Journal of KONES Powertrain and Transport, Vol. 19, No. 2 2012

STUDY OF COMBUSTION CHAMBER WITH A ROTATING DETONATION

Borys Łukasik, Artur Rowiński, Andrzej Irzycki, Krzysztof Snopkiewicz

Institute of Aviation
Krakowska Av. 110/114, 02-256 Warsaw
tel.: +48 22 8460011 ext. 426, fax: +48 22 1883776
e-mail: borys.lukasik@ilot.edu.pl, artur.rowinski@ilot.edu.pl

Abstract

Institute of Aviation in Warsaw realizes the project concerning the application of the phenomenon of combustion with rotating detonation to the combustion chamber designed and destined for turbine engines. The test chamber is adapted for supplying both with liquid (aviation kerosene) and gaseous fuels in the form of mixture with compressed air. It is equipped with a probe for pressure and temperature measurements inside the flame tube as well as at its inlet and outlet sections. The measuring system allows measurement of physical phenomenon at low (1 kHz) and high (1 MHz) frequencies. Electric signals representing temperature and pressure sensor's measuring quantities, fuel and compressed air supply systems parameters and ignition-triggering values are collected using data acquisition system controlled by a computer.

The prototype of the combustion chamber was examined at the especially designed test facility to determine at quasi-static operating conditions its following characteristics: speed of inside shock wave, exhaust gas thermodynamic parameters and ignition and going-out limits of gaseous fuel.

In this article construction of test bench, schematic diagrams of measurement and power supply systems as well as the research process, the way of measurement data analysis recorded during the carried-out experiments and data validation manner are detailed described. The method of measurement data processing, the resulting graphs, and the conclusions of the study are presented as well.

***Keywords**: internal combustion engine, turbine engines, combustion chamber, rotating detonation*

1. Introduction

Since December 2009 in Institute of Aviation, Warsaw, Poland, research of rotating detonation phenomena has being conducted as a part of the project of “Turbine engine with rotating detonation combustion chamber”, which is co-financed by the EU's Innovative Economy programme. The research group, which works under the supervision of Prof. PhD. Eng. Piotr Wolański, carries out several tasks in order to design a turbine engine with a combustion chamber which uses the rotating detonation phenomena and which is fed by the heterogeneous or heterogeneous/homogenous mixtures. Expected benefits from the use of a new chamber, in which a classical deflagration combustion process would be replaced with a rotating detonation combustion, come from greater efficiency of Fickett-Jacobs cycle (corresponding to the detonation combustion) in comparison with “classical” Brayton cycle (deflagration combustion). The theoretical benefits of the cycle itself, is showed in a graph below (Fig. 1).

Last year, the studies were carried out in the chamber with a diameter of 0.5 m and an 8 mm channel width, fed by homogeneous mixtures (mixture of air and hydrogen with different composition). Various methods of initiation of a detonation were tested, and the possibility of self-maintain of the rotating detonation process was examined by introducing geometrical changes of the chamber. In subsequent experiments, the length of detonation chamber and the geometry of the fuel and oxidizer injectors were modified. These studies also had to set boundaries of the mixture, for which detonation once initiated would be sustained. Equally important were also parameters and stability analysis of the phenomenon of detonation, which occurs in the chamber with such a large diameter. An additional goal of this study was to test the fuel supply system, which was to be used in next studies.

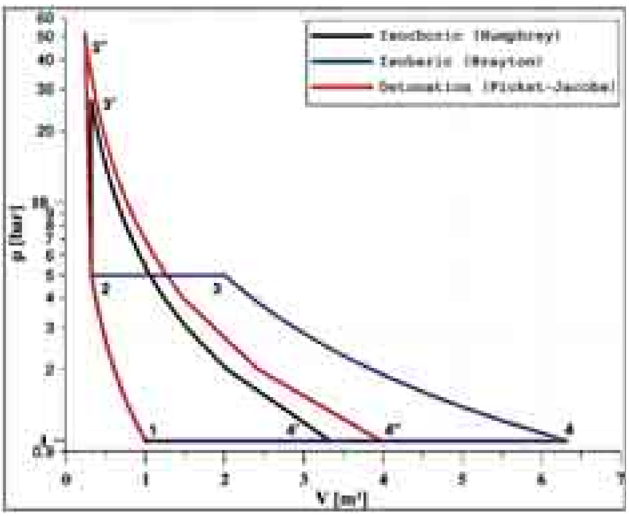

Fig. 1. Comparison of Humphrey and Brayton cycles with the theoretical detonation cycle (Ficket-Jacobs) [4]

2. The design of the research stand

The chamber was designed in the way to simplify dismantling and to make easy any modifications of the research stand parts, as well as to create many sockets for sensors deployment around the perimeter of the chamber. The chamber was designed to work in the vertical position. The body of the chamber consisted of two cylinders: the central one with an outer diameter of 0.5 m and the external one with an internal diameter 0.516 m. The walls of the both cylinders formed the detonation chamber, closed from the top by the fuel and oxidizer injectors ring. Figure below shows the scheme of the chamber (Fig. 2).

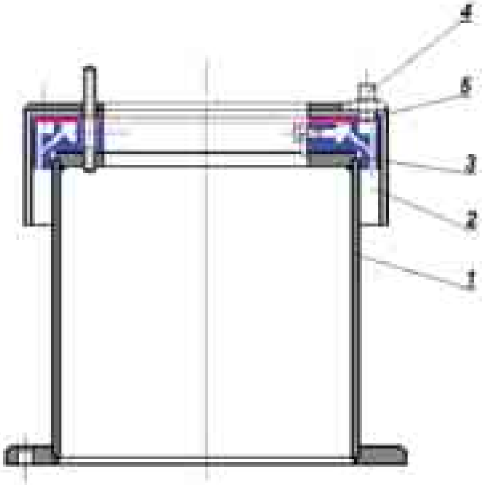

Fig. 2. The scheme of detonation chamber, 1. The Body; 2. Space in which detonation occurs; 3. The injectors ring; 4. Air supply; 5. Hydrogen supply

The chamber was fed by mixture of air and hydrogen. Fuel was supplied from four coupled cylinders, with a total volume of 0.16 m^3. After the valve opening the fuel got into the fuel manifold, in which the hydrogen flow parameters were measured (stagnation temperature, total pressure, and static pressure). Mass flow calculations were based on these parameters. Using eight wires, fuel came into the fuel injector's ring, where it was distributed among 180 injectors evenly spaced around the circumference. The injectors had the form of tubules with a diameter of 1mm each. Air was supplied from the tank with a volume of 1.35 m^3, which was pumped, by the compressor, to the desired pressure before each test After the valve opening, air got into the manifold, in which the flow parameters (on which the air mass flow calculations were based on) were measured. Passing through the manifold air using 8 wires flew into the injector's ring where it was distributed to the 180 tubules with a diameter of 3mm each. Scheme of the research stand was presented below (Fig. 3). The initiator, as well as the fuel and air valves, was controlled by a computer system.

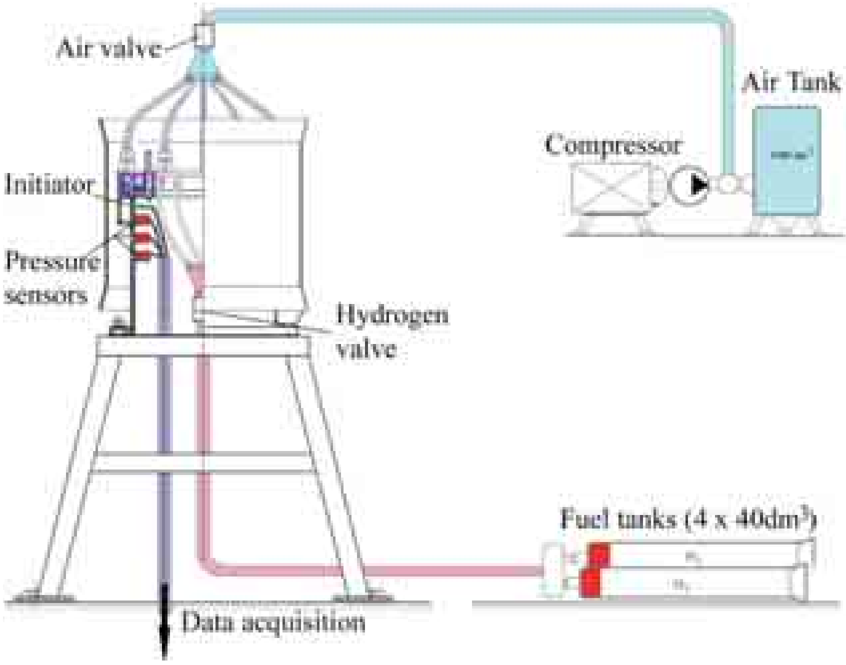

Fig. 3. Scheme of the research stand

3. The measuring system

Research stand is equipped with probes for measuring pressure and temperature inside the detonation chamber. The measuring system allows performing measurements for both low frequencies (of about 1 kHz) and high frequencies (1 MHz) phenomena. The process of the detonation combustion is identified on the basis of gas pressure in the detonation wave observation (pressure “peaks”), measured by piezoelectric sensors, with a frequency of 1MHz. Data acquisition system, which collect data from sensors measuring both the fuel supply system parameters and the compressed air parameters, as well as the pressure and temperature inside the chamber were controlled by a computer system. Measurement data were stored in two files. The firs file contained measured low frequencies parameters when the second one contained high frequency parameters (amplitude of the pressure in the detonation wave).

Based on data contained in each file, after each test series charts, showing the changes of various parameters, were drawn. On the basis of the pressure in the detonation wave, three graphs were made. The first graph shows the course of pressure changes during the entire test, while the second one shows only a time slice, which shows changes of pressure amplitude (pressure “peaks”). Both graphs are shown below. The third graph is a chart of a velocity of the detonation wave propagation, calculated from the circumference, of the chamber, divided by the time, between successive peaks of pressure.

Measurement instruments, wiring and hydrogen supply pipes were placed inside the cylindrical base of the stand. This type of mounting protected them from high temperature exhaust gases. Sockets for fixing the pressure sensors and initiating devices were made so that it was possible to place sensors and initiators at different distances from the exit of the injectors. Sockets, not used in a test, were clogged with special stoppers.

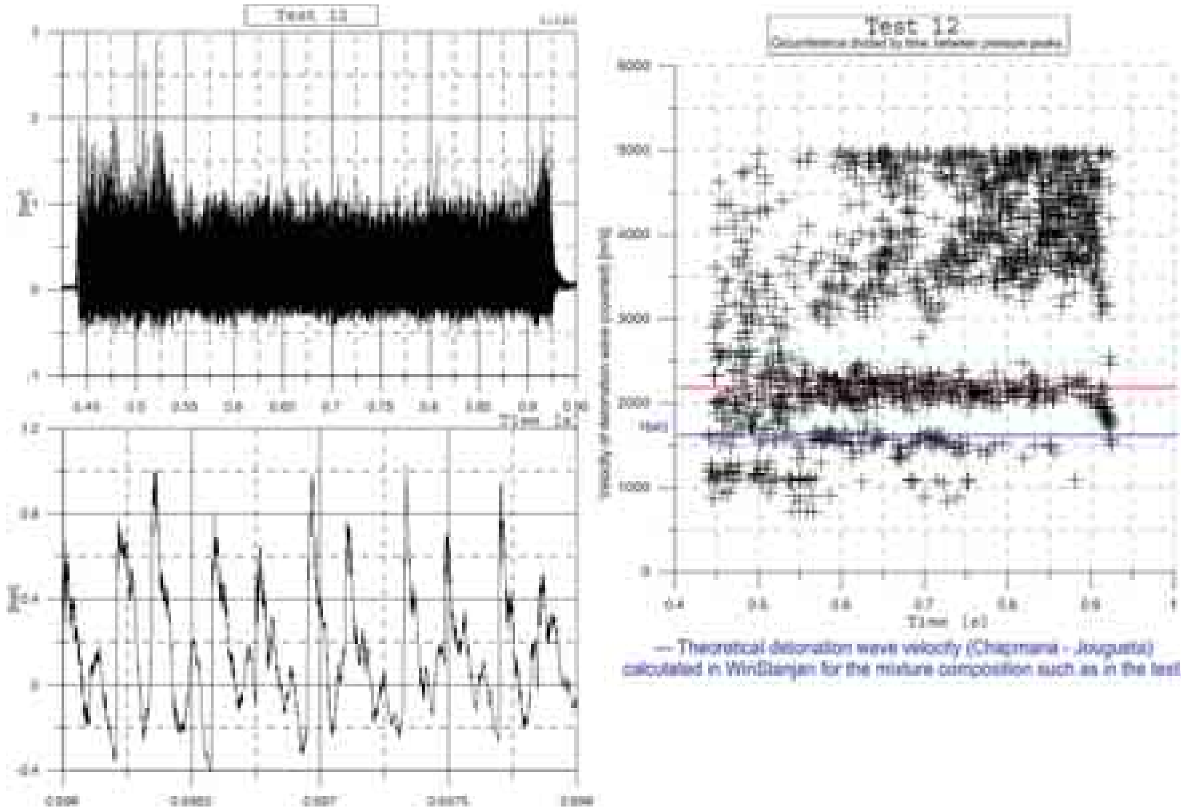

Fig. 4. Charts of pressure in the chamber and the calculated wave velocity

4. Tests performed

Chamber tests began by examining the different methods of detonation process initiation in the chamber. The use of the initiators: blank cartridges, spark plugs, high-voltage system and detonation primers, with different weight loads and their various settings relative to the flow, were tested. Impact of a distance, of the initiator to the injection point, was also tested. Experiments showed that the most repeatable and reliable test results were achieved for blank cartridges, while the spark energy was too small to initiate detonation in any case. More about the experiments of detonation initiation can be read in a separate article.

The first successful tests, in which the rotating detonation occurred, were carried out using an injectors ring with a pre-mixing of fuel and oxidant (the hydrogen injectors were injecting fuel in to the air tubules). These tests showed that the amplitude of the pressure in the detonation wave (pressure "peak") is lower than the expected (order of one bar, while the literature [5] states, that the pressure behind the detonation wave is expected to grow 20 to 30 times). This allowed to conclusions that after the initiation, the detonation wave follows the fresh mixture and moves toward the injection point. In the second phase of the tests, it was decided to split the two channels of the injectors and thus withdraw the injection point so that to increase the space for mixing process. Cross sections of both rings are shown in the figure below (Fig. 5).

Changing the configuration of the injectors changed practically nothing. Detonation wave parameters (pressure "peaks") achieved were still low. Further experiments showed that small increases of pressure during detonation wave transitions are characteristic for such a large chamber with the not choked exhaust outlet - amplitude is affected by the ratio of air pressure before critical section of the chamber to static pressure inside the chamber. In addition, for most tests calculated detonation wave velocity was about 3000 to 4000m/s while the theoretical detonation velocity is about 1500 - 2000m/s, from that can be deduced that in the chamber two detonation waves were formed, rotating one after another. The tests results showed that for cases, in which there were two detonation waves, the pressure of the wave (in pressure "peak") was approximately two times

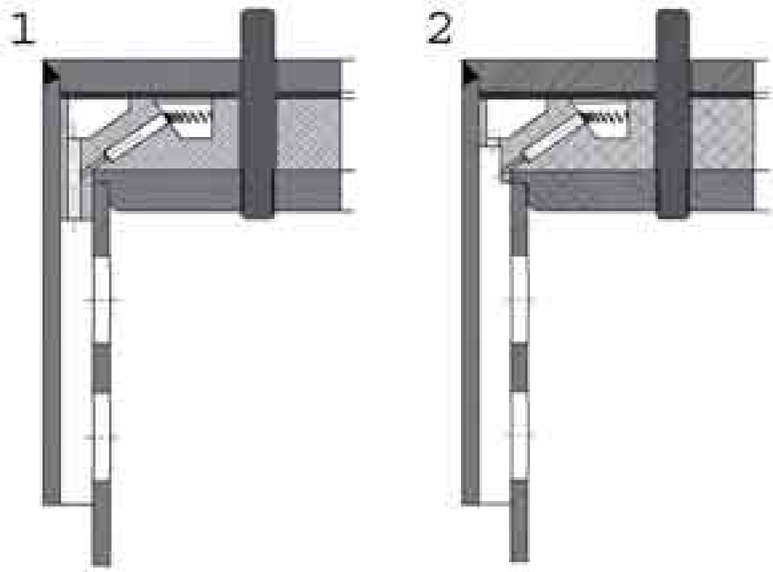

Fig. 5. Cross section of the detonation chamber with two different injectors rings 1. With the preliminary mixing of fuel and oxidizer 2. With the fuel injection directly into the chamber

lower compared with the cases for which there was only one wave. This is shown on the example of test in which just after the initiation, of a phenomenon, there was only one wave and then the second one was created. The charts below (Fig. 6) show that in the same time when the pressure amplitude decreases, the calculated wave velocity increases, that are evidence of the emergence of the second wave.

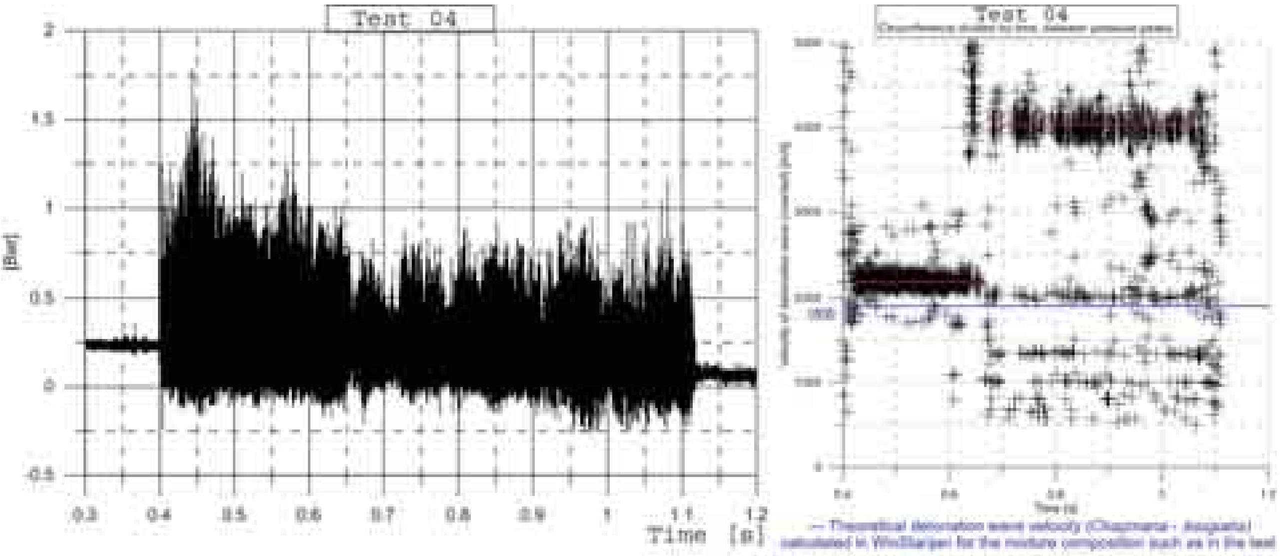

Fig. 6. Charts shows a detonation wave pressure and a calculated wave velocity changes in time when second detonation wave occurs

Further tests were performed to check the possibility of self-sustaining of the rotating detonation process. The test was planned so that to disconnect the air injection shortly after the initiation of the process so that the vacuum zone, directly behind the detonation wave, would cause sucking the air from the ambient. Due to the very short time between the successive pressure peaks (about 5.23E-04s for the cases with two waves, which run one after the other), it was decided to shorten the chamber so that air could be sucked easily. The chamber was shortened so that the length, between the place of fuel injection and the end of the chamber, was 10mm long (Fig. 7).

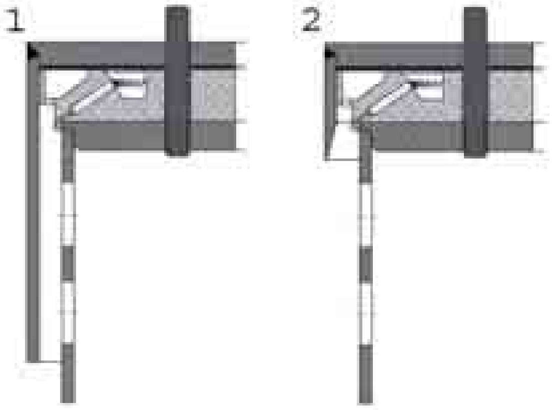

Fig. 7. Cross section of the detonation chamber with two different lengths of the chamber 1. Chamber before shortening 2. Chamber after shortening (10mm length from the fuel injection point)

However, on the chamber prepared thus it failed to initiate the process of detonation using any of mentioned method of initiation (blank cartridges, detonation primers, or high voltage system). The chamber was too short and in the point of ignition, the mixture was not mixed properly to ignite. In order to further tests the external screen was designed which was to extend the chamber and to allow the flow of oxidant from the environment to the chamber through a thin gap between the right chamber and the screen. The screen was designed in the way that it could be raised or lowered at any length thus shortening or lengthening the length of the detonation chamber. The screen lowered maximum downwards gave the chamber of the same length of what it had before shortening. Cross-section through the chamber with an additional screen is shown in the picture below. (Fig. 8).

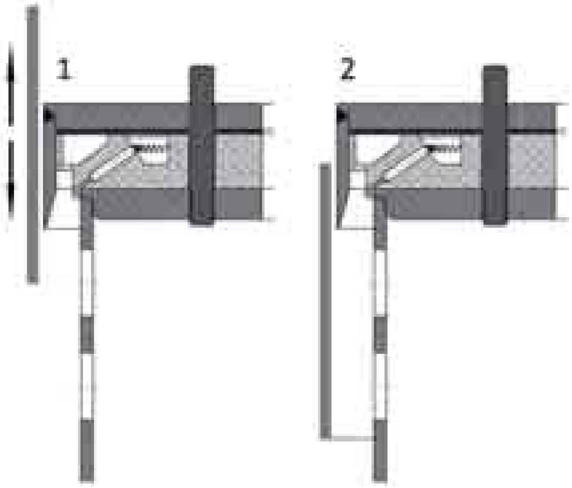

Fig. 8. Cross section of the detonation chamber with movable screen in different positions

The tests, with screen, schedule assumed, checking the possibility of self-sustaining detonation with screen lowered to the lowest position (i.e. the length of the chamber as before shortening). It was really important to check whether the gap between the remaining chamber and the screen will ensure an adequate flow of air into the chamber after cutting off oxidant injection. Next, the screen was to be gradually lifted up thus to reduce the chamber.

With the screen placed on the lowest position there was not any problems to initiate the process of detonation. Tests were repeatable and gave almost identical results as experiments performed on the stand before the chamber shortening. The test results showed that changes of the detonation chamber channel width from 8 to 12 mm did not affect the process of rotating detonation.

However, the tests of the self-sustaining detonation at this configuration of the chamber were not successful. Almost immediately after the cutting off air injection into the chamber, the mixture became too rich and the process of detonation fizzles out. The gap between the chamber and the screen was too small to allow air to be sucked into the chamber.

The following charts show the course of the test, in which injection of oxidizer was cut off shortly after the initiation of detonation. The first graph shows the course of total and static pressure in the fuel and oxidizer manifolds. (Fig. 9). Looking at the course of pressure it can be seen that the air supply was cut off much earlier than the fuel supply. Comparing times for both charts, we can see that shortly after flow of air was cut off (about 1s), the detonation became extinct.

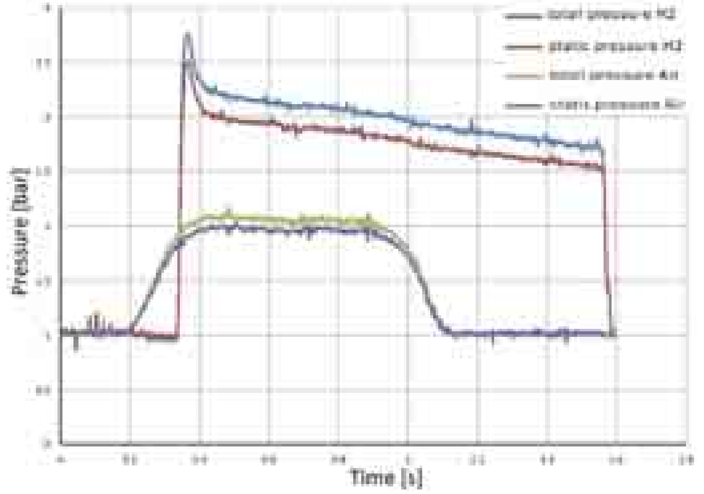

Fig. 9. Chart of the pressure in the fuel and oxidizer manifolds

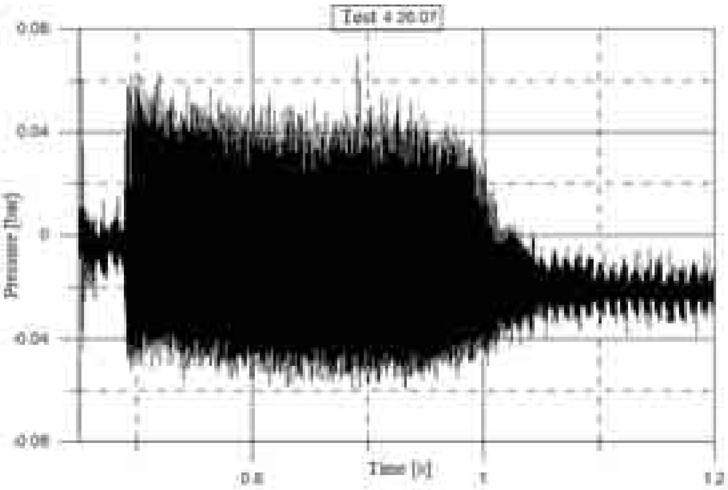

Fig. 10. Chart of the pressure in the detonation chamber

5. Summary and conclusions

Tests on the research stand showed that the process of spinning detonation of air and hydrogen mixture is relatively simple to obtain with the proper configuration of the chamber. The blank cartridges provide sufficient power to initiate the detonation if only the initiator is located in the zone where the fuel is mixed with the oxidant sufficiently. This shows that the factor that defines the chamber length is the fuel and oxidizer mixing zone. While the detonation wave parameters, obtained for the chamber with a large diameter of 0.5 m, are lower than expected and do not exceed approximately 2bar, they practically do not depend on whether the pressure sensor is placed on the inner or outer mantle of the chamber (there is no impact of the rotating exhaust gases mass inertia at the pressure distribution). Research shows that in the chamber with mentioned diameter usually two waves, which move at the speed of about 1700 m/s, are formed. While the temperature of exhaust gases, calculated on the basis of indications of a thermocouple with short time constant (less than 0.4s), is dependent on the composition of the mixture, but do not exceed 1650°C, even with a composition similar to stoichiometric.

For this configuration of the chamber, it failed to achieve self-sustaining rotating detonation process. After the cutting off of oxidizer flow, the process discontinues. The time between successive wave transitions is probably too short to allow fresh air being sucked from the chamber outflow. This raises the scope for further research on the chamber with a different hydrogen injector's design that could provide air sucking using the ejection effect.

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