EXPERIMENTAL RESEARCH ON THE ROTATING DETONATION ENGINE IN HYDROGEN-AIR MIXTURES

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Abstract

Experimental research on rotating detonation carried out at Warsaw University of Technology is presented in this paper. Research is focused on evaluation of the geometry of the detonation chamber and of the conditions at which the rotating detonation is propagating in cylindrical channels. Lean hydrogen-air mixtures were tested in the experiments. Pressures measured at different location were used to check the detonative nature of the combustion. Also analysis of relationship between detonation velocity and the operational conditions is provided in the paper.

Introduction

One of way of improving performance of a jet engine is increasing its thermal efficiency. This goal can be achieved by using detonation mode of combustion instead of deflagration. Detonative combustion can be realized in different ways, for example: by application of pulsed detonation process in so called Pulsed Detonation Engine (PDE), or continuously rotating detonation in so called Rotating Detonation Engine (also known as Continuous Detonation Wave Engine). Advantage of PDE are relatively simple design and high efficiency, disadvantages are small frequency, necessity of initiation of each cycle, long length and initiation distance, variation of thrust and high level of noise and intensive vibrations. On the other hand, the detonation in RDE propagates continuously in a cylindrical chamber. The engine is more compact; there are smaller variations of thrust and engine mass is smaller. Additionally, once initiated detonation propagates continuously.

Recently interest of detonation researchers has been focused on development of the Rotating Detonation Engine, known also as the Continuous Detonation Wave Engine, since it offers significant improvements of thermal efficiency and simultaneously simplification of design. Many experimental research are conducted in this filed at numerous laboratories. Voitsekhovskii, Metrofanov and Topchian performed first experiments on continuously rotating detonation in early sixties of the last century [1],[2]. In 2004, Wolanski, Fujiwara with cooperation with Mitsubishi Co. applied for a patent on the Rotating Detonation Engine (RDE) [3]. The principle of work of Rotating Detonation Engine (RDE) is based on generation of a continuously propagating detonation in a disk-like combustion chamber (toroidal or ring-like shape). The fresh mixture is supplied from one side and combustion products are escaping from the other side of the chamber.

Recently more research is focused on RDE. Research on RDE are carried out in Russia, France, Poland and Japan. Bykovskii et al. [4],[5] reported results of experimental research on the continuously rotating detonation, Hishida et al. [6] describes theoretical backgrounds and numerical calculation. Davidenko et al. [7],[8] presented numerical results of the rotating detonation in the rocket engine. Bykovskii et al. [9] described experimental study for hydrogen-oxygen mixture. Very extensive research on application of rotating detonation to propulsion systems and numerical calculations are performed in Poland as well [10],[11].

Research stand

The research facility consists of following parts (Fig 2): detonation chamber (1), damp tank (3), fuel and air feed system, measurement system and initiation system. While the main part of the study was seeking the optimal geometry for the detonation the cylindrical detonation chamber (Fig. 1) has been built with use of easily changeable elements. It allows changing internal diameter of the chamber, length of the channel and shape of the inner wall of the chamber. The chamber was equipped with several pressure transducers. Two of them were placed in the manifolds and the others were installed in the chamber at locations shown in Fig. 2. The detonation chamber was connected to the dump tank (volume was about $0.63m^3$), then it was possible to carried out experiments for the wide range of initial pressure from range 0.05÷2.5bar what is controlled by the pressure in the damp tank. The schematic diagram and view of the research stand is shown in Fig. 2.

Fuel and air is injected to the chamber by two kinds of injectors: fuel by large number of small holes (diameter in the range of 0.7÷1.0mm) and air by a narrow slit of changeable width. Detonable mixture is created downstream of the injectors. Injection of fuel and air into the cylindrical chamber was controlled by two electromagnetic valves operated automatically by a electronic control unit..

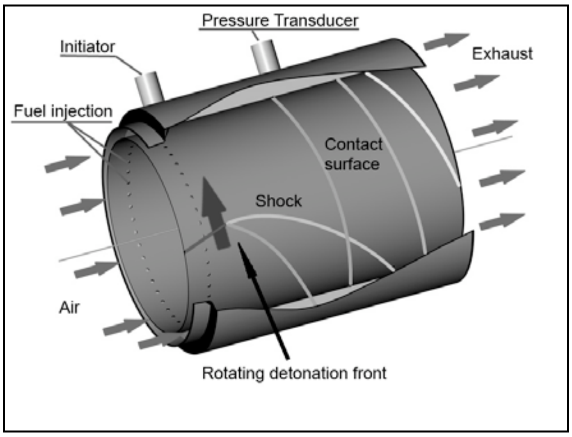


Fig. 1 Sketch of detonation chamber used in the experiments.

The stand for short time experiment

The rotating detonation process was initiated by a strong shock wave produced by an gaseous initiator attached to the detonation chamber. The initiator was filled with stiochiometric acetylene-oxygen mixture at high pressure and ignited by an electric spark. Between the chamber and the initiator a thin plastic membrane was placed separating the two volumes before experiment. Immediately after starting flow of the fuel and air (mixture formation), the electric spark was used to detonate mixture in the initiator. It produced a strong shock wave in main chamber, which eventualy triggered rotating detonation. Typical experiment duration time was 80÷150ms, but in some experiments it was extended up to one second. The time depended on initial pressure in the chamber or kind of cooling system of the pressure transducers.

a) b)

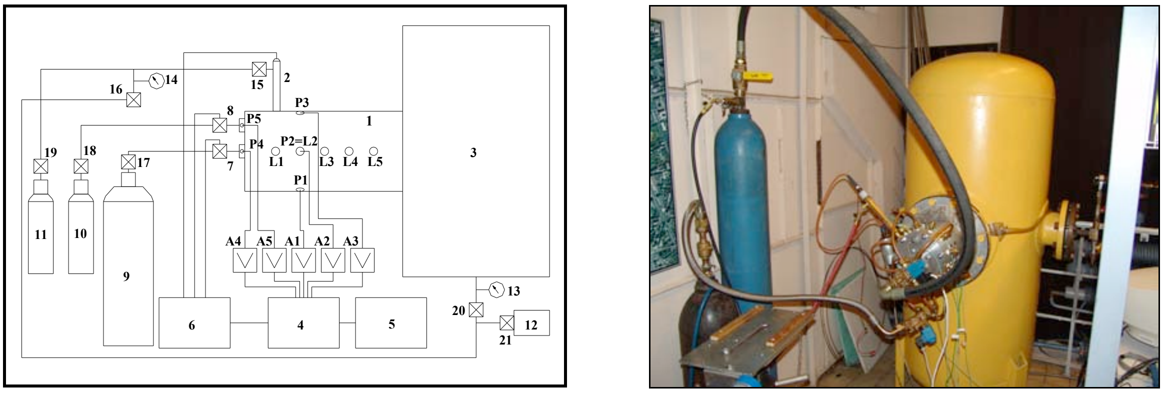


Fig. 2 Research stand: a) schematic diagram: P1÷P3 – pressure transducers placed in one plane inside chamber, L1÷L5 – pressure transducers placed in one line inside the chamber, P4,P5 – pressure transducers for manifolds: fuel and air, A1÷A5 – amplifier's, 1 – detonation chamber, 2 – initiation tube, 3 – dump tank, 4 – acquisition card, 5 – computer, 6 – control system, 7,8 – electromagnetic valves, 9 – tank with the air, 10 – tank with the fuel, 11 – bottle with initiation mixture, 12 – vacuum pump, 13,14 - manometers 15÷21 – valves; b)view of the stand.

The stand for continuous operation

The stand was equipped with a bigger air and fuel tank. The dump tank was connected to atmosphere, so experiments could be run up to 5s. Picture of this stand is shown in Fig. 3. The limitation of the experiment duration were capacity of the fuel and air tanks. Anyway the time was long enough to show possibility of continuous work of the chamber with rotating detonation. Additionally exhaust gases temperature measurements by thermocouple has been performed on this stand. A thermocouple with relatively small time constant was used. For pressure measurements, Kistler pressure gauges were used with application of a small layer of a silicon grease on the front surface of the pressure transducer. It protected the sensor from intensive heating from hot detonation products.

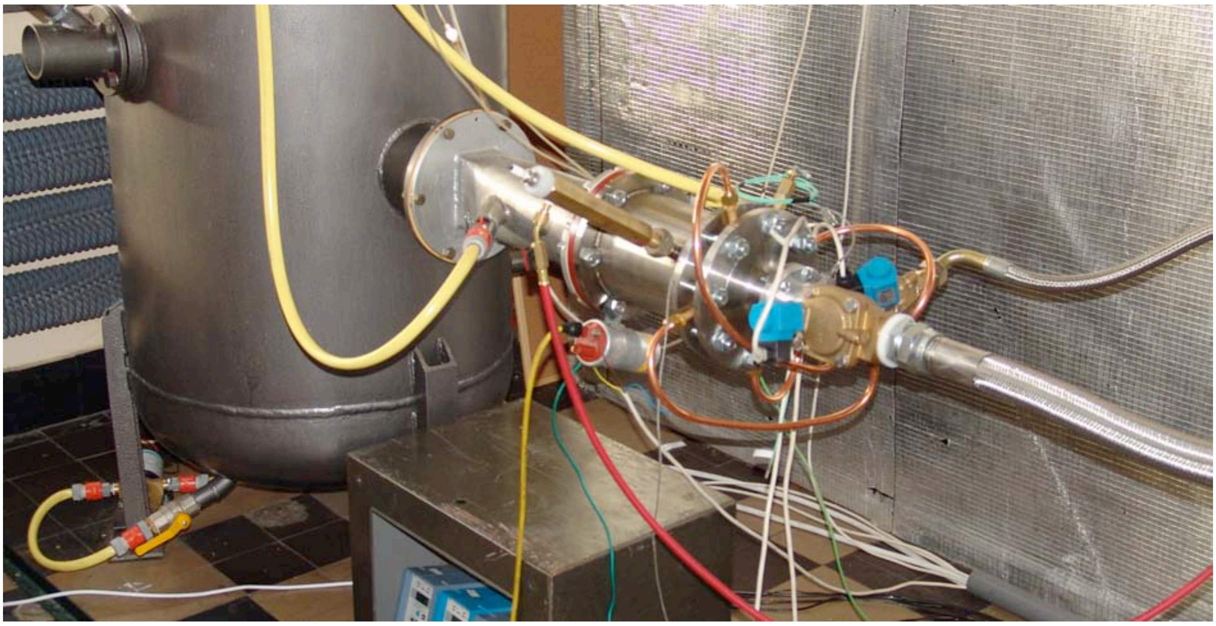


Fig. 3 Research stand for continuous flow.

Experimental results

The experiments for hydrogen-air mixture were carried out in three chambers: the small chamber (outer diameter was 95mm), the medium chamber (outer diameter was 150mm) and in the continuous flow medium chamber (outer diameter was 134mm). In all chambers pressure in the manifolds and in the chamber were measured. Detonation velocity and flow rate of the both gases were calculated from the recorded pressures. Additionally, in continuous flow chamber, exhaust gases temperature was measured. Fig. 4 shows pressure-time history of pressure in the manifolds, point (1) is the initiation moment, and point (2) indicates closing of the valves which cut-off the flow of gases from the air and fuel tanks. Observed drop of the pressure in the manifolds is a result of a small volume of the tank (fuel and air). For the case presented in Fig 4, volume of the fuel tank is only 69 liters, that secured only 5÷6s of continuous work of the stand. Although such short time it was possible to measure all mentioned parameters and optimize the detonation chamber geometry.

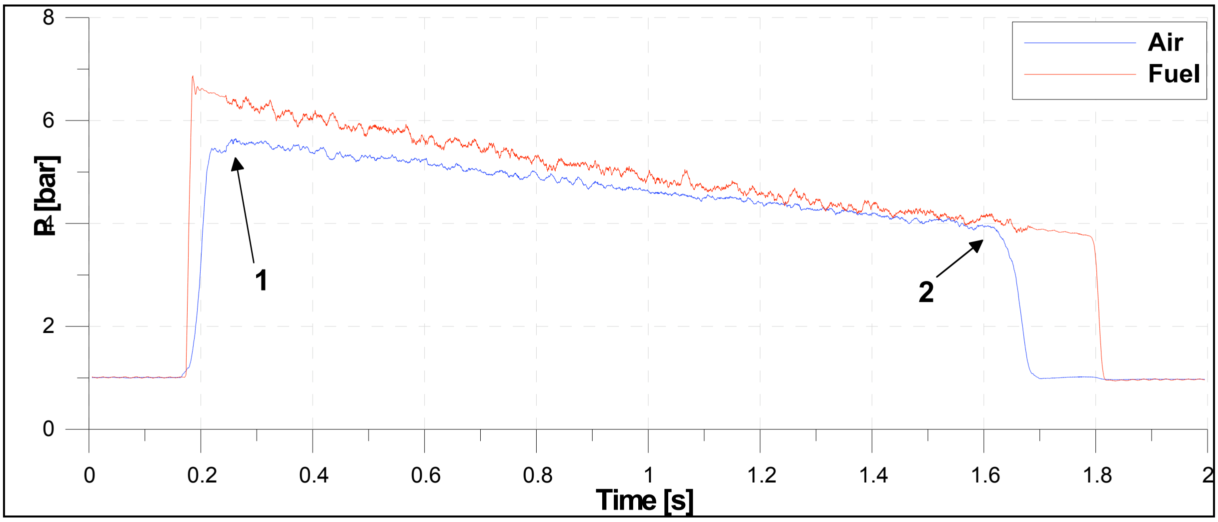


Fig. 4 Typical pressure courses in the manifolds: fuel and oxidizer during experiments: 1 – moment of initiation detonation in the chamber; 2 – closing of the valves.

Velocity and temperature measurement

Detonation velocity is calculated from period between successive pressure peaks measured during experiment. Since the calculations were carried out for all detonation peaks, different values of instant detonation velocity were obtained. Average detonation velocity was then calculated as the mean value from instantaneous velocity measurements.

Fig. 6 shows temperature measurements made by thermocouple. Typical temperature profile obtained during experiment, can be divided into three parts: T_n is time period necessary for stabilization of measurement (which depend on thermocouple time constant). After this time temperature reach steady level and this segment of measurements indicate real temperature of the products, which depend mainly on mixture composition and pressure in the chamber. After closing supply of fuel and air valves (stopping propagation of the detonation in the chamber) the temperature is decreasing mainly due to stopping exhaust gases and cooling of the thermocouple by radiation.

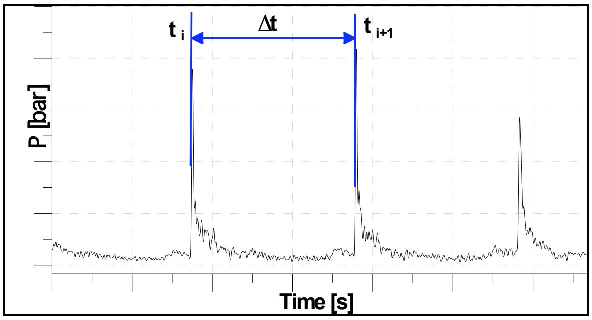


Fig. 5 Detonation velocity measurements from pressure data.

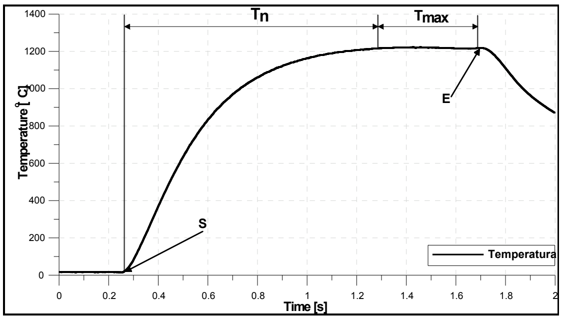
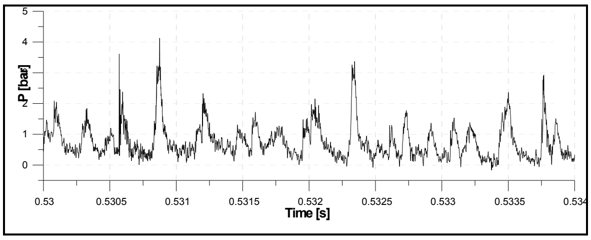


Fig. 6 Layout of temperature of exhaust gas measurement (S – moment of initiation of detonation; E – gas supply system close) .

Pressure measurement

The pressure gauges are working in extreme conditions of detonation and they should measure pressure variation with high frequency and high accuracy. The main problem is high temperature environment. In order to counteract overheating of the sensor, the front of the gauge was covered by a layer of the silicon grease, however thickness of the layer, influenced the measurement. Fig. 7÷ Fig. 9 shown three cases of the measurement for the same hydrogen-air mixture, with three thickness of the silicon grease layer were used for 3mm, 1mm and 0.3mm respectively. The comparison provides useful information about distortion of pressure signal by silicon grease layer. It is noticeable especially for the thicker silicon layer. The layer influences: shape of pressure profile, maximum value (usually lower pressure is indicated) and has some effect on calculation of the detonation velocity. For the 3mm thick layer, calculated velocity has mean value about 1400 m/s with ±300 m/s oscillations (for period 0.4s) for comparison these values for 0.3mm layer are 1500±50 m/s. Concluding, very small grease layer and short duration experiments is necessary for examination the structure of the front of detonation wave, but for measurement of the temperature of the exhaust gases the time of experiment must be extended and thick layer on the pressure transducer surface must be used.

a)



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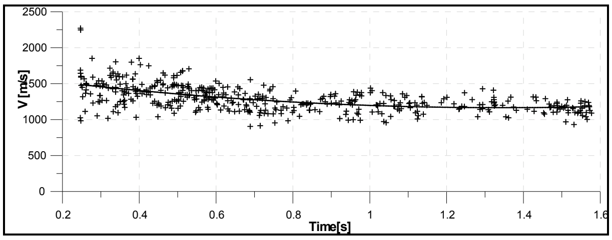
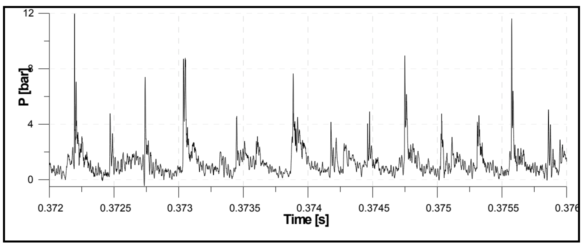


Fig. 7 Results of experiment for pressure gauge with 3mm thickness of isolation layer: a) pressure-time history; b) calculated detonation velocity.

a)



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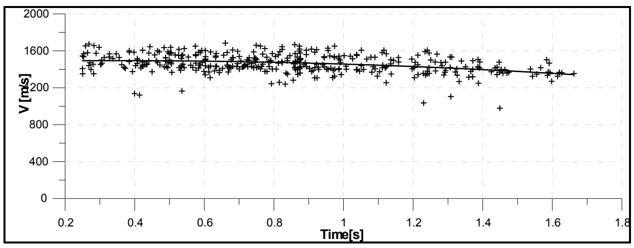

Fig. 8 Results of experiment for pressure gauge with 1mm thickness of isolation layer: a) pressure-time history; b) calculated detonation velocity.

a) b)

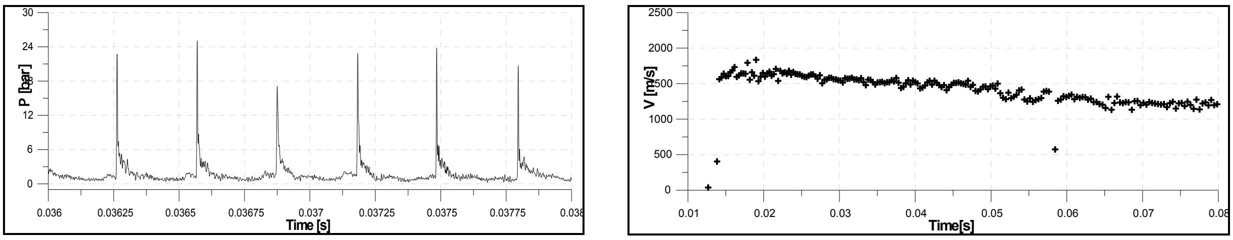

Fig. 9 Results of experiment for pressure gauge with 0.3mm thickness of isolation layer: a) pressure-time history; b) calculated detonation velocity.

Influence of chamber diameter and the width of the channel

Experiments were carried out for three different outer diameter of the chamber. In each case it was also possible to change width of the channel, from 5 mm to 20 mm. Fig. 10 and Fig. 11 show pressure measurements and calculated detonation velocity as a function of time for two different channel widths. In both experiments, the initial pressure in the chamber was equal to 1 bar (absolute). In these cases pressure peaks were not high and detonation was unstable. For small channel diameter, time of one revolution of the detonation front around the chamber is relatively short, consequently the refilling time is short and the fuel and air do not mix sufficiently and the amount of mixture is small. If the fuel and air is not mixed properly and mixture occupied only small volume, detonation parameters are decreasing (lower detonation pressure and lower detonation velocity) and time of detonation front revolution increases. This allows better mixture formation (longer time for mixing) and larger volume is occupied by fresh mixture and thus higher detonation pressure and higher detonation velocity is observed in next cycle. This constitutes a mechanism of instability which leads to observed fluctuation of pressure and velocity. In such case the pressure fluctuation are high and the detonation velocity varies approximately from 1000 to 2000m/s.

Fig. 12÷Fig. 13 present results for the bigger chamber of 150mm diameter. Two channel widths were used 5mm and 10mm. One can notice, that 10mm channel give the best results, the pressure peaks are nearly equal and detonation is very stable (deviation of the velocity around the mean value is less than 4%). In this case there is sufficient time for formation of mixture during one detonation wave revolution. For the same mixture parameters revolution time is nearly 2.5 time longer. It means that selection of proper geometry, for given mixture parameters, is the crucial for elimination of the instability. When the diameter of the detonation chamber increases to larger size, time of mixture formation might be too long and two or more detonation waves will propagate in the chamber.

a) b)

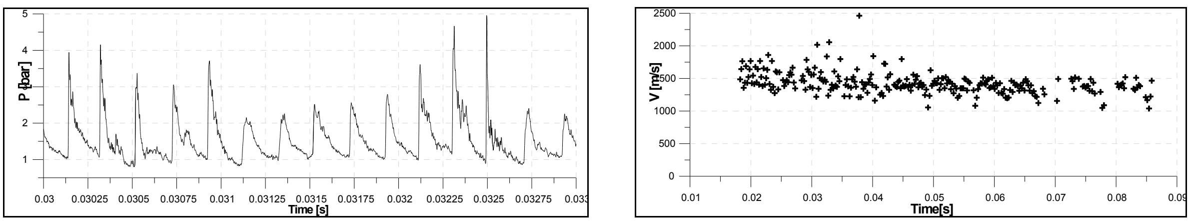

Fig. 10 Detonation in hydrogen-air mixture, in 95mm chamber (5 mm width of the channel): a) pressure profile; b) detonation velocity.

a) *b)*

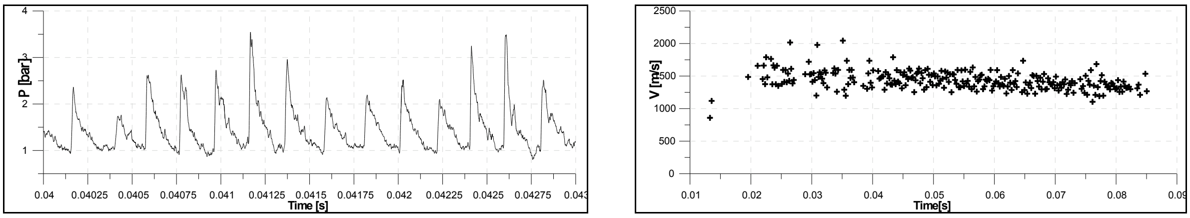

Fig. 11 Detonation in hydrogen-air mixture, in 95mm chamber (10 mm width of the channel): a) pressure profile; b) detonation velocity.

a) *b)*

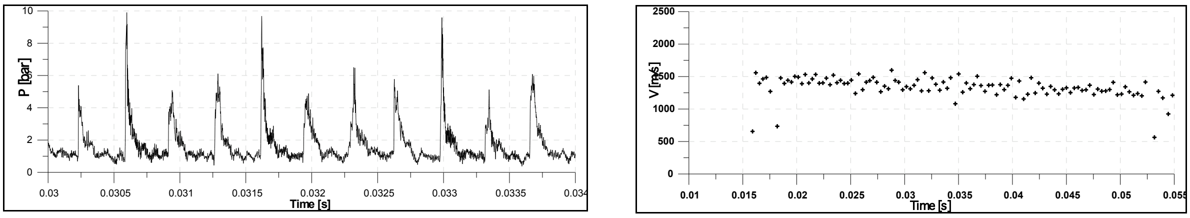

Fig. 12 Detonation in hydrogen-air mixture, in 150mm chamber (5 mm width of the channel): a) pressure profile; b) detonation velocity.

a) *b)*

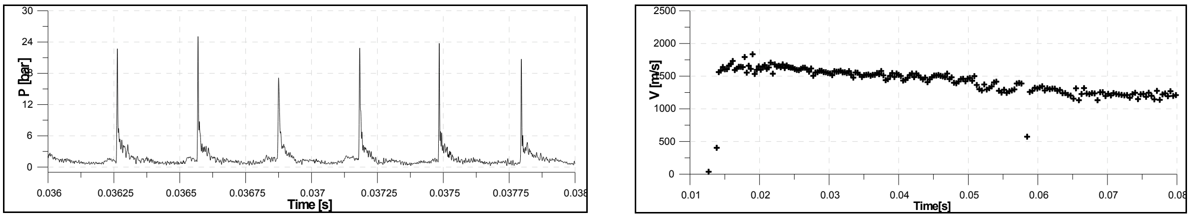

Fig. 13 Detonation in hydrogen-air mixture, in 150mm chamber (10 mm width of the channel): a) pressure profile; b) detonation velocity.

Temperature as a function of equivalence ratio

Many experiments were carried out for temperature measurements. The results are shown in Fig. 14 as a function of equivalence ratio. For the mixture stoichiometric coefficient in range 0.25÷0.6 (lean mixtures) the temperature are between 800 and 1200 centigrade. Obtained values of the temperature are in good agreement with results from numerical simulations reported by Kobiera et al. [12]. It indicates of the possibility of using such the chamber with rotating detonations in a conventional jet engine as a combustion chamber. The low temperature at the exit is achieved here without a system of dilution air. It can significantly simplify structure of the combustion chamber reducing its size and weight. This solution can also improve thermal efficiency [13].

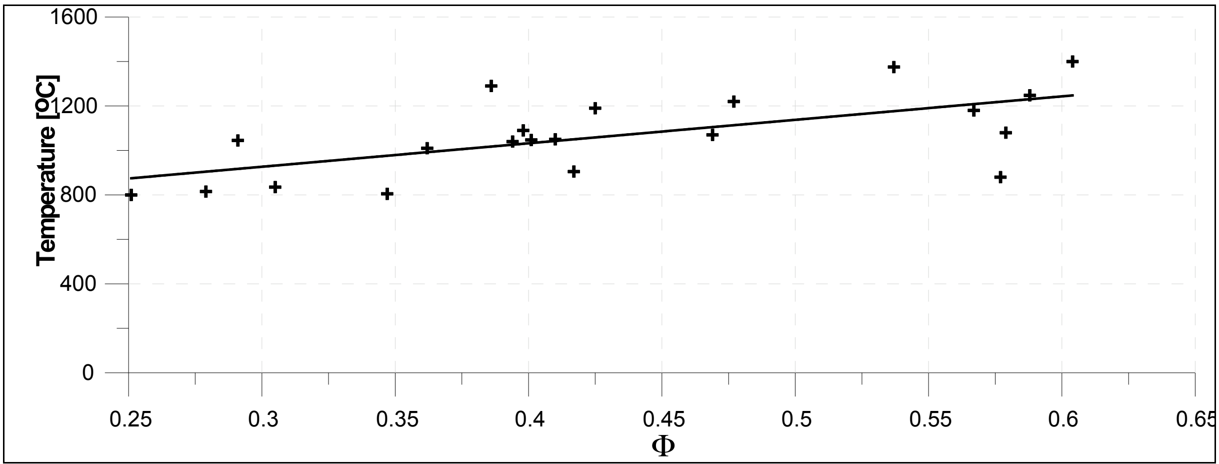

Fig. 14 Temperature of exhaust gases from experiment as a function of equivalence ratio for hydrogen-air mixture.

Summary

The presented experiments clearly showed possibility of establishment of the continuously propagating rotating detonation in different cylindrical chambers for wide range of lean hydrogen-air mixtures. Velocity of revolution of the detonation wave is function of thermodynamics parameters and composition of the mixture. In some cases an instability of the wave was observed. The mechanism of this instability can be explained by relationship between the revolution time and time necessary for refilling and mixing of the gasses in the chamber. The obtained results clearly indicate, that if properly arranged, such process could be applied in jet engines for improvement of their performances. It can be achieved by increasing cycle efficiency and reducing size and weight of the combustion chamber. The next step of research should be, however, a systematic study of detonation propagating in a mixture of air and jet fuel.

Acknowledgments

This work was supported by Polish Ministry of Science and Higher Education, project no. 4 T12D 024 29

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