High-frequency pulsed detonation combustion

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Abstract

The main idea of these studies is to use the energy release distribution associated with a 3-D geometry of the combustor and fuel-oxidizer flows for self-amplification of combustion driven shock wave up to critical state when the onset of detonation or supersonic deflagration occur. A high-frequency pulsed detonation combustor is considered here as a single self-consistent system, where evolution of reactive flows should regenerate and multiply the local regions of high-energy release “hot spots”, sustaining the continuous propagation of detonation and supersonic deflagration along the certain trajectory of the device. The proposed concept implies the using of combined operation regimes at usual and detonation combustion modes. The combination of pulse detonation cycle, or constant volume cycle, with other air-breathing and rocket cycles offer can increase overall system performance at various flight conditions.

The experimental investigations showed the possibility of steady quasi-continuous high-frequency pulse detonation operation with acetylene-air mixtures. The stable self-sustained pressure oscillations with frequency of $\approx 2.5\ kHz$ and amplitude of about $2.5\ atm$ have been detected at the thrust wall of the device during several experimental runs with acetylene-air mixtures at different equivalence ratios.

1. Introduction

The detonation can offer a net advantage over usual combustion due to rapid energy release and higher temperature of combustion products. This regime supports very high mass flow rate and is promising for propulsion applications in terms of specific power, efficiency and simplicity. During past decades, several principal schemes of propulsion systems operating at the detonation combustion mode have been proposed and tested experimentally. The first one applies fuel combustion in a rotary transverse detonation wave propagating in annular cylindrical chambers [1-3]. In this case, a high-frequency continuous operation of the device is supported by transverse detonations running along the closed path, where the reaction products are pushed out towards the exit cross-section and substituted by a fresh mixture. The second pattern uses fuel combustion in a standing detonation wave. This implies that the incident flow Mach number is higher than the normal Chapmen-Jouguet (CJ) detonation velocity of the mixture used for propulsion [4]. The third scheme (the pulsed detonation engine, or PDE) applies fuel combustion in occasionally generated detonations traveling along the combustor [5-8].

Pulse (>60 Hz) detonation combustors have been developed over the past 25 years by several commercial companies and laboratories in configurations consistent with aerospace propulsion applications. These combustors have an advantage over traditional near-constant pressure combustors in being more thermodynamically efficient by approximating constant volume (pressure gain) combustion. Pulse detonation based propulsion systems can be broadly classified into three categories. Pulsed Detonation Engines (PDE's) are the simplest systems consisting of an array of detonation tubes, an inlet, and a nozzle. Combined-cycle PDE systems consist of a PDE combined with a ramjet/scramjet flow path or other propulsion cycle. Hybrid PDE's make use of detonative combustion in place of constant pressure combustion, usually in combination with turbomachinery. Claimed advantages of PDE’s over usual propulsion devices are the following: no moving parts; high thermodynamic efficiency; operating in a potential large Mach number range (from 0 to 4-5); simplicity and flexibility of geometrical configuration; easy integration to the vehicle; low cost.

For any of PDE’s systems, the unsteady detonation and combustion processes occur at complex boundary and flow conditions and have major impacts on propulsion performance at all. The main idea of this study is to use the energy release distribution associated with a 3-D geometry of the combustor and fuel-oxidizer flows for self-amplification of combustion driven shock wave up to critical state when the onset of detonation or supersonic deflagration occur. The high-frequency pulsed detonation combustor (HFPDC) is considered here as a single self-consistent system, where development of reactive flows should regenerate and multiply the local regions of high energy release “hot spots”, sustaining the continuous propagation of detonation and deflagration along the certain trajectory inside the device. The HFPDC design is based on the flame acceleration up to detonation velocities in the part of reacting flow across the device. This acceleration is produced by local pressure and temperature amplifications along a privilege direction resulting in a short auto-ignition time of incoming mixture. The leading shock wave converging on flow and mixture inhomogeneities and shock reflections from confinement walls [9-14] create the spatial pressure and temperature distributions required for continuous self-sustained detonation propagation.

The goal of the project is to develop hybrid air-breathing PDE’s operating at high-frequency (> 2.0 kHz) pulsed detonations. The continuous work of the device should be attained by self-amplification of combustion driven shock wave along the closed trajectories inside the combustor due to flow and mixture inhomogeneities, and geometry of the device. A surrounding fuel-air mixture will react at near constant pressure combustion cycle. Thus, the proposed concept implies the using of combined operation regimes at usual and detonation combustion modes.

2. Experimental setup

Figure 1 presents the schematic diagram of high-frequency pulsed detonation (HFPD) chamber. The HFPD device operates as follows:

When starting up the device, the fuel and an oxidant simultaneously enter both auxiliary detonation chambers $\varnothing 12$-mm in diameter (2) and primary detonation chamber $\varnothing 71$ mm in diameter (1) in which the mixture is ignited. The formed detonation wave propagates both in primary and auxiliary combustion chambers.

Rarefaction zones accompany the outflow of combustion products and facilitates filling of the device with fresh fuel-air mixture. The lengths of primary L_1 and auxiliary combustion chambers L_2 are selected so that when the shock wave that is reflected from the thrust wall of the primary detonation chamber (3) and reaches the output section of the auxiliary chambers (2), they are already partly filled with fresh reactive mixture by means of injectors for fuel and oxidizer (4). Incident shock wave is reflected from concave end wall of the auxiliary chamber (5) and initiates locally detonation wave due to the shock focusing. When detonation wave leaves the auxiliary chamber (2), the primary chamber (1) is already filled with fresh reactive mixture. The emerging detonations reignite it and propagate towards the thrust wall of the primary chamber (3). Simultaneously, combustion products outflow from the auxiliary chamber and it is filled with fresh fuel-air mixture through fuel oxidizer ports (4). Then the process recurs.

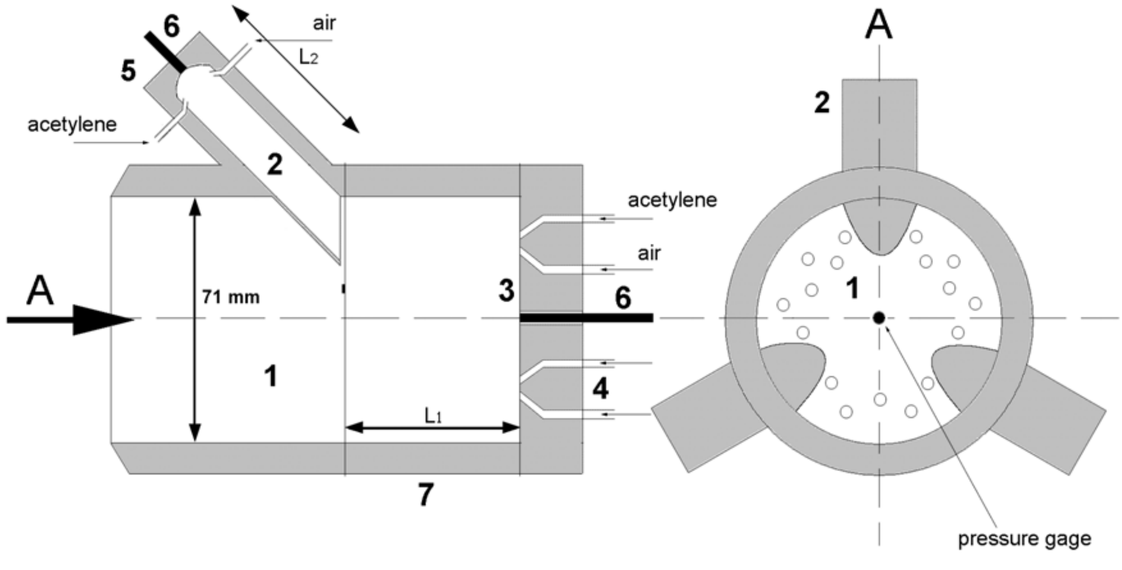

Figure 1: Schematic diagram of High-Frequency Pulsed Detonation Chamber: 1- primary detonation chamber; 2- auxiliary detonation chambers; 3 –thrust wall; 4- fuel –oxidizer ports; 5 – concave end wall of auxiliary detonation chamber; 6 – high-frequency pressure sensors; 7 - insert.

The using of profiled end walls of the auxiliary chamber (5) allows initiating stable detonations, increasing functioning cycle frequency, and decreasing device dimensions. Several auxiliary chambers (2) are mounted along the perimeter of the primary chamber to increase the stability and operation efficiency of high-frequency pulsed detonation device. Lateral and front views of HFPD combustor are given in Figure 1. High frequency pulsed detonation device consists of primary detonation chamber and three auxiliary detonation ones. Fuel and air are supplied to primary detonation chamber at ambient temperature using *6-mm* tubes connected with *25* injecting apertures. A number of $\varnothing$ *1.2-mm* apertures uniformly distribute fuel and oxidizer along circumference of the primary chamber. To improve the mixing fuel and oxidizer jets are fed at $90°$ towards each other. Similarly, auxiliary detonation chambers are filled with fuel and air by means of two $\varnothing$*1.2 mm* injecting apertures directed at $45°$ to the axis of auxiliary chamber.

The used fuel-oxidizer supply system provides the total mass flow rate through HFPDC of up to *150* grams per second. Acetylene–oxygen and acetylene–air mixtures were used in experiments. The mass flow rate per each individual fuel-air ports is controlled via pressure meters. Fuel and oxidizer mass flow rates in the auxiliary and primary detonation chambers as well as equivalence ratio of resulting mixture were controlled by setting the values of initial pressure at pressure meters prior to opening of electromagnetic valves switching on fuel-oxidizer flows. Mass flow rates were calculated, assuming the supercritical pressure drop at injecting apertures.

The design of high frequency detonation chamber allows varying quickly and flexibly its major geometrical dimensions and parameters. For example, replacing a part (3) (Fig. 1) allows modifying mixing geometry and thrust wall shape. Changing insert (7) makes it possible to vary the volume, length and shape of the primary detonation chamber. By replacing inserts (5), one can vary the volume and shape of auxiliary chambers. Thus, experimentally one can empirically select the most efficient dimensions and geometry of the design for each particular mixture and flow conditions.

To record and analyze operating modes of HFPD combustor, piezoelectric pressure transducers (6) were mounted on the axis of the thrust wall and the bottom of an auxiliary chamber. Fig. 2 shows a typical pressure records when making calibration procedure behind the reflected shock wave. As seen in the figure, these sensors provide non-resonant ultra-high frequency output when subject to instantaneous, reflected (face-on) shock wave inputs. All pressure sensors were equipped with electronic converters which convert pressure input into a high frequency response output signal insensitive to cable length. Pressures were registered continuously by using six-channel digital oscilloscope interfaced with PC. Signal registration was made at the rate of up to *10* Msamples per second within up to *1.5* seconds.

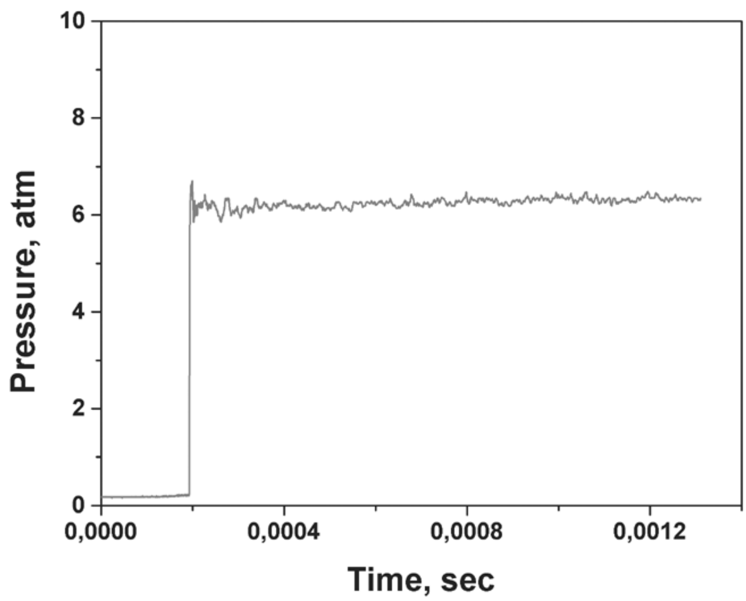

Figure 2: Typical pressure records behind reflected shock wave in air for piezoelectric sensors used for pressure measurements in High Frequency Pulsed Detonation Combustor.

3. Experimental data on high-ferquency pulsed detonation operation in acetylene-air mixtures.

Both means have been applied to adjust the high-frequency self-sustained pulsed detonation combustion. The first one supposes the changing of apparatus geometry. As is seen in Figure 1, HFPDC design allows modifying lengths L_2 , L_1 of auxiliary (2) and primary (1) detonation chambers. The second means implies varying mixture compositions and mass flow rates in different fuel-air ports. These tools have been applied to attain a stable quasi-continuous HFPD combustion.

About *20* experimental runs of HFPDC in quasi-continuous regime were made with acetylene-air mixtures. Some relevant experimental conditions for acetylene and air runs are given in Table 1. The typical operation time for each run was about *0.7 sec*.

Figures 3, 4 present the typical pressure records during HFPDC tests observed for several test conditions. As seen in the figures, the stable self-sustained pressure oscillations with frequency of ≈ *2.5 kHz* and amplitude of about *2.5 atm* have been detected at the thrust wall and at the bottom of auxiliary combustion chamber. Fourier analysis of pressure signals also reveals a low-frequency component of pressure variations from *100* to *300 Hz* with approximately the same amplitude at the trust wall of the primary combustion chamber. Such steady self- oscillating combustion behavior in HFPDC was observed during several experimental runs in acetylene-air mixtures with different equivalence ratios. A movie of HFPDC operation corresponding to these self- oscillating regimes shows flames coming out the back of the device and a pressure trace with high frequency and relatively low amplitude.

Table 1: Experimental data for HFPD operation

	Primary detonation chamber			**Auxiliary detonation chambers**				
Exp. N	**Air flow rate g/sec**	**C_2H_2 flow rate g/sec**	**Equivalence ratio ϕ**	**Air flow rate g/sec**	**C_2H_2 flow rate g/sec**	**Equivalence ratio, ϕ**	**Test time sec**	**Result**
1	41	5.9	1.9				1	No detonation
2	53.5	5.9	1.5				1	No detonation
3				10.0	1.48	1.95	1	No detonation
4				13.0	1.48	1.51	1	No detonation
5	***41***	***6***	***1.94***	***10***	***1.48***	***1.95***	***0.75***	***HFP operation Fig.3***
6	43.3	4.9	1.48	13.0	1.48	1.51	0.75	***HFP operation***
7	55	5.4	1.3				0.75	No detonation
8				15	1.5	1.32	0.75	No detonation
9	***55.0***	***5.4***	***1.3***	***15***	***1.5***	***1.32***	***0.75***	***HFP operation Fig.4***
10	40	3.1	1.03				0.75	No detonation
11	55	4	0.96				0.75	No detonation

4. Conclusions

The visibility of high-frequency pulsed detonation operation is demonstrated experimentally in the device consisting of main and auxiliary combustion chambers.

Performed experimental investigations showed the possibility of steady quasi-continuous HFPDC operation with acetylene-air mixtures. The stable self-sustained pressure oscillations with frequency of ≈ *2.5 kHz* and amplitude of about *2.5 atm* have been detected at the thrust wall of the device during several experimental runs with acetylene-air mixtures at different equivalence ratios.

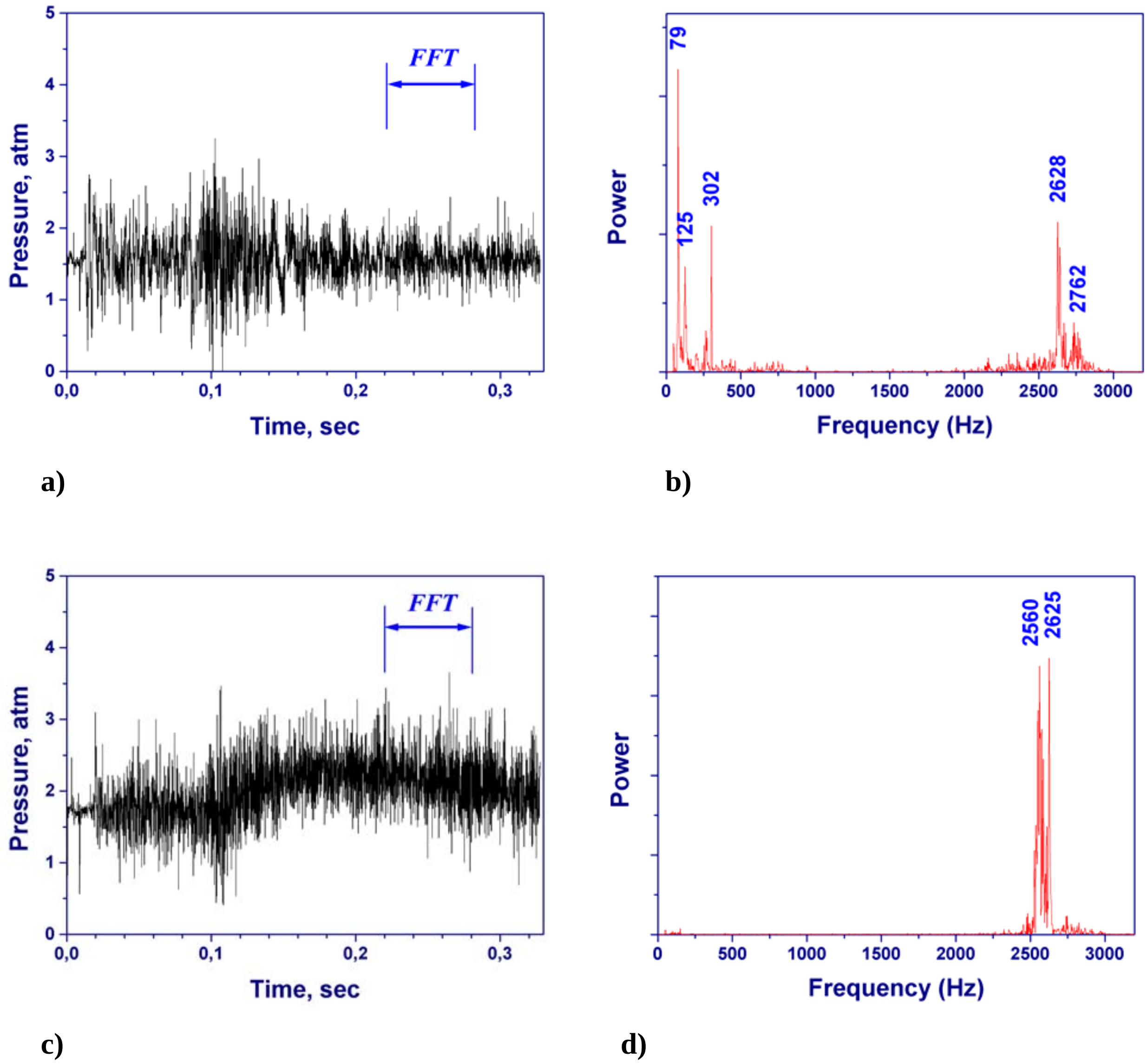

Figure 3: Pressures at the thrust wall (A), at the bottom of auxiliary chamber (C), the corresponding power spectral densities of the pressure variation (A)$\rightarrow$(B) and (C) $\rightarrow$ (D). The working mixture is a rich acetylene-air composition with equivalence ratio $\phi = 1.95$. The total mass flow rate through HPDC is about $G \approx 60$ grams per second.

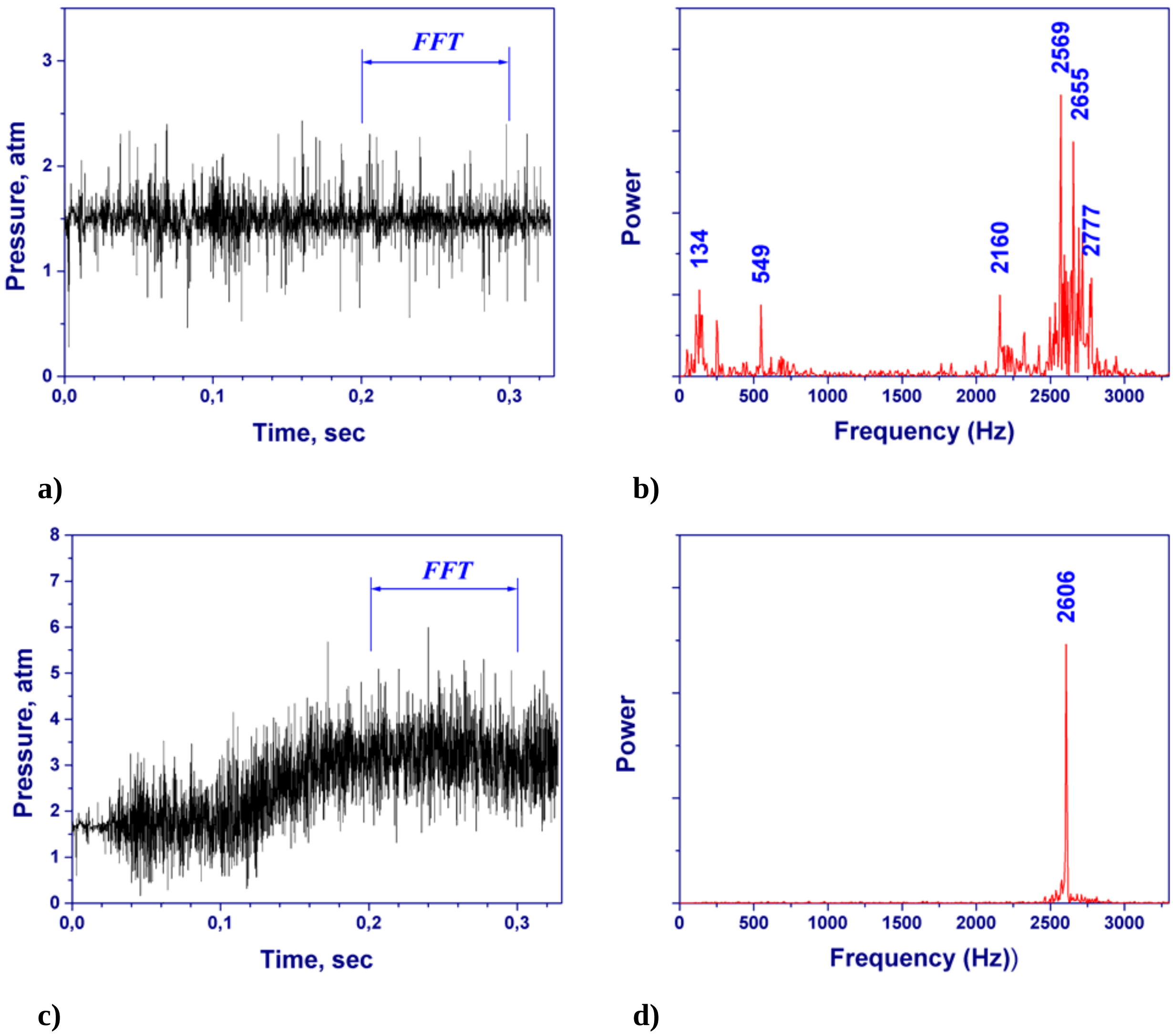

Figure 4: Pressures at the thrust wall (A), at the bottom of auxiliary chamber (C), the corresponding power spectral densities of the pressure variation (A)→(B) and (C) → (D). The working mixture is a rich acetylene-air composition with equivalence ratio $\phi = 1.3$. The total mass flow rate through HPDC is about $G \approx 74$ grams per second.

Acknowledgements

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References

[1] Voitsekhovskii B. V. Stationary detonation. *Dokl. Acad. Sci. USSR*, 129 (6): 1254-1256, 1959.

[2] Bykovskii F. A. and Mitrofanov V. V.. Detonation combustion of a gas mixture in a cylindrical chamber. *Combustion Explosion Shock Waves*, 16 (5): 107-117, 1980.

[3] Bykovskii F. A., V. V. Mitrofanov and Vedernikov E. F. Continuous detonation combustion of fuel-air mixtures. *Combustion Explosion Shock Waves*, 33 (3): 120-131, 1997.

[4] Nicholls J. A. and Dabora E. K. Recent results on standing detonation detonation waves. *8th Symposium (Int.) on Combustion Proceedings*, Pittsburgh, PA: The Combustion Institute: 644-655, 1962.

[5] Nicholls J. A., Wilkinson H. P. and Morrison R. B. Intermittent detonation as a thrust-producing mechanism. *Jet Propulsion*, 27(5):534-41, 1957.

[6] Krzycki L. J. Performance characteristics of an intermittent-detonation device. NAVWEPS Report 7655, 1962.

[7] Helman D., Shreeve R. P. and Eidelman S. Detonation Pulse Engine, AIAA-86-1683, 24th Joint Propulsion Conference, Huntsville, 1986.

[8] Zitoun R. and Desbordes D. Propulsive Performances of Pulsed Detonations. *Combustion Sci. and Tech*., 144: 93–144, 1999l.

[9] Borisov A. A, Gelfand B. E., Zamanskii V. M., Lisyanskii V. V., Skachkov G. L and Troshin Ya. K. Ignition of gaseous combustible mixtures in focused shock waves. *Sov J. Chemicheskaya Phys.*, 7(12): 1387-1391, 1988.

[10] Chan C.K., Lau D., Tibault P. and Penrose J.D. Ignition and detonation initiation by shock focusing, *AIP Conf. Proc*., 208: 161 –168, 1990.

[11] Achasov O. V., Labuda S. A., Penyazkov O. G., Pushkin R. M. and Tarasov A. I. Shock wave initiation of detonation in a semiclosed cavity. *Journal of Chemical Physics*, 12(5):714 -716 1993 (in Russian).

[12] Achasov O. V., Labuda S. A., Penyazkov O. G. and Ragozin D. S. Shock wave and jets initiation of gaseous detonation. *Archivum Combustionis*, 15(3-4): 253- 274, 1995.

[13] Medvedev S. P., Gelfand B. E., Khomik S.V., Grönig H., Olivier H. Shock tube study of hydrogen-air detonation induced by shock focusing. Int. Workshop on Detonation under Geometrical Constraints, RWTH Aachen, 15-17 December, 1998.

[14] Penyazkov O. G., Ragotner K. A., Tangirala V. E., Dean A. J. and Varatharajan B. Experimental and numerical studies of propane autoignition at elevated temperatures and pressures. In: Pulse and Continuous Detonation Propulsion. Eds. G. Roy, S. Frolov. Moscow: TORUS PRESS, 21-42, 2006.

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