Detonation Acceleration Research in Pulsed Combustor

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1 Introduction

Nowadays many scientific laboratories and aerospace research centers have a reasoned interest in developing absolutely new engines so-called "Pulsed Detonation Engines" (PDE) based on the use of detonation for combustible mixtures combustion [1–6]. PDE is a semienclosed tube which fills up with the combustible mixture, where a detonation wave triggers. Reaction products flowing out of the open tube end at a high speed create the jet thrust. This work describes the features of the deflagration-to-detonation transition at a weak initiation in the pulsed combustor (PC), i.e. the model of the pulsed detonation engine. Also the work presents the evaluation of the possibility and degree of acceleration of the DDT under the same conditions of initiation in the PC fitted with an obstacle of different porous structures prior to the flame front propagation. The hydrogen / oxygen / air mixture is used as a working charge in different fuel / oxidizer ratios.

2 Experimental design

The pulsed combustor (PC) – a model of the PDE – has been designed in the laboratory of physical-chemical hydrodynamics of A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus in two versions. The PC consists of semienclosed sectionalized steel tube 1 with mixing chamber 2 (figure 1): the first version is of d = 21 mm in diameter and L = 760 mm in length; the second version is of d = 25 mm in diameter and L = 740 mm in length. The ignition of the combustible mixture is carried out by an automotive spark plug. The PC is provided with a gaseous panel and a digital measuring system to control input parameters and signals on the actuating mechanisms, collection, processing and storage of test data.

Mixing chamber 2 has three sections with the special configuration elements which provide separate feeding of the combustible mixture components (hydrogen, oxygen, air) and their mixing in the tube (figure 3, a).

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The working process of the PC is of cyclical nature with the capacity to combust hydrogen / oxygen / air mixture in the wide range of equivalent ratio ϕ.

Different initial parameters of the PC working process were examined during the experiment in the wide range of the variation: the number of the fed hydrogen, oxygen and air in one cycle, the frequency and total amount of cycles, the duration of an electric signal on the spark plug, the delay duration of the gaseous inflow start and lighting.

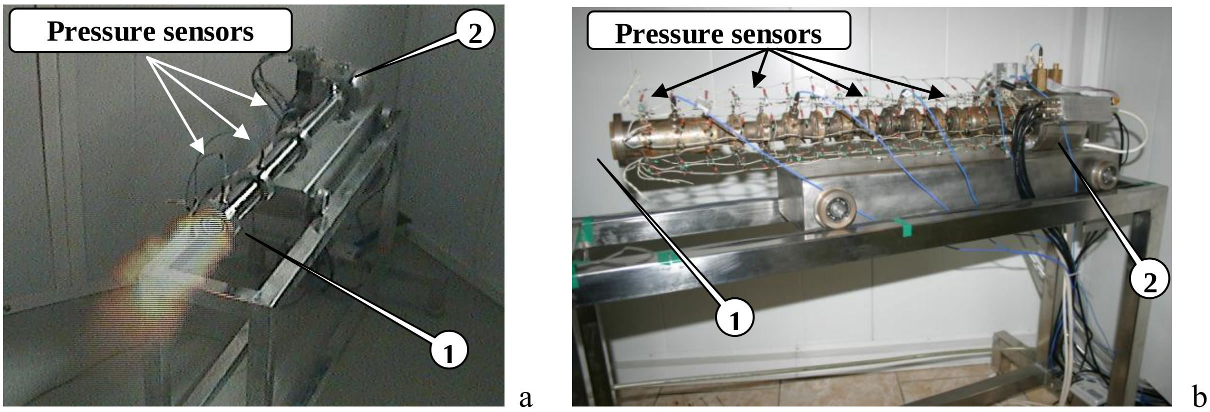


Figure1. General view of pulsed combustor (two versions)

The detonation wave velocity in the tube can be determined using the basic method of the signals of piezoelectric pressure gages Piezotronics PCB (figure 1). The gages are placed along the tube and form: two measuring bases in the first tube version of L_1 = 213 mm and L_2 = 160 mm in length; three identical measuring bases in the second tube version of L = 157 mm in length (in the direction of the flame front).

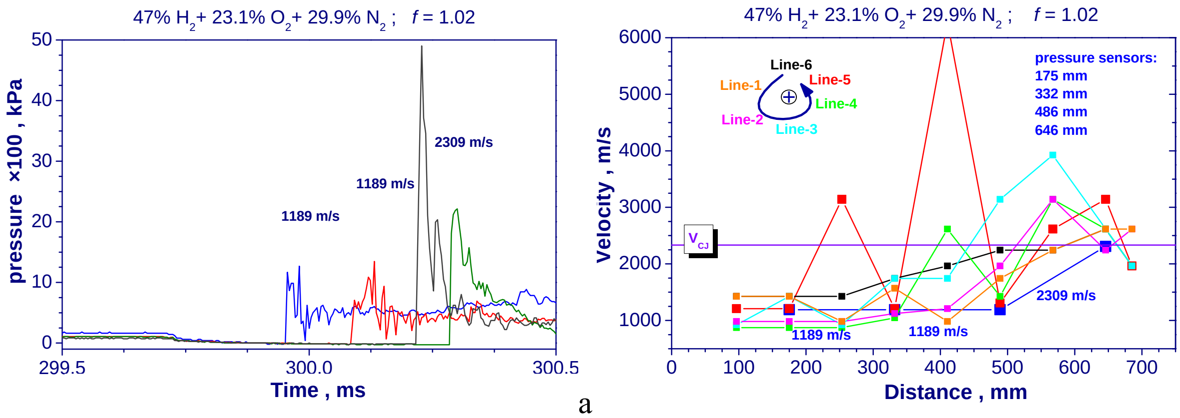
3 Test results and interpretation

Different conditions of detonation excitation and progress were studied in the PC. The dynamics of the wave velocity in the hydrogen / oxygen / air mixtures at ϕ = 1.02 measured with the help of four piezoelectric pressure gages and 54 ion probes is showed in figure 2. Pressure gages are located along the tube and form three identical measuring bases L_1 = 157 mm in length each. Ion probes are placed in orthogonal order produced by nine cross-sections located at the same distance from each other and six longitudinal lines evenly wrapped around the tube throw every 60 º with the anticlockwise numbering (figure 2, *b*). Ion probes form 8 identical measuring bases L_2 = 78.5 mm in length each along the tube.

It can be seen on figure 2, that the flame front velocity rises rapidly and detonation practically generates in all cycles at the distance of 20–22 of the combustor diameter. It makes about 500–550 mm from the igniter. Therewith, if the wave velocity at ϕ = 1.814 reaches 1805 m/s on the third measuring base (less than the velocity in Chapman-Jouguet point), the detonation wave at ϕ = 0.982 becomes over-compressed and speeds up to 2453 m/s at the same distance from the igniter. This means, that the positive influence of the turbulent flow on the detonation forming shows better in the range of the stoichiometric composition mixture than at the combustion of lean and rich mixtures due to the availability of a huge volume of ballast nitrogen or a significant lack of the oxidizer in the mixture.

The ion probes fixed simultaneously the detonation wave advancing in different points both along the tube and its section perimeter. This shows, that the detonation wave has a difficult configuration and a multispectral structure, and its velocity is irregular not only regarding the chamber length, but also time and space.

The quantitative assessment of the flow turbulization of the combustible mixture shows, that the Reynolds number has high values ($Re > 2 \cdot 10^4$), which apparently is a key factor in the flame front acceleration and detonation waves formation both by time and space. This conclusion can be proved by the work [7] which states that, the flame velocity is determined by the pulsation turbulent velocity only and does not depend on the normal speed, i.e. on the chemical factors (mixture composition, fuel type, etc..) at the intensive large-scale turbulence (its scale is much bigger than the combustion zone width).

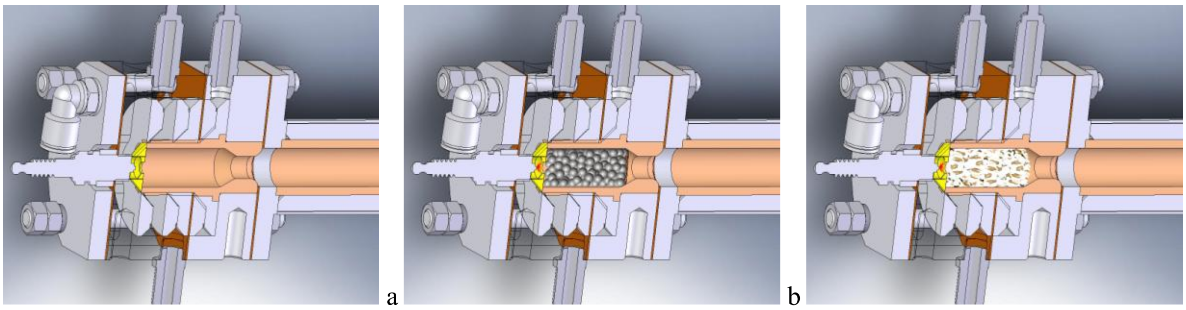


b

Figure 2. The diagram of the wave expansion at the combustion of the hydrogen/oxygen/air mixture with ϕ = 1,02: *a* – pressure in four tube sections; *b* – detonation velocity (by the signals of the ion probes)

One of the effective methods to reduce the predetonation length is the use of obstacles of different types, namely, modifications of the Shchelkin spiral. Thus, the authors of [8] describe the method of reducing the predetonation period and the distance in a pipe by placing regular profiled obstacles for the flame front propagation. It is shown that profiled parabolically-shaped obstacles are more efficient for the combustion-into-detonation transition than rectangular ones.

The aim of the second part of present work is the evaluation of the possibility and degree of acceleration of the combustion-into-detonation transition under conditions of weak initiation in a pulsed combustor (PC) fitted with an obstacle of porous structure prior to the flame front propagation. We decide to test and compare two types of porous media (figure 3): 95 steel balls (d_b = 5.5 mm) and ceramic porous body (L = 48 mm; d = 21 mm), that were used in our different previous experiments. A mixture of hydrogen with oxygen and air was used as a working body.



a b c

Figure 3. Mixing chamber of the PC with: a) a hollow cavity; b) 95 steel balls (d_b = 5.5 mm); c) a ceramic porous body (L = 48 mm; d = 21 mm)

The excitation conditions, measured pressures, detonation and thrust velocities for mixtures of hydrogen with oxygen and air are given in Table 1.

Table 1: Parameters of the operating process of the PC with a porous obstacle and without it during combustion of mixtures of hydrogen with oxygen and air (the values of V_{CJ} are calculated with the aid of program Chemkin-III)

Central void of tube	**Frequency, Hz**	ϕ	**V_D, m/s**		**V_{CJ}, m/s**	**Porosity ψ**
			Base 1 (*L* = 213 mm)	**Base 2 (*L* = 160 mm)**		
Empty	12.5	0.83	1238	1739	2184	1.00
Balls	12.5	0.70	2365	1952	2057	0.50
Ceramic	16.67	0.80	2219	1905	2169	0.83

Figure 4 presents the dependences of pressure and detonation wave velocity on time and the distance from the PC axis for a lean mixture of hydrogen with oxygen and air in the presence of a porous obstacle and without it in the pipe. It is seen that during the propagation of the flame front in a hollow channel, the transient regime appears only on the second base at a distance of about 28 PC diameters from the source of ignition, with the failure for the velocity to reach the Chapman—Jouguet point. In the presence of a porous obstacle for the flame front, the pattern of combustion development is different.

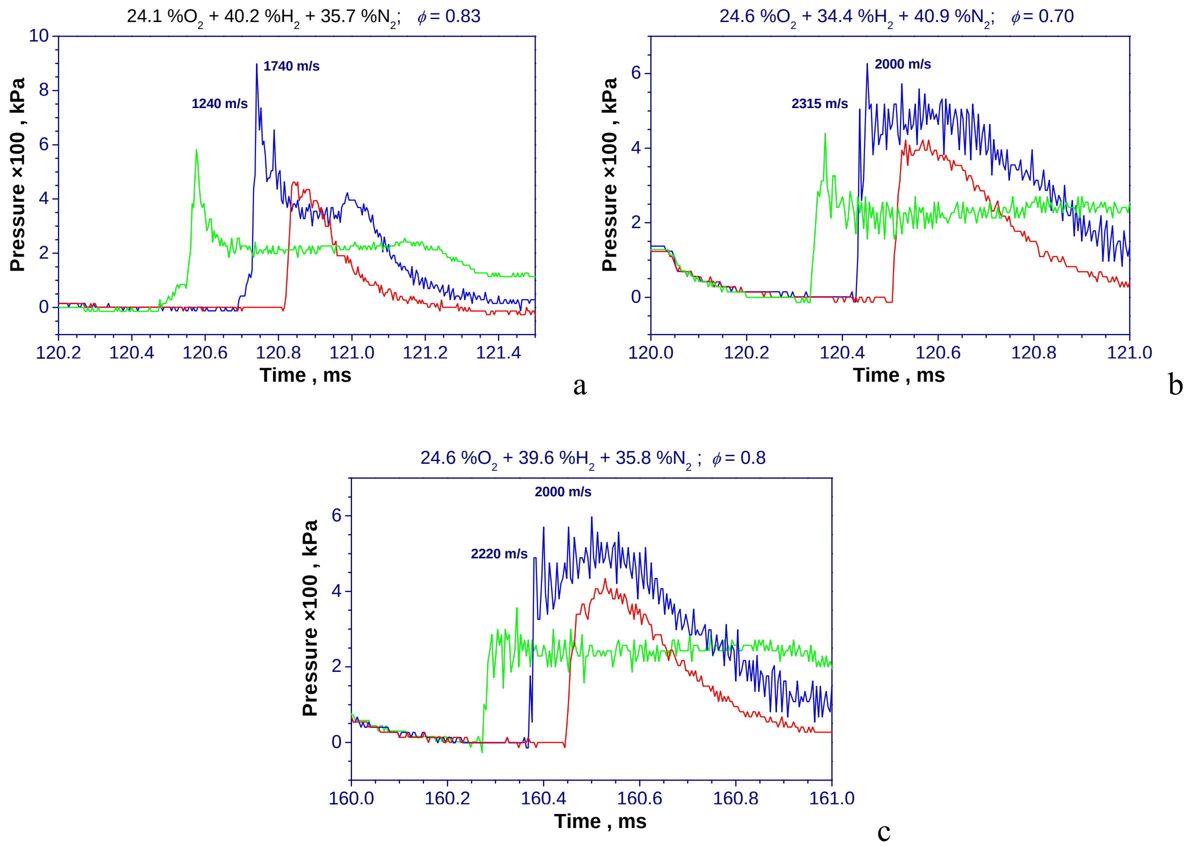


Figure 4. Diagram of combustion-into-detonation transition in mixtures of hydrogen with oxygen and air in the PC with: a) a hollow cavity; b) 95 steel balls (d_b = 5.5 mm); c) a ceramic porous body (L = 48 mm; d = 21 mm)

While in the absence of an obstacle, the flame front at the 18th gauge accelerates up to 1230—1250 m/s and by the end of the 28th gauge up to 1730—1750 m/s, then during propagation in a pipe with a porous obstacle the detonation wave becomes overcompressed already on the first measuring base and on the second base it decelerates to about 2000 m/s. In this case, a porous obstacle in the form of metal balls more favorably influences the formation of detonation than the ceramic material. The detonation velocity in the pipe filled with balls exceeds the velocity of the wave passing through the ceramic medium by about 7% despite the fact that the combustible mixture in the former case has a lower energy density (by about 12%) than in the latter.

Based on the foregoing, we may conclude that the use of a porous obstacle makes it possible to attain a steady-state detonation and reduce the predetonation length by about 40%.

4 Conclusions

The capacity of the detonation formation in the hydrogen / oxygen / air mixtures in the pulsed detonation combustor of small lengths is established.

The detonation waves generate owing to intensive turbulent pulsations and flow irregularity created due to a special form of the mixing chamber elements. It leads to the reduction in the pre-detonation area and speeding up of the combustion to detonation transition.

It is established, that detonation velocity in the hydrogen / oxygen / air mixtures makes 1800-2500 m/s depending on the PC configuration, the initial conditions and the equivalent coefficient (ϕ = 0.65–1.82).

The presence of a porous obstacle for the flame front, irrespective of the nature and structure of this obstacle, results in a different pattern of the formation of detonation consisting in the reduction (by about 40%) of the predetonation distance and in the increase (by about 36%) of the upper value of the velocity of detonation wave.

Detonation is more sensitive to a porous medium involving steel balls where the detonation wave velocity exceeds that in a pipe with a ceramic insert by about 7% despite the fact that a combustible mixture in the former case has a lower energy density (by about 12%) than in the latter case.

The problem of reducing the predetonation period and distance solved within the framework of the present investigation will allow one to improve the specific characteristics of PC by decreasing its length and mass.

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