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Continuous Spin Detonations

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Results on controlled continuous spin detonation of various fuels in liquid-propellant rocket motors and ramjet combustors are reported. Schemes of chambers, combustion in transverse detonation waves, and typical photographic records of transverse detonation waves are given. The flow structure, existence conditions, and basic properties of continuous detonation are considered. An analysis of physical, chemical, and geometric parameters determining spin detonation is presented. Results of studying continuous spin detonation of $C_2H_2 + \mathrm{air}$ and $H_2 + \mathrm{air}$ mixtures in an annular ducted chamber 30.6 cm in diameter are reported. The range of existence of continuous spin detonation in fuel-air mixtures is determined as a function of the governing parameters. In the case of high-quality mixing, the transverse detonation wave velocity and structure are extremely stable in a wide range of the ratios of propellant components and in the examined range of pressures in the chamber.

Nomenclature

a	=	size (width) of the self-excited cell of the detonation front
c	=	velocity of sound
D	=	transverse detonation wave velocity
$D_{\text{C-J}}$	=	velocity of ideal Chapman–Jouguet detonation
d	=	mean diameter of the annular channel, $d = d_c - \Delta$
d_c	=	diameter of the outer wall of the chamber
$(d_c)_{\min}$	=	minimum diameter of the chamber
f	=	frequency, kHz
G	=	total flow rate of the mixture
g	=	specific flow rate of the mixture
h	=	height of the combustible mixture layer
$h*$	=	critical height of the combustible mixture layer
I_{sp}	=	specific impulse
J	=	enthalpy
L	=	length of the chamber
L_f	=	distance from the end of the chamber to the fuel injector
$L_{\min}$	=	minimum length of the chamber
L_{opt}	=	optimal length of the chamber
l	=	distance between the neighboring transverse detonation waves
M_z	=	Mach number, v/c
n	=	number of transverse detonation waves
p	=	pressure
p_a	=	ambient pressure (counterpressure)
p_c	=	static pressure in the chamber near the end wall
q	=	absolute value of the flow-velocity vector
S_c	=	cross-sectional area of the annular cylindrical chamber, $\pi(d_c - \Delta) \cdot \Delta$
u	=	x component of the velocity vector
v	=	z component of the velocity vector
x	=	coordinate counted along the midcircumference of the chamber
z	=	coordinate aligned with the chamber centerline
α	=	p_x/p_z
γ	=	specific heat ratio
Δ	=	distance between the walls of the annular channel

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Δ^* = minimum distance between the walls of the annular channel of the chamber
δ = width of the annular slot
θ = angle of inclination of streamlines to the x axis
λ = total length of the reaction zone
π = pressure difference in the injectors
ρ = density
τ_d = duration of the process
ϕ = stoichiometric ratio
φ = angle of downstream expansion of the chamber

Subscripts

C − J = Chapman–Jouguet
f = fuel
m = parameters in the manifold
ox = oxidant
0 = stagnation parameters
1 = mixture upstream of the detonation-wave front
2 = mixture downstream of the detonation-wave front

I. Introduction

THE method of detonation burning of fuels is currently considered as an alternative for traditional burning of fuels. It allows more intense, more thermodynamically beneficial, and more stable burning of various fuels in smaller chambers, the size of which is determined by the characteristic scale of the detonation-wave front. Researchers have analyzed the use of detonation in combustors of liquid-propellant rocket motors (LRM), ramjets, and pulsed detonation engines (PDE). A detailed review on recent accomplishments in basic and applied research on pulse detonation engines (PDE) and various PDE design concepts was performed by Roy et al. [1]. Only the problems of the continuous regime of detonation are considered in the present paper. The term *continuous* means here that detonation proceeds as long as the fuel components are fed and the reaction products are removed.

Zel'dovich [2] was the first to consider the theoretical problem of the detonation method of fuel combustion. He showed that the detonation regime of combustion under identical initial conditions is more beneficial than deflagration because the reaction products have lower entropy in the case of detonation. The first experimental investigations in this field appeared 20 years after Zeldovich's paper [3–9]. These papers dealt with continuous detonation combustion, where there were no restrictions on the time of combustor filling by the fuel mixture. The works were performed in two directions. Some investigators tried to reverse the process and obtain a stable detonation wave in a supersonic incoming flow. Implementation of this regime was of practical and fundamental scientific interest for more convenient investigations of the flow structure in the detonation wave. Because of ignition of the mixture on the walls of the supersonic nozzle, however, the stationary regime could be obtained only for very lean mixtures.

Nicholls et al. [3] performed fuel burning in steady shock waves generated by a supersonic jet entering the atmosphere. In these experiments, the fuel was injected to the center of a supersonic oxygen jet to prevent premature ignition. Dunlap et al. [4], Gross [5], and Gross and Chinitz [6] performed similar experiments with detonation burning of the mixture in shock waves in the Mach configuration formed on the wedge in the supersonic part of the wind tunnel. As in previous investigations, the combustible mixture was rather lean, and fuel was injected in the subcritical section of the wind tunnel. Because the temperature behind the steady shock waves was lower than the temperature of self-ignition, the reaction behind these shock waves was due to transport phenomena. Soloukhin [7,8] and Bazhenova and Soloukhin [9] ensured combustion of a supersonic jet in a pulse shock originating upstream of a blunt body. He selected a combustible mixture with a large ignition delay to prevent premature burnout of the channel walls. The development of supersonic aviation stimulated investigations of supersonic combustion in chambers of hypersonic ramjets [10–12]. According to calculations, in specific cases, detonation burning has some advantages over deflagration [12].

Voitsekhovskii [13,14] proposed an alternative method of implementation of continuous detonation combustion. He used an analogy with the process of mixture burning in a running wave in the case of spin detonation in a circular tube [15], where the spin moves along the leading shock front, following a helical trajectory with respect to the tube, and burns the shock-compressed mixture. The leading shock front was replaced by a wall impermeable for detonation; the combustible mixture was injected through a slot in this wall. Combustion of the mixture occurred in a transverse detonation wave (TDW) moving perpendicularly to the main direction of the mixture and combustion products. Mixture renewal occurred behind the TDW front. The continuous detonation process was called by Voitsekhovskii the "steady spin detonation" or "continuous spin detonation" (CSD).

The first chamber wherein Voitsekhovskii [13,14] realized the continuous process of detonation burning of premixed acetylene–oxygen mixtures comprises a plane annular channel. The mixture was supplied through a narrow slot, and reaction products were ejected through a wider outer gap. The transverse detonation wave propagated normally to the incoming mixture inside the channel, and the TDW velocity along the channel was close to the velocity of sound in reaction products. An effective method of registration of the TDW structure was used in these experiments. It was used earlier in studying the detonation spin structure in circular tubes [15,16]. This was the so-called velocity-compensation method when the film velocity is equal to that of image displacement in magnitude and direction. A triangular glowing region without visible shock-detonation fronts was recorded for the continuous detonation (CD) process in a plane annular channel. The assumed flow structures in the channel were obtained; the combustion zone was placed behind the oblique shock wave. Investigations of the process of continuous detonation in plane annular channels were continued by Mikhailov and Topchiyan [17]. They also obtained transonic regimes. They measured the pressure profiles in transverse waves by high-frequency transducers made of barium titanate. The optical record performed by the velocity-compensation method showed only the luminescent triangular area without visible compression shocks. The wave structure was not resolved completely in these papers.

Continuous detonation combustion of ethylene in a tubular annular channel with ejection through an annular slot was obtained by Edwards [18]. The wave velocities in his experiments were close to acoustic ones in combustion products. The wave structure was not resolved optically. An important result was the measurement of pressure jumps in the TDW front, which exceeded the initial pressure by a factor of 2 to 8. In theoretical works by Shen and Adamson [19] and Adamson and Olsson [20], all detonation parameters for a cylindrical chamber with a constricted outlet were calculated on the basis of a two-dimensional steady model. The TDW front occupied the whole length of the chamber in the first work and only the area adjoining to the mixture-injection zone in the second work. The condition of sonic exhaustion assumed in these models did not permit any advantages of spin detonation to be realized in those chambers in comparison with conventional combustion. Moreover, in the first model, part of the fuel was ejected from the chamber to the atmosphere before combustion started. Note that phenomena similar to the continuous detonation process were registered in the case of high-frequency instability in liquid-propellant jet engines [21–23]. There are several U.S. patents on the use of CD processes in rocket engines and in power plants [24–26].

The present paper summarizes the results of the continuous spin detonation investigations performed by Mitrofanov with the group of investigators [27–41] at the Lavrentyev Institute of Hydrodynamics. The goal of these investigations was to obtain and investigate continuous detonation combustion of a variety of fuels to be used in engines and power plants.

Regimes of continuous detonation burning of almost all widely known fuels have been obtained in chambers with different geometries: annular cylindrical chamber (Fig. 1a), annular chamber

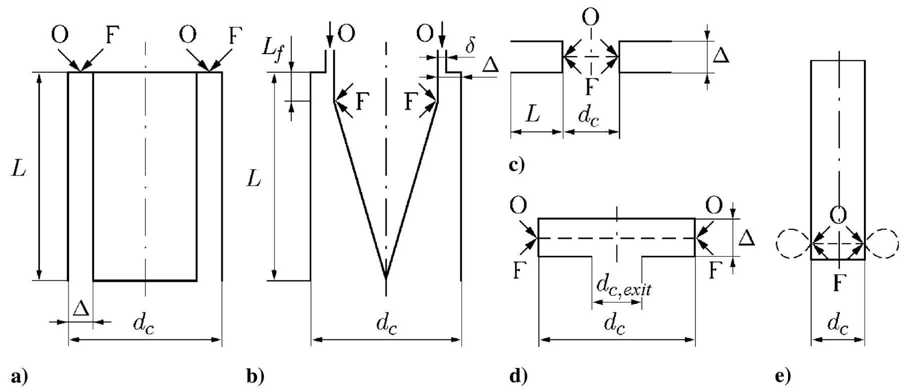


Fig. 1 Schemes of detonation-combustion chambers.

with channel expansion (Fig. 1b), and plane-radial chamber with expansion of combustion products toward the periphery (Fig. 1c) and toward the center (Fig. 1d); detonation burning of fuels was also obtained in an annular region in space without walls (Fig. 1e). The oxidant was gaseous oxygen and, in some cases, liquid oxygen or air. The main conditions providing the existence of a flow with a transverse detonation wave in test chambers were found experimentally and theoretically. A Russian patent on the fuel combustion method was obtained [42]. For optical record of the process, a special photorecorder that allows one to resolve the microsecond-range processes in TDWs for a long time (up to 1 s) was developed [43].

II. Continuous Spin Detonation in Rocket-Type Combustion Chambers

Regimes of continuous detonation burning of gaseous, two-phase, and liquid fuels with TDWs in chambers of annular cylindrical geometry are best examined [27–30,38]. All chambers had collectors, one for the fuel and the other one for the oxidant. The manifolds had connections with the chamber cavity by series of small injector holes uniformly distributed over the circumference. For detonation initiation, all chambers had an electrical bushing, and it was possible to have a high-voltage breakdown or to set an exploding wire or a detonator with an explosive. For optical registration of the process, all chambers had narrow and long windows made of Plexiglas®. The direction of wave rotation was defined by a certain predetermined orientation of the initiating channel.

Figure 2a shows a schematic of the continuous spin detonation process. In rocket-type chambers with a front end face, the initial components of fuel and oxidizer 1 are injected separately into the annular duct 2 through a row of orifices uniformly distributed over the end face of the chamber. At a certain distance from the end face, the components are mixed, and one or several TDWs 4 propagate (in the crossflow direction) over the mixture 3 being formed. The number of TDWs increases with an increase in some parameters, such as the chemical activity and degree of mixing of the components and also the chamber diameter (two TDWs are shown in this figure). Behind the TDW front, in the rarefaction wave adjacent to the Chapman–Jouguet surface, the chamber is continuously filled by new components with an adjacent TDW (or the same wave in the one-wave mode) propagating over the mixture of the fresh products. A tail 7 is adjacent to the detonation front; the tail is an oblique shock wave formed when the products 5 flow around a high-pressure region behind the front 4. The detonation products are ejected through the open end of the chamber. The products 8 can also penetrate into the injection system from the high-pressure region behind the front 4. The detonation products 5 are separated from the mixing zone 3 by a contact discontinuity 6 transformed into the combustion front.

A series of typical photographic records of continuous spin detonation are shown in Figs. 2b–2d for propane–gaseous oxygen, acetone–gaseous oxygen, and kerosene–liquid oxygen, respectively. The parameters of detonation regimes for these fuel–oxygen mixtures (FOM) are listed in Table 1.

The TDWs and the flow in their vicinity were recorded onto a film through the longitudinal window of the chamber by the method of velocity compensation [15]. The structure of shock waves is registered in an undistorted form, and the flow in the wave vicinity corresponds to the flow in the wave-fitted system. Incomplete compensation of film and image velocities by ±20% has practically no effect on the quality of photographic records. The slopes of the waves and product trajectories, however, become different; if necessary, they have to be recalculated to the case with complete compensation. In computer processing of the records, this operation can be performed by changing the scale of the photographs. In the photographs, the bright narrow band near the upper butt-end face of the chamber is the transverse detonation front, the bright boundary branching from the front is the tail, and the glowing lines are the trajectories of detonation products. All photographs correspond to the one-wave mode, that is, they show the same wave periodically passing through the longitudinal window. It can be easily seen that the TDW structure resembles the spin structure [15] in circular tubes, but it has no leading front, which is replaced by the wall. All waves

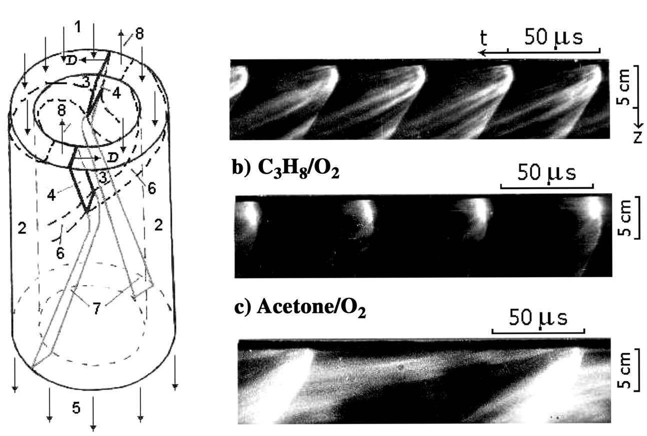


Fig. 2 Diagram and typical pictures of a TDW.

Table 1 Parameters of detonation regimes of the FOM

Fuel	C_3H_8/O_2 (gas)	Acetone/O_2 (gas)	Kerosene/O_2 (liquid)	
d_c, mm	40	40	100	280
L, mm	95	95	100	60
Δ, mm	5	10	10	10
$p_c \cdot 10^{-5}$, Pa	2.25	3	12	26
p_m/p_c	3	4	4.1	2.4
G, kg/s	0.077	0.1	2.0	12.3
ϕ	1.0	0.92	1.22	0.95
n	1	1	1	1
D, km/s	2.27	2.0	2.46	2.2
$D/D_{C\text{-}J}$	0.94	0.8	0.95	0.85

moved in the same direction visible in the photographic records. The spinning direction did not change during the entire experiments. In some cases, however, the waves started moving in the opposite direction, and this was observed not only after initiation but also during the process. The time needed for changes in the number of waves or in the spinning direction is rather short: only several revolutions of the wave.

It is seen from Table 1 that the TDW velocity is lower than the velocity of the ideal Chapman–Jouguet detonation because of partial mixing of the propellant components and their outburning [29] and also because of the loss of momentum of detonation products due to TDW front bending [44]. As the chamber diameter increases, the value of p_m/p_c at which stable TDWs are formed decreases (see the last column in Table 1). In some experiments, TDWs were observed at $p_m/p_c = 1.1$.

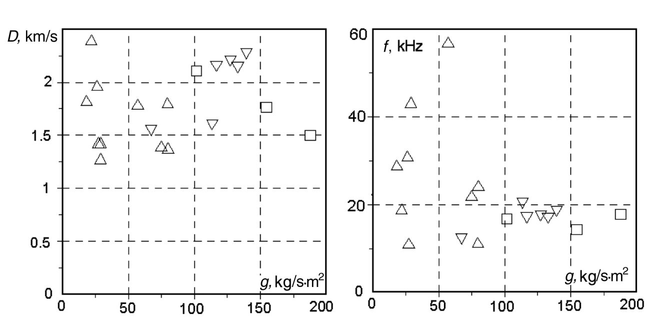
A. Gaseous Components

Continuous spin detonation was experimentally studied [27,28] with injection of gaseous components of the fuel and oxidizer into the combustion chamber for three gas mixtures: C_2H_2–O_2, C_3H_8–O_2, and CH_4–O_2. The geometric parameters of the cylindrical chamber were varied: $d_c = 40$ and 100 mm, $L \in (20–100)$ mm, and $\Delta \in (2.5–10)$ mm. The following parameters were also varied: the flow rate of the mixture $G \in (0.01–0.2)$ kg/s, the fuel-to-oxygen equivalence ratio $\phi \in (0.85–9)$, and the type of the fuel injector. The structure of the chamber and the system of injection of components allowed us to change the specific flow rate of the combustible mixture $g = G/S_c = (18–188)$ kg/s · m^2. The experimental values of D (km/s) and f (kHz) are plotted in Fig. 3 as functions of the specific flow rate of the mixture. The spin detonation velocity varied in the range of $D \in (1.2–2.4)$ km/s; $n \in (1–4)$; $p_c \in (0.12–4) \cdot 10^5$ Pa.

In the case of combustor operation in the continuous spin detonation mode (CD regime), there are no low-frequency vibrations (below 100 Hz). Indeed, the chamber operating in the CD regime radiates the sound of frequency $f = D/l = D \cdot n/(\pi d_c)$. The experimental results allow us to determine the range of frequencies of pressure oscillations in the chamber f for the continuous spin detonation mode. The corresponding data are shown in Fig. 3b. It is seen that the CD regime for gaseous hydrocarbon–oxygen mixtures is a high-frequency mode with an operating frequency range $f = 10–50$ kHz.

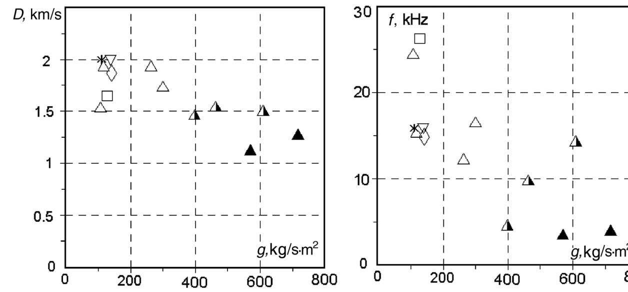
B. Two-Phase Components

Continuous spin detonation was observed [38] in chambers of annular cylindrical geometry for all liquid fuels being tested: kerosene, gasoline, benzene, ethyl alcohol, acetone, and diesel fuel, if oxygen was used as an oxidizer. The geometric parameters of the cylindrical chamber were varied: $d_c \in (40–100)$ mm, $L \in (1–2.5) \cdot d_c$, and $\Delta \in (10–15)$ mm. The following parameters were also varied: the flow rate of the mixture $G \in (0.1–2.9)$ kg/s, the fuel-to-oxygen equivalence ratio $\phi \in (0.8–1.7)$, and the type of the fuel injector. The specific flow rate of the two-phase mixture varied in the range $g \in (106–340)$ kg/s · m^2. The quantitative experimental data on D (km/s) and f (kHz) are plotted in Fig. 4 as functions of the specific flow rate of the two-phase mixture. The experiments with oxygen dilution by air were carried out in the chamber ($d_c = 100$ mm) with kerosene as a fuel. The initial pressure of the oxidizer in the receiver p_{ox} was varied in the interval of $(40–100) \cdot 10^5$ Pa. The wave parameters decreased with increasing nitrogen concentration. Stable detonation regimes could be obtained only if the nitrogen–oxygen volume ratio was not more than 50/50 (36/64 for the oxygen–air mixture) for the mean pressure in the chamber of about $8 \cdot 10^5$ Pa and for the specific flow rate increased to approximately 700 kg/s · m^2 (see Fig. 4).



a) TDW velocity b) Operation frequency

Fig. 3 Detonation parameters of the gas mixture.



a) TDW velocity b) Operation frequency

Fig. 4 Detonation parameters of the two-phase mixture.

C. TDW Structure

The generalized TDW structure and the flow in the TDW vicinity are shown in Fig. 5 in the wave-fixed coordinate system. The TDW structures for gaseous, two-phase, and liquid components do not have any principal differences. The line BC is the TDW. The system of coordinates rotates together with the TDW. The coordinate z is parallel to the chamber centerline, and the coordinate x is measured along the medium circumference of the chamber. The fuel components are injected through the orifices in the butt-end face of the chamber (plane $z = 0$). The detonation products behind the wave BC gradually expand and are entrained downstream by new portions of the fuel that enters the chamber on the segment AB' (the fuel ceases to enter the chamber on the segment BA because of the high counterpressure). The propellant mixture fills the region $AB'C'$. Some part of the combustion products from the previous wave can mix with the fresh mixture. The dashed curve AC' is not a streamline: this is the lower boundary of the mixing region. A streamline emanating from the point M on the front BC reaches the point C'. The vertical size of the region $AC'MB$ gradually decreases owing to mixing of the products and almost vanishes ahead of the next wave. An abrupt increase in pressure in the detonation front BC is accompanied by subsequent adiabatic expansion of the products and by an increase in their velocity. Lateral expansion of the products leads to appearance of the shock wave CN. The flowfield in the chamber is periodical in terms of x. The length of the period is $l = \pi d$ if there is only one TDW in the chamber and $l = \pi d/n$ if there are n TDWs simultaneously. The periodicity of the flow is clearly visible in the photographic records of the process (see Fig. 2). Figure 5 schematically shows a one-and-a-half period of the flow. The wave

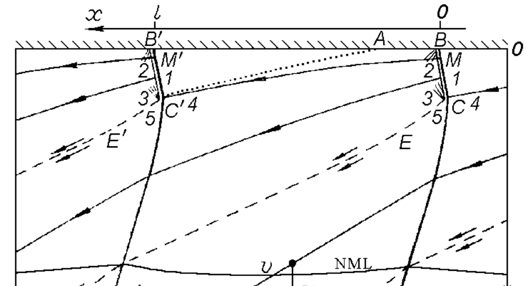


Fig. 5 TDW structure and flow picture in the coordinate system of a wave.

$B'C'N'$ is identical to the wave BCN here. This is either the same wave after full rotation if $n = 1$ or two waves following one another if $n > 1$.

With free exhaustion of the products from the open end of the chamber, the shock wave CN observed in the upper part of the chamber is either approximately vertical or slightly inclined backward (to the left), as in Fig. 5. With increasing z, its inclination increases and intensity decreases. Adjustment of the flow behind the transverse wave and the wave CN in the vicinity of the conjugate point C occurs through a centralized rarefaction wave. The initial slope of the shock wave CN is calculated from the condition of equality of pressure and flow direction along the contact discontinuity CE.

D. Influence of Physical, Chemical, and Geometric Parameters on the CD Process

The main features that make the CD process distinct from conventional spin and multiheaded detonation in tubes are as follows:

1) The mixture ahead of the TDW is not exposed to preliminary heating in the normal shock, but its temperature is increased by adding part of the combustion products remaining from the previous wave or formed as a result of the burning of the fresh mixture in zones of contact with the old combustion products and heated walls.

2) The mixture ahead of the TDW is mixed nonideally because it forms in the same chamber during the relatively short period of time between the successive passes of TDWs.

3) The TDW affects the upstream state of the mixture because this state is formed by interaction of the new mixture entering the chamber and detonation products of the previous cycle of the same TDW or another identical TDW moving ahead of any considered wave.

4) Because of high (though short) pressure peaks in the TDW, the latter can exert a reverse action on the fuel- and oxidizer-injection systems. In particular, injection of the products through injector orifices into manifolds can occur. This effect is particularly pronounced in the case of subsonic exhaustion of fuel components from the injectors.

5) Steady TDWs propagate only in closed ring channels with an identical direction of TDW rotation.

The governing factor in obtaining an effective CD regime belongs to mixing in the region of TDW propagation. The gaseous components of the fuel mixture should be mixed at the molecular level, and the liquid components should be preliminary fractured so the mixture at the molecular level could be obtained in the reaction zone of reaction. The nonmixed fraction of fuel components behaves as an inert additive and decreases the detonation parameters.

The necessary condition for CD implementation is the continuous renewal of the layer of the combustible mixture ahead of the TDW front. The height of this layer h should be not smaller than the critical value h^* for detonation. Fine dispersion of liquid jets and rapid mixing of the components of the combustible mixture reduce the value of h^* and make it possible to reach the CD mode in smaller chambers. The minimum size of the chambers will be estimated later in the paper.

Let us cite some additional data on the influence of various parameters on the CD process. A twofold, threefold, etc., increase in the minimum chamber diameter increases the number of TDWs by the same factor. In the steady process, we have $h^* \leq h < 2h^*$. A change in L in annular cylindrical chambers within certain limits has a weak effect on the detonation process. A too large increase in L increases the boundary layer, which decreases the effective cross section of the channel; the total heat momentum losses on the walls increase. A decrease in L below the critical value leads to TDW instability because of the decrease in pressure ahead of the TDW. Moreover, the combustible mixture ahead of the TDW can partly flow outside without combustion. The experiments show that the value of L should be 1.5 to 2 times higher than h for obtaining stable TDWs. The minimal size of the chamber increases as the mixing quality decreases.

The minimum distance between the walls of the annular duct of the chamber Δ is several times greater than the critical values for detonation propagation Δ^*. Therefore, the value of Δ does not directly affect the TDW but affects only the initial pressure in the chamber and, to a certain extent, the quality of mixing of the components. For two-phase and liquid components, the value of Δ was chosen from the condition of minimization of liquid sedimentation on the walls. Constriction of the chamber exit partly retained the TDWs, but they were attenuated by simultaneous intensification of turbulent combustion upstream of the wave. Mounting of radial partitions in the chamber initiates wave reflections, which violates the formation of a constant-height detonation-capable layer of the mixture. As a result, only weak TDWs close to acoustic waves remain.

The influence of the ratio of components and methods of their injection was investigated. The maximum of the detonation velocity D lies in the range of stoichiometry. The maximum overfueling of the mixture by liquid fuel (well-sprayed kerosene) is $\phi = 3$ in the region of existence of relatively strong TDWs. The TDWs are still observed for liquid fuel with $\phi = 10$, but the TDW parameters decrease to the values of acoustic waves. The TDW parameters remain almost unchanged, however, if the tenfold excess fuel is injected into the products downstream of the TDW region. As in the case of detonation in tubes, there exists the lower limit of detonation in terms of the mean pressure or pressure ahead of the TDW p_1, which is 2 to 3 times lower than the mean pressure in the chamber p_c. The limits in terms of pressure for the TDW are higher than those for detonation waves in tubes, since there is no gas precompression in the shock wave and ideal mixing of the mixture ahead of the front is not provided.

Stable TDWs were seen to exist down to $p_f/p_c = 2$ and $p_{ox}/p_c = 3$. Lower values of $p_{f(ox)}/p_c$ corresponded to unstable regimes. The limiting ratio of pressures decreases to $p_f/p_c = 1.2$ and $p_{ox}/p_c = 1.2$ in some experiments as the chamber diameter increases.

The theoretical notion of continuous detonation and our experience suggest that TDWs are formed in the chamber if the mixture layer depth h is close to the critical (minimum) value needed for detonation propagation [15,28]. The critical value of h is related to the λ of the reaction zone in the detonation wave. Considering geometric conditions of TDW propagation in the chamber (rigid walls on three sides and only one free surface of the "charge"), an analysis of various approaches [45,46] establishing a required link provides the averaged relation

$$h \cong h^* \cong (17 \pm 7)\lambda \tag{1}$$

The value of λ is determined by the time of physical processes for formation of an explosive mixture (fragmentation of drops behind the leading shock wave, evaporation, diffusion, and turbulent mixing of fuel components) and by the subsequent time of the chemical reaction. If there are no physical processes (premixed gaseous mixture) or their time is relatively little, the characteristic chemical length of the zone can be approximated [15,47] as

$$\lambda \cong 0.7a \tag{2}$$

in terms of the width of the self-excited cell of the detonation front a. The value of a is easily measured experimentally in tubes and is already known for many mixtures; it can also be calculated by the known method [48] from the physicochemical data of the mixture. Integration of two established relations for gas mixtures yields

$$h \cong (12 \pm 5)a \tag{3}$$

The last formula correlates well with the experimental data obtained for gas mixtures when the detonation-cell size (based on the mean pressure in the chamber) of the concerned mixture is taken as a.

An important geometric parameter of the process under discussion is the relation

$$K = l/h = \pi d_c/nh \tag{4}$$

The experiment reveals that the value of K is roughly constant for all annular cylindrical chambers involving a gaseous oxidizer, namely, $K = 7 \pm 2$. For similar chambers with the use of a liquid oxidizer, the mean value of K is larger by a factor of 1.5–2.

Knowing K, for $n = 1$, we can estimate the minimum chamber diameter from Eq. (4):

$$(d_c)_{\min} = hK/\pi \tag{5}$$

because the value of h for the mixture of interest with a prescribed mean pressure in the chamber can also be estimated from the foregoing relations. For chambers operating on a gaseous oxidizer, we have $(d_c)_{\min} \cong 40\lambda$.

According to the analysis and numerical simulation of the flow in annular cylindrical chambers [33], the value of K coincident with experimental data corresponds to the mixture temperature of approximately 1000 K ahead of the TDW front. It immediately yields the following relations for the pressure ratios

$$p_2/p_1 \cong 10 \pm 4, \qquad p_2/p_c \cong 4 \pm 1 \tag{6}$$

where p_2 and p_1 are the pressures ahead of the TDW front and behind it, respectively.

The mean value of the exhaustion rate is independent of p_1 and is primarily determined by the values of p_2 and K. The value of p_2 is defined almost solely by thermodynamic data of the mixture and its specific mass flow rate through the chamber.

The minimum length of chambers is determined experimentally. It is approximated by the equations

$$L_{\min} \cong 2h \cong d_c/n \tag{7}$$

in which the foregoing formulas are also used. But the CD process existing under the condition $L < 3h$ is not quite efficient; it proceeds with incomplete combustion of fuel. The optimal length is two to three times greater than the minimum length:

$$L_{\text{opt}} \geq 4h \cong 0.7l \cong 2d_c/n \tag{8}$$

The minimum possible radial size Δ can be found from the expression

$$\Delta \geq \Delta^* \cong 0.2h \tag{9}$$

As for h, it is determined by the critical conditions of detonation propagation due to, in this particular case, the wall friction and heat losses of TDWs.

All chambers operating in the CD regime radiate the sound of frequency

$$f = D/l = D \cdot n/(\pi d_c) = D/(\pi d_c)_{\min} \tag{10}$$

Continuous spin detonation was obtained for all gaseous and liquid fuels being tested, provided that gaseous or liquid oxygen was used as an oxidizer. In most experiments, the CD-process duration was 0.1 to 0.3 s, being determined by the time of injection of fuel components into the chamber. The pressure in the chamber with TDWs varies with the TDW rotation frequency; its maximum values are attained in the TDW front, and they are three to five times higher than the mean pressure p_c, whereas the minimum pressure is two to three times lower than p_c.

To sustain the continuous spin detonation process in rocket-type chambers, the pressures of fuel and oxidizer injection (p_f and p_{ox}) have to exceed p_c by a factor of two to three. On diluting oxygen with nitrogen in the oxidizer channel, the region of TDW existence shrinks down, and the minimum size of the chamber increases.

E. Theoretical Analysis of Flow in the Cylindrical Chamber for the CD Process

The processes of continuous spin detonation in rocket-type chambers were extensively studied theoretically. Several physicomathematical models were developed, which allow one to calculate parameters of continuous detonation for chambers with constriction of the exit cross section [19,20] and without constriction [28,31–33].

An important thermodynamic feature of detonation as compared with conventional combustion is that the entropy increase is smaller for an identical heat release. For this reason, a large fraction of chemical energy of the fuel can be employed to perform mechanical work. Favorable possibilities for this arise in the case of burning of a fuel mixture by means of strong TDWs in an annular cylindrical chamber without outlet constriction. In this case, the yield is the work of expansion of detonation products, which is spent on increasing their kinetic energy and momentum. The maximum acceleration of detonation products is reached with isentropic expansion behind the TDW front. The exhaustion rate is supersonic at the end of a constant-section chamber, whereas it is known to be sonic in the one-dimensional process of conventional combustion.

Let us consider the flow in rocket-type chamber (d, Δ, and L) with the rotating detonation wave. Considering the flow in the annular chamber space to be two-dimensional and stationary with respect to the TDW, we use the flow pattern depicted in Fig. 5 and corresponding experimental data.

We will assume heat loss at the walls and friction to be negligible, with the state of the mixture ahead of and directly behind the transverse wave being homogeneous along the wave front. We further assume the entire gas to be ideal, with constant heat capacity ratio γ, that the chemical reaction is frozen at all points behind the wave, that the flow at large z is homogeneous. We will assume TDW to be a self-sustaining Chapman–Jouguet wave with instantaneous chemical reaction in the plane front.

These assumptions permit writing a first group of equations, relating the flow parameters in regions 1 and 2 (see Fig. 5) in the form of known relationships on the detonation front:

$$\begin{gathered}\rho_1 q_1 = \rho_2 q_2, \qquad p_1 + \rho_1 q_1^2 = p_2 + \rho_2 q_2^2, \qquad p_2 = \rho_2 q_2^2/\gamma \\ 2J_1 + q_1^2 = (\gamma+1)/(\gamma-1) q_2^2, \qquad J_1 = \gamma/(\gamma-1) p_1/\rho_1 + H_1 \\ \theta_1 = \theta_2\end{gathered} \tag{11}$$

The enthalpy J_1 includes the heat of formation of the mixture components H_1, with the reference level chosen so that in the state behind the wave $H_2 = 0$.

Region 2 behind the wave, where $q_2 = c_2$ in view of the Chapman–Jouguet condition, is the critical one for the stationary regime under consideration. The pressure p_2 is maximum with respect to all remaining points of the flow, and the flow outside region 2 is supersonic everywhere relative to the transverse detonation wave. Exceptions are the inner region (chemical spike region), which will not be analyzed, and possibly the small region 5 behind the oblique shock wave CN in the vicinity of the point C. The medium ahead of the transverse wave is a mixture of the fuel and oxidizer, the products of their possible combustion, and also the detonation products behind the preceding wave, which later dilutes the mixture, reducing the H_1.

Because of flow expansion behind the wave, the products can arrive in region 1 only from the upper zone of the preceding wave, denoted arbitrarily in Fig. 5 by the streamline MC'. The fraction of the mass flux through this zone as compared with the total mass flux is denoted by κ. In view of the periodicity of the process, this fraction can be considered as continually circulating in the transverse zone, and it enters the total mass flux through the transverse zone but does not appear in the fuel flow rate G entering the chamber in the z direction. The fuel flow rate G_1 for a single wave is then equal to the other part of the mass of material that passes through the wave below the streamline MC' per unit time:

$$G_1 = (1-\kappa) h \Delta \rho_1 q_1 = h_1 \Delta \rho_2 q_2 \tag{12}$$

Here h is the size of the transverse detonation wave; $h_1 = (1-\kappa)h$.

Along this boundary streamline MC', whose form is unknown in the general case, there occurs an interaction of the flow entering the wave with the "pure" detonation products of the preceding wave located below the flow. We introduce a notation of mean pressure forces acting between these flows in the corresponding directions, together with their ratio

$$p_z = (l - h_1 \sin\theta_1)^{-1} \int_{MC'} p(x,z)dx$$
$$p_x = (h_1 \cos\theta_1)^{-1} \int_{MC'} p(x,z)dz, \qquad \alpha = p_x/p_z \tag{13}$$

where integration is performed along the streamline MC' between two neighboring waves. Then, from the equations for the projections of momentum on the x and z axes,

$$D \cdot G_1/\Delta = (p_2 + \rho_2 q_2^2 - p_x)h_1 \cos\theta_1$$
$$p_c l + v_{0z} \cdot G_1/\Delta = (p_2 + \rho_2 q_2^2)h_1 \sin\theta_1 + p_z(l - h_1 \sin\theta_1)$$

after transformations, we obtain

$$D/q_2 = \gamma^{-1}[(\gamma+1) - p_x/p_2]\cos\theta_1$$
$$p_c/p_2 + \gamma(v_{0z} + q_2)h_1/l = (\gamma+1)h_1 \sin\theta_1 + (1 - h_1 \sin\theta_1/l)p_z/p_2 \tag{14}$$

where v_{0z} is the mean velocity of the original gases when drafted into the chamber. To find the projection of the mixture velocity relative to the walls ahead of the wave u_{1x}, we use the kinematics equation

$$D + u_{1x} = q_1 \cos\theta_1$$

from which, after dividing by q_2 and using Eqs. (1) and (4) , we find

$$u_{1x}/q_2 = (p_x/p_2 - p_1/p_2)/\gamma \cdot \cos\theta_1 \tag{15}$$

The energy flux through region 1 is written in the form

$$\rho_1 q_1 (J_1 + q_1^2/2)\Delta h = G_1(J_0 + D^2/2) + \kappa\rho_2 q_2 (J_2 + q_2^2/2)\Delta h$$

With consideration of Eqs. (11) and (12), we have

$$(2J_0 + D^2)/q_2^2 = (\gamma+1)/(\gamma-1) \tag{16}$$

Here J_0 is the total stagnation enthalpy of the entering mixture. Dilution of the flow ahead of the wave by burned-up products of the preceding wave does not change the form of the energy equation, due the stationary nature of the flow and its periodicity in x.

For model A, we further assume [28] that the exhaust velocity at the chamber section is sonic

$$v = c \tag{17}$$

At condition [Eq. (17)], the stationary flow parameters in the chamber exit section, the pressure, and the specific impulse are independent of the internal flow in the chamber and are completely determined by the parameters of the injected gas and the geometry by means of the equations

$$v = q \cdot \sin\theta = [2(\gamma-1)J_0/(\gamma+1)]^{1/2}, \qquad \rho = g/v$$
$$p = gv/\gamma, \qquad p_c = g(v(\gamma+1)/\gamma - v_{0z})$$
$$I_{sp}^* = (p + \rho v^2)/g = 1/\gamma[2(\gamma^2-1)J_0]^{1/2}$$

From these relations we can see that for model Eqs. (11–17) the I_{sp}^* be so for usual combustion, because the detonation character of the transformation was taken into account only in the analysis of the internal structure of the flow in the chamber. Here $g = G_1/\Delta l$ is the specific flow rate of the fuel.

For model B, we add [33] to Eqs. (11–16) the isentropic nature of the expansion of the products of detonation downstream from the TDW

$$p/p_2 = (\rho/\rho_2)^\gamma \tag{18}$$

Then the stationary flow parameters in the chamber exit section q, p, ρ, and θ (quantities without numerical subscripts) are determined by means of the equations

$$g = \rho q \cdot \sin\theta, \qquad (p_2 + \rho_2 q_2^2 - p_x)\eta\cos\theta_1 = g \cdot q \cdot \cos\theta$$
$$(p_2 + \rho_2 q_2^2)\eta \sin\theta_1 + p_z(1 - \eta\sin\theta_1) = p + gq \cdot \sin\theta$$
$$2\gamma/(\gamma-1)p_2/\rho_2 + q_2^2 = 2\gamma/(\gamma-1)p/\rho + q^2$$
$$p/p_2 = (\rho/\rho_2)^\gamma \tag{19}$$

Here $\eta = h_1/l$. Excepting in the system Eq. (19) q, p, and θ we obtain the equation for dimensionless density $\beta = \rho/\rho_2$

$$\alpha[\beta^\gamma + \gamma\eta^2/\beta - (\gamma+1)\eta\sin\theta_1] = (1 - \eta\sin\theta_1)\{\gamma + 1 - \gamma \times [(\gamma + 1 - 2\beta^{\gamma-1})/(\gamma-1) - \eta^2/\beta^2]^{1/2}/\cos\theta_1\} \tag{20}$$

after its solution, subsequently calculating all the remaining quantities in the exit section of the chamber

$$p/p_2 = \beta^\gamma, \qquad q/q_2 = [(\gamma + 1 - 2\beta^{g-1})/(\gamma-1)]^{1/2}$$
$$\sin\theta = \eta(q_2/q)/\beta, \qquad I_{sp} = (p + \rho q^2 \sin^2\theta)/g \tag{21}$$
$$\Delta I = I_{sp} - I_{sp}^*$$

The parameters η, α, and θ_1 are chosen from some additional considerations [28]. Here I_{sp} and I_{sp}^* are the specific impulses of the chamber in vacuum at considered regime of work and in regular one-dimensional regime, correspondingly.

Some results of calculations in which the quantities η, α, $\sin\theta_1$, and γ were treated as parameters subject to variation are shown in Table 2. Here $M_z = v/c = q \cdot \sin\theta/c$ is the Mach number and the quantities without numerical subscripts correspond to a uniform flux at the end of the chamber.

The data presented in Table 2 show that the outflow of the detonation products is supersonic for all variants. Simultaneously, I_{sp} is more than for regular combustion in the same chamber without nozzle at the regular pressure. For a considered model, flow advantage in specific impulse is very essential. However, it is necessary to take into account that a pressure in a chamber near the injection zone at regular combustion will be lower than the average

Table 2 **Results of calculations for model B**

γ	η	$\sin\theta_1/\eta$	α	$D/\sqrt{2J_0}$	p/p_2	θ, deg.	M_z	$I_{sp}/\sqrt{2J_0}$	$\Delta I/I_{sp}^*$
1.15	0.1	2	1/2	0.523	0.043	41.6	1.91	0.574	0.163
1.2	0.15	1	1	0.540	0.064	43.2	1.86	0.629	0.138
	0.15	1	1/2	0.600	0.079	40.0	1.53	0.591	0.068
	0.1	2	1/2	0.608	0.039	40.7	1.94	0.639	0.155
1.25	0.2	1	1	0.571	0.092	42.3	1.72	0.660	0.100
	0.15	1	1	0.607	0.060	42.4	1.88	0.679	0.132
	0.1	1	1	0.647	0.034	42.8	2.12	0.707	0.178
	0.1	2	1/2	0.685	0.037	39.8	1.97	0.689	0.148

pressure p_c in the same zone at continuous detonation, approximately in relation to I_{sp}^*/I_{sp}. It can be increased to the value p_c by corresponding contraction of the chamber exit. In this case, the difference of specific impulses will be decreased by two–three times, therefore, the ideal detonation will provide advantage in specific impulse at 5–7%. The advantage will be decreased due to incomplete combustion of the fuel in TDW at a nonideal CD process and because of the increase of the flow entropy in the shock wave CD. This effect has been eliminated previously.

The validity of the assumption in Eq. (18) that the flow behind the TDW is isentropic can be checked by calculating the additional increment to the entropy on the oblique shock CN (Fig. 5). The greatest increment to the entropy S occurs near the point C, where the angle the front makes with the incident flow is maximum. This angle is calculated from the conditions that the flow behind the shock wave be compatible with the centered wave of rarefaction behind the TDW. As the calculation shows, for the choice of the solution with the supersonic flow behind the shock wave, S is always less than the increment to the entropy in a plane wave of combustion with sonic outflow from the chamber. Away from the point C the intensity of the shock CN drops and the increment to the entropy on it decreases. For this reason, there are grounds for expecting outflow of the detonation products with $M_z > 1$ at the end of the chamber. If the last inequality holds, the advantage in the specific impulse of the CD process is also retained.

Numerical simulation of the spin detonation problem in a two-dimensional formulation showed [33] that a transonic transition is formed in a constant-section channel. Figure 6 shows the calculated two-dimensional structure of the flow (two periods) for a stoichiometric propane–oxygen mixture ($C_3H_8 + 5O_2$). Injection of the mixture through the top end of the chamber forms a layer (the interface is shown by the dashed line) that burns down in the TDW, expands, and passes through the shock wave of the next period. After this, part of the layer of detonation products flows out through the boundary Γ_2 and part of the layer once again is subjected to shock compression. In front of the curvilinear TDW, the thickness of the layer of the fuel mixture injected through Γ_1 over one period is $0.12l$, and the gas-dynamic parameters in the layer are nonuniform. The pressure ratio on the front of the attached shock wave decreases from 4.7 to 1.7; therefore, the entropy jump also decreases. The isobars p/p_θ show a rapid decrease in pressure downstream from the TDW.

On the right side of Fig. 6, in the horizontally hatched subdomain, the characteristics of the second family have a negative slope ($M_z = v/c < 1$). One can see that the width of the hatched subdomain decreases with distance from Γ_1 along the z axis and vanishes at $z/l \approx 1.13$. For $z/l > 1.13$, any sonic disturbance is entrained downstream. In the interval $0.12 < z/l < 1.13$, there exists a line that is the envelope of the characteristics of the second family. We shall call it the neutral Mach line (NML). An analysis of the solution showed that the NML lies in a neighborhood of the coordinate $z = 0.81l$ and closes on itself after one period. Reduction of the relative length of the chamber $L/l = 1.25 \div 0.82$ does not result in any changes in the solution above the NML.

Thus, the previously developed two-dimensional numerical model of continuous detonation in an annular cylindrical chamber can be used to predict and analyze the parameters of a periodic gas-dynamic flow. It was established that there is a neutral Mach line inside the chamber, below which the axial flow is supersonic on the average. The transonic transition occurs in a constant-section channel owing to the special structure of the flow.

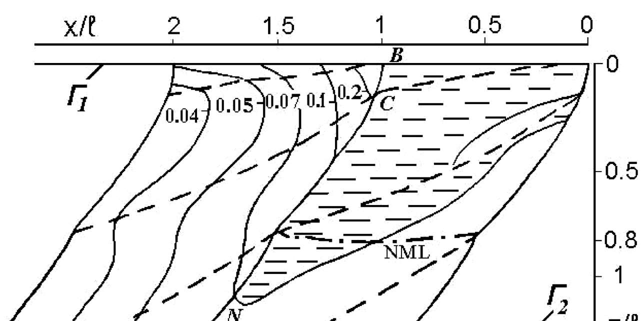


Fig. 6 Calculated structure of a CD process for gaseous mixture $C_3H_8 + 5O_2$.

III. Continuous Spin Detonation in Ramjet-Type Combustion Chambers

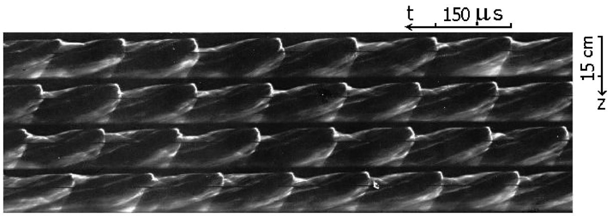
Recently, it became possible to extend the area of applicability of the spin detonation principle to ramjet-type combustors [39–41]. Experimental models have been developed in which the oxidizer is injected into the chamber through a slot at the entrance of the annular channel of the chamber. In experiments, the ducted variant of the combustor with conditions similar to a ramjet-type combustor was obtained: the oxidizer was fed as a continuous flow, and the fuel was injected through an injector. In this case, mixing was poorer because of the lower turbulence and smaller contact area of the components, and the wave structure became coarser. To satisfy the previously considered conditions of existence of the continuous detonation mode, the size of the detonation chamber had to be increased, especially for air used as an oxidant. The use of active fuel components (oxygen–acetylene) allowed obtaining detonation regimes in moderate-sized chambers: $d_c = 4$ and 10 cm; for air used as an oxidant, detonation regimes were obtained in a chamber with $d_c = 30.6$ cm with acetylene and hydrogen used as a fuel.

A. Fuel–Oxygen Mixtures

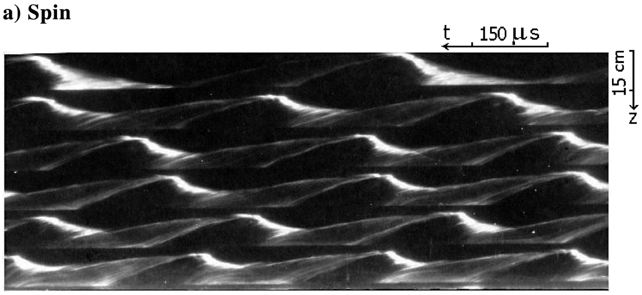
If the fuel injector is located near the slot for the oxidizer injector ($L_f = 0.1$ cm), the wave structure in the annular cylindrical chamber (chamber A) at $\Delta = 0.5$ cm (see Fig. 1a) and in the expanded duct (chamber B) at an angle of $\varphi = 8.5$ deg (see Fig. 1b) is almost the same as that in Fig. 2a. In the acetylene–oxygen mixture, the contact discontinuity 6 transforms into a clearly expressed combustion front responsible for the burning of up to 20% of the mixture being formed [39].

If, in a chamber of the diameter $d_c = 10$ cm, the acetylene injection occurs at a distance of one half of the chamber diameter ($L_f = 5$ cm) from the slot ($\delta = 0.2$ mm) for oxidizer injection, the oxygen flow issuing from the slot with a sonic velocity is decelerated when approaching the mixing zone, occupies the entire cross section of the duct, and acquires the mean velocity of about 25 m/s. Mixing conditions become worse. If the cross-sectional area behind the injector remains constant (chamber A), there is no detonation: conventional turbulent mixing occurs, where the combustion front is located 0.5–0.6 cm away from the acetylene-injection point. Detonation arises only if the duct expands in the mixing region and further downstream (chamber B). In this case, a one-wave mode with transverse detonation waves is formed, whose photographic record is shown in Fig. 7a. The duration of each fragment is ≈1.2 ms, and each subsequent line in the fragments is shifted in time by 12.5 ms. The TDW structure is even more coarse and differs from the previously considered structures by the presence of a shock wave emanating from the TDW front upstream of the oxygen flow. The width of the transverse front is worth noting, which reaches $h =$ 4–5 cm or 400–625a.

In combustor B [of smaller diameter ($d_c = 4$ cm) with varied position of the fuel injector ($L_f = 1.3$–20 cm)], spin detonation was not achieved, because no detonation-capable layer of the mixture in the tangential direction was formed. But detonation does not disappear and acquires a pulsed character in the axial direction: the combustion front is periodically entrained by the flow, then it is accelerated and is transformed to a detonation front (Fig. 7b) with a frequency $f = (2.2$–$6)$ kHz. At first glance, the photographic record is similar to the previous pictures, but it is a time sweep of axial motion of the fronts and products or an x-t diagram. As in the previous case, the oxygen flow is subsonic (about 25 m/s), and the detonation-capable layer is formed in the rarefaction wave adjacent to the shock front remaining from the detonation complex at the entrance of the detonation wave into the oxygen flow. The

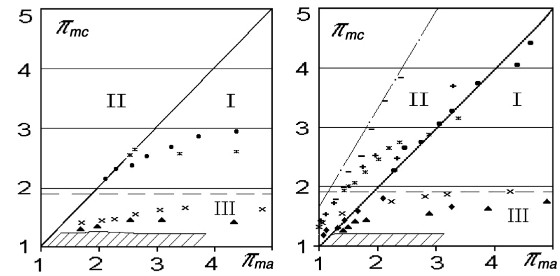


a) Spin



b) Pulsed

Fig. 7 Photographic record of detonation modes in the C_2H_2–O_2 mixture.



a) Chamber A **b) Chamber B**

Fig. 8 Range of existence of continuous spin detonation (p_{a0}= $0.2 \cdot 10^5$ Pa).

parameters of the characteristic modes of detonation combustion of the acetylene–oxygen mixture for $\delta/\Delta = 0.04$ are listed in Table 3.

It should be noted that the values of p_c in chamber B are lower than the total pressure of the flow, whereas these values in chamber A are close to each other.

By varying the relative width of the annular slot for oxidant injection within the range $\delta/\Delta \in (0.055–0.5)$, we obtained the range of existence of continuous spin detonation with TDWs vs the governing parameters: pressure in the oxidant manifold $p_{m\mathrm{ox}}$, pressure in the chamber p_c, and ambient pressure p_a. Figure 8 shows the experimental results in the coordinates of the pressure ratio in the annular slot $\pi_{mc} = p_{m\mathrm{ox}}/p_c$ and $\pi_{ma} = p_{m\mathrm{ox}}/p_a$ for regimes with TDWs in chamber A (Fig. 8a) and chamber B (Fig. 8b).

The domain of continuous detonation in chamber B is located in two subdomains separated by the straight line $p_c = p_a$ (solid curve): subdomain I ($p_c > p_a$) and subdomain II ($p_c < p_a$). The range of TDW existence in chamber A is smaller and is located only in subdomain I. To analyze the results presented, it also makes sense to identify a region of subsonic exhaustion of oxygen from the annular slot (subcritical pressure ratio $1 < \pi_{mc} < 1.89$): subdomain III. It follows from Fig. 8 that spin detonation is realized in subdomain III as the pressure difference π_{mc} decreases and tends to the limit of its existence (to the left bottom "corner" with the apex in the vicinity of the unity) with a simultaneous decrease in the parameters π_{mc} and π_{ma}. For chamber A, the limit of detonation is located in the corner with the apex $\pi_{mc} \approx 1.27$ and $\pi_{ma} \approx 1.6$. In the vicinity of the apex of this corner, burnout of the mixture in the turbulent flame front is amplified, and detonation waves are attenuated and degenerate into acoustic waves. In chamber B, we managed to obtain detonation modes with the pressure difference in the slot reduced to $\pi_{mc} = 1.2$ with TDW velocities $D = 1.2–1.3$ km/s. Thus, the straight line $\pi_{mc} = 1.2$ is the lower boundary of the corner sector of TDW existence. In our experiments, the maximum decrease in pressure in chamber B in the case of detonation was $p_c = 0.6p_a$. Therefore, the straight line $p_c = 0.6p_a$ (dashed and dotted lines in subdomain II, Fig. 8b) determines the left boundary of the corner sector of TDW existence.

An increase in flow rates of the components by increasing the injection pressure with an unchanged geometry of the chamber is favorable for the spin detonation mode, because π_{mc} remains unchanged with accuracy of losses and the ratio π_{ma} increases, thus, decreasing the influence of the ambient pressure on the process in the chamber.

B. Fuel–Air Mixtures

Continuous detonation burning of fuel–air mixtures (hydrogen, methane, kerosene, or diesel fuel used as a fuel) was achieved [37] in a plane-radial vortex chamber of the rocket-type with exhaustion toward the center (Fig. 1d). The chamber diameter was $d_c = 20.4$ cm, and the distance between the two flat radial walls was $\Delta = 1.5$ cm. The detonationlike combustion process with a circumferentially rotating wave with a velocity of 1.68–2 km/s was observed for specific flow rates of the combustible mixture $g \in (285–500)\ \mathrm{kg/s \cdot m^2}$ and pressure in the chamber p_c= $25–35 \cdot 10^5$ Pa.

A specific interest for practical investigation is the continuous detonation of fuel–air mixtures in conditions characteristic of scramjets. Therefore, a problem was posed to obtain a regime of continuous detonation burning of C_2H_2–air and H_2–air mixtures in a ducted cylindrical chamber.

The detonation-combustion chamber used by us was a coaxial channel of diameter $d_c = 30.6$ cm, length $L = 65.5$ cm, and width $\Delta = 2.3$ cm (Fig. 1a). Air was delivered into the chamber from a circular manifold with an axial cross section of 29.6 cm^2 through a circular slit with a gap of width $\delta = 0.1, 0.2, 0.3, 0.6,$ or 1.0 cm. At the same time, fuel was delivered into the chamber through a spray nozzle supplied with in-pair counterflow channels with the total cross-sectional area $S_{\delta f} = 2$ or 0.4 cm^2, situated at a distance L_f downstream of the air-supply slit, and inclined at the angle of 45 deg. The channels are uniformly distributed over the chamber circumference. The gases were delivered from separate receivers with volumes $V_{\mathrm{rA}} = 79.8l$ for air and $V_{\mathrm{rf}} = 13.3l$ for fuel through electrically driven fast valves. Detonation products exhausted directly into the atmosphere. The duration of the process was set

Table 3 Parameters of detonation modes for the acetylene–oxygen mixture

Parameter	$d_c = 4$ cm				$d_c = 10$ cm			
	$\varphi = 0$		$\varphi = 8.5$ deg		$\varphi = 0$		$\varphi = 8.5$ deg	
L_f, cm	0.1	5	0.1	20	0.1	5	0.1	5
$p_c \cdot 10^{-5}$, Pa	1.14	1.14	0.65	1.1	1.4	1.4	0.6	0.8
$p_a \cdot 10^{-5}$, Pa	0.1	0.1	0.1	0.06	0.2	0.2	0.2	0.2
G, g/s	32	32	32	32	107	107	75	75
ϕ	1.05	1.05	1.05	1.05	1.06	1.06	0.97	0.97
n	1	Combust.	1	-	3	Combust.	3	1
D, km/s	2.14	-	1.75	1–2	0.92	-	0.93	0.82
$D/D_{\mathrm{C\text{-}J}}$	0.88	-	0.72	0.4–0.82	0.92	-	0.93	0.82

within the time range $\tau_d \in (0.3–0.55)$ s by a control system. The detonation was initiated by an electrical detonator with an explosive mass of 0.2 g.

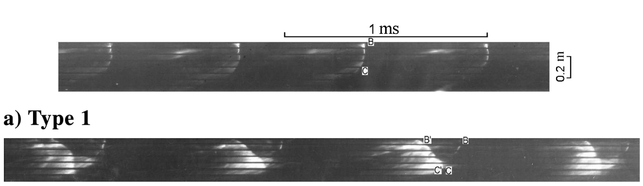
The entire process was photographed through the longitudinal windows of the detonation chamber on photographic film by a photochronograph with a falling drum [43]. To illuminate the wave structure and detonation products, a small acetylene jet was injected into the chamber beginning oppositely to the corresponding window. In the case of detonation of the H_2–air mixture, an oxygen jet was injected coaxially to the acetylene jet. Using illuminated trajectories, we determined the axial component of the flow velocity $v = k \cdot v_{\mathrm{pf}} \tan\psi$. Here, $k = 37.8$ is the image-diminution factor, ψ is the inclination angle of a trajectory with respect the horizontal line, and $v_{\mathrm{pf}} = 50$ m/s is the speed of photographic-film motion. Pressure-sensor signals from the gas receivers, collectors, and detonation chamber were registered by a computer system.

1. *Acetylene–Air Mixture*

The flow rate of the components varied within the limits $G_{A0} = 5.3–2.12$ kg/s and $G_{f0} = 0.3–0.21$ kg/s. The annular slot width varied within the limits $\delta = (0.1–1)$ cm. The fuel-excess factor was $\phi = 0.44–1.37$. We have realized processes characterized by one rotating wave ($n = 1$). Instantaneous patterns of the process featuring a transverse detonation wave ($\delta/D = 0.043$) moving from left to right are presented in Fig. 9a ($g = 146\ \mathrm{kg/s \cdot m^2}$, $p_c = 2.2 \cdot 10^5$ Pa, $\phi = 1.35$, and $D = 1.5$ km/s) and Fig. 9b ($g = 114\ \mathrm{kg/s \cdot m^2}$, $p_c = 1.2 \cdot 10^5$ Pa, $\phi = 1.3$, and $D = 1.1$ km/s). The patterns were obtained by the velocity-compensation method. The flow in the vicinity of a detonation wave corresponds to the flow in the coordinate system associated with the detonation wave. In each revolution over the chamber circumference, the transverse detonation wave passes the path of 4.5 cm by the longitudinal windows of the chamber (the distance between the windows is 1.5 cm). An absence of counterflow transverse detonation waves was found. The shock wave front BC (Fig. 9) is illuminated sufficiently well due to a purposefully targeted small acetylene jet.

Two characteristic types of the transverse detonation wave have been observed. The first has a chemical reaction (combustion) front adjoining the leading shock wave front BC (type I, Fig. 9a). The second is the retarded pulsating combustion front (type II, Fig. 9b). As a rule, the latter structure corresponds to a lowered pressure in the chamber, to the case when the ratio between the components is close to the ultimate ratio ($\phi = 0.7$), and to the case when the transverse detonation wave strongly affects the state of air in the collector ($\delta/\Delta = 0.435$). For waves of type II, in spite of the unsteadiness of the flow beyond the leading shock front, the average wave velocity is stable and has no deviations exceeding 1% for adjacent revolutions.

The size of the type-I transverse detonation wave at the average pressure in the chamber $p_c = (1–2.5) \cdot 10^5$ Pa attains the value $h = 23\ \mathrm{cm} \approx (25–60)a$. The constant value of the quantity h is explained, apparently, by the readiness of the mixture to detonate, that is, by the mixing processes of the components, which slightly depends on the value of p_c. The glow zone beyond the front BC of the type-I detonation wave attains about 1.0 cm, that is, about two cells each of size a, at $p_c = 2.2 \cdot 10^5$ Pa. For waves of type II, the size of the transverse detonation wave is larger than $h \approx 35\ \mathrm{cm} \approx (35–45)a$ and varies negligibly within the pressure range $p_c = (1–1.3) \cdot 10^5$ Pa. In the case of good mixing, the ratio h/a for fuel–air mixtures turns out to be higher by three to fivefold than for gas fuel–oxygen mixtures. The ratio of the transverse detonation-wave size to the distance between the waves is $h/l = 1/3–1/4$ ($l = \pi d_c$ for $n = 1$). For fuel–oxygen mixtures [28], the ratio is $h/l = 1/10–1/5$. The difference in the relative width of the detonation front for the fuel–air mixtures is attributed to several causes. These are the absence (or undeveloped nature) of the combustion front from the product side, as well as the supersonic velocity of the mixture ahead of the transverse detonation-wave front. The measured axial velocity of the mixture passing through the lower part of the front attains about 600 m/s and approaches the maximum possible velocity $v_{\max} = [2/(\gamma - 1)]^{0.5} \cdot c_0$, where γ and c_0 are the adiabatic index and sonic velocity for air in the receiver, respectively.



a) Type 1

b) Type 2

Fig. 9 Fragments of TDW photographic records in C_2H_2–air mixture ($\delta/\Delta = 0.043$).

Table 4 Basic parameters of detonation regimes for the acetylene–air mixture

δ/Δ	0.043	0.087	0.13	0.435
D, km/s	1.1–1.27–1.23	1.48–1.43	1.35–1.27	0.89–0.7 unstable
$p_m \cdot 10^{-5}$, Pa	6.67–3.4	3.6–1.82	2.7–1.34	1.53–1.12
$p_c \cdot 10^{-5}$, Pa	1.2–1.0	1.27–1.0	1.3–1.0	1.22–1.06
p_m/p_c	5.66–3.4	2.83–1.82	2.03–1.34	1.25–1.06

For input pressures of air and acetylene, $P_{A0} = 15 \cdot 10^5$ Pa and $P_{f0} = 10.9 \cdot 10^5$ Pa, respectively, and for the corresponding flow rates $G_{A0} = 2.12$ kg/s and $G_{f0} = 0.214$ kg/s, the basic parameters of the detonation regimes are presented in Table 4 for varied values of the parameter δ and within the range of the current flow rates $G_A = (1.98–1.03)$ kg/s, $G_f = (0.187–0.1)$ kg/s, specific flow rate $g = (106–55)\ \mathrm{kg/s \cdot m^2}$ and for $\phi = 1.26–1.29$.

As is seen from Table 4, stronger transverse detonation waves (possessing a higher detonation velocity) arise in the case of air inflow to the chamber through the slits with width $\delta = 0.2$ and 0.3 cm. The characteristics of the waves are virtually not violated even for subsonic air inflow. The air supply through narrow ($\delta/\Delta = 0.043$) and broad ($\delta/\Delta = 0.435$) slits, apparently, does not ensure a sufficient degree of mixing. The air inflow through the gap of width $\delta = 1.0$ cm is subsonic over the entire duration of the process. The comparison of detonation velocities for this regime and for the regime corresponding to $\delta/\Delta = 0.13$, for which the subsonic inflow also mainly dominates, directly indicates insufficient mixing of the components in the zone of the rotation of the transverse detonation-wave front for $\delta/\Delta = 0.435$. According to data in Table 4, the operation frequency of the process is within the range $f \in (0.8–1.54)$ kHz.

The increase in the flow rate of the mixture components, with respect to the data presented previously, proportionally elevated the pressure in the detonation chamber and extended the region of existence of waves of the first structure. In this case, the transverse detonation-wave velocity, as a rule, also increased: its maximum corresponded to 1.58 km/s.

2. *Hydrogen–Air Mixture*

The experiments were performed in the following ranges of parameters: $\delta = 0.2–1$ cm, $G_{A0} = 4–2.7$ kg/s, $G_{f0} = 0.1–0.28$ kg/s, $\phi = 0.4–3.34$, and $p_c = (1.06–2.5) \cdot 10^5$ Pa. A typical photographic record of the detonation process is shown in Fig. 10 (each subsequent line in the fragments is shifted in time by 25 ms), and the time evolution of pressure in the air manifold p_m and in the detonation chamber p_c are plotted in Fig. 11.

It should be noted that the TDW velocity and their structure are extremely stable in the examined range of pressures in the chamber. The flow rates of the components decreased during the experiment, but the flow rate of hydrogen decreased faster than the flow rate of air. As a result, the mixture became leaner, and the TDW velocity decreased. The experimental values of the TDW velocity D and the frequency f are plotted in Fig. 12 as functions of the specific flow rate of the mixture g for two values of the parameter δ/Δ.

The spin detonation parameters were varied within the following ranges: $D \in (1.1–1.43)$ km/s, $n \in (1–3)$, $f \in (1.15–4.46)$ kHz,

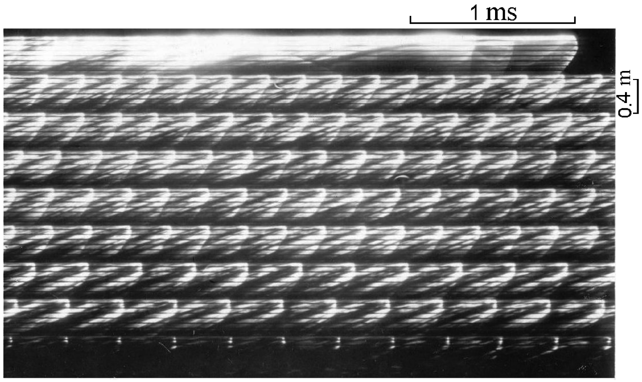


Fig. 10 Fragments of TDW photographic records in H_2–air mixture ($\delta/\Delta = 0.087$, $n = 3 \rightarrow 2$).

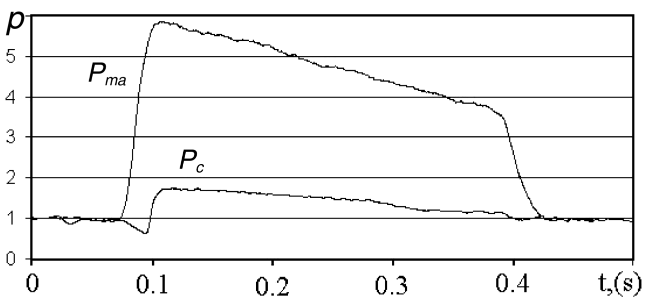
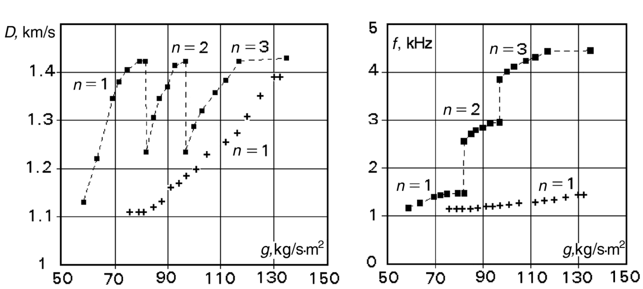


Fig. 11 Oscillograms of pressures p_{ma} and p_c for H_2–air mixture ($\delta/\Delta = 0.087$).

and $\phi \in$ (1.94–0.8). Three transverse detonation waves are formed at first in the chamber in the examined range of flow rates of the mixture with supercritical exhaustion of air through the slot ($\delta/\Delta = 0.087$) and hydrogen from the injector ($S_{\delta f} = 0.4$ cm^2); the TDW velocity monotonically decreases from 1.43 km/s to 1.23 km/s with decreasing flow rate g. The flow is reconstructed at $g = 97$ kg/s $\cdot$ m^2, and two transverse detonation waves propagate in the chamber; the TDW velocity also monotonically decreases from 1.42 km/s to 1.23 km/s with decreasing g. At $g = 82$ kg/s $\cdot$ m^2, another flow reconstruction occurs, and one TDW continues to propagate in the chamber. In other experiments, breakdown of spin detonation with TDWs and transition to conventional combustion were observed when the flow rate was reduced to $g = 46$ kg/s $\cdot$ m^2. The ratio of components was close to the stoichiometric value, the pressure in the chamber was 1.03 atm, the pressure in the air manifold was 2 atm, and the detonation velocity was 1.17 km/s.

In the case of subcritical exhaustion of air from the slot ($\delta/\Delta = 0.26$), only one TDW is formed in the chamber; its velocity monotonically decreases from 1.39 km/s ($g = 132$ kg/s $\cdot$ m^2) to 1.11 km/s ($g = 76$ kg/s $\cdot$ m^2) with decreasing specific flow rate of the fuel–air mixture.



a) TDW velocity **b) Operation frequency**

Fig. 12 Detonation parameters of the H_2–air mixture; $\delta/\Delta = 0.087$ (■), $\delta/\Delta = 0.26$ (+).

In the previously indicated range of flow rates of components at the fuel injector with the cross-sectional area $S_{\delta f} = 2$ cm^2 ($\delta/\Delta = 0.13$), we determined the values of ϕ that can be regarded as the limiting values for existence of continuous spin detonation: $\phi = 2.7$ (upper limit) and $\phi = 0.65$ (lower limit). Unstable detonation regimes were observed outside these limits with prevalence of conventional turbulent burning. The specific flow rates of the fuel mixture g were in the range shown in Fig. 12. As the slot width δ increased, the range of stable detonation regimes decreased in terms of ϕ.

The width of the TDW front in the H_2–air mixture was $h \approx 24/n$ cm with $n \in$ (1–3). A comparison of the detonation-front structure in transverse detonation waves considered shows that the number of waves in the H_2–air mixture with $\delta/\Delta = 0.087$ and maximum specific flow rates (see Fig. 12) is three times greater than that in the C_2H_2–air mixture. For stoichiometric mixtures prepared beforehand, the cell size a for the C_2H_2–air mixture is approximately 1.5 times lower than for the H_2–air mixture [49]. This unexpected results can be related to the prevailing influence of physical processes of mixing of components over the chemical properties of mixtures, in particular, more intense mixing of the hydrogen–air components because of the greater difference in jet velocities at the contact boundaries determining the intensity and scale of turbulence. This conclusion is supported by experiments with $\delta/\Delta = 0.26$ (Fig. 12) and $\delta/\Delta = 0.435$, where only single-wave detonation modes were observed.

The normalized width of the air-injection slot being varied within $\delta/\Delta \in$ (0.043–0.435), the range of existence of continuous spin detonation in the fuel–air mixture is obtained as a function of the following governing parameters: p_m, p_c, and p_a. Figure 13 shows the experimental results for detonation modes with transverse detonation waves in the coordinates $\pi_{mc} = p_m/p_c$ and $\pi_{ma} = p_m/p_a$. As for the fuel–oxygen mixture (see Fig. 8a), the range of TDW existence in a cylindrical chamber for fuel–air mixture is located in domain I ($p_c > p_a$). It follows from Fig. 13 that spin detonation is formed in the subdomain of subsonic exhaustion of air from the annular slot (domain III) as the pressure difference π_{mc} decreases; with a simultaneous decrease in the parameters π_{mc} and π_{ma}, detonation tends to the limit of its existence: to the bottom left corner. For a cylindrical chamber, the limit of detonation existences in the C_2H_2–air and H_2–air mixtures is located in the corner with the apex at $\pi_{mc} \approx 1.1$ and $\pi_{ma} \approx 1.06$. In the vicinity of the corner apex, burnout of the mixture in the turbulent flame front is stronger, and detonation waves are attenuated and degenerate to acoustic waves.

IV. Conclusion

Regimes of controlled continuous detonation of various fuels in rotating transverse detonation waves in rocket and ramjet-type combustors have been obtained and extensively considered both experimentally and theoretically. A method for continuous photographic recording of the process with a microsecond resolution and total duration up to 1 s has been developed. This information can be used to develop promising engines of flying vehicles.

1) Investigations performed in rocket-type combustors show that almost all gaseous or liquid hydrocarbon fuels mixed with gaseous oxygen can be burnt in annular cylindrical chambers in the regime of continuous spin detonation. Tests with air as well as liquid oxygen used as an oxidizer have been also successful.

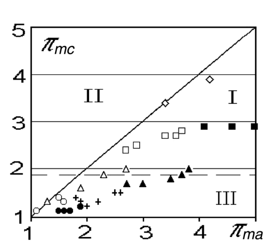


Fig. 13 Range of existence of continuous spin detonation in C_2H_2–air and H_2–air mixtures.

A continuous detonation process can be ensured in combustion chambers with dimensions larger than the minimum critical size determined by the detonation-wave front width. In chambers whose size is smaller than the critical value, continuous self-sustaining (not requiring valve devices) pulsed detonation modes with longitudinal waves are possible. The simple geometric shape of the chamber, such as an annular cylinder without duct constriction, is suitable for most cases. It is possible to change the chamber shape and to use conical, plane-radial, or more complicated shapes of combustors. In a highly active fuel mixture, continuous detonation can be sustained even in a free annular fuel charge above the outer surface of the cylindrical injector device. A substantial effect of mixing processes on the limits of existence and stability of TDWs in the chamber was experimentally observed. The experiments revealed a significant influence of mixing on the range of existence and stability of transverse detonation waves in the chamber.

It has been demonstrated experimentally, theoretically, and numerically that a transonic transition occurs in the flow in the CD process if the cross-sectional area of the chamber is unchanged. According to numerical calculations, an ideal CD process ensures a higher specific thrust of the chamber than that produced by conventional combustion in the same chamber without the nozzle. The pressure in the chamber in the zone of transverse detonation waves oscillates with the frequency of TDW revolution; the maximum pressures are reached in the TDW front and are three to five times higher than the mean pressure in the chamber p_c.

To maintain the CD process, one has to ensure fuel- and oxidizer-injection pressures (p_f and $p_{\rm ox}$) two or three times higher than p_c. The limiting ratio of pressures can be reduced in some cases to $p_f/p_c = 1.2$ and $p_{\rm ox}/p_c = 1.2$ by increasing the chamber diameter and improving mixing of components.

Oxygen being diluted by nitrogen, the range of TDW existence decreases, and the minimum size of the chamber increases. In chambers with plane-radial geometry and centripetal exhaustion, the rotational motion of the fuel mixture can be used as a factor for a substantial increase in pressure at the chamber periphery and for reducing the threshold of detonation excitation. Spin detonation modes of burning of fuel–air mixtures with both gaseous (hydrogen, methane) and liquid (kerosene, diesel oil) fuels were obtained and studied in these chambers.

2) The range of applicability of the spin detonation principle has been extended to ramjet-type combustors. Experiments performed in ducted ramjet combustors show that it is possible to burn fuel–oxygen and fuel–air mixtures in the continuous spin detonation mode.

Stable controlled regimes of burning of acetylene–oxygen mixtures in spin detonation waves with supercritical and subcritical ($\approx$1.2-fold) ratio of oxygen pressures on the annular slot and under the influence of intrachamber processes on the entire flow in the injection system have been obtained. It has been found that strong transverse detonation waves can continuously exist as the annular slot is opened up to one-half of the combustor-duct section, when the total pressure losses on the oxidizer-injection slot decrease to 1% according to the estimates performed.

By varying the pressure of oxygen injection in the chamber and in the ambient medium, the range of existence of continuous detonation with transverse detonation waves is determined, and it is shown that continuous spin detonation in a chamber with channel expansion can proceed with a pressure in the chamber lower than the ambient pressure.

A controlled regime of continuous spin detonation with transverse detonation waves in acetylene–air and hydrogen–air mixtures in a cylindrical annular chamber 30.6 cm in diameter with separate injection of propellant components was ensured for the first time.

Two typical TDW types were identified: with the chemical reaction (combustion) front adjacent to the leading shock front and with the pulsed combustion front that lags behind the leading shock front. The latter structure is normally observed in the case of a reduced pressure in the chamber, ratio of components close to the limiting value, insufficient quality of mixing, and strong influence of TDWs on the state of air in the manifold with subsonic exhaustion of air from the slot. An increase in flow rates of components of the mixture leads to an increase in pressure in the chamber and expands the range of existence of waves with the first structure. The velocity and the number of transverse detonation waves usually increase as well.

The range of existence of continuous spin detonation in fuel–air mixtures is determined as a function of the governing parameters: pressure in the air manifold p_m, pressure in the chamber p_c, and ambient pressure p_a. For a cylindrical chamber, the limit in terms of detonation of C_2H_2–air and H_2–air mixtures is reached: $\pi_{mc} \approx 1.1$ and $\pi_{ma} \approx 1.06$. Near the limit, transverse detonation waves become irregular and attenuated, and burnout of the mixture in the turbulent flame front is intensified.

In the case of high-quality mixing, the TDW velocity and their structure are extremely stable (except for the instant when the number of detonation waves is changed) in a wide range of the ratios of propellant components and in the examined range of pressures in the chamber.

Acknowledgments

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References

[1] Roy, G. D., Frolov, S. M., Borisov, A. A., and Netzer D. W., "Pulse Detonation Propulsion: Challenges, Current Status, and Future Perspective," *Progress in Energy and Combustion Science*, Vol. 30, Sep. 2004, pp. 545–672.

[2] Zel'dovich, Y. B., "To the Question About Energetic Use of Detonation Combustion," *Journal of Technical Physics*, Vol. 10, No. 17, 1940, pp. 1453–1461.

[3] Nicholls, J. A., Dabora, E. K., and Gealler, R. A., "Studies in Connection with Stabilized Gaseous Detonations Waves," *7th Symposium (International) on Combustion and Detonation*, Butterworths, London, pp. 766–772.

[4] Dunlap, R., Brehm, R., and Nicholls, J. A., "A Preliminary Study of the Application of Steady-State Detonative Combustion to a Reaction Engine," *Jet Propulsion*, Vol. 28, No. 7, 1958, pp. 451–456.

[5] Gross, R. A., "Research of Supersonic Combustion," *ARS Journal*, Vol. 29, No. 1, 1960, pp. 63–72.

[6] Gross, R. A., and Chinitz, W., "A Study of Supersonic Combustion," *Journal of the Aero/Space Sciences*, Vol. 27, No. 7, 1960, pp. 517–524.

[7] Soloukhin, R. I., "Pulsating Combustion of Gas Far Shock Wave in Supersonic Flow," *Soviet Journal of Applied Mechanics and Technical Physics*, No. 5, Sep.–Oct. 1961, pp. 57–60.

[8] Soloukhin, R. I., "Shock Waves and Detonation in Gases," State Publishing House of Physical and Mathematical Literature, Moscow, 1963, pp. 159–165.

[9] Bazhenova, T. V., and Soloukhin, R. I., "Gas Ignition Behind the Shock Waves," *7th Symposium on Combustion*, pp. 866–875.

[10] Shchetinkov, E. S., "The Physics of Combustion of Gases," State Publishing House of Nauka, Moscow, 1965, pp. 1–739.

[11] Baev, V. K., Golovichev, V. I., and Tret'iakov, P. K., "Combustion in Supersonic Flow," *Siberian Division of the USSR Academy of Science*, Novosibirsk, Russia, 1984, pp. 1–304.

[12] Vlasenko, V. V., and Sabel'nicov, V. A., "Numerical Simulation of Inviscid Flows with Hydrogen Burning Behind the Shocks and in Detonation Waves," *Combustion, Explosion, and Shock Waves*, Vol. 31, No. 3, 1995, pp. 118–133.

[13] Voitsekhovskii, B. V., "Stationary Detonation," *Doklady Akademii Nauk UzSSR*, Vol. 129, No. 6, 1959, pp. 1254–1256.

[14] Voitsekhovskii, B. V., "Stationary Spin Detonation," *Soviet Journal of Applied Mechanics and Technical Physics*, No. 3, May–June 1960, pp. 157–164.

[15] Voitsekhovskii, B. V., Mitrofanov V. V., and Topchiyan, M. E., "Structure of a Detonation Front in Gases," *Siberian Branch of the USSR Academy of Science*, Novosibirsk, Russia, 1963, pp. 1–168; also Wright–Patterson AFB Rept. FTD-MT-64-527 (AD-633, 821), 1966 (in English).

[16] Rakinova, H. A., Troshin, Ya. K., and Shchelkin, K. I., "Spin Near Limits of Detonation," *Soviet Journal of Technical Physics*, Vol. 17,

No. 12, 1947, pp. 1409–1410.
[17] Mikhailov, V. V., and Topchian, M. E., "To the Studies of Continuous Detonation in an Annular Channel," *Combustion, Explosion, and Shock Waves*, Vol. 1, No. 4, 1965, pp. 12–14.
[18] Edwards, B. D., "Maintained Detonation Waves in an Annular Channel: A Hypothesis, Which Provides the Link Between Classical Acoustic Combustion Instability and Detonation Waves," *16th Symposium (International) on Combustion*, The Combustion Inst., Pittsburgh, PA, 1976, pp. 1611–1618.
[19] Shen, P. I., and Adamson, T. C., "Theoretical Analysis of a Rotating Two-Phase Detonation in Liquid Rocket Rotors," *Astronautica Acta*, Vol. 17, No. 4/5, 1972, pp. 715–728.
[20] Adamson, T. C., and Olsson, G. R., "Performance Analysis of a Rotating Detonation Waves Rocket Engine," *Astronautica Acta*, Vol. 13, No. 3, 1967, pp. 405–415.
[21] Barrere, M., Jaumotte, A. A., Webek, B. F., and Wandenkerhove, Zh., *Rocket Propulsion*, Elsevier, New York, 1960, pp. 660–674.
[22] Mel'kumov, T. M., Melik-Pashaev, N. I., Chistiakov, P. G., and Shiukov, A. G., *Rocket Engines*, Mashinostroenie, Moscow, 1968, pp. 126–136.
[23] David T. Harrje, and Frederick H. Reardon, "*Liquid Propellant Rocket Combustion Instability*," NASA, Washington, 1972, pp. 25–53, 633–748.
[24] Morrison, B. B., and Rerry, O., "Rotary Detonation Power Plant," U.S. Patent, Class 60-35, G, N 3240010. J. 2.02.61, filed Mar._1966.
[25] Lange, O. H., Stein, R. J., and Tubbs, H. E., "Detonation Reaction Engine," U.S. Patent, Class 60-356, N 32634/8. J. 6.12.65, filed Aug. 1966.
[26] Lange, O. H., Stein, R. J., and Tubbs, H. E., "Continuous Detonation Reaction Engine," U.S. Patent, Class 60-358, N 3336754. J. 21.03.66, filed Aug. 1967.
[27] Bykovskii, F. A., Klopotov, I. D., and Mitrofanov, V. V., "Spin Detonation of Gases in a Cylindrical Chamber," *Doklady Akademii Nauk UzSSR*, Vol. 224, No. 5, 1975, pp. 1038–1041.
[28] Bykovskii, F. A., and Mitrofanov, V. V., "Detonative Combustion of Gas Mixture in a Cylindrical Chamber," *Combustion, Explosion, and Shock Waves*, Vol. 16, No. 5, 1980, pp. 107–117.
[29] Bykovskii, F. A., "Effect of Mixing of Gases on Detonation Parameters," *Dynamics of Continuous Media*, No. 62, Inst. of Hydrodynamics, Novosibirsk, Russia, 1983, pp. 23–31 (in Russian).
[30] Bykovskii, F. A., "About Some Properties of Flow by Continuous Detonation in a Ring Cylindrical Chamber," *Proceedings of the 8th Symposium on Combustion and Explosion*, Inst. of Chemical Physics, Chernogolovka, Russia, pp. 16–19 (in Russian).
[31] Zhdan, S. A., Mardashev, A. M., and Mitrofanov, V. V., "Mathematical Modeling of Detonative Combustion of Gaseous Mixture in Cylindrical Chamber," *Proceedings of the 8th Symposium on Combustion and Explosion*, Inst. of Chemical Physics, Chernogolovka, Russia, pp. 118–121 (in Russian).
[32] Zhdan, S. A., and Mardashev, A. M., "The Structure of Spin Detonation in a Ring Cylindrical Chamber," *Dynamics of Continuous Media*, No. 83, Inst. of Hydrodynamics, Novosibirsk, Russia, 1987, pp. 88–98.
[33] Zhdan, S. A., Mardashev, A. M., and Mitrofanov, V. V., "Calculation of the Spin Detonation Flow in a Ring Chamber," *Combustion, Explosion, and Shock Waves*, Vol. 26, No. 2, 1990, pp. 91–95.
[34] Bykovskii, F. A., "Thermal Fluxes into Combustion Chamber Walls by Unsteady Thermal Regime," *Combustion, Explosion, and Shock Waves*, Vol. 27, No. 1, 1991, pp. 72–75.
[35] Bykovskii, F. A., and Vedernikov, E. F., "Self-Sustaining Pulsating Detonation of Gas-Mixture Flow," *Combustion, Explosion, and Shock Waves*, Vol. 32, No. 4, 1996, pp. 442–448.
[36] Bykovskii, F. A., and Vedernikov, E. F., "Continuous Detonation Combustion of an Annular Gas-Mixture Layer," *Combustion, Explosion, and Shock Waves*, Vol. 32, No. 5, 1996, pp. 489–491.
[37] Bykovskii, F. A., Mitrofanov, V. V., and Vedernikov, E. F., "Continuous Detonation Combustion of Fuel-Air Mixtures," *Combustion, Explosion, and Shock Waves*, Vol. 33, No. 3, 1997, pp. 344–353.
[38] Bykovskii, F. A., and Mitrofanov, V. V., "A Continuous Spin Detonation in Liquid Fuel Sprays," *Control of Detonation Processes*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, Elex–KM Publishers, Moscow, 2000, pp. 209–211.
[39] Bykovskii, F. A., and Vedernikov, E. F., "Continuous Detonation of a Subsonic Flow of a Propellant," *Combustion, Explosion, and Shock Waves*, Vol. 39, No. 3, 2003, pp. 323–334.
[40] Bykovskii, F. A., Zhdan, S. A., and Vedernikov, E. F., "Continuous Spin Detonation in Ducted Annular Combustors," *Application of Detonation to Propulsion*, edited by G. Roy, S. Frolov, and J. Shepherd, Torus, Moscow, 2004, pp. 174–179.
[41] Bykovskii, F. A., Zhdan, S. A., and Vedernikov, E. F., "Spin Detonation of Fuel-Air Mixtures in a Cylindrical Combustor," *Doklady Akademii Nauk*, Vol. 400, No. 3, 2005, pp. 338–340.
[42] Bykovskii, F. A., Voitsekhovskii, B. V., and Mitrofanov, V. V., "Method of Fuel Burning," Russian Patent No. 2003923, Application No. 4857837/06, Aug. 1990; also, "Bulletin of Inventions," Nos. 43–44, Poisk, Moscow, 1993, p. 134.
[43] Bykovskii, F. A., "High Velocity Waiting Photoregister," *Soviet Journal of Science and Applied Photograph and Cinemagraph*, Vol. 26, No. 2, 1981, pp. 85–89.
[44] Mitrofanov, V. V., "Certain Critical Phenomena in Detonation Associated with Momentum Losses," *Combustion, Explosion, and Shock Waves*, Vol. 19, No. 4, 1983, pp. 531–536.
[45] Vasili'ev, A. A., and Zak, D. V., "Detonation of Gas Jets," *Combustion, Explosion, and Shock Waves*, Vol. 22, No. 4, 1986, pp. 82–88.
[46] Mitrofanov, V. V., "Energy Criterion of Detonation Initiation," *Lavrentyev Readings on Mathematics, Mechanics and Physics*, Lavrentyev Inst. of Hydrodynamics, Novosibirsk, Russia, Sep. 2000, p. 139.
[47] Vasil'ev, A. A., Zhdan, S. A., and Mitrofanov, V. V., "Initiation of Gaseous and Heterogeneous Systems," *Gaseous and Heterogeneous Detonations: Science to Applications*, edited by G. D. Roy, S. M. Frolov, K. Kailasanath, and N. N. Smirnov, ENAS Publishers, Moscow, 1999, pp. 25–38.
[48] Vasil'ev, A. A., and Nikolaev, Yu. A., "Closed Theoretical Model of a Detonation Cell," *Acta Astronautica*, Vol. 5, No. 11–12, 1978, pp. 983–996.
[49] Vasil'ev, A. A., Mitrofanov, V. V., and Topchian, M. E., "Detonation Waves in Gas," *Combustion, Explosion, and Shock Waves*, Vol. 23, No. 5, 1987, pp. 109–131.

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