Continuous spin and pulse detonation of hydrogen-air mixtures in a supersonic flow generated by a detonation wave

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1 Introduction

Regimes of continuous spin detonation burning of acetylene in a subsonic oxygen flow were obtained and studied in [1]. A question arises whether it is possible to burn the fuel in a supersonic oxidizer flow, which is of great practical importance for flying vehicles. The objective of the present work was to check the principal possibility of continuous detonation burning of hydrogen in a supersonic air flow in a flow-type combustor.

2 Experimental Setup

The experimental combustor with a diameter d_c = 306 mm consists of two parts: an annular cylindrical channel *1* of length L_1 = 150 mm with a distance Δ = 7 mm between the walls and a combustion chamber *2* of length L_2 = 420 mm, which has an annular channel expanding at an angle of 15° (Fig.1).

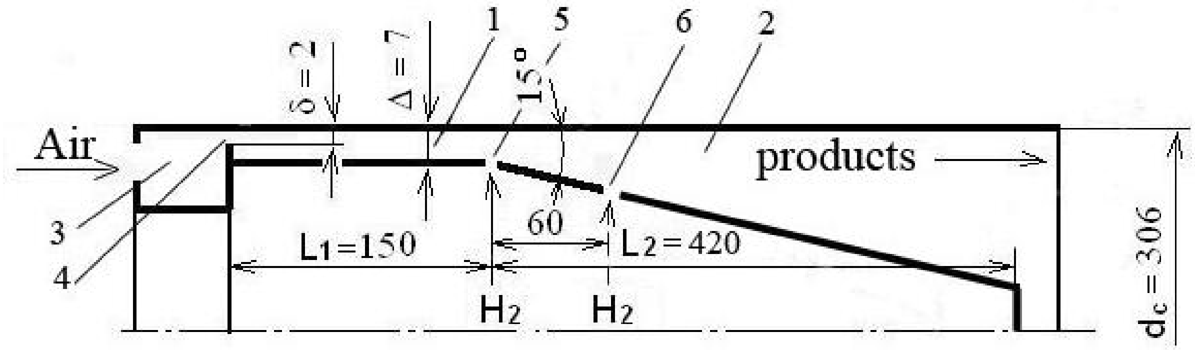

Figure 1. Sketch of the combustor.

Air was fed into the combustor from a receiver V_{rA} = 78.9 liters (not shown in the figure) through a manifold *3* and an annular slot *4* of width δ = 2 mm. Hydrogen from a receiver V_{rH} = 10 liters (not shown in the figure) was injected into the gas flow escaping from the channel *1*; hydrogen was injected through injectors *5* or *6* at the beginning of expansion of the chamber *2* or at a distance of 60 mm from the beginning of expansion. The injectors *5* and *6* had 100 pairs of opposing orifices with a cross-sectional area of 1x1 mm^2, which were uniformly distributed over the inner side of the combustor wall. The flow rates of the injected species were G_A = (4.3 – 3) kg/s (air) and G_H = (0.23 – 0.05) kg/s (hydrogen). The fuel-to-air equivalence ratio was varied within ϕ = 1.86 - 0.52. The process was initiated at the beginning of the chamber *2* by burning aluminum foil with energy release of approximately 5 J. The products exhausted into the atmosphere. Optical registration of the processes was performed through a set of longitudinal Plexiglas windows (8 mm wide and 45 mm long), which were glued into the outer wall of the combustor with 15-mm gaps. The size of the windows served as a linear scale of the wave structure and the flow in the vicinity of the wave in the longitudinal direction. A photorecorder with a falling drum [2] was used, which operated in the regime of continuous unfolding with partial compensation of velocity of transverse detonation waves (TDWs). The detonation waves and the flow of the products were illuminated by injecting an acetylene filament and a coaxial oxygen filament at the beginning of the channel *1*. The parameters measured during the entire experiment were the static pressure (P_1) at a distance of 15 mm from the slot for air supply *4*, the total and static pressures at a distance of 110 mm (P_{20} and P_2), and the static pressures at distances of 210 mm (P_3) and 300 mm (P_4) and at the combustor exit (P_5). The signals from the pressure transducers were recorded and processed on a computer.

3 Experimental results

Hydrogen injection at the beginning of the expanding part of the combustor. A fragment of photographic records of a typical detonation regime for the entire period of registration is shown in Fig. 2,a. Each band is shifted in time by Δt = 25 ms. One TDW moving from left to right is seen. The pressure oscillograms in the system for supplying air and hydrogen for the same regime are plotted in Fig. 2,b, and the pressure in the combustor is shown in Fig. 2,c. The parameters of the detonation regime are summarized in Table 1 (test No. 1).

Table 1: Parameters of the detonation process.

No	G_A, kg/s	G_H, kg/s	ϕ	D, km/s	f, kHz	n
1	4.23→3.1	0.2→0.05	1.64→0.52	1.72→1.07	–	1
2	4.33→3.1	0.23→0.054	1.86 →0.59	–	0.77→1.1	–

Here D is the TDW velocity calculated with respect to the outer wall of the combustor and n is the number of TDWs; the arrows indicate the changes in parameters during the experiment. The circumferential velocity of the TDWs was determined by the formula $D = (\pi d_c/n\Delta l)\cdot v_p$, where Δl is the distance between the TDWs on the photographic film and v_p = 50 m/s is the linear velocity of film motion.

When the valves are opened (see Fig. 2,c), a subsonic flow is formed in the slot *4,* which becomes supersonic at a distance of 15 mm ($1.86P_1 < P_{20}$ even with ignored losses); further downstream, at a distance of 110 mm (55 δ), however, the pressure transducers P_2 and P_{20} register a subsonic flow. In the expanding part of the combustor *2,* the flow acquires a supersonic character. In 2-3 ms after initiation (t_{in}), stable continuous spin detonation is developed in the combustor. The detonation front BC (see Fig. 2,a) has an inflection at the point C^1, which becomes more pronounced at the end of the experiment. The front height BC^1 decreases, and the segment CC^1 increases. At some time instants, the front segment CC^1 is aligned horizontally, i.e., coincides with the plane of the combustor cross section. The mixture starts to form on the segment BB^1; hence, the detonation front transforms to the shock front here, and the resultant mixture burns in a conventional turbulent flame. In the region affected by the shock wave, the air income into the combustor is decelerated. Hydrogen, however, is continuously injected into the combustor. Therefore, a certain part of hydrogen entering the combustor also burns down owing to its contact with the products, which contain excess oxygen. The lower part of the tail CD (shock wave in the products, which is adjacent to the detonation front BC) moves forward, which is a consequence of channel expansion: with approximately identical values of the velocity of sound in the products and the angular velocity of detonation-wave rotation, the tail structure becomes stabilized with respect to the mean diameter of the channel, whose value decreases in the downstream direction.

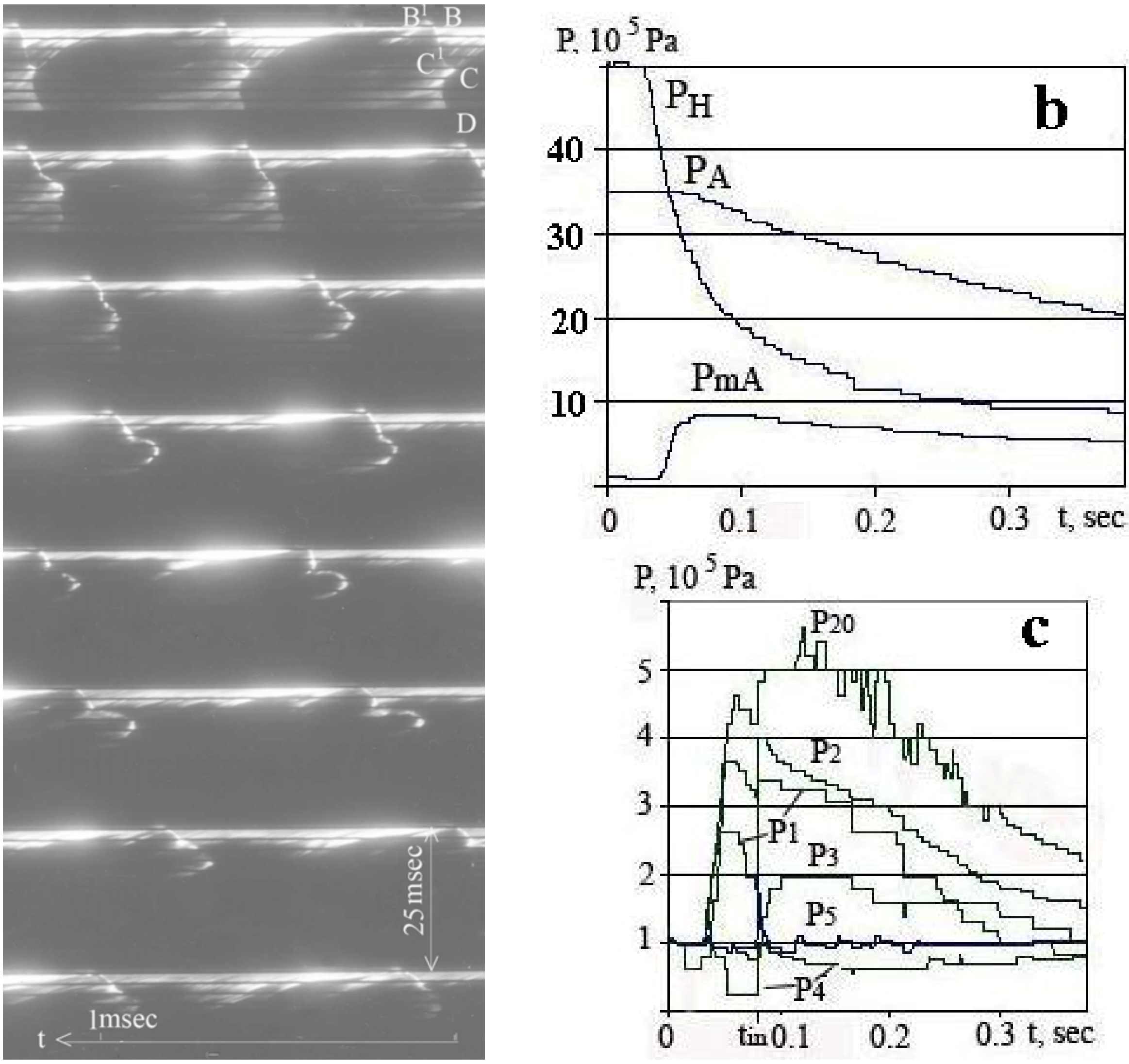

Figure 2. Continuous spin detonation in the combustor (test No. 1). Left: Fragment of photographic records. Right: Pressures of the mixture components in the injection system (b); pressures in the cylindrical and expanding channels (c).

Ahead of the front BC, the velocity of the mixture $v_z = k \cdot tg\alpha \cdot v_p$ (k = 40 is the zoom-out coefficient and α is the angle of inclination of the trajectory) continuously increases in the downstream direction as v_z = 0.57→2.37 km/s at the beginning of the experiment and as v_z = 0.54→1.15 km/s at the end of the experiment. At these maximum values of v_z, the detonation-front segment CC^1 is aligned at an acute angle to the streamlines. The horizontal detonation-front segment CC^1 is observed if the incoming flow velocity is greater than the Chapman-Jouguet detonation velocity (D_{CJ}) for a particular composition of the products (ϕ) at a given time in the axial direction [3]. Such a phenomenon is fairly natural in supersonic flows [4,5]. Thus, a situation occurs where the detonation-wave segment CC^1 ceases to move in the axial direction, but continues to rotate, because the entire detonation complex rotates over the circumference.

Hydrogen injection in the expanding part of the combustor. In these experiments (see Table 1, test No. 2), the distance between the outer wall of the combustor and the injector was 23 mm; therefore, mixing of the species was deteriorated, and the structure of the spin detonation wave was inevitably expected to be enlarged. Already in experiments with hydrogen injection at the beginning of channel expansion, however, there was only one spin detonation wave, i.e., the limiting regime in terms of the number of waves was already realized. Therefore, hydrogen injection in the expanding part of the channel could only ensure pulse detonation regimes with longitudinal detonation waves and with a frequency f = 0.77→ 1.1 kHz (Fig. 3).

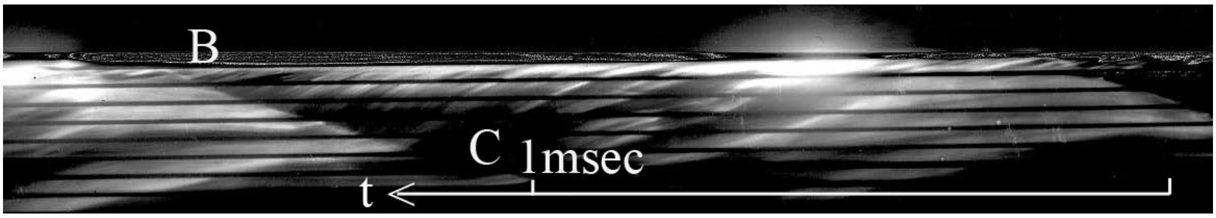

Figure 3. Fragment of photographic records of pulse detonation in the combustor (see the data in Table 1, test No. 2)

In a particular example of the process illustrated by the fragment of photographic records in Fig. 3, the flow velocity on the segment BC changes as v_z = 0.73 – 1.7 km/s, and the detonation-wave velocity calculated by the method of unfolding $D_{pz} = k \cdot tg\alpha \cdot v_p$ changes as D_{pz} = 1.4 – 0.61 km/s. Thus, the detonation velocity with respect to the flow is D_{pv} =2.13 – 2.31 km/s. These values are higher than the ideal Chapman-Jouguet detonation velocity, whose value in the stoichiometric region is D_{CJ} = 1.87 km/s [3]. Such a situation was observed previously for spin waves with hydrogen injection at the beginning of the expanding part of the channel (see Fig. 2,a). The process of pulse detonation is more stable in the stoichiometric region. Irregular TDWs appeared at the end of the process and were later replaced by unstable longitudinal waves.

4 Summary

Thus, stable continuous regimes of spin and pulse detonation of a hydrogen-air mixture in a supersonic flow generated in the rarefaction wave of the detonation wave were realized for the first time.

5 Acknowledgement

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