VIBRATIONLESS PULSE DETONATION ENGINE

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Abstract

The work is devoted to compression of air behind a piston driven by a detonation wave as well as dynamics of the piston movement. The report will present numerical and experimental studies conducted on detonation tube equipped with pressure transducers, light gauges and detectors of piston displacement. Observations in compression of air behind the piston driven by detonation wave and dynamics of piston movement is described in the paper.

Keywords: detonation, detonation formation, pulse engine, compression

Introduction

One of the greatest milestones in the history of aviation and propulsion was the creation of gas turbine jet engine. Lots of improvements has been proposed and done to push its performance to the limits. The thing that makes one being stunned at least no less than the engine itself is the industry needed to create these sophisticated mechanisms.

However, the concept of turbine jet engine cannot be improved further to achieve greater specific impulse while having lower Specific Fuel Consumption (SFC). Rate of chemical energy release in combustion and cycle thermodynamic efficiency are limiting factors for conversion of fuel energy into propulsion energy of a vehicle. In 1940 Y.B. Zel'dovich [1] showed that thermodynamic efficiency of fuel combustion at detonation regime is greater than at deflagration regimes [1]. The rates of energy release in detonation modes of gas combustion are three orders of magnitude higher than in deflagration combustion modes. This theoretical result gave rise to numerous studies of possibility of creation and utilization of a detonation engine for aviation needs [2,3].

Fundamental idea behind detonation engine is a usage of a detonation cycle of fuel combustion in jet engines. Due to the sharp increase of pressure behind detonation wave, detonation cycle occurs at quasi-constant volume. Thus, it is very similar to Humphrey cycle at constant volume. Humphrey cycle is well known to be more efficient than conventional Brayton cycle at constant pressure. In Figure 1 comparison in Coefficient of Efficiency (COE) for Brayton, Humphrey, and Detonation cycles is depicted

[1-3]. At compression rate of 15, that is typical in applications, COED=1.05COEH=1.35COEB. Consequently, according to the theoretical analysis, 30%-50% benefit in lower SFC is possible.

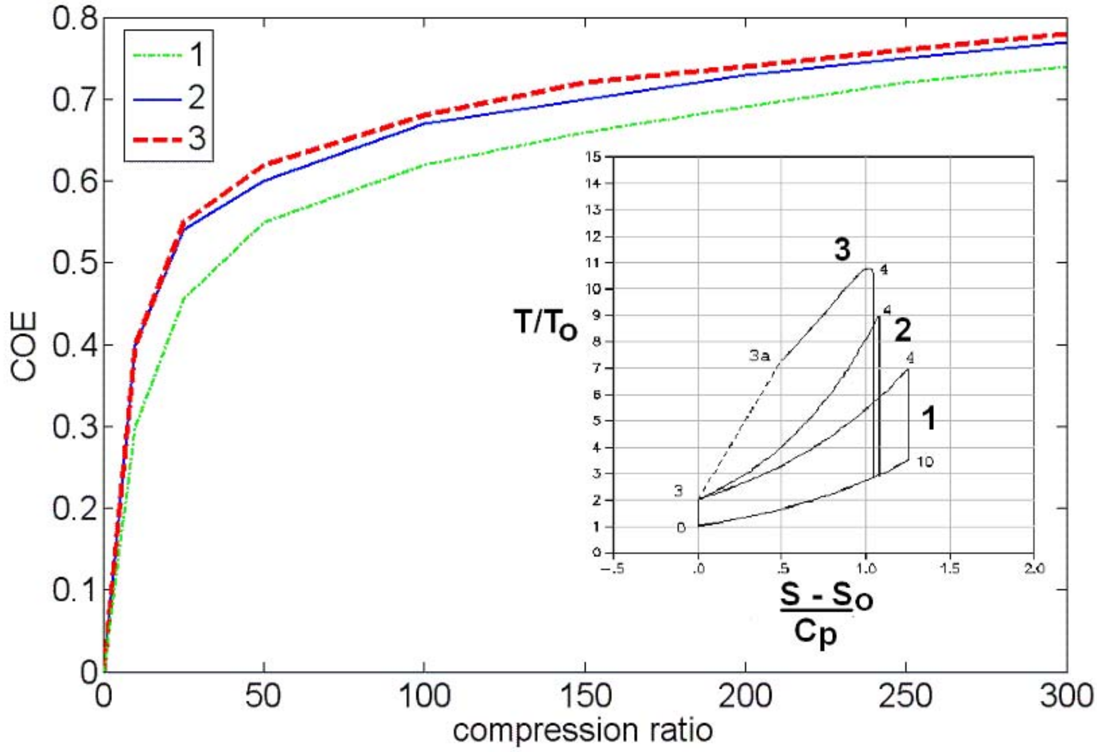


Fig. 1. Comparison in Coefficient of Efficiency (COE) for Brayton (1), Humphrey (2), and Detonation (3) cycles

In the last century it was proved that continuous stationary detonation combustion is impossible to achieve. The fact necessitates that for an energy converter pulsed operation mode should be used. It leads to the concept of a Pulse Detonation Engine (PDE). Operation of a PDE relies on pressure-rise detonation combustion rather than constant-pressure deflagration currently used in conventional engines, for instance, piston engines, gas turbine engines, and scramjets. High thermal efficiency of PDE attracts researchers to apply it as a new technology for aerospace propulsion.

The chance that PDE will eventually find its place among other propulsion mechanisms can be great only if most of its attractive features are preserved. Namely, it is the simplicity of the construction design (considerably fewer moving parts), thermodynamic efficiency of fuel combustion, operation range from zero up to supersonic velocities, and great thrust or high specific impulse [2,3]. Here we are not talking about more engineering problems such as reliability, noise level allowance, and overall production costs that mainly depend on the field of application.

Currently, development and application of PDE faces at least two problems: possibility of air intake directly from the atmosphere and severe vibrations [4]. In our opinion, the way these problems are tackled now makes pointless further development of PDE, because the proposed solutions obliterate all fascinating features of the original concept.

In this paper, a new PDE concept is suggested; according to this concept, the compression of oxidizer at zero velocity (M = 0) is performed without involving a compressor. The goal of the paper was to predict compression ratio in the new concept numerically and compare it with experimental results.

PDE-concept

Schematic of a PDE according to the new concept is shown in Figure 2. The thrust wall of the closed end of detonation chamber 9 is a movable piston 2. Ambient air delivered via air intake 3 is compressed by the piston 2 in the compressor chamber 5 to a pressure of 10 kg/cm^2 and delivered to the detonation chamber 9. Compressed air is delivered to the detonation chamber 9 along bypass channel 6 via bypass openings 7 in the piston and 8 in the channel. The compressor chamber 5 is designed for pre-compression of flowing-in air, and the detonation chamber 9 is designed for the combustion of fuel. The pressure difference and the spring pusher 4 are used for returning the piston 2 to the initial position.

At the first stage of stroke I (detonation stage), the piston is in the extreme right position. In the detonation chamber there is already a combustible mixture. The pressure is developed in the detonation chamber 9 due to detonation combustion of fuel; in so doing, the piston 2 starts moving toward the compressor chamber 5. The combustion products flow out via nozzle 11 and provide for the engine thrust.

At the second stage of stroke I (compression stage), the piston walls cover the opening of air intake 3, and air is compressed in the compressor chamber 5 to a pressure of 10 kg/cm2 (Fig. 2C.).

At the third stage of stroke I (supply stage), the openings 8 of the bypass channel are aligned with the bypass openings 7 of the piston 2 (Fig. 2D.), which have a larger diameter compared to that of the openings of the bypass channel 6. Compressed air is delivered to the detonation chamber 9 along the bypass channel 6. The fuel is delivered via fuel injector 10. A combustible mixture is formed in the detonation chamber 9. In so doing, the spring pusher 4 starts contracting.

During cycle II of engine operation (Fig. 2E.), the piston 2 returns to the initial position under the effect of the spring pusher 4 and of the changed pressure drop. The walls of the piston 2 uncover the opening of air intake 3. Ambient air is sucked into the compressor chamber 5 via air intake 3 owing to rarefaction developed by motion of the piston 2.

The cycle is repeated. The PDE according to the suggested concept does not require valves and compressor. The usage of the concept could lead to pressure increase in the combustion chamber. As a result, fuel consumption decreases due to implementation of more efficient thermodynamic cycle that is similar to the cycle at constant volume. Both detonation and deflagration combustion regimes are possible.

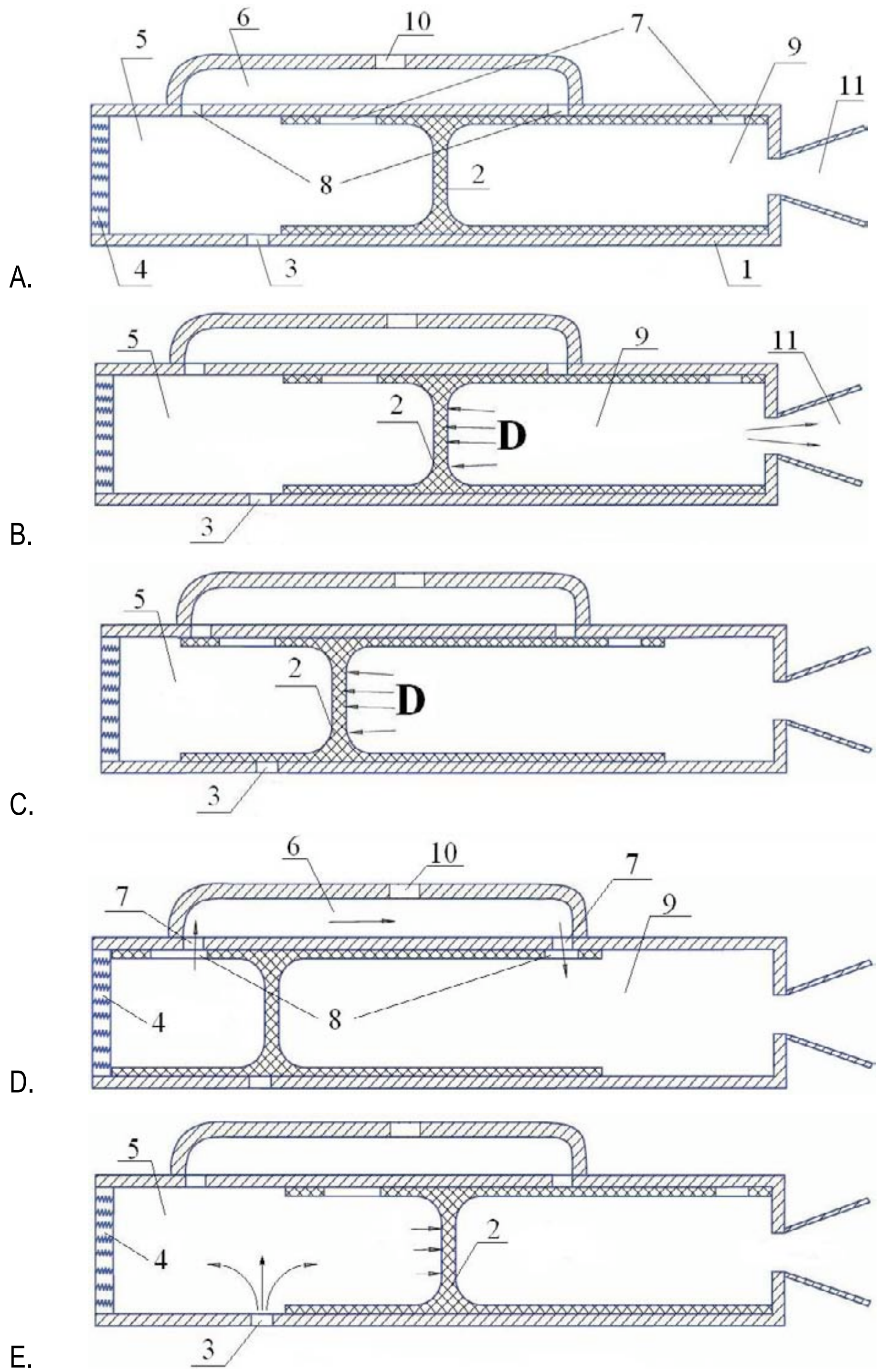
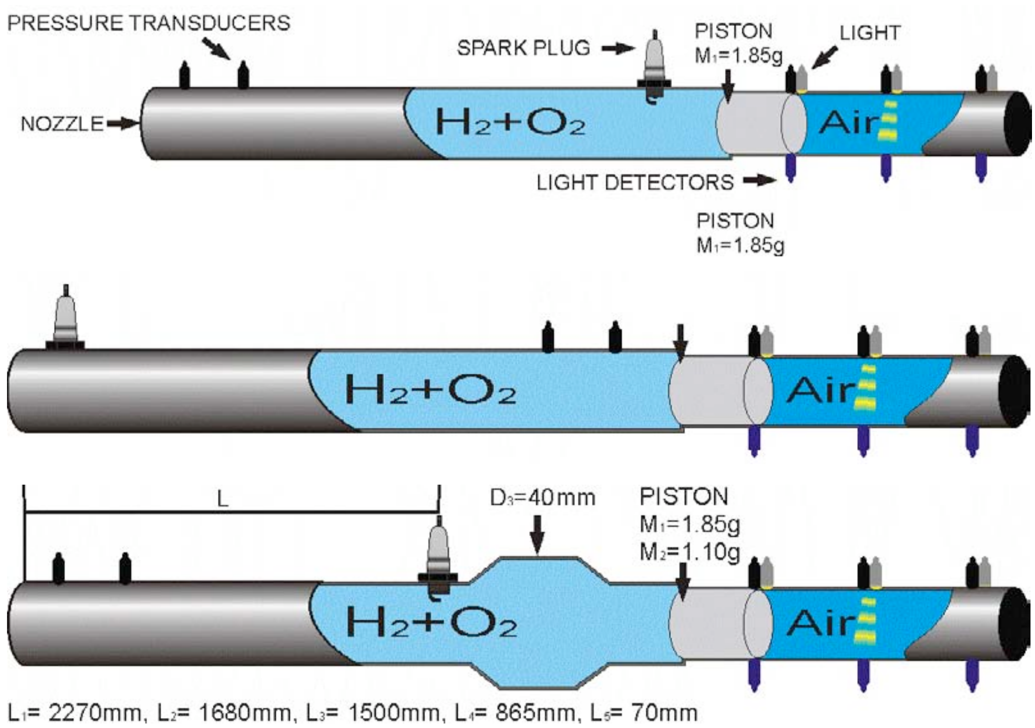


Fig. 2. Schematic of a PDE according to the new concept (A) and stages of engine operation (B,C,D,E). 1 – body; 2 - piston; 3 - air intake; 4 - spring pusher; 5 - compressor chamber; 6 - bypass channel; 7 - bypass openings in the piston; 8 - bypass openings in the channel; 9 - detonation chamber; 10 - fuel injector; 11 - nozzle. B. – detonation stage, C. – air compression stage, D. – supply stage, E. – air intake

PDE-demonstrator

The scheme of PDE-model setup and its modifications are presented in Figure 3. It consisted of detonation combustion chamber DCC (left) and compressor chamber (right). The length of the detonation chamber was 2000 mm, internal diameter – 16 mm, the length of the compressor one was 450 mm, diameter – 11 mm. Before each experiment free moving piston was located between chambers. The length of the piston was 17 mm, mass – 1,85 g.



A.

B.

C.

Fig. 3. PDE-model setup with modifications. A. – DCC with spark plug located close to open end, B. – DCC with spark plug located close to piston, C. – DCC with expansion chamber

Detonation chamber was equipped by pressure transducers PCB, compressor chamber was equipped by pressure transducers and pairs of light-emitting-photo diodes to register piston location. Distance between pressure transducers (pairs of diodes) was 160-170 mm.

Stoichiometric mixture of oxygen and hydrogen was used in experiments at 1 atm. Compressor chamber was filled with air at pressure 1 atm. After ignition of detonation mixture the piston was brought to motion by products of combustion or by a detonation/shock wave. Figure 4 shows shock wave diagram and trajectory of the piston in the compressor chamber.

At ignition when spark plug is located near open end of the detonation chamber detonation wave drove the piston. The latter compressed air in compressor chamber. After compression the piston began to move backwards to the open end of the tube because rarefaction wave led to the pressure drop in the detonation chamber. Hot products of detonation were cooling. Therefore the piston moved through initial location. Pressure in the compressor chamber is lower then in detonation chamber and the piston again compresses air in the compressor chamber.

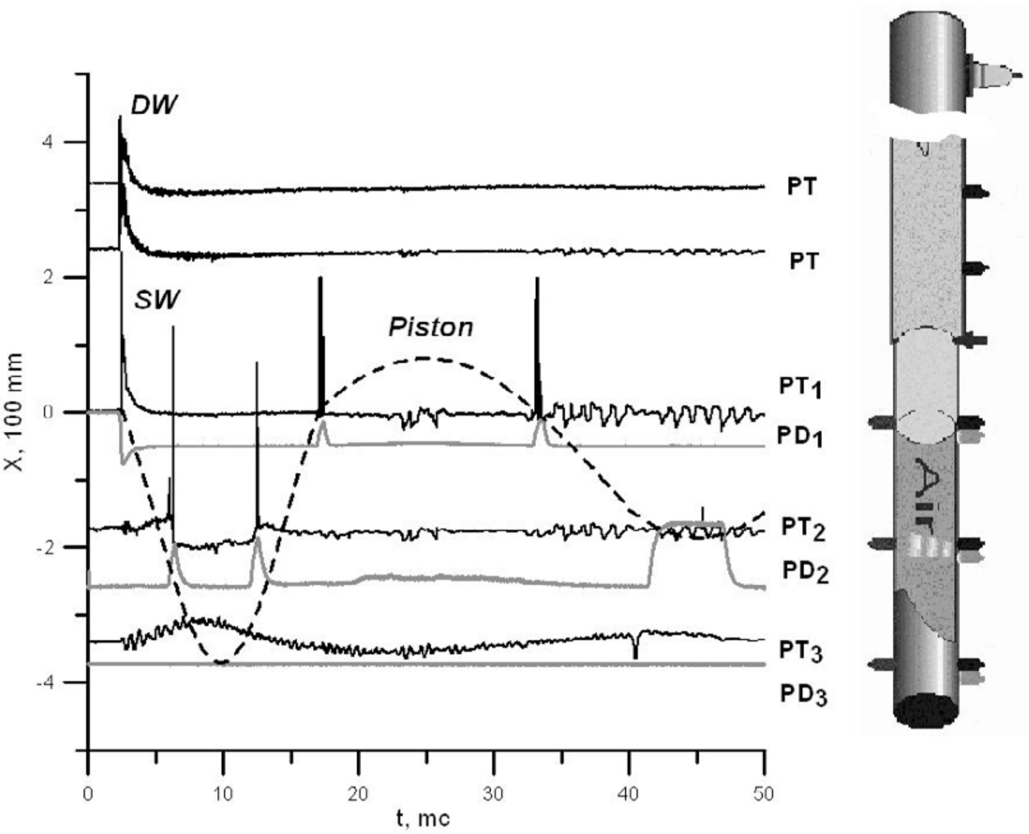


Fig. 4. Readings of pressure transducers in detonation chamber (PT), in compressor chamber (PT1-PT3) and readings of photodiods in compressor chamber (PD1-PD3). Trajectory of piston in compressor chamber after detonation wave impact. DW – detonation wave, SW – shock wave

Numerical modelling

To evaluate the feasibility of the new concept some numerical studying has been done. The goal was to investigate the possibility of performing the oxidizer compression by a piston moving under the effect of shock waves. Previous our estimations [5] were made numerically and shown the dependences of pressure behind the piston on the piston mass and frequency of detonation pulses repetition.

The problem was simulated in the one-dimensional (1D) and two-dimensional (2D) cases. In 1D case, the flow was described by the Lagrangian hydrodynamic equations. The Lax-Wendorff scheme was used for calculation. It is an explicit scheme of the second order of accuracy with respect to time and space. In 2D case, the Euler equations were solved. The method of large particles of [6] was used for calculation. This is an explicit method of the first order of accuracy with respect to time and of the second order of accuracy with respect to space.

The computational domain includes a tube 2000 mm long and surrounding atmosphere 500 mm long. The pipe diameter is 20 mm, and the bypass channel diameter is 5 mm. The pipe is divided by the piston in two parts. At the initial instant of time, the piston is located at a distance of 500 mm from the closed end. The combustor (from the piston to the open end of the pipe) was filled with a combustible mixture. The initial parameters of gas throughout the computational domain were taken to be as follows: P=105 Pa, T=300 K.

The chemical constants were selected such that the detonation wave velocity and the pressure shock at the front would be in the case of a hydrogen-air mixture. The grid comprised 30×1000 points.

In the calculation, the piston mass was varied, and the time of compression was determined when the oxidizer compression ratio became equal to 10. Figure 5 [5] gives the compression time as a function of piston mass.

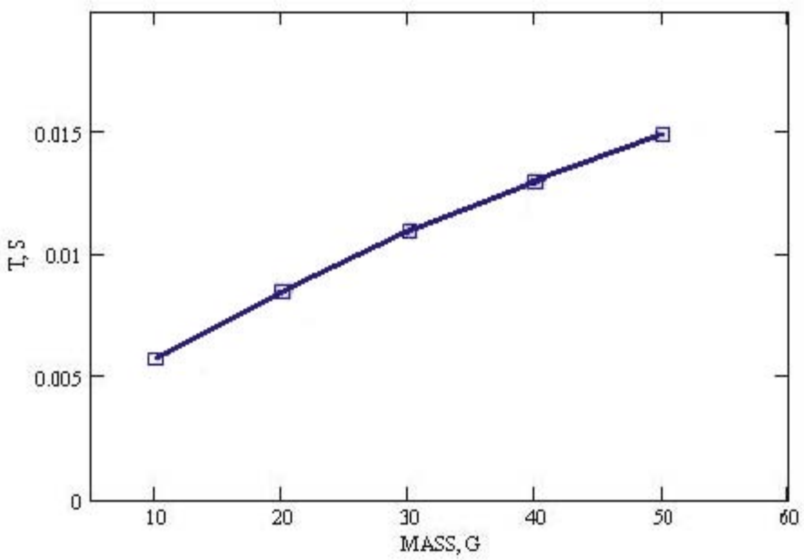


Fig. 5. Compression time as a function of the piston mass

The time dependence of pressure (Fig. 6 [5]) on the closed end of the pipe was further used to estimate the specific impulse of the engine per operating cycle. It amounted to 1600 s for the piston mass of 25 g.

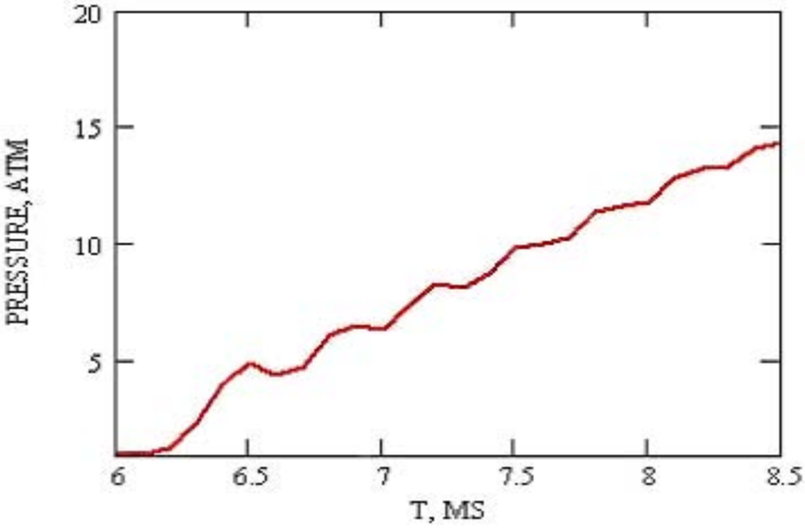


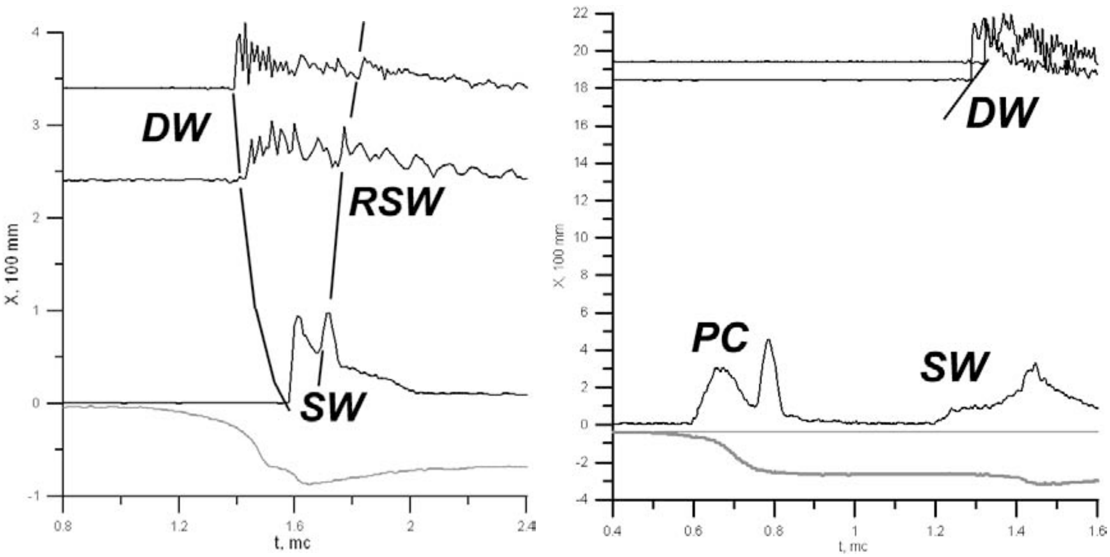
Fig. 6. Time dependence of pressure at the close of the compressor chamber

Influence of spark plug location on the compression ratio

Figure 7 gives initial stages of moving the piston in compressor chamber at ignition of mixture in the detonation chamber at the open end (left) and close end (right). In the first case the piston was driven by detonation/shock wave. However photodiodes registered opening of light diodes before the shock wave. It may be explain by weak waves in tube in front of the detonation wave. Compression of air was registered by pressure transducers in chamber. Initial velocity of the piston was about 35 m/s. Velocity of the piston at moving back to initial location was equal to 45 m/s.

In the second case the piston was driven by a shock wave generated by spreading products combustion. Initial velocity of the piston in this mode was about 24 m/s.

Thus, experiment shows the average velocity of the piston is 25-35 m/s at down and upstream modes of ignition. Velocity of detonation wave in two modes achieved meaning of 3000-3200 m/s. Pressure in the compressor chamber was 2 atm in two cases.



A. B.

Fig. 7. Readings of pressure transducers in detonation and compressor chambers and readings of photodiod (PD1) in compressor chamber. A. – DCC with spark plug located close to open end, B. – DCC with spark plug located close to piston. DW – detonation wave, SW – shock wave, RSW – reflected shock wave, PC – products of combustion of hydrogen-oxygen mixture

Detonation initiation with expansion chamber

Experimental setup with a prechamber was used to increase pressure of air in the compressor chamber. Summary results are presented in Figure 8. Increasing of the detonation chamber length reduces the wave of rarefaction from the open end of the detonation chamber. In addition, this accelerates detonation formation. It leads to an increase of pressure and piston velocity.

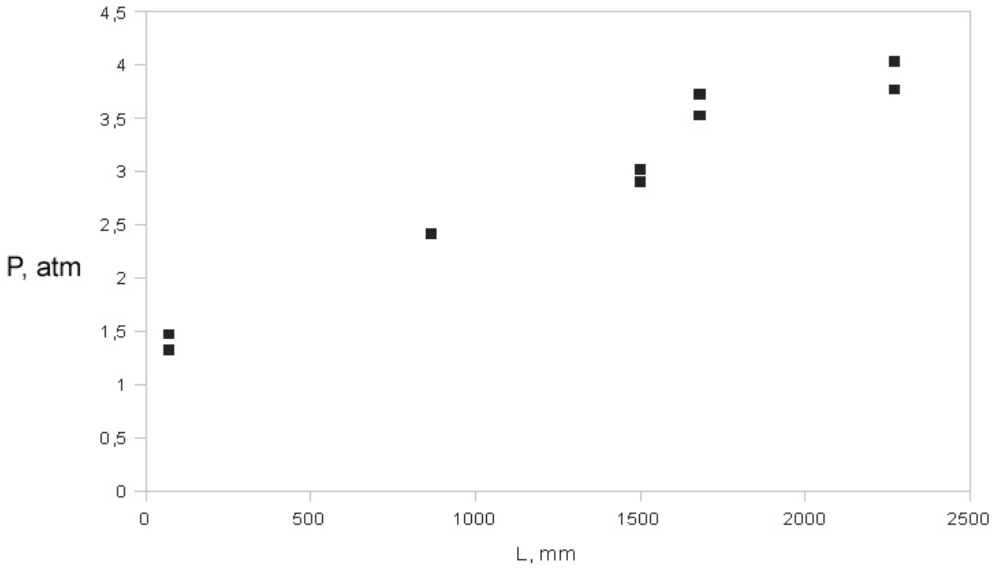


Fig. 8. Compression in compressor chamber at different lengths of the detonation chamber

Maximum pressure in the compressor chamber was 4 atm. The difference from calculated pressure may be explained by different mechanisms of combustion in the detonation chamber. Numerical algorithm implied detonation combustion of all mixture in the chamber. But deflagration-to-detonation transition takes place in the real detonation chamber.

Conclusion

The possibility of oxidizer compression in a pulse detonation engine without involving a compressor and turbine has been investigated for the first time.

It has been demonstrated numerically that the oxidizer compression ratio of ten may be attained for the piston mass of 25 g.

Increasing the length of the detonation chamber leads to an increase of pressure in the compressor chamber.

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