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THE STUDY OF THE CONTINUOUSLY ROTATING DETONATION COMBUSTION CHAMBER SUPPLIED WITH DIFFERENT TYPES OF FUEL

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Abstract

The paper summarizes research that was conducted last year as part of the project of "Turbine engine with detonation combustion chamber". In this project, throughout 2012 and early 2013, tests were carried out on a test stand connected to the compressed air system. Research, of the rotating detonation phenomena, was carried out for a number of detonation chambers with different interior channel geometry. In addition, for each geometry configuration, tests were carried out for different levels of choking of the chamber outlet and hence for different pressures conditions inside the detonation chamber. This article presents the results of tests carried out for gaseous (hydrogen), hybrid (hydrogen + kerosene) and liquid (Jet-A) fuels, using different types of fuel injectors and for different fuel injection configuration settings (inside the chamber, or in front of the chamber). During these tests, parameters such as pressure behind the detonation wave (using piezoelectric sensors), the static pressure in front of and inside the detonation chamber and temperature: before, inside and at the outlet of the chamber, were measured. Research was performed for the various mass flow rates of air and fuel injected into the chamber that means for the different air-fuel equivalence ratios (Lambda). The main achievement of this study was to obtain a stable and reproducible rotating detonation of air and heated kerosene (Jet-A) mixture, thus the results presented in this paper presents mainly these tests as the most interesting to the reader.

Keywords: *rotating detonation, air/Jet-A detonation, detonation combustion chamber, internal combustion engine*

1. Introduction

The Institute of Aviation, Warsaw is the beneficiary of the "Turbine engine with rotating detonation combustion chamber" project, which is co-financed by the EU's Innovative Economy programme. The project is carried out at the Propulsions Laboratory. The main goal of this project is to design detonation combustion chamber that would replace standard combustion chamber of the GTD350 turboshaft engine. In order to do this for four years the research group led by Piotr Wolański, Prof. Ph.D. Eng. has conducted research of rotating detonation phenomena.

Throughout 2012 and early 2013 research was focused at the task to design internal channel geometry of the chamber that would allow to initiate detonation in air – kerosene (Jet-A) mixture. More than 700 tests were carried out at different geometry configuration of the internal channel, for different types of fuel and for different fuel injection systems and configurations.

2. Test stand

All tests were carried out at the test stand connected to the compressed air supply system. This system allows to fluently modifying the parameters of the air that supplies the chamber. It enables to change mass flow rate and temperature of the air. Fuel (for both hydrogen and kerosene) were supplied from the separate tanks and the composition of the mixture was set up by pressure inside the tank (gas pressure for hydrogen tank and gas cushion pressure for the kerosene tank). Fuel injection was opened by a solenoid valves controlled by a computer. One valve before the hydrogen collector and four separate valves before the kerosene collector. Scheme of the research stand was presented below (Fig. 1).

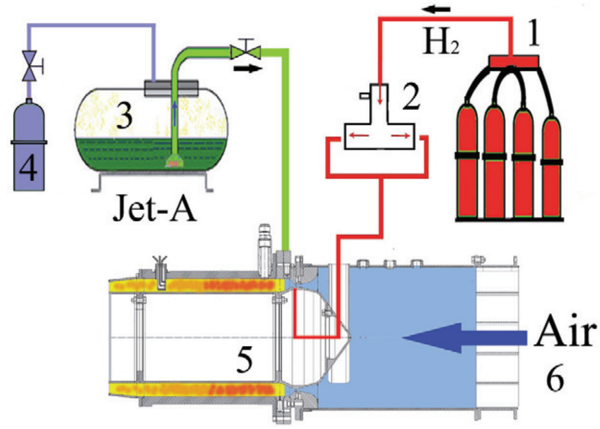

Fig. 1. Scheme of the research stand: 1 – hydrogen tanks, 2 – hydrogen manifold, 3 – kerosene tank, 4 – nitrogen tank to control gas cushion pressure in the kerosene tank, 5 – detonation chamber, 6 – compressed air inlet

3. Measurement system

Pressure and temperature inside the detonation chamber were measured by sensors which allows to perform measurements for low frequencies (of about 1kHz) and for high frequencies (1MHz) phenomena. Low frequencies probes allows to measure temperature and static pressure, while the high frequencies pressure changes in the detonation wave (pressure "peaks") were measured by piezoelectric sensors. After each test series, charts showing the changes of various parameters, were drawn, based on data collected by the data acquisition system. For each single test two graphs of the pressure in the detonation wave 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 a pressure amplitude (pressure "peaks"). Example graphs are shown below (Fig. 2).

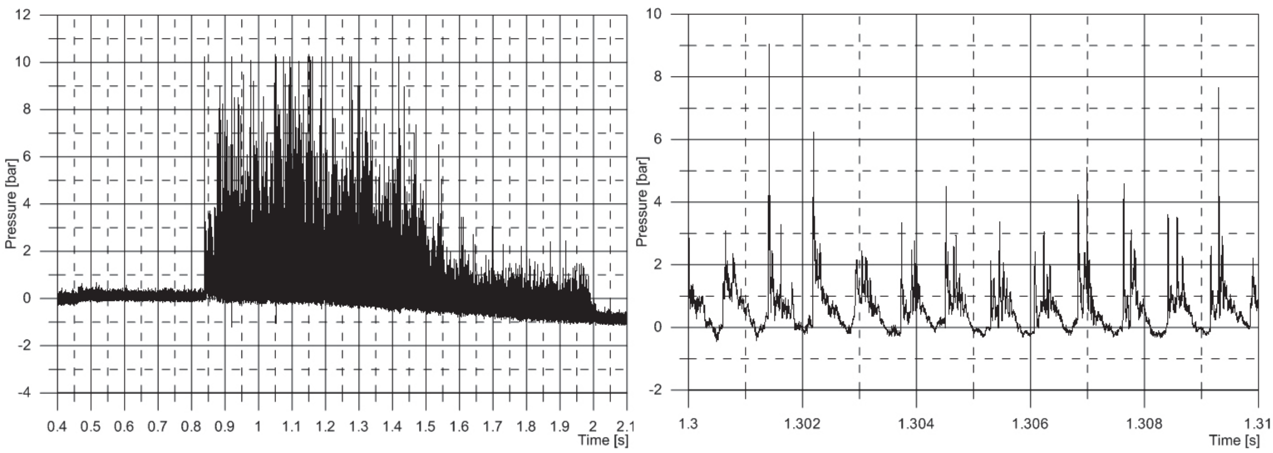

Fig. 2. Example graph of pressure course inside the chamber, with visible pressure "peaks", which are the result of succeeding detonation wave transitions through the plane of the piezoelectric sensor

4. Tests performed

The first studies were aimed at the selection of the inner channel geometry of the chamber so that it was possible to obtain a stable and repeatable rotating detonation process for hydrogen-air mixtures. Hence, the first considered chamber geometry had the 20 mm height channel, which corresponded to the detonation cell size for hydrogen-air mixtures.

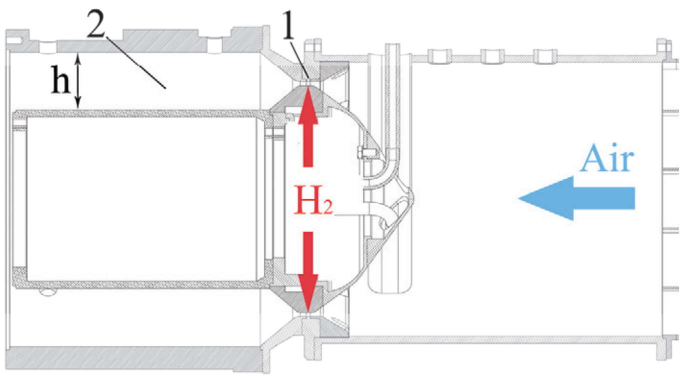

Fig. 3. Scheme of the first test chamber to study the rotating detonation phenomenon for air-hydrogen mixture: 1 – detonation chamber inlet throat, 2 – detonation chamber, h – height of the channel

The first attempts were already successful. It manage to initiate the process of rotating detonation. The best results were obtained for the air-fuel equivalence ratio (Lambda) of about 1-1.5, and for the air mass flow rate 0.75-1.0 kg/s. For such conditions, initiation of rotating detonation was repetitive and the detonation process, once initiated, continued until the fuel injection was cut-off. However, the first results were not satisfactory. Analysis of pressure measured in the detonation wave using piezoelectric sensors showed that the detonation wave is very faint – the pressure jumps behind the wave are small. Moreover, the pressure increase times (in the pressure "peak") were relatively long – the detonation wave was fuzzy. Finally, the graph of pressure course in the chamber, measured during detonation, presents the image of small and not really sharp pressure "peaks" which can be seen on the chart below (Fig. 4).

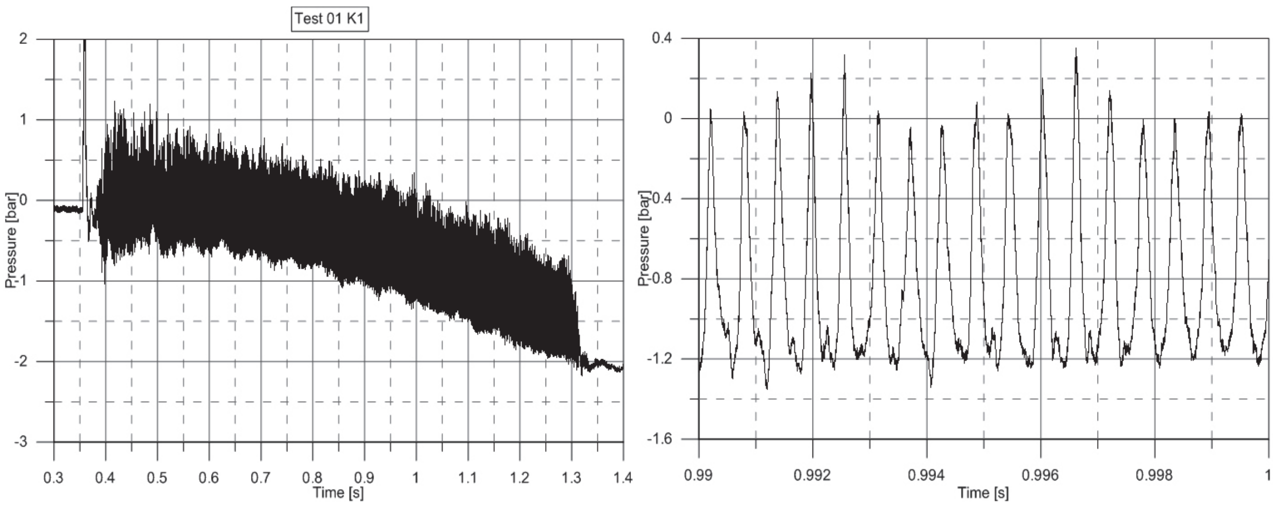

Fig. 4. Course of pressure in the chamber for one of the first tests in which the rotating detonation was achieved in a mixture of air and hydrogen

Further tests revealed that detonation wave is sensitive to the pressure ratio inside and in front of the chamber. In other words, the pressure in detonation wave depend on whether the throat at the entrance to the detonation chamber has a critical cross-section or not. Critical cross-section in the throat at the entrance to the chamber is a kind of "support" for the detonation wave. In addition, critical flow, at the throat, cuts off (separates) that what happens before the chamber from the parameters inside the chamber, so that there are no effects such as e.g. thermal throttling. As a result, pressure growths in the detonation wave are high (about 10 bar even at 1 bar initial pressure), in turn, pressure increase times are very short. The graph gives an image of sharp and high pressure "peaks". This relationship has an impact on the prospective possibilities of choking the chamber at the outlet. Any attempts to choke the chamber outlet causes increase of static pressure inside the chamber (during detonation) and if the ratio of pressure before and after the chamber throat is not large enough (about 2) this results in loss of critical flow, what makes detonation wave being fuzzy. The graphs below (Fig. 5) show the course of the pressure in the chamber for the test with non-choked outlet. A significant improvement in qualitative and quantitative readings of the pressure sensor can be seen.

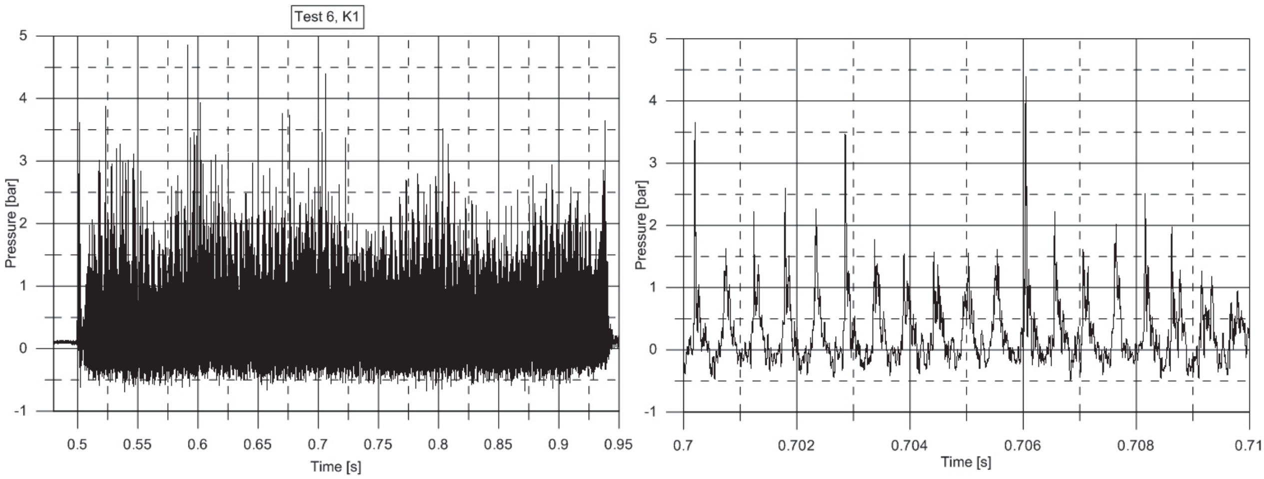

Fig. 5. Course of pressure in the chamber for the test with critical flow at the chamber throat. Clearly seen high and sharp pressure peaks

Next, the chamber adapted for hybrid mixtures (hydrogen-kerosene-air) was tested. Geometry of the inner channel was adjusted to detonation cell size. In front part of the chamber it was adjusted to hydrogen-air mixture (channel height of about 20 mm) and in the further part, it was expanded to the size of the theoretical detonation cell size for a kerosene-air mixture (channel height of about 50 mm). Kerosene (Jet-A) injectors were placed inside the chamber, at the beginning of the wider part of the channel. The scheme of the chamber is shown in the figure below (Fig. 6).

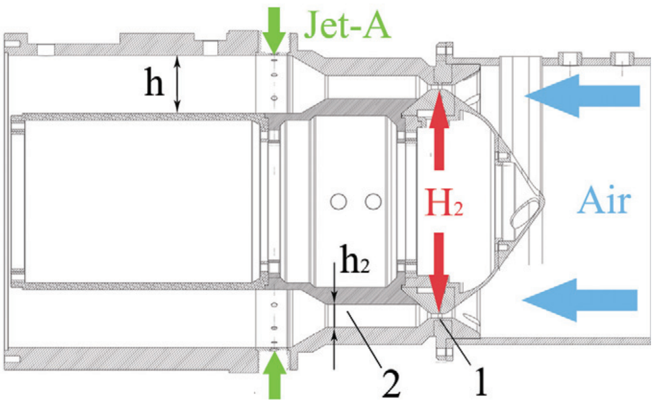

Fig. 6. Scheme of the chamber, with inner channel adjusted to hybrid mixtures: 1 – detonation chamber inlet throat, 2 – detonation chamber, h – height of the channel adjusted to detonation cell size of Jet-A-O_2 mixture (50 mm), h_2 – height of the channel adjusted to detonation cell size of H_2-O_2 mixture (20 mm)

The main goal of this research was to examine the impact of kerosene injection on the pre-initiated process of rotating detonation. Such a test consisted of pre-initiation of rotating detonation process in a mixture of hydrogen and air and then injection of kerosene into the chamber. It was desirable to check how the kerosene injection would affect the course of pressure in the detonation wave. The possibility of sustaining the pre-initiated process of rotating detonation, in the mixture of kerosene with air was also checked, by prior cutting the hydrogen supply off.

The results of these tests were not successful. Analysis of pressure course in detonation wave, allow drawing the conclusions that the kerosene injection has a minor effect on the process of rotating detonation. In tested configuration of injectors (in the wide part of inner channel), kerosene injection seems to work more like an afterburner. Kerosene burns in hot exhaust gases – hydrogen detonation products, near the outlet of the chamber, or even outside the chamber. It does not take an active part in the process of detonation. In addition, it was found that the kerosene itself was not able to sustain the process of rotating detonation. After the hydrogen injection had been cut off the detonation was suppressed soon, despite a further kerosene injection. It can be clearly seen at the graph below (Fig. 7).

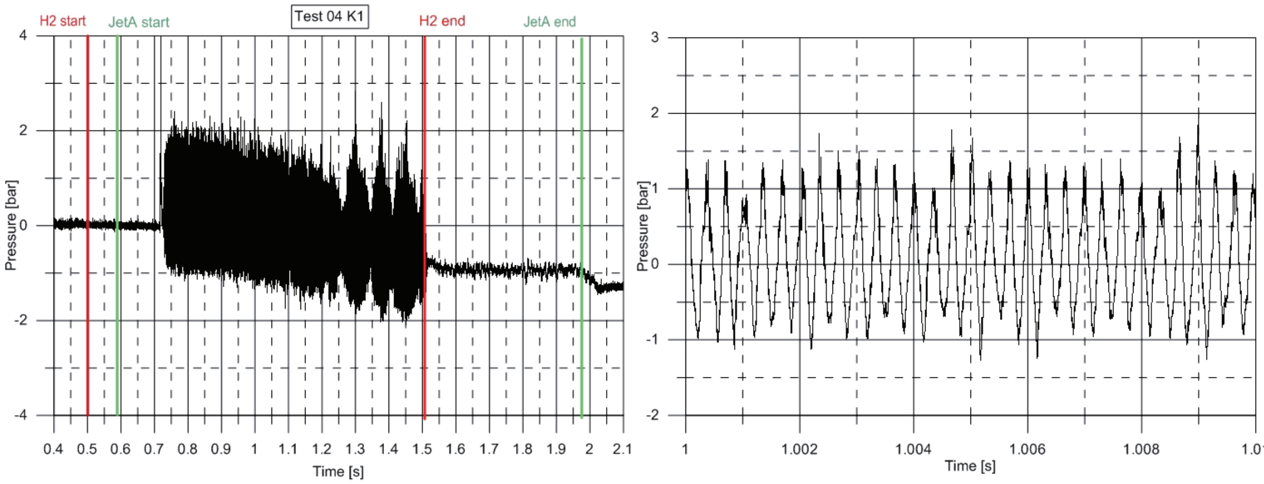

Fig. 7. Graph of pressure course, with kerosene and hydrogen injection times marked. Extinguishment of rotating detonation process, after the hydrogen was cut off, is clearly seen

Once again it was proved that the critical cross-section in the throat of the chamber have significant effect on detonation wave. Test was repeated once again for the same parameters, only this time for a completely non-choked chamber. Ratio of pressure before and inside the chamber was greater than 2 so that at the throat of the chamber critical flow was obtained. Image of pressure course of detonation wave was significantly improved. The pressure "peaks" of up to 10 bar can be observe at the graph below (Fig. 8). It can be clearly seen that the jumps of pressure magnitude times are also very short.

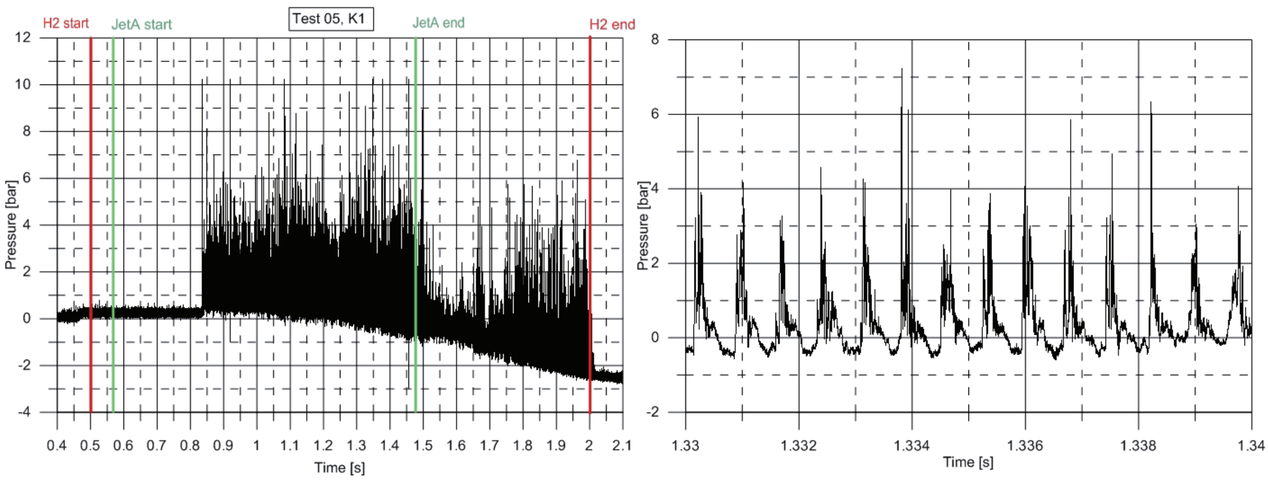

Fig. 8. Graph of pressure course in the chamber, for the test with completely non-choked chamber outlet and with high air mass flow rate. High and sharp pressure peaks are clearly seen

Because of the minor effects and non-appreciable influence of kerosene, the configuration of the chamber was changed. The kerosene injectors were transferred before the detonation chamber.

Kerosene injector's manifold was placed before the throat of the chamber and the chamber geometry was changed by an additional element of inner channel placed between narrow and wide part (a width of 37 mm). Scheme of this configuration of the chamber can be seen in the image below (Fig. 9).

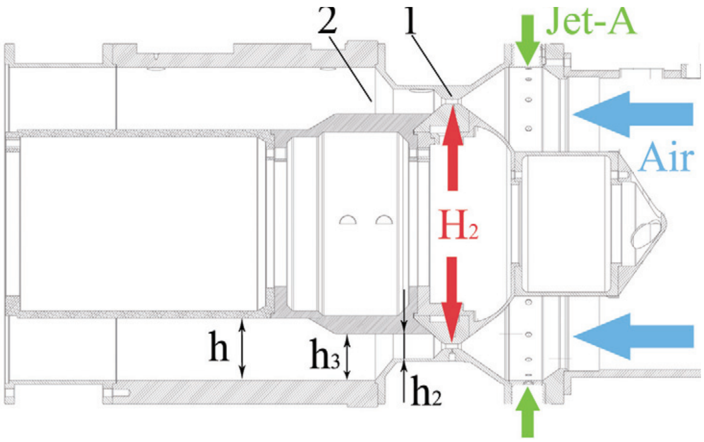

Fig. 9. Scheme of the chamber with three-part inner channel: 1 – detonation chamber inlet throat, 2 – detonation chamber, h – height of the channel adjusted to detonation cell size of Jet-A-O_2 mixture (50 mm), h_2 – height of the channel adjusted to detonation cell size of H_2-O_2 mixture (20 mm), h_3 – height of the transfer passage between the wide and narrow part

For this configuration of the chamber, once again the influence of kerosene injection on the pre-initiated rotating detonation was tested. The impact of kerosene injection with 20% addition of the IPN (isopropyl nitrate – which raises the cetane number) was also examined.

For the injectors placed before the throat of the chamber, test results were much more promising. A series of tests showed that both the kerosene and kerosene with a 20% IPN addition was able to sustain pre-initiated rotating detonation process. After cutting the hydrogen off, detonation has been sustained until the liquid fuel injection was cut-off (Fig. 10)

Unfortunately, it failed to initiate the rotating detonation in the mixture of air and kerosene or kerosene with IPN. What is more, pressure values obtained in the pressure "peaks" were really small. However, tests have shown that sitting the injectors before the throat of the chamber and in front of the hydrogen, injector allows for better kerosene-air mixture preparation. Through partial evaporation of kerosene, as well as due to the rotating detonation phenomenon (which shatters the kerosene droplets and significantly raises the temperature inside the chamber) mixture of kerosene with air was able to sustain pre-initiated detonation.

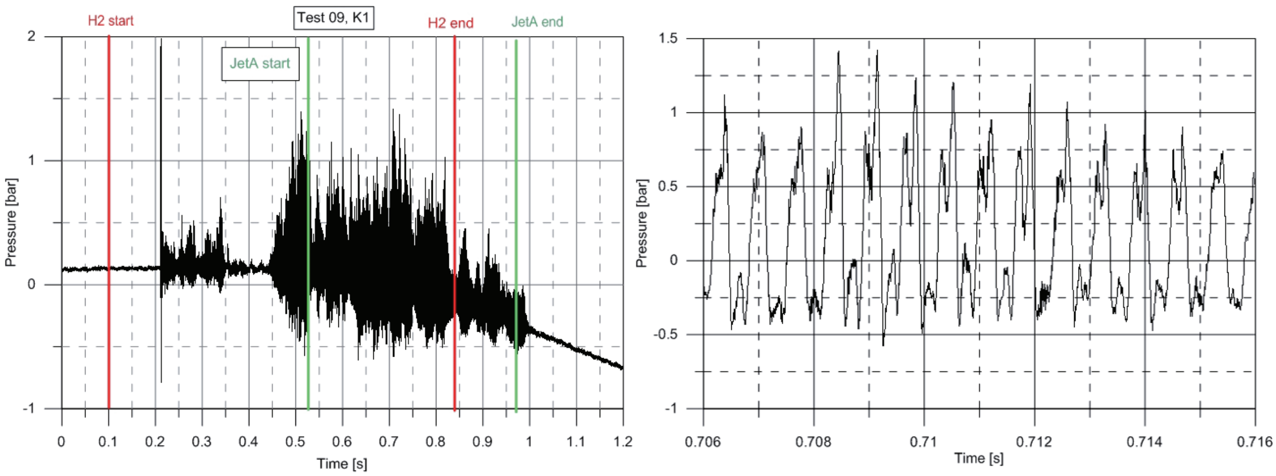

Fig. 10. Graph of pressure course in the chamber, for the test with kerosene injectors situated before of the throat

Further tests were carried out for the same configuration of the chamber as the previous one, but only for the mixture of air and kerosene (without hydrogen). The air was heated to about 130°C and the kerosene was pre-heated in the manifold to about 170°C, which gave a temperature of injected kerosene of about 80°C. For this configuration of the chamber and for the air-fuel equivalence ratio (Lambda) of 1.4, it was successfully to initiate the process of rotating detonation, which has persisted until the fuel supply cut off. For certain conditions the received detonation was stable and repeatable. However, the pressure amplitudes were small (about 1 bar) and times of pressure magnitude jumps were relatively long. Example chart of these tests is shown below (Fig. 11).

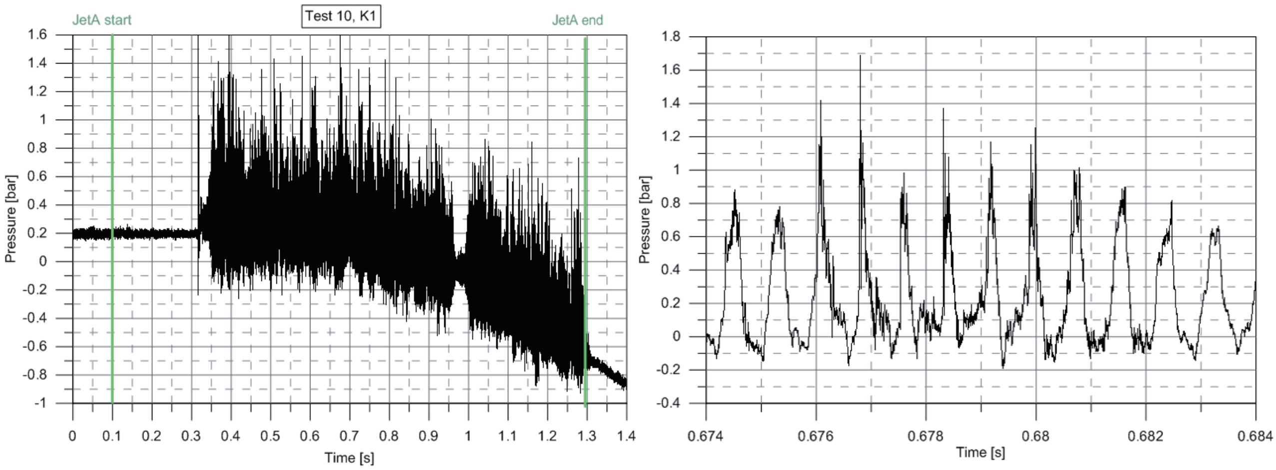

Fig. 11. Graph of pressure course in the chamber, for the detonation initiated in the mixture of air and kerosene

Once again the impact of a critical cross section in the throat of the chamber was proved (without critical flow that is kind of support for rotating detonation, the wave is blurred). Critical cross-section was possible to achieve for greater air flow rates, however, it has required a kerosene injectors with higher flow rate, which were no able to spray fuel properly and prepare the mixture well.

5. Summary and conclusions

One of the main conclusions of the experiments is the impact of the critical flow, at the throat of the chamber, on the pressure magnitude in the detonation wave and on pressure rise times (jumps of pressure value). It has been proven that it is relatively easy to obtain the rotating detonation process with sharp pressure "peaks" for hydrogen-air mixture.

Tests have shown that the initiation of the rotating detonation process in a mixture of kerosene and air is perfectly possible. The possibility of kerosene-air mixture detonation is a matter of mixture preparation and the energy required to initiate detonation. Good preparation of mixture (good kerosene evaporation) reduces the energy required to initiate the process Initiation of detonation in a mixture of heated air and the pre-heated kerosene was possible for a relatively small energy initiators (it manage to initiate detonation using a spark plug from the K15 engine, of about 7 J energy). But this was done only with the intermediate phase of deflagration to detonation transition. Conducted research allowed to determine the approximate inner channel geometry of the target detonation chamber. Tests have not only shown the essential elements for a stable and repetitive process of rotating detonation, but also the key factors that need to be obey during design of future detonation combustion chambers.

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