite direction with respect to the photographic film. The detonation fronts are seen as smeared glowing regions, and the tail are almost invisible. A change in the direction of TDW rotation is a frequent phenomenon observed if the propellant components are injected symmetrically about the chamber centerline; this was also the situation in the present experiments. Initiation of detonation in a channel located in the chamber wall and tangentially directed toward the annular channel and the presence of the tangential component of velocity of one or both components normally determine the TDW rotation direction. There are situations, however, where random disturbances or other features of the flow change the direction of TDW rotation even in the course of the process. The velocities of continuous spin detonation (D) and the number of TDWs (n) in chamber A for several values of the parameter δ are listed in Table 1.

Typical oscillograms in the oxygen and acetylene receivers ($P_{\rm r,ox}$ and $P_{\rm r,f}$), in the oxygen and acetylene manifolds ($P_{\rm m,ox}$ and $P_{\rm m,f}$), in the chamber at a distance of 5 mm from the end-face wall ($P_{\rm ch}$), and in the tank for exhaustion of detonation products ($P_{\rm a}$) for $\delta = 0.275$ mm and $P_{\rm a,0} = 0.2 \cdot 10^5$ Pa are plotted in Fig. 3 (for chamber A and chamber B). The oscillograms of the corresponding pressures are almost identical, except for the pressure in the chamber $P_{\rm ch}$. A specific features of chamber A is an almost constant static pressure in the vicinity of the end face during the entire process, $P_{\rm ch} \approx (0.64–0.7) \cdot 10^5$ Pa, despite a significant decrease in flow rates of the components. Moreover, with identical flow rates of the acetylene–oxygen mixture but with atmospheric exhaustion of detonation products ($P_{\rm a} = P_{\rm a,0} = 1.01 \cdot 10^5$ Pa), the pressure in the chamber was approximately the same: $P_{\rm ch} = (0.72–0.65) \cdot 10^5$ Pa (Fig. 4a), i.e., the pressure in chamber A in the case of detonation became lower than the ambient pressure.

In a series of experiments where the detonation products exhausted into a tank with an initial ambient pressure $P_{\rm a,0} = 1.01 0^5$ Pa, the pressure in cham-

TABLE 1

δ, mm	D, km/sec	n	$P_{\text{m,ox}}$, 10^{-5} Pa	P_{ch}, 10^{-5} Pa	P_{a}, 10^{-5} Pa	$P_{\text{m,ox}}/P_{\text{ch}}$	$P_{\text{ch}}/P_{\text{a}}$
0.275	2.26	3	3.17	0.63	0.4	5.03	1.6
0.5	1.75	3	2.15	0.42	0.28	5.1	1.5
0.75	2.21	3	1.87	0.83	0.33	2.25	2.5
1.25	2.31	2	1.39	0.79	0.28	1.76	2.8
2.5*	2.20	1	1.08	0.6	0.3	1.64	2
	2.33	2	0.96	0.66	0.6	1.45	1.1

Note. *Regime parameters for different times.

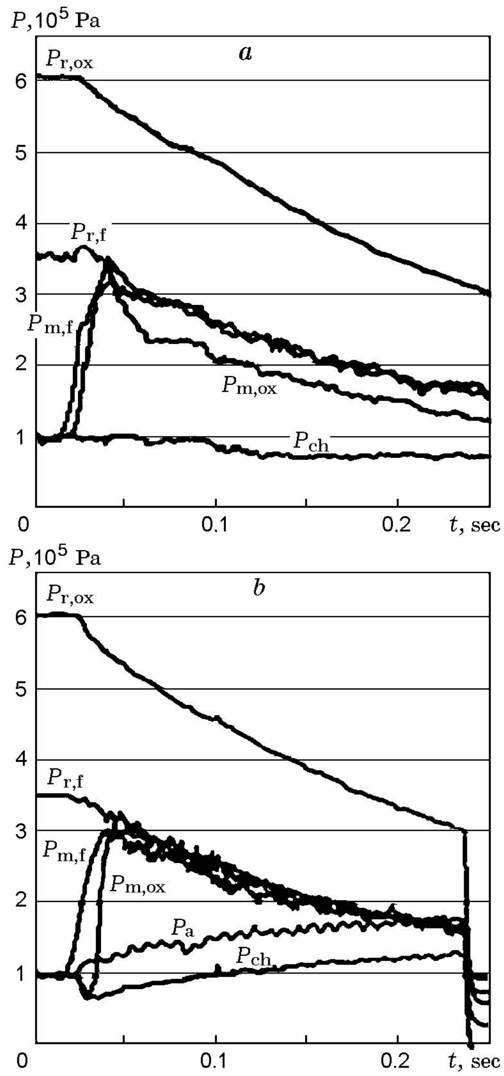

Fig. 4. Oscillograms of pressures in the oxygen and acetylene receivers and manifolds in chamber A: the products exhaust into the atmosphere (a) or into a tank with an initial ambient pressure $P_{\text{a},0} = 1 \cdot 10^5$ Pa (b).

ber A first decreased to $P_{\text{ch}} = 0.69 \cdot 10^5$ Pa (Fig. 4b). After that, with an increase in the ambient pressure caused by accumulation of the products in the tank, the pressure in the chamber started to increase monotonically; the difference in these pressures $\Delta P = P_{\text{a}} - P_{\text{ch}} \approx (0.3\text{–}0.4) \cdot 10^5$ Pa was approximately the same both in the presence of TDWs and after their decay (0.163 sec from the beginning of the process) in the course of turbulent combustion. Because of the difference in pressures, the end of the combustion process proceeded at pressures in the oxygen and acetylene manifolds lower than the pressure in the tank for detonation products. In the acetylene path (see Fig. 4b), even the pressure in the receiver became lower than the ambient pressure. Elucidation of the actual reason for the observed behavior of pressure in the combustor with an expanding cross section of the annular channel requires further research.

DISCUSSION OF RESULTS

A possible reason for stabilization of pressure in chamber A is the geometric factor generating a higher pressure gradient behind the TDW front than that in a constant-section channel, which promotes an increase in velocity of the incoming mixture and stability of the detonation-front width; a constant pressure in the chamber is sustained by decreasing the dynamic component of the pressure in the flow: the total pressure of the incoming mixture decreases monotonically. The pressure in chamber B is close to the stagnation pressure and decreases in proportion to the decrease in flow rate. A similar situation is observed in the chamber with constriction of the exit section in the case of turbulent combustion of the fuel [10]. Indeed, the transition of the flow through the velocity of sound in the axial direction in a constant-section chamber with a sufficiently high pressure, as compared to the ambient pressure, occurs near the open end of the chamber [11, 12]. The total pressure at the frontal (closed) end face is recovered, because the streams of the propellant components are rapidly decelerated.

Particular values of pressure in the chamber, types of propellant components, and degree of their mixing provide a certain specific TDW front width (h). In the case of good mixing of the components, the value of h is close to the critical value for detonation $h_* = (12 \pm 5)a$, where a is the cell size of multifront detonation in tubes (characteristic distance between TDW collisions [13]), which is equal on the average to one half of the diameter of the detonation output to a free volume [14]. The scatter of the values of h_* is mainly related to the mixing process strongly depending on the injector structure. In the case of incomplete mixing of the components (continuous flow of oxygen or oxygen injection into the chamber through the annular slot), the width of the incoming layer of the mixture h is five and more times greater than the detonation-capable layer of the mixture formed by injectors with good mixing in LRM-type chambers. In the present experiments, we had $h \approx$ 10–12 mm. An almost constant pressure at the frontal end face of chamber A promotes TDW stability, because the width of the incoming detonation-capable layer h_* is stabilized: the competing accelerating flame front and detonation front choose certain positions.

A strong effect of the ambient pressure on the TDW structure and intensity was found. For $P_{\rm ch}/P_{\rm a} < 4$, the shock waves, which are always present in detonation products during their exhaustion into the ambient space, penetrated into the chamber, reached the slot for oxidizer injection, and affected the formation of the detonation-capable layer of the mixture. For $P_{\rm ch}/P_{\rm a} < 1.8$, acoustic disturbances started penetrating into the mixing zone from outside. In each experiment, the rate of $P_{\rm ch}$ reduction decreased with time, and the pressure gradually approached $P_{\rm a}$. Normally, this intensified the combustion ahead of the TDW front; the latter included only a narrow layer of insufficiently mixed propellant components, and its width was additionally reduced because of the decrease in the pressure ratio in the slot $\pi_{\rm m,ch} = P_{\rm m,ox}/P_{\rm ch}$. As a result, the transverse detonation waves decayed, degenerating in the limit into acoustic waves in combustion products. If the products exhausted into the atmosphere or into a tank with an initial ambient pressure $P_{\rm a,0} = 1 \cdot 10^5$ Pa, these trends of the detonation regime were manifested from the very beginning of the process and were more pronounced in chamber B.

From the practical viewpoint, it is important to know the total pressure losses for the oxidizer during its flow through the slot, because the stagnation pressure of air in an air-breathing engine is rather low ($\approx 2 \cdot 10^5$ Pa at the level of the Earth's surface at a transonic velocity), whereas it is desirable to have a maximum possible pressure in the combustor for obtaining a large degree of expansion of the products. Based on experimental data, we estimated the total pressure losses of oxygen flowing from the manifold to the chamber through slots of different widths δ. The known relations [15] were used, which describe the flow in the steady-state approximation:

$$\begin{gathered}\Delta P_{\zeta,\rm ox} = (\zeta_{\rm ent,ox} + \zeta_{\rm exit,ox})\rho_{\rm ox} v_{\rm ox}^2/2, \\ \Delta P_{\lambda,\rm ox} = \zeta_{\rm ox}\rho_{\rm ox} v_{\rm ox}^2/2,\end{gathered} \qquad (2)$$

$$G_{\rm ox} = \mu_{\rm ox}\rho_{\rm ox} v_{\rm ox} S_{\rm ox} = m\frac{P^* q(\lambda)}{\sqrt{T^*}}\mu_{\rm ox} S_{\rm ox}.$$

Here $\Delta P_{\zeta,\rm ox}$ are the total pressure losses of the oxygen flow at the entrance and exit of the slot, $\Delta P_{\lambda,\rm ox}$ are the pressure losses due to friction, $G_{\rm ox}$ is the oxygen flow rate through the annular slot, $\rho_{\rm ox}$ and $v_{\rm ox}$ are the density and velocity of the gas flow at the slot exit, T^* is the stagnation temperature in the receiver, P^* is the stagnation pressure at the entrance of the annular slot, $\lambda = v_{\rm ox}/c_{\rm cr}$ is the reduced velocity, $q(\lambda) = \rho_{\rm ox} v_{\rm ox}/(\rho_{\rm ox} v_{\rm ox})_{\rm cr}$ is a gas-dynamic function, $\mu_{\rm ox} = 0.98$ is the flow-rate coefficient of the oxidizer injected through the slot, $\zeta_{\rm ent,ox} = 0.03$ is the local drag coefficient for a slot with smooth rounding of the entrance, $\zeta_{\rm exit,ox} = (1 - S_{\rm ox}/S_\Delta)^2$ is the local drag coefficient at the slot exit for Reynolds numbers $\mathrm{Re} = \rho_{\rm ox} v_{\rm ox}\delta/\eta_{\rm ox} > 3.5 \cdot 10^3$ [16], $\zeta_{\rm ox} = \Lambda k_{\rm ox} l/\delta$, Λ is the friction coefficient, $k_{\rm ox}$ is the shape factor of the slot, l is the slot length, $\eta_{\rm ox} = 1.99 \cdot 10^{-5}$ kg/(m·sec) is the dynamic viscosity of oxygen, $m = [\gamma/R(2/(\gamma+1))^{(\gamma+1)/(\gamma-1)}]^{1/2}$, R is the universal gas constant, and γ is the ratio of specific heats at constant pressure and at constant volume.

For flows through the slot, the above-given formulas yield the expressions

$$\begin{gathered}\Delta P_{\zeta,\rm ox} = (\zeta_{\rm ent,ox} + \zeta_{\rm exit,ox})[G_{\rm ox}/2\mu_{\rm ox} S_{\rm ox}]v_{\rm ox}, \\ \Delta P_{\lambda,\rm ox} = \zeta_{\rm ox}[G_{\rm ox}/2\mu_{\rm ox} S_{\rm ox}]v_{\rm ox}.\end{gathered} \qquad (3)$$

For oxygen, with $R = 259.825$ J/(kg·K) and $\gamma = 1.4$, we find $m = 0.0425$ sec·K$^{0.5}$/m, $\Lambda \approx 0.02$ for $10^4 < \mathrm{Re} < 5 \cdot 10^4$, $k_{\rm ox} = 1.5$ [16], and $l = 3$ mm.

Generally speaking, the flow in the slot is unsteady: oxygen injection is terminated in the high-pressure region behind the TDW front, and some portion of the products enters the manifold; the direction of the pressure gradient changes in the rarefaction wave behind the detonation front. For strong TDWs, the velocity of filling the chamber by oxygen is close to the velocity of sound in the initial mixture. A similar flow was observed in [4]. In the case of the oxygen flow through

TABLE 2

δ, mm	$G_{\rm ox}$, g/sec	$v_{\rm ox}$, m/sec	$\Delta P_{\zeta,\rm ox}$, 10^5 Pa	$\Delta P_{\lambda,\rm ox}$, 10^5 Pa	$(\Delta P_{\zeta,\rm ox} + \Delta P_{\lambda,\rm ox})/P_{\rm m,ox}$
0.275	70	298	1.27	0.448	0.54
0.5	70	235	0.503	0.107	0.284
0.75	80	185	0.272	0.043	0.168
1.25	80	138	0.097	0.011	0.078
2.5*	80	84	0.015	0.002	0.016
	60	71	0.01	0.001	0.011

Note. *Regime parameters for different times.

the slot with the velocity of sound, however, the off-design portion is a small region behind the TDW front (no more than 5% of the distance between the neighboring waves); hence, the influence of detonation on the injection system was ignored in our estimates, and the value of $\Delta P_{\zeta,\rm ox}$ was calculated by formula (3). For test conditions described in Table 1, we estimated the total pressure losses of the oxygen flow in the oxidizer-injection slot for chamber A; the results are presented in Table 2.

It follows from the data in Table 2 that the total pressure losses of the incoming flow in chamber A in the case of burning the fuel in strong transverse detonation waves can be reduced to 1% by expanding the annular slot for oxidizer injection. They can be limited to friction-induced losses by contouring the slot cross section or by providing detonation combustion in a continuous subsonic oxidizer flow. In these cases, the losses will be even lower than the values indicated in the last column of Table 2. Though the total pressure losses of the oxygen flow in the slot are insignificant, the pressure ratio in the slot $P_{\rm m,ox}/P_{\rm ch}$ (see Table 1) could be reduced to 1.45 only.

The friction-induced losses in the orifices of the fuel injector and the total pressure losses at the entrance and exit of the orifices in the injectors were found similar to losses in the oxidizer-injection slot:

$$\Delta P_{\zeta,\rm f} = (\zeta_{\rm ent,f} + \zeta_{\rm exit,f})[G_{\rm f}/2\mu_{\rm f} S_{\rm f}]v_{\rm f},$$

$$\Delta P_{\lambda,\rm f} = \zeta_{\rm f}[G_{\rm f}/2\mu_{\rm f} S_{\rm f}]v_{\rm f},$$

$$G_{\rm f} = \mu_{\rm f}\rho_{\rm f} v_{\rm f} S_{\rm f}.$$

Here, $\zeta_{\rm ent,f} = 0.5$ and $\zeta_{\rm exit,f} \approx 1.0$ are the local drag coefficients at the entrance and exit of the injector orifice with sharp edges, $G_{\rm f}$ is the flow rate of acetylene, $\mu_{\rm f} = 0.875$ is the flow rate coefficient of the fuel injected through the injector [17], $\zeta_{\rm f} = \Lambda_{\rm f} k_{\rm f} l_{\rm f}/\delta_{\rm f}$ and $\delta_{\rm f} = 0.6$ mm are the hydraulic diameter of the injector orifice, $\Lambda_{\rm f} \approx 0.03$, $k_{\rm f} = 1.5$, and $l_{\rm f} = 2$ mm.

The critical velocity of injection and the density of acetylene in the injector were determined as

$$v_{\rm f*} = [2/(\gamma_{\rm f} + 1)]^{0.5} c_{\rm f,0},$$

$$\rho_{\rm f*} = [2/(\gamma_{\rm f} + 1)]^{1/(\gamma_{\rm f}-1)} \rho_{\rm f,0} P_{\rm m,f}/P_{\rm f,0},$$

where $\gamma_{\rm f} = 1.23$ is the ratio of specific heats for acetylene, $c_{\rm f,0} = 337$ m/sec is the velocity of sound in acetylene at $T_0 = 290$ K, $P_{\rm f,0}$ is the initial pressure of acetylene in the receiver, and $P_{\rm m,f}$ is the pressure in the acetylene manifold. As the initial pressure of acetylene in the receiver and the cross-sectional area of the injectors in all experiments were unchanged, we determined only the maximum losses of the total pressure of the flow after the maximum pressure in the manifold was reached. By setting the experimental values of the quantities $G_{\rm f} = 22$ g/sec, $P_{\rm f,0} = 3.5 \cdot 10^5$ Pa, and $P_{\rm m,f} = 2.92 \cdot 10^5$ Pa, we obtain $\Delta P_{\varsigma,\rm f} = 1.5 \cdot 10^5$ Pa and $\Delta P_{\lambda,\rm f} = 0.15 \cdot 10^5$ Pa. The estimates show that the total pressure losses in the fuel injector reach more than half of the pressure value in the manifold.

It seems of interest to consider the domain of existence of continuous spin detonation with TDWs as a function of the governing parameters: pressure in the oxidizer manifold $P_{\rm m,ox}$, pressure in the chamber $P_{\rm ch}$, and ambient pressure $P_{\rm a}$. Figure 5 shows the experimental results for regimes with transverse detonation waves in chamber A and in chamber B in the coordinates $\pi_{\rm m,ch} = P_{\rm m,ox}/P_{\rm ch}$ and $\pi_{m,a} = P_{\rm m,ox}/P_{\rm a}$. The same figure also shows the data of [4] for continuous detonation in a subsonic flow of an acetylene–oxygen mixture occupying the entire cross section of a cylindrical chamber. It is seen that the domain of continuous detonation in chamber A is located in two subdomains separated by the straight line $P_{\rm ch} = P_{\rm a}$ (solid line): domain I ($P_{\rm ch} > P_{\rm a}$) and domain II ($P_{\rm ch} < P_{\rm a}$). The domain of TDW existence in chamber B is smaller and is located in domain I only. To analyze the results obtained, it is convenient to identify a subdomain of subsonic exhaustion of oxygen from the annular slot ($1 < \pi_{\rm m,ch} < 1.89$): domain III. It follows from Fig. 5 that spin detonation is observed in domain III with decreasing pressure ratio $\pi_{\rm m,ch}$; if both parameters $\pi_{\rm m,ch}$

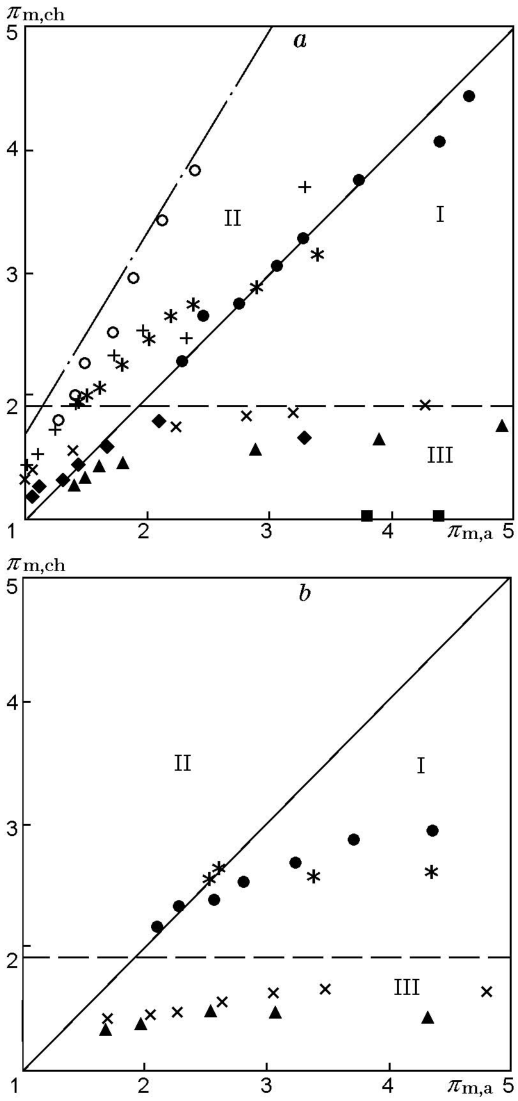

Fig. 5. Domain of existence of continuous spin detonation with TDWs in chambers A (a) and B (b) for $P_{\rm a,0} = 1 \cdot 10^5$ Pa and $\delta = 0.275$ mm (points ∘), $P_{\rm a} = P_{\rm a,0} = 1 \cdot 10^5$ Pa and $\delta = 0.275$ mm (points +), $P_{\rm a,0} = 0.2 \cdot 10^5$ Pa and $\delta = 0.275$ (•), 0.5 (∗), 0.75 (×), 1.25 (▲), and 2.5 mm ( ), and $P_{\rm a,0} = 0.2 \cdot 10^5$ Pa and $\delta = 5$ mm (points ■) [4].

and $\pi_{\rm m,a}$ decrease, detonation tends to the limit of its existence: to the left bottom "corner" whose apex is located in the vicinity of the unity. In chamber A, it was possible to obtain detonation regimes with the pressure ratio in the slot reduced to $\pi_{\rm m,ch} = 1.2$; the TDW velocity was $D = 1200$–1300 m/sec. This means that the straight line $\pi_{\rm m,ch} = 1.2$ defines the lower boundary of the corner sector of the domain of TDW existence. In our experiments, the ultimate decrease in pressure in chamber A with detonation was $P_{\rm ch} = 0.61 P_{\rm a}$. Therefore, the curve $P_{\rm ch} = 0.61 P_{\rm a}$ (dot-and-dashed curve in domain II; Fig. 5a) defines the left boundary of the corner sector of the domain of TDW existence. In the experiment with exhaustion of the products into a volume with an initial ambient pressure $P_{\rm a,0} = 1 \cdot 10^5$ Pa, the pressure $P_{\rm ch} = 0.7 P_{\rm a}$ was established in the chamber after the detonation passed to the turbulent combustion mode. This means that the domain of turbulent combustion is narrower than the domain of TDW existence. The "peculiarity" of this experimental fact can be explained by the specific features of the flow in the domain of transverse detonation waves and by a special role of the rarefaction wave behind the detonation front, which provides a detonation-capable layer of the mixture at a lower mean pressure in the chamber.

Thus, the domain of existence of detonation regimes in chamber A extends to infinity on the right (vacuum operation conditions in the chamber) for a fixed value $\pi_{\rm m,ch} \geqslant 1.2$ and up to the intersection with the left boundary of the domain of TDW existence ($P_{\rm ch} = 0.61 P_{\rm a}$) for a fixed value of $\pi_{\rm m,a}$. In chamber B, the domain of TDW existence is located inside domain I, and the detonation limit is located in the "corner" with the apex at $\pi_{\rm m,ch} \approx 1.27$ and $\pi_{\rm m,a} \approx 1.6$. Burnout of the mixture in the turbulent flame front increases in the vicinity of the "corner" apex, and detonation waves are attenuated and degenerate into acoustic waves. An increase in flow rates of the components by increasing the injection pressure with an unchanged chamber geometry is favorable for the detonation regime, because the ratio $\pi_{\rm m,ch}$ remains unchanged with accuracy to losses in the system, and the ratio $\pi_{\rm m,a}$ increases, thus, decreasing the effect of the ambient pressure on the process in the chamber.

In a subsonic oxidizer flow occupying the entire cross section of the chamber [4], the value of $\pi_{\rm m,ch}$ is close to unity, because the pressure $P_{\rm m,ox}$ differs from $P_{\rm ch}$ by the value of the dynamic component of pressure of the oxygen flow, which does not exceed 1% of $P_{\rm m,ox}$ if the flow velocity is subsonic (≈25 m/sec). In this case, the chamber diameter should be sufficient for formation of the detonation-capable layer of the mixture and transverse detonation waves. Otherwise, pulsed detonation or turbulent combustion modes are observed, which correspond to $\pi_{\rm m,ch} \approx 1$.

It should be noted that there are limits of spin detonation in terms of the absolute value of pressure in the chamber, which depend on the chemical activity of the mixture, method of injection and quality of mixing of the components, geometry of the chamber, and ambient pressure. Figure 6 shows the velocity of spin detonation of an acetylene–oxygen mixture as a function of pressure in the combustor and of the number of TDWs in chamber A and in chamber B. This figure also shows

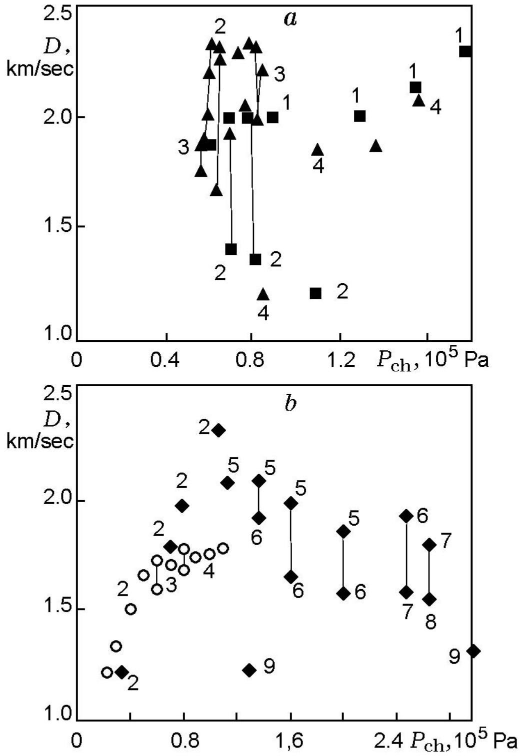

Fig. 6. Domain of existence of continuous spin detonation with TDWs in terms of pressure in chambers A (a) and B (b): (a) points ▲ and ■ refer to $L_\mathrm{f} = 1$ and 50 mm, respectively; (b) points and ○ refer to chamber of an air-breathing engine and chamber of the LRM-type engine [18], respectively; the numbers at the points indicate the values of n.

the data of [18] for an annular cylindrical chamber with a diameter $d_\mathrm{ch} = 40$ mm of the LRM type with the oxidizer and fuel fed through injectors and good mixing of the components.

The detonation processes in chamber A involved a smaller number of transverse detonation waves than those in chamber B, but the waves in chamber A were stronger. Apparently, the reason is that the velocity of turbulent combustion is lower in the chamber with an expanding cross section of the annular channel because of an elevated pressure gradient behind the TDW front, and a greater amount of the mixture is retained for detonation. It is seen from Fig. 6a that the TDW velocity drastically increases as the number of waves decreases, because a greater amount of the pre-mixed mixture remaining from the previous burning of the mixture enters the front of each TDW. The case without the ambient pressure (upper points $n = 2$ and 3) ensured a higher velocity of continuous detonation. This case also corresponds to two upper points that refer to fuel injection into a subsonic oxygen flow ($L_\mathrm{f} = 50$ mm). The experiments were performed at $P_\mathrm{ch} = (0.6\text{–}1.6) \cdot 10^5$ Pa; hence, the limits of detonation in terms of pressure in the chamber were not identified. The parameters of detonation for chamber A with the distance between the end face of the chamber and the acetylene injector $L_\mathrm{f} = 50$ mm are lower than those for $L_\mathrm{f} = 1$ mm because of the worse mixing of the components. The lower limit in terms of pressure was $P_\mathrm{ch,min} = 0.6 \cdot 10^5$ Pa, and the upper limit could not be reached because of the limited capabilities of the setup.

More complete information on the limits of spin detonation in terms of pressure in the chamber was obtained in chamber B. It is seen from Fig. 6b that there are lower ($P_\mathrm{ch,min}$) and upper ($P_\mathrm{ch,max}$) limits with the spin detonation velocity tending to 1200–1300 m/sec when reaching these limits. The data in the left part of the figure (pressure ratio $P_\mathrm{ch}/P_\mathrm{a} > \pi_\mathrm{cr} \approx 1.85$) refer to the case where two transverse detonation waves decreased their velocities and simultaneously ceased to exist as the pressure was reduced to $P_\mathrm{ch,min} \approx 0.3 \cdot 10^5$ Pa, but the flow regime was not changed to turbulent combustion. Hence, $P_\mathrm{ch,min}$ for detonation can be not lower than that for turbulent combustion. The lower limit in terms of pressure is caused by a strong increase in ignition delays of the mixture behind a decaying leading shock front. Note, under the influence of the ambient pressure on the detonation process ($P_\mathrm{ch}/P_\mathrm{a} < \pi_\mathrm{cr}$), the pressure was $P_\mathrm{ch,min} > 0.3 \cdot 10^5$ Pa because of the preliminary burnout of the mixture ahead of the wave. In the case of a single-wave mode, detonation breakdown can occur at pressures in the chamber higher than the lower limit if the wave structure and the flow in its vicinity are greater than the size of the annular channel. This is the factor determining the minimum diameter of the chamber, $d_\mathrm{ch,min} = (2\text{–}3)h_*$, whose value is inversely proportional to the pressure in the chamber, as is seen from this relation.

In contrast to the usual multifront detonation of mixtures [13], continuous spin detonation has also (at $P_\mathrm{ch}/P_\mathrm{a} > \pi_\mathrm{cr}$) the upper limit in terms of the pressure $P_\mathrm{ch,max}$ (see Fig. 6b). It is caused by more intense burnout of the mixture in the combustion front and by reduction of the size of the mixing layer of the propellant components. With increasing pressure, the number of transverse detonation waves in the annular channel increased (in our case, up to $n = 9$), their intensity decreased, and the waves degenerated into acoustic waves on the background of turbulent combustion. The most intense TDWs were observed in the range $P_\mathrm{c} = (1\text{–}1.5) \cdot 10^5$ Pa (the maximum value $D = 2350$ m/sec was obtained for $n = 2$). The TDW velocity increased in a jumplike manner as the number of waves decreased: a greater amount of the pre-mixed mixture that did not experience the preliminary burnout entered the TDW front.

A comparison of the dependences $D(P_{\rm ch})$ for chamber B and for the LRM-type chamber shows that the velocity of continuous detonation in the LRM-type chamber is lower far from the limit in terms of pressure in the chamber. This suggests an unexpected conclusion: effective detonation combustion of a chemically active fuel does not require good mixing of the propellant components in a immediate vicinity of the injectors, because preliminary burnout of the mixture formed should be avoided. This means that there is an optimal mixing process for each fuel. This conclusion agrees with the results of experiments on continuous spin detonation of a gas–droplet mixture of the components H_2 (gas) and O_2 (liquid) in an annular cylindrical chamber of the LRM type: detonation is not observed if mixing occurs in the wake of small oxygen droplets [19].

CONCLUSIONS

For chamber A with an expanding cross section of the annular channel, we obtain:

• In the range of ambient pressures (0.06–1.6) $\times 10^5$ Pa, stable controllable regimes of combustion of acetylene–oxygen mixtures in spin detonation waves at supercritical and subcritical (by a factor of ≈1.2) ratios of oxygen pressure in the annular slot were obtained. In the latter case, the processes in the chamber have a significant effect on the entire flow in the injection system;

• Strong transverse detonation waves can continuously exist if the annular slot width is smaller than half of the open cross section of the combustor; in this case, according to the estimates performed, the losses of the total pressure of the flow in the oxidizer slot decrease to 1%;

• Self-tuning of the detonation-combustion mode to a constant pressure in chamber A was observed;

• The process of continuous spin detonation can proceed at a pressure in the chamber lower than the ambient pressure;

• By varying the pressure of oxygen injection into the chamber and the ambient pressure, the domain of existence of continuous detonation with transverse detonation waves was determined, which was found to be greater in chamber A than in chamber B with the same flow rates of the propellant components.

For chamber B, the lower and upper limits of existence of continuous spin detonation in terms of pressure in the chamber were found; the lower limit is caused by breakdown of the chemical reaction behind the leading shock front, and the upper limit is caused by intensification of turbulent combustion ahead of the TDW front.

For chambers of both types, an adverse effect of the ambient pressure on TDW intensity was found near the limits of existence.

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