Initiation of Detonation of Hydrogen-Air Mixtures in a Flow-Type Annular Chamber

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1. Introduction

The issue of detonation initiation in fuel-air mixtures is of principal importance for practical applications of detonation combustion, including combustion in detonation engines [1,2]. It was demonstrated [3-5] that the detonation-initiation energy can be reduced to 0.1 J owing to formation of a special vortex flow [6,7] of the hydrogen-air mixture, and even self-ignition with a transitional regime within tenths of a millisecond can be ensured. Depending on the combustor geometry and its purpose, the primary detonation wave can be used to develop continuous spin detonation in this chamber or to initiate detonation in another fuel mixture outside the combustor. The objective of the present work was an attempt to initiate both pulse and continuous spin detonation in hydrogen-air mixture flows generated in a flow-type annular cylindrical combustor with the help of a detonation wave formed in a plane-radial vortex chamber.

2. Experimental setup

A sketch of the experimental setup is shown in Fig. 1. The setup consists of a flow-type annular cylindrical combustor *1* and a plane-radial vortex chamber (initiator) *2*. The combustor *1* had the following parameters: diameter d_{c1} = 306 mm, length L_{c1} = 520 mm, and channel width Δ_{c1} = 23 mm. The vortex chamber *2* has a diameter d_{c2} = 204 mm, the distance between the flat walls is Δ_{c2} = 15 mm, and there is an output coaxial channel *3*, which is 255 mm long and is formed between the outer wall (Ø 70 mm) and the shaft (Ø 40 mm). The initiator *2* is connected to the combustor *1* by the coaxial channel *3* and by a directed channel *4*, with a length of 200 mm and a distance of 20 mm between the curved walls. The distance from the end face of the combustor *1* to the channel *4* (L_i) was varied, and the values used were L_i = 27, 15.5, or 2 cm. The structure of the combustor *1* is completely identical to that where stable regimes of continuous spin detonation of the hydrogen-air mixture were obtained [8], and the structure of the vortex chamber *2* ensured fast initiation of detonation after self-ignition or the action of a low-energy heat pulse [3-5]. The fuel injected into chambers *1* and *2* was hydrogen.

Air was fed into the combustor *1* as a continuous flow through the annular slot *5* from the manifold *6*, and the fuel was injected through injectors *7* uniformly distributed over the chamber circumference, from the manifold *8*. The fuel and air mixed with each other and created a detonable flow of the mixture. The width of the slot *5* for air was δ = 2 mm, and the sizes of the injectors used (F1) are listed in Table 1.

Air was fed into the initiator *2* through the tangentially directed channels *9* from the manifold *10*, and hydrogen was fed through the channels *11* directed at an angle to the air channels, from the manifold *12*. The channels in the initiator for air (A2) and fuel (F2) were uniformly distributed over the circumference; their sizes are indicated in Table 1.

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The components of the mixture were injected from the receivers with the following volumes (not shown in Fig. 1) and initial pressures: for air fed into the combustor *1,* V_{rA1} = 79.8 liters and P_{rA10} = $23{\cdot}10^5$ Pa; for air fed into the vortex chamber *2,* V_{rA2} =3.2 liters and P_{rA20} = $93{\cdot}10^5$ Pa; for hydrogen fed into the combustor *1,* V_{rf1} = 13.3 liters and P_{rf10} = $(35 – 50){\cdot}10^5$ Pa; for hydrogen fed into the vortex chamber *2*, V_{rf2} = 1.75 liters and P_{rf20} = $78{\cdot}10^5$ Pa. The following initial flow rates of air were provided: G_{A10} = 2.8 kg/s into the combustor *1* and G_{A20} = 2.5 kg/s into the vortex chamber *2*. During the test, which lasted approximately 0.4 s, the flow rate of air decreased by a factor of 1.8, and that into the vortex chamber *2* decreased by more than tenfold. The initial flow rate of hydrogen into the combustor *1* was G_{f10} = 0.095 – 0.067 kg/s and decreased by a factor of 2.4 by the end of the process, and that into the vortex chamber *2* was G_{f20} = 0.044 kg/s and decreased by a factor of 7.5. The products exhausted into a tank 60 m^3 with a pressure $P_a = 10^5$ Pa.
The detonation in the initiator was excited by blasting a wire with an energy of ~5 J. The process in the combustor *1* was recorded in a manner similar to that described in [2]. To illuminate the process, a small acetylene jet and a coaxial oxygen jet were injected above the first window (in the vicinity of the slot for air injection). The exit of the channel *4* was located on the chamber surface opposite to that where the windows were located. The pressures in the receivers, air manifold *6* (P_{mA}), and fuel manifold *8* (P_{mf}), and the pressures in the combustor (P_{c1}, P_{c2}, P_{c3}) at a distance of 1.5, 10, and 52 cm (at the exit of the annular channel) and the moment of wire blasting were recorded by a computer-aided system. The flow rates of the gaseous components were determined by the method described in [5] in the transitional regime and by the method described in [9] in the steady-state regime.

3. Test results

To determine the effect of the location of the exit point of the initiating detonation wave (L_i) on the efficiency of initiation of spin detonation in the hydrogen-air mixture in the combustor *1,* the experiments were performed for three values of the parameter L_i = 2, 15.5, and 27 cm.
Figure 2 shows the oscillograms of pressures in the receivers and manifolds (Fig. 2,a) and in the combustor *1* (Fig. 2,b) for a typical test with an exit **distance L_i = 15.5 cm**. The pressure of hydrogen injection was $P_{rf10} = 35{\cdot}10^5$ Pa. This experiment involved the formation of spin detonation waves whose fronts first did not pass down to the channel *4*, but then partly crossed the channel. Thus, situations were observed, which were more clearly seen in tests with L_i = 27 or 2 cm described below.
When electromagnetic valves are opened, the transitional process of exhaustion begins, which involves filling of the manifolds and the combustor *1* by the mixture components. When the maximum pressures in the manifolds for both components are reached, the process of exhaustion from the injection system can be conventionally considered as steady, because the flow rates level off in the transitions mentioned above. As the components are injected from finite-volume receivers, the flow rates and pressures in the injection system and in the combustor decrease, but their values do not change as fast as in the transitional regime.
The time of initiation t_{in} (moment of wire blasting) is illustrated in Fig. 2,a. During the time of about 0.2 ms, the detonation wave formed in the vortex chamber *2* (see [4,5]) enters the combustor *1* with a jumplike increase in pressure (see Fig. 2,b). The following flow rates of the components were reached at the moment of detonation initiation: into the combustor *1,* G_{A1} = 2.02 kg/s and G_{f1} = 0.059 kg/s (ϕ = 1); and into the chamber *2,* G_{A2} = 2.53 kg/s and G_{f2} = 0.041 kg/s (ϕ = 0.56). The probe located at a distance of 10 cm from the slot showed the maximum static pressure: $P_{c2} \approx 4{\cdot}10^5$ Pa; the minimum pressure $P_{c3} \approx 2{\cdot}10^5$ Pa was recorded at the chamber exit.
The photographic records in Fig. 3 show the beginning of the transitional process of formation of continuous spin detonation in the combustor and its further evolution. The first wave observed in the windows was the detonation wave propagating over the mixture accumulated in the combustor; the wave moved in the direction defined by the channel *4* (see Fig. 1). After passing the channel *4,* the wave covered half of the combustor circumference. Then, 0.1 ms later, a smeared shock wave appeared. This is the image of the degenerate detonation wave that started from the channel *4* in the opposite direction. After these waves traveled several times over the combustor circumference, there

appeared tangential instability in the form of acoustic disturbances on the background of combustion of the mixture entering the chamber. This instability was developed into continuous spin detonation during a rather significant time: about 10 ms. By that time, the fuel-to-air equivalence ratio became ϕ = 0.74 and decreased only slightly by the end of the experiment: ϕ = 0.63. Three spin detonation waves formed had a velocity D = 1423 m/s (D/D_{CJ} = 0.84, where D_{CJ} is the velocity of the ideal Chapman-Jouguet detonation for the mixture with this composition [10]). As the flow rates of the components decreased, the detonation velocity also decreased. In 40 ms, there occurred a rapid change in the number of waves (n = 3 → 2), and the detonation velocity had a jump: D = 1104 → 1207 m/s (D/D_{CJ} = 0.65 → 0.71). The two-wave regime lasted approximately for 200 ms, and then it suddenly transformed to the one-wave regime (in figure 3 is not shown): n = 2 →1 and D = 1170 → 1345 m/s (D/D_{CJ} = 0.68 → 0.8). The one-wave detonation regime was observed until the end of the process with the detonation velocity decreasing to D = 1160 m/s (D/D_{CJ} = 0.7).

In the test series with L_i = 2 cm, detonation was initiated when the flow in the vortex chamber *2* was steady and the flow in the combustor *1* was unsteady. The initial pressure of hydrogen in the receiver of the combustor *1* was $P_{rf10} = 50\cdot10^5$ Pa. The remaining parameters of injection of the components into both chambers were unchanged. The propagation of the primary detonation and shock waves in the combustor *1* was similar to that considered above (L_i = 15.5 cm). Yet, the time needed for the tangential instability to be developed into stable spin detonation waves increased to 80 ms. Four waves were formed; their velocity was D = 1422 m/s (D/D_{CJ} = 0.75); after 45 ms, the structure transformed to three waves: n = 4 → 3 and D = 1233 → 1363 m/s (D/D_{CJ} = 0.65 → 0.71). The three-wave regime lasted for 175 ms, after which the number of waves again decreased, and the wave velocity changed: n = 3 → 2 and D = 1333 → 1520 m/s (D/D_{CJ} = 0.7 → 0.8). The two-wave regime existed until the end of the process, with a monotonic decrease in wave velocity and flow rates of the components, whose ratio remained close to the stoichiometric value. The flow rates of the components in the vortex chamber *2* during the process was similar to that considered above.

In the test series with L_i = 27 cm, detonation initiation was performed both with steady injection of the initial components into the combustor *1* and in the transitional regime. Some cases were observed with self-ignition of the vortex flow of the mixture with a rapid transition to detonation in the vortex chamber *2*. In the oscillogram, the self-ignition was accompanied by an abrupt increase in pressure in the combustor *1* before wire blasting in the vortex chamber *2*. Detonation regimes where the initiating detonation wave entered the combustor *1* before the components were injected were also obtained. The following flow rates were reached in the vortex chamber *2* at the moment of detonation initiation: $G_{A2} \approx 2.04$ kg/s and $G_{f2} \approx 0.036$ kg/s (ϕ = 0.61). In the combustor *1*, the initiating detonation wave degenerated into a shock wave, but the detonation products ignited the acetylene-oxygen jets. The flow rate of the acetylene-oxygen mixture was estimated as approximately 20 g/s ($\phi \approx 1$). As the components were fed into the combustor *1* (first air and then hydrogen), hydrogen ignited, and the tangential instability transformed to stable spin detonation waves 7 ms after hydrogen ignition. During this time, the flow rates of the components in the combustor acquired the following values: G_{A1} = 2.6 kg/s and $G_{f1} \approx 0.095$ kg/s (ϕ = 1.26), and the static pressures in the combustor P_{c1}, P_{c2}, and P_{c3} were 3.5, 2.5, and $2.4\cdot10^5$ Pa, respectively. The spin detonation regime had the following sequence: the four-wave spin detonation regime with D = 1405 m/s (D/D_{CJ} = 0.74); 100 ms later it transformed into the three-wave regime (D = 1207→1345 m/s and D/D_{CJ} = 0.64 →0.71); after that, 140 ms later, it transformed into the two-wave regime (D = 1254→1460 m/s and D/D_{CJ} = 0.67→0.78), which lasted until the end of the experiment.

4. Analysis of experimental results

In all tests, the detonation of the hydrogen-air mixture was transferred from the vortex chamber *2* into the combustor *1*. An input of a small amount of energy (wire blasting or even self-ignition) was capable of initiating detonation in the initiator within fractions of a millisecond and transferring it to the flow of the mixture in the annular cylindrical combustor. In the experiments, the energy of the electric discharge on the wire was deliberately increased to 5 J to ensure detonation initiation in the vortex chamber *2* in a wide range of equivalence ratios. If the injection of the mixture into the combustor *1* is accurately synchronized with the initiation time, the discharge energy can be reduced, and even self-ignition in the vortex chamber *2* can be achieved [5].

It was found that the primary detonation wave or two primary waves (for L_i = 2 cm) developed in the annular cylindrical channel and moving toward each other do not involve direct initiation of spin detonation waves. Note that a similar delay was observed in initiation of the continuous spin regime in the annular combustor by means of an electric detonator [8]. There may be only one reason: the detonation of the combustible mixture formed in the combustor *1* and outside it affects (via the shock wave and the flux of products) the system of injection of the components and violates their nominal injection into the combustor. This primarily refers to air injection, which enters the combustor through the annular slot.

Detonation in the combustor *1* was accompanied by exhaustion of the products from the vortex chamber *2*. This circumstance affected the value of pressure in the combustor *1* and the dynamics of formation of continuous spin detonation. It turned out that continuous spin detonation becomes established most rapidly if the exit of the channel *4* is located at a distance L_i = 27 cm, and the time of the transitional process approaches that obtained in [8]. In this variant, the upper edge of the channel *4* was always located below the TDW front even in the one-wave regime, where the height was $h \approx 24$ cm. In the case of a greater number of waves, the TDW front height became even smaller: 12, 6, and 4 cm, respectively, for the number of waves n = 2, 3, and 4. Therefore, the detonation products arriving from the vortex chamber *2* did not reach the mixing zone in the combustor *1*. The emergence of the fourth wave at the beginning of the process is related to the pressure increase in the combustor (almost by a factor of 2), as compared with the situation in [8], without additional injection of the products from the vortex chamber *2*. When the flow rate of the products from the vortex chamber *2* significantly decreased ($G_{A2} \approx 0.6$ kg/s, $G_{f2} \approx 0.01$ kg/s after 0.2 s), the height of the TDW front started to correlate with the data obtained in [8]. Nevertheless, the influence of the products generated in the chamber *2* was manifested as an increase in pressure in the mixing region.

In the variant with L_i = 15.5 cm, the products from the chamber *2* did not enter the mixing region at the stage of the spin detonation regime with three and two waves; at n = 1, however, they entered the mixing region, at least, in the vicinity of the channel *4*. This did not produce any noticeable changes in the process; moreover, the one-wave regime emerged at the end of the process with reduced flow rates of the products from the chamber *2*.

At L_i = 2 cm, the beginning of the process revealed a strong influence of the products escaping from the chamber *2* on the mixing in the combustor *1*, because the exhaustion of the products always occurs in the region of propagation of the TDW front. It was only when the flow rates of the products decreased by a factor of 2 ($G_{A2} \approx 1.1$ kg/s and $G_{f2} \approx 0.028$ kg/s for hydrogen) that the spin detonation in the combustor *1* became stabilized. It should be mentioned that the length of the air manifold of the combustor *1* in this case was L_m = 21 cm, instead of 7 cm in the previous cases. This increase, however, did not affect the stable detonation process.

The presence of a long transitional process of stabilization of the continuous spin detonation regime in the case of initiation by the detonation wave suggests that combustion products can be used for this purpose. This method has gained wide application for startup of rocket and aircraft engines. Our experiments also confirm that the jet of hot products initiates continuous spin detonation, and the duration of the transitional process is not longer than that in the case of direct initiation by the detonation wave. Ranque tubes seem to be fairly suitable for generation of the jet of the products; these tubes can operate even on a kerosene-air mixture in regimes admitting self-ignition [11]. Possibly, a powerful electric discharge can also be used, which can ignite the fuel-air mixture in the main chamber with a further transition to continuous spin detonation. The most “soft” and reliable conditions of initiation are provided thereby.

5. Conclusions

1. Detonation transfer into a flow of a hydrogen-air mixture is ensured by means of an initiating detonation wave formed within fractions of a millisecond with addition of a small amount of energy or self-ignition of the hydrogen-air mixture in a plane-radial vortex chamber.
2. The formation of continuous spin detonation of the hydrogen-air mixture in a flow-type combustor by this method involves a transitional process that lasts for several milliseconds, which is due to the action of the initiating wave onto the injection system and violation of injection of the components of the mixture, especially of air.
3. The transitional process displays conventional combustion of the mixture and evolution of tangential instability with a transition to a stable detonation regime. Therefore, “soft” jet-induced initiation of continuous spin detonation of the fuel-air mixture by combustion products can be provided in a flow-type combustor.

Acknowledgments

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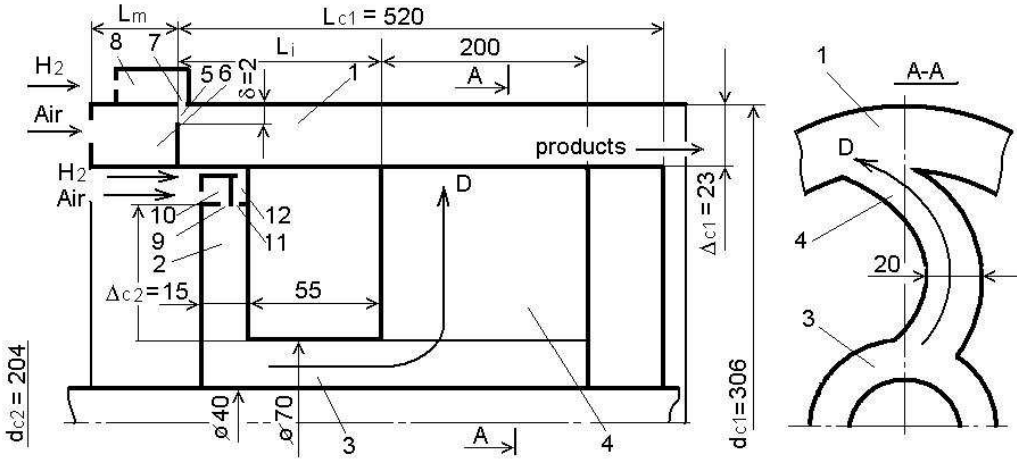

Figure. 1. Experimental setup.

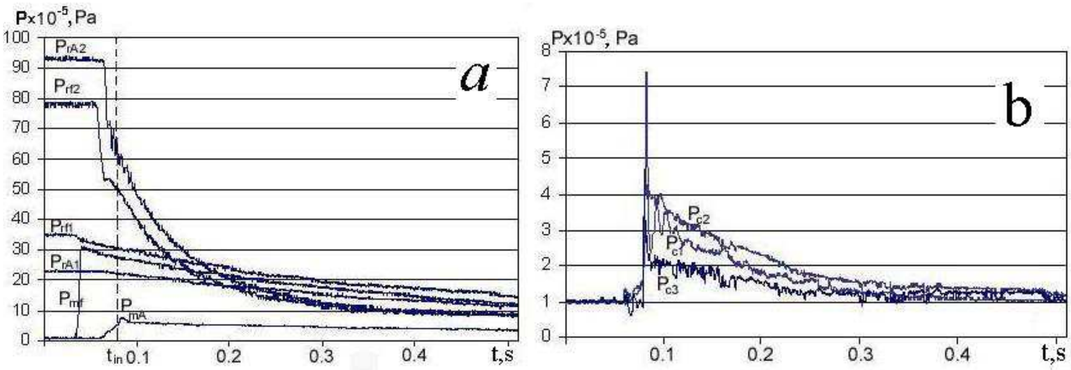

Figure 2. Oscillograms of pressures in the receivers and manifolds (a) and in the combustor *1* (b).

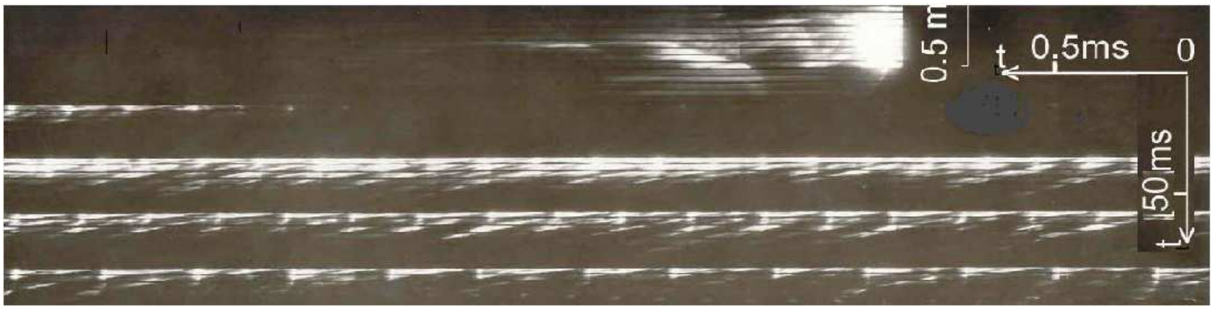

Figure 3. Photographic records with the beginning of the transitional process and further development of continuous spin detonation in the combustor.

Table 1. Parameters of injectors.

Injector	Cross-sectional area of the orifices, mm^2	Number of orifices	Total cross-sectional area of the orifices, mm^2
F1	1.0x1.0	200	200
F2	0.25x0.3	180	13.5
A2	1.0x4.0	50	200