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Rotating Detonation Hollow Combustor for Kerosene – Air Mixture

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Abstract

The paper gives short information about detonative propulsion systems, their advantages, and the possibility of application to the propulsion systems. The research was conducted on a specially designed test stand which allowed to measure propulsion performance. For comparison, two different chambers were tested: annular and hollow. It was shown that the hollow chamber is superior over the annular as concerns of initiation and detonation stability, and also the hollow chamber showed better propulsive performance.

1. Introduction

Continuously rotating detonation (CRD) was discovered at the beginning of the sixties of the last century [1,2], however, attempts to apply it to the propulsion system were not successful at those times [3-5]. Only at the end of the XX century and the beginning of the XXI century research on possible applications of the CRD to propulsion systems was reinitiated nearly simultaneously in France, Poland, and Russia [6]. Since that time research on this topic accelerate and most research on the application of detonation to propulsion systems is focused on CRD and more complex studies on the development of rotating detonation engines (RDE) recently intensive research on that subject are carried out at many laboratories [7-9]. Also at the Lukasiewicz – Institute of Aviation extensive research on this subject are carried out for more than thirteen years. The gas turbine with the detonative combustion chamber was tested and the world's first experimental rocket powered by a rotating detonation engine was successfully launched [10-12]. During the last few years intensive research on the development of CRD chamber fed with liquid fuels were carried out. The development of such a chamber is essential for the introduction of detonative propulsion to aeronautical engines. Most important in those research is a development of a detonation chamber that will support stable detonation for jet fuel-air mixtures. Additionally, it is very important to minimize pressure losses during mixture formation and simultaneously prevent a flashback of flame to the mixing zone. A few different systems of mixture formation were already tested and some of those systems were also patented [13]. Extensive tests were carried out for the development of a detonation chamber that will support CRD for kerosene (Jet-A fuel) air mixtures. Initial research was conducted for annular chambers with a diameter of 225 mm with different fuel injection systems in which stable detonation was achieved for both kerosene-air and gasoline-air mixtures [10,14,15]. One of the open questions in this research is the problem of the so-called "pressure gain" of the system. Theoretically, rotating detonation engines (RDE) is the system that offers significant pressure gain as well as a considerable improvement of efficiency over classical combustion chambers used in recent propulsion systems [6-7, 9-10]. Up to now experimentally tested detonation chambers have not yielded the theoretically promised pressure gain, but most often demonstrated the pressure losses. Most advanced systems show only minimum pressure losses and total "pressure gain" close to zero. To obtain a real advantage of the CRD the developed chambers have to demonstrate positive pressure gain of the system. Only that will allow for the practical introduction of the CRD to the propulsion system. A few different systems of the CRD chamber supplied by jet fuel-air mixtures are recently tested at the Łukasiewicz – Institute of Aviation (Ł – IoA). One of the promising

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systems may be the hollow detonative combustion chamber. Selection of the hollow detonation chamber allows lower heat losses in comparison to the annular chambers which are most often used in tested RDE. In this paper, different aspects of the development of the hollow detonation chamber which should demonstrate the positive pressure gain and might be applied in future aeronautical propulsion systems are discussed.

2. Experimental test stand and measurement system

A special test stand was adapted for this research which includes a high-pressure air tank from which high pressure is supplied to either one of two different detonation chambers: annular or hollow, a fuel supply system, a pressure and temperature measurement system as well as a video recording system. Details of those systems are described below.

2.1 Experimental test stand

A schematic diagram of the test stand is presented in Fig.1. It consisted of the 2 m^3 pressure tank. The tank initially was filled by a high-pressure air compressor up to 9 bar pressure. Compressed air was heated by an electrical heater to obtain a temperature of about 150^0C just before introduction to the combustion chamber. At the exit of the tank, a special quick-response valve was installed. Below the valve, there are installed extra heaters and a flow mass measuring system. At the end of the vertically hanging tube test, the chamber is attached. The fuel supply system connected to the chamber is pressurized separately from the air supply system. Products from the detonation chamber are directed to the special exhaust system. A vertical tube with an attached detonation chamber is placed beneath the dynamometer providing direct thrust measurement during the whole test after introducing sufficiently high preload force. A picture of the experimental test stand is shown in Fig.2.

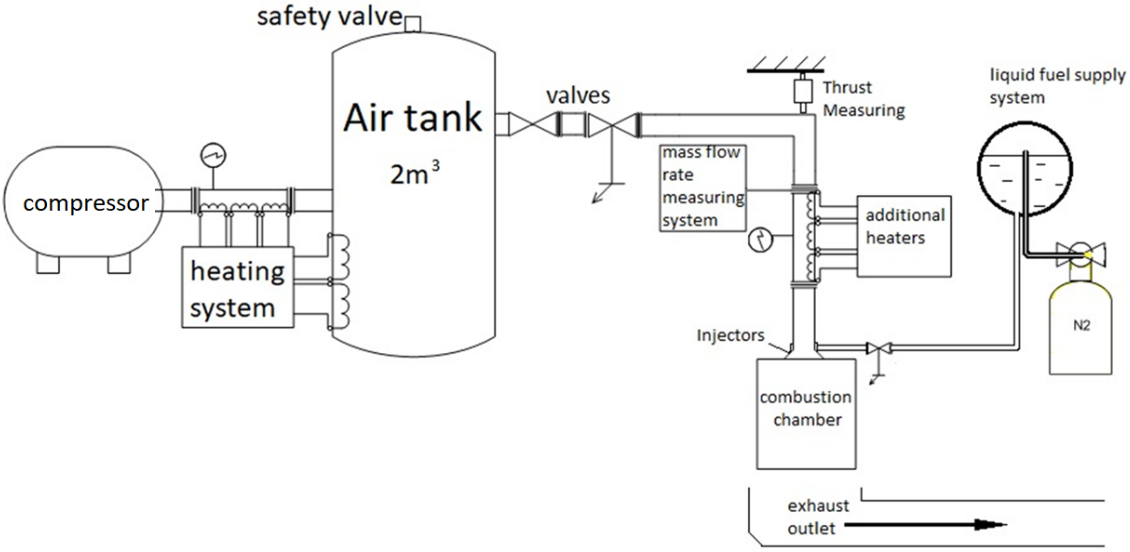

Fig.1. Schematic diagram of the experimental test stand

2.2 Test chambers

Two different geometries of the test chambers were tested, one was the annular and another was the hollow one. Both chambers have a channel outer diameter of 140 mm. Such geometries were chosen to show the effect of geometry on chamber performance. In both chambers, a special igniter providing considerably high energy was installed to guarantee reliable ignition of the tested mixtures.

2.3 The measurement system

Experiments were controlled by a computer that was connected to the main valve, which initiated the flow of air to the detonation chamber, ignition system, and data acquisition system. Also before each test video recorder was

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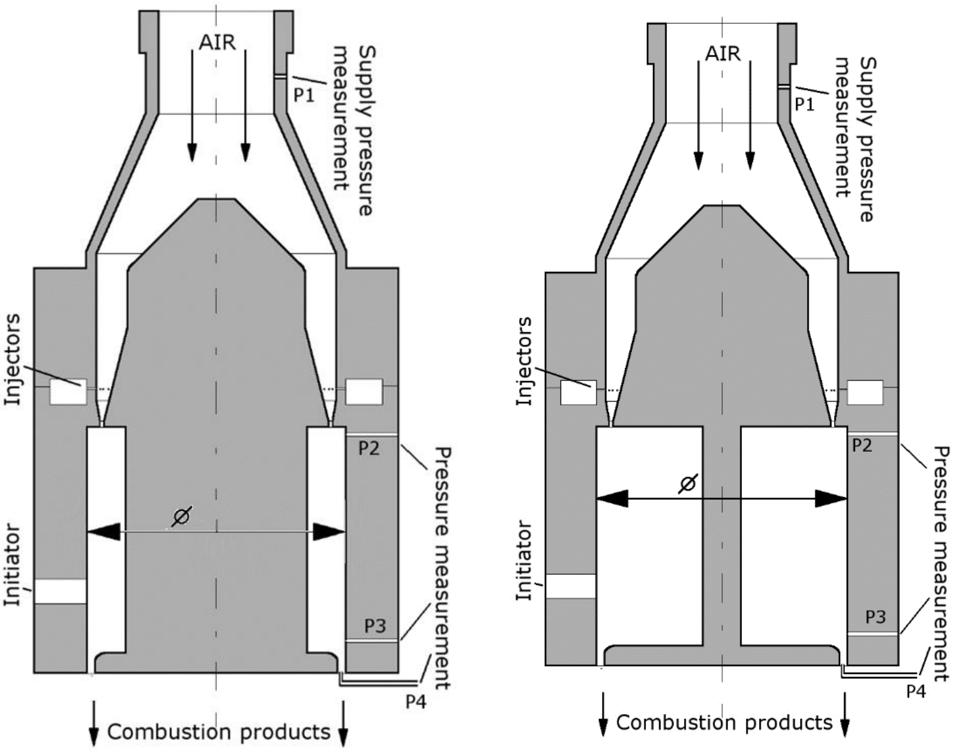
Fig.2 View of the experimental test stand.

activated to monitor the flow of products from the detonation chamber. All data were carefully stored and analysed before the selection of the next test.



a) b)

Fig.3. Schematic diagram of the tested chambers, both of 140 mm external chamber diameter:
a) annular chamber, b) hollow chamber

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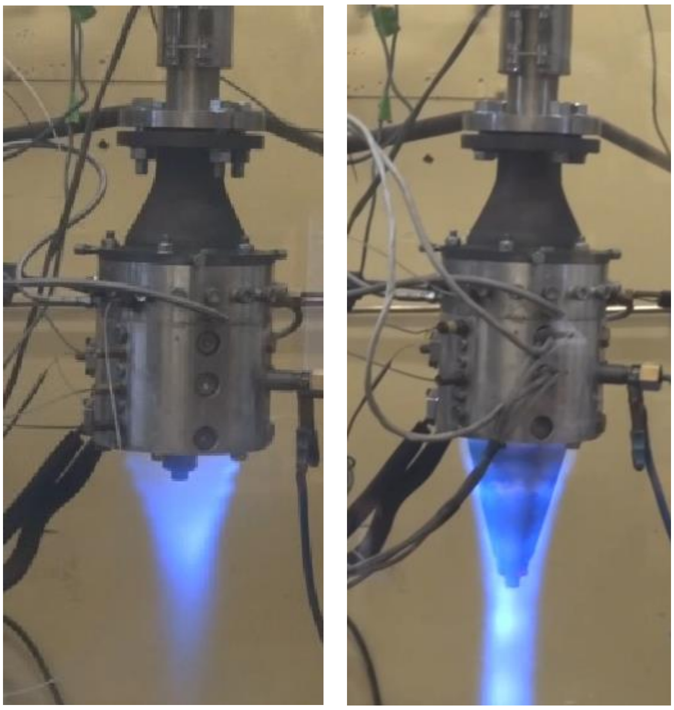

Fig.4. Picture examples of operating hollow chambers without and with an aerospike nozzle.

In several tests, a total pressure probe was used to measure the total pressure of the combustion gases at the outlet from the chamber and compared to the static pressure inside the chamber. A probe was small enough to have a negligible influence on the total outlet area and was inserted sufficiently into the throat at a minimum distance of its own diameter accordingly to Bach et al. [16]. The measurements showed that dynamic pressure is a minor part of total pressure and in further steps, it will allow for a comparison of both methodologies – direct total pressure measurement and indirect total pressure evaluation from thrust measurement.

3. Research

A short description of the conducted research is given below. The research was conducted for kerosene (jet fuel) with air for a different fuel-air equivalence ratio. The most important parameters acquired concerned thrust, pressure records, and derived from that the stability of the process. Variations of the recorded pressure allowed to determine the combustion mode in the chamber as “deflagration” or “detonation” as well as the process stability. Below examples of different pressure records and combustion modes are presented.

3.1 Annular chamber

The most common shape of the combustion chamber for an RDE engine is the annular chamber. Unfortunately for a higher mass flow rate, such a shape of the chamber requires high energy for the initiation of detonation combustion, which is due to the increased velocity of the mixture in the annular channel. Detonative combustion was initiated with spark plugs or a weak pre-initiator which was carried as follows: spark plug energy ignites the mixture, which initially burns in a deflagration mode and after a short time the deflagration may transfer into detonation mode (so-called DDT). The stability of CRD in the annular channel depends on many parameters, such as the mixture composition and mass flow rate of the tested mixture. In the experiments conducted, we were only to achieve an unstable detonation process for a kerosene-air mixture at the mass flow rate of up to 0.8 kg/s. Typical recorded pressure variations in the annular chamber are presented in Fig.4, and the variation of the pressure inside the annular chamber was measured.

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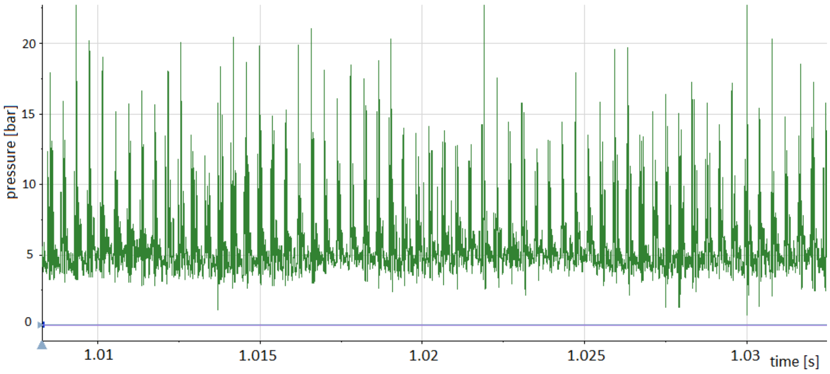

Fig.4. Piezoelectric pressure sensor record of unstable detonation in the annular combustion chamber for kerosene-air mixture.

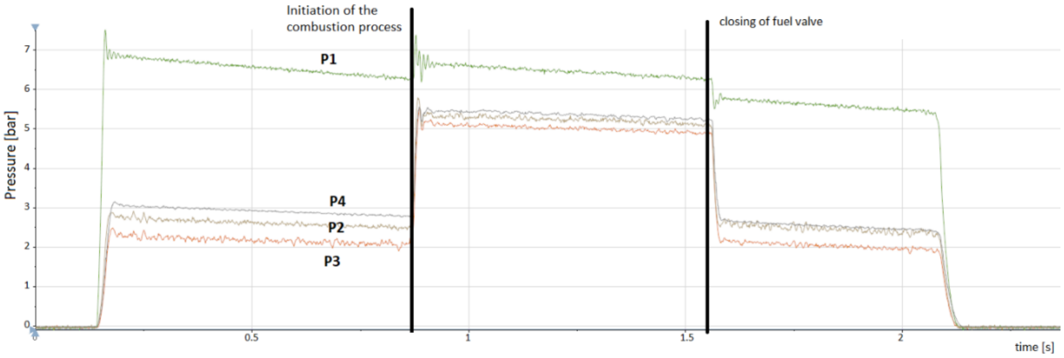

Fig.5. Pressure records in the supply duct and inside the combustion chamber

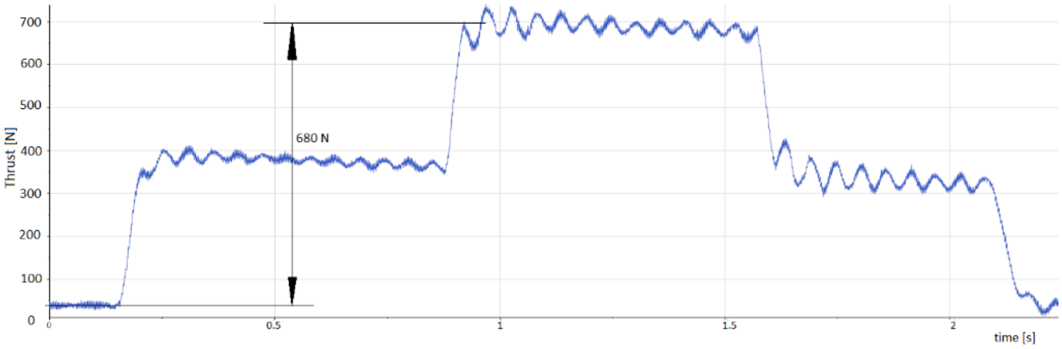

Fig.6. Thrust measured in the test.

In the above test, the total mass flow rate of 0.57 kg/s was measured. The specific thrust reached a value of 1200 N/(kg/s). Increasing the mass flow by throttling the chamber (increasing the inlet and outlet gaps) hindered the formation of detonation combustion. Most often, combustion took place outside the combustion chamber or switched into deflagration mode. In this case, the specific thrust did not exceed 1000 N/(kg/s). The calculated pressure gain was still negative and reached the value of approximately -15%.

3.2 Hollow chamber

In the face of difficulties in initiating the process in an annular chamber with a flow rate higher than 0.8 kg/s, a hollow-type geometry with a slotted nozzle was used. Some comparative experiments were also performed with an aerospike nozzle. Experimental results for a 140 mm hollow chamber are shown below.

Tests conducted in a chamber with a diameter of 140 mm have shown that the most common combustion mode in hollow chambers had the nature of the so-called high-frequency instabilities (HFI) [17]. Typically, the measured pressure oscillations indicated high amplitudes, of the order of several bars. These oscillations had a frequency of 3.5 kHz (Fig 7-9).

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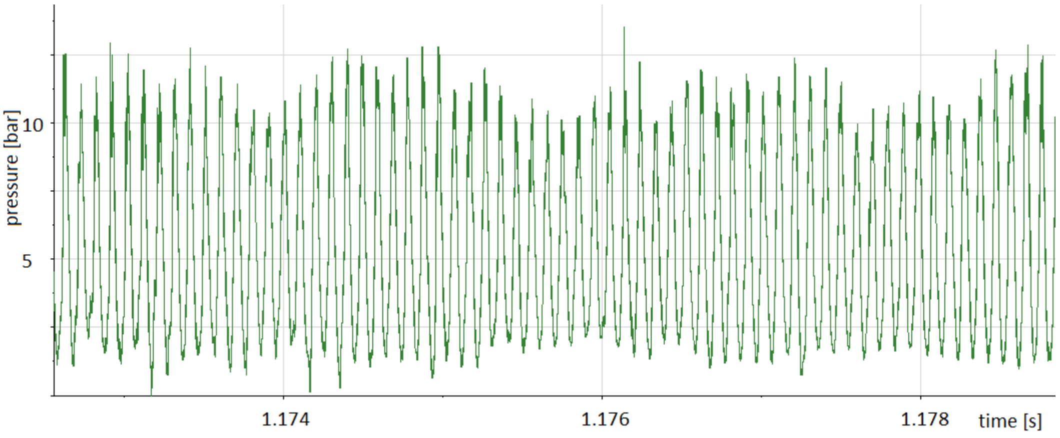

Fig. 7. High-frequency piezoelectric pressure sensor record of HFI in the hollow combustion chamber for kerosene-air mixture.

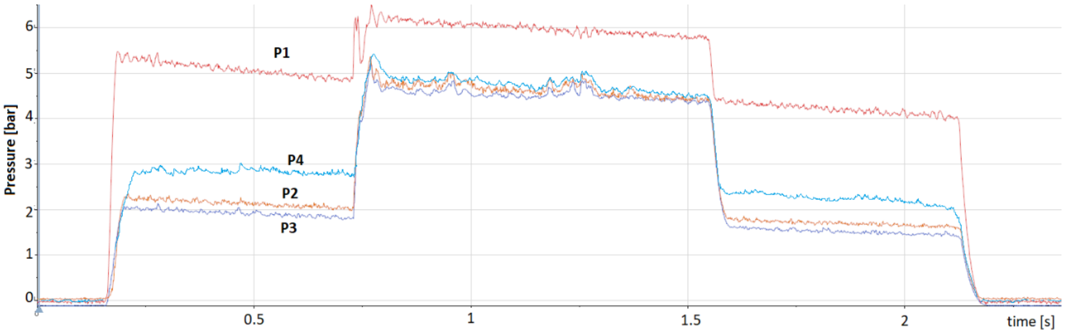

Fig.8. Low-frequency pressure records in the supply duct and inside the hollow chamber.

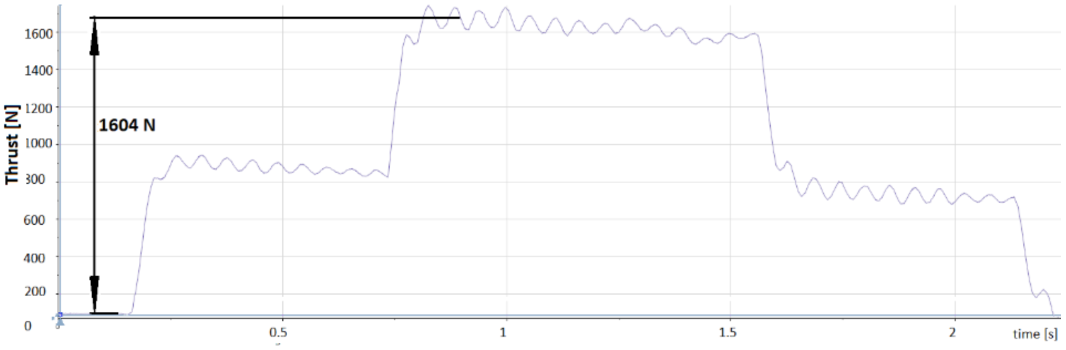

Fig.9. Thrust measured during the test in the hollow chamber.

In the conducted study, a stable detonation process was not obtained for all tested conditions. Only fast deflagration and HFI mode, was recorded. For a relatively large mass flow rate of 1.1kg/s, the recorded pressure peaks are slightly lower than for the annular chamber unstable detonation. The maximum recorded thrust was about 1600N and the maximum specific thrust is close to 1450 N/(kg/s), and the calculated pressure gain was still negative, which was about -20%.

Achieving detonation required increasing the outlet slit relative to the combustion chamber inlet slit. The modification made it possible to obtain a detonative mode of combustion. The introduction of such a modification results in higher pressure losses in the combustion chamber (PG is even lower). The detonation process itself is also not completely stable. The detonation has a so-called galloping (or winning-waxing) character (Fig.10). To make the process more stable, the supply pressure to the combustion chamber would have to be increased.

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In the next step, a hollow chamber with a larger diameter (180mm) was tested. Increasing the diameter dramatically improved the stability of the process. A stable process was observed already at a small mass flow rate – (of the order of 0.45kg/s). A typical pressure waveform is shown in Fig. 11.

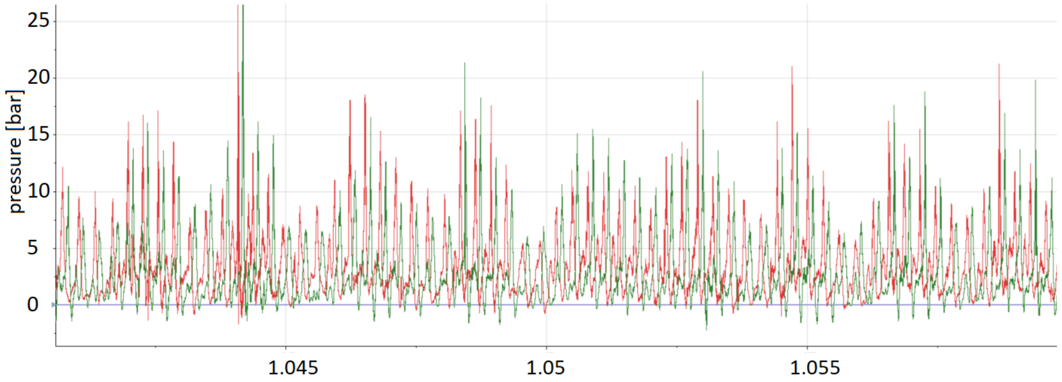

Fig.10 Unstable detonation process in a 140 mm hollow chamber

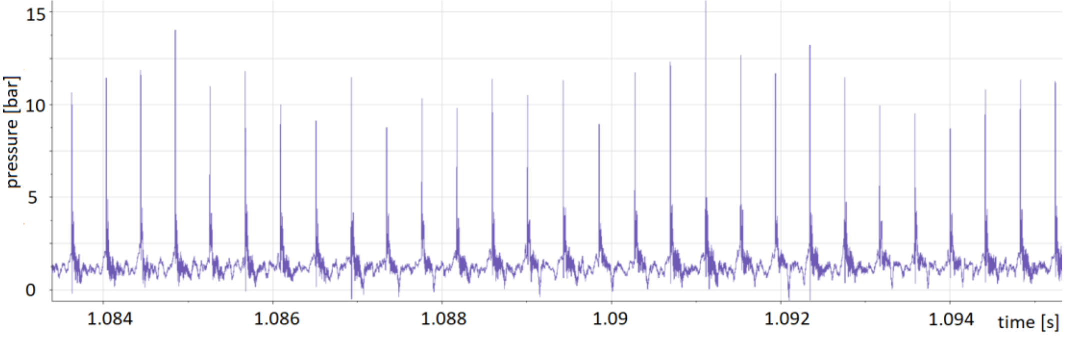

Fig.11 Stable detonation process in a 180 mm hollow chamber

For the mass flow rate, ranging from 0.88 to 1.1 kg/s, the dependence of specific thrust as a function of fuel-air equivalence ratio is presented in Fig.12. The measured specific thrust was compared with theoretical calculations from NASA CEA [19] for Jet A1-air mixture combustion. Discrepancy between each point varies however the trend is quite similar between both curves. Also, variation of the specific thrust as a function of the pressure gain/losses is presented in Fig. 11.

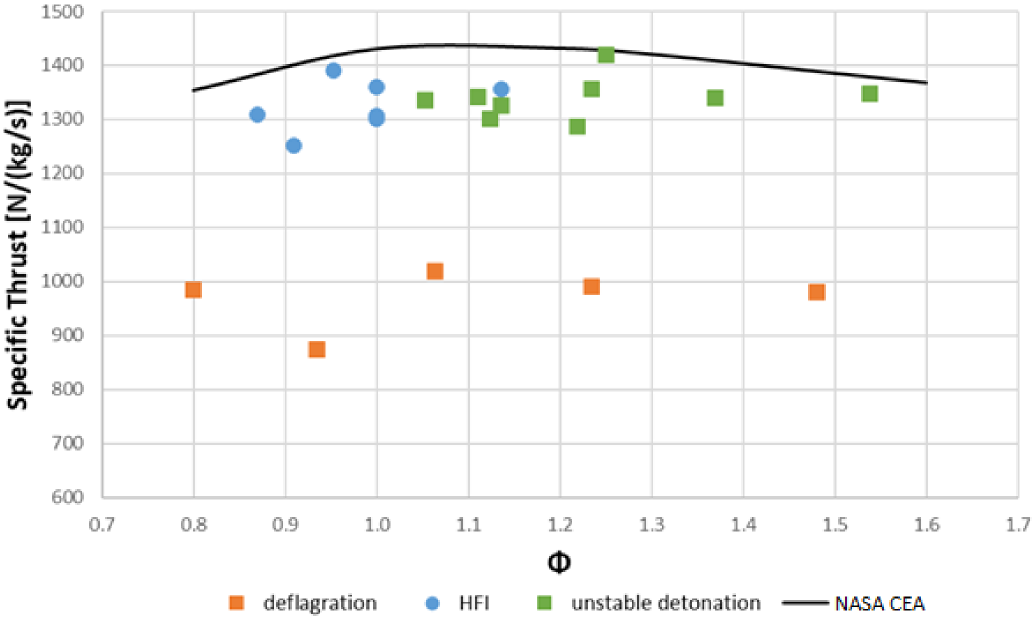

Fig. 12 Specific thrust vs. Fuel-air ratio.

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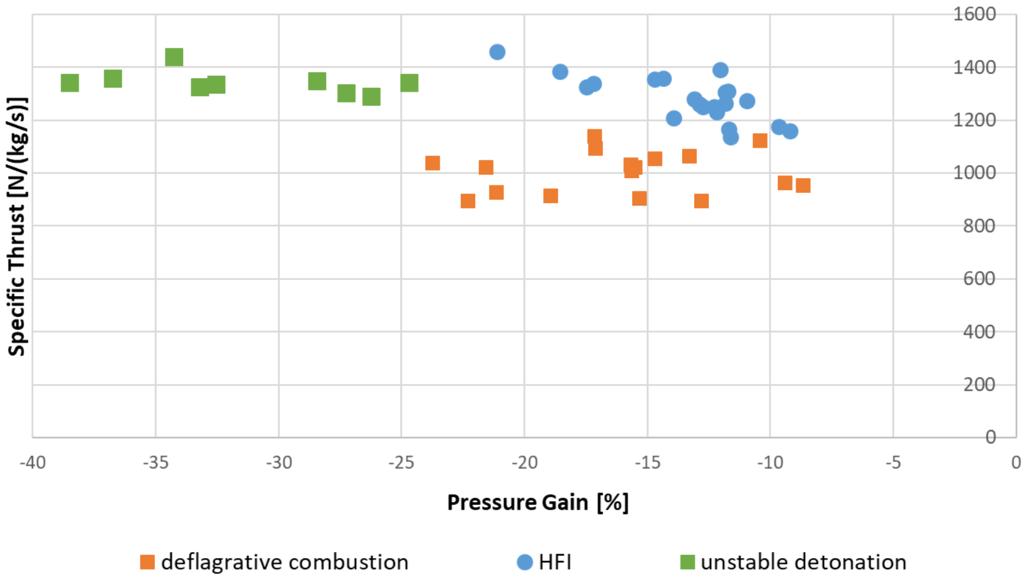

Fig. 13. Dependence of the specific thrust as a function of pressure gain.

4. Discussion and conclusions

During the course of research it turned out that due to technical challenges to initiate detonation in flow with high velocity (higher mass flow rate for the annular chamber), it was necessary to introduce the hollow geometry to slow down the incoming flow which heavily changed the aerodynamics of the chamber and increased pressure losses. Pressure gain was experimentally measured and compared with indirect methodology which is based on thrust measurement. The total pressure probe placed at the engine's outlet proved its proper work. It confirmed that the total pressure of the exhaust gases could be approximated to the combustion chamber static pressure measurement. It also showed a certain discrepancy between direct measurement and indirect pressure-gain calculation (based on thrust measurement and Equivalent Available Pressure – EAP calculation [18]).

In terms of propulsive performance, the detonation combustion and even fast deflagration outperforms deflagration allowing to release of more heat in a given time unit hence giving combustion products higher velocity and eventually higher thrust of the engine. However, comparing results from tests with deflagrative and detonative combustion might be ambiguous due to the probability that incomplete combustion of mixture takes place for the deflagration process as a result of a too short combustion chamber. This might be the cause of achieving lower pressure losses for deflagration on one hand at the expense of lower performance on the other.

Extensive research on applications of detonation combustion was conducted for two different chambers, annular and hollow. During all tests, the performance of tested chambers was evaluated which allowed for comparison of both chambers' overall performance. It was found that:

- in the annular chamber unstable detonation only was recorded,
- in the hollow chamber fast deflagration (with HFI), close to unstable detonation was only recorded,
- a variation of thrust and specific thrust was calculated for the hollow chamber as a function of the fuel-air equivalence ratio and the pressure gain parameter was evaluated.
- for larger diameter (180mm) of the hollow chamber the stable detonation was observed.

Obtained results in the hollow chamber indicated that the chamber geometry should be modified for future research, especially its configuration and diameter as well as injection system and outlet geometry to decrease the pressure losses and improve the stability of Continuously Rotating Detonation.

References

[1] B.V. Voitsekhovskii, J. Appl. Mech. Technol. Phys. 3 (1960) 157–164 (in Russian).
[2] Voitsekhovskii, B. V., Mitrofanov, V. V., and Topchiyan, M. E. 1963. "Structure of the Detonation Front in Gases." Izdatielstvo SO AN SSSR, Novosibirsk (in Russian).

DOI: 10.13009/EUCASS2023-371

[3] J.A. Nicholls, R.E. Cullen, The Feasibility of a Rotating Detonation Wave Rocket Motor, Report No. RPL-TDR-64-113, The University of Mich.,1964.

[4] Nicholls J.A., Cullen R.E., Ragland K.W., 1966, "Feasibility studies of a rotating detonation wave rocket motor", Journal of Spacecraft and Rocket, 3 (6), pp. 893-898

[5] Adamson, Jr, T. C., and Olsson G. R., "Performance Analysis of a Rotating Detonation Wave Rocket Engine", Acta Astronautica, Vol.13, pp.405-415, (1967)

[6] Wolański P., "Detonative Propulsion", Proceedings of the Combustion Institute, 34, pp.125-158, Elsevier (2013);

[7] Wolański P.,:" "Detonation Engines", Paper, Journal of KONES, Vol.18 (2011), No.3 pp.515-521;

[8] Xie Q., Jia Z., Wena H., Renc Z., Wolanski P., and Wang B., „Review on the rotating detonation engine and typical problems", Transaction on Aerospace Research", 2020 4(261) 2020, pp.107-163 DOI: 10.2478/tar-2020-002

[9] Hishida M., Fujiwara T., and Wolanski P., "Fundamentals of rotating detonation", Shock Waves. 19 (2009), pp.1-10

[10] Wolański, P. Ed.: "Research on detonative propulsion in Poland", Institute of Aviation Scientific Publication No. 60, Warsaw: Łukasiewicz Research Network – Institute of Aviation, 2021. ISBN 978-83-63539-45-0.

[11] Wolański, P., Kalina, P., Balicki, W., Rowiński, A., Perkowski, W., Kawalec, M., Łukasik, B.: „Development of gas turbine with detonation chamber", Detonation Control for Propulsion, Springer, 2017, pp 23-37.

[12] Kawalec M., Wolański P.: Development of Rocket Engine with Continuously Rotating Detonation Supplied by Liquid Propellants, Proceedings of the EUCASS 2022. DOI: 10.13009/EUCASS2022-46479

[13] Wolański P., Balicki W., Kalina P., Perkowski W., „Injector of an over-enriched fuel-and-air mixture to the combustion chamber of internal combustion engines". EU Patent No.3434979, US Patent Applications No. US 11,149,702 B2 Oct. 19, 2021

[14] Wolański P., Balicki W., Perkowski W., and Bilar A., "Experimental Research of Liquid Fueled Continuously Rotating Detonation Chamber", Shock Waves,(2021), DOI10.1007/s00193-021-01014

[15] Wolański, P.: "RDE research and development in Poland", Shock Waves, (2021) 10.1007/s00193-021-01038-2

[16] Bach, E., Thethy, B. S., Edgington-Mitchell, D., Haghdoost, M. R., Paschereit, Ch. O., Stathopoulos, P., Bohon, M., "Kiel Probes for Stagnation Pressure Measurement in Rotating Detonation Combustors", AIAA Journal, (2022), 60(12):1-12, DOI:10.2514/1.J061061

[17] Anand V., George A., Luzan C.F., Gutmark E., Rotating detonation wave mechanics through ethylene-air mixtures in hollow combustors, and implications to high-frequency combustion instabilities, Experimental Thermal and Fluid Science, Volume 92,2018, Pages 314-325, ISSN 0894-1777, https://doi.org/10.1016/j.expthermflusci.2017.12.004.

[18] Kaemming, T.A., Paxson, D.E., Determining the Pressure Gain of Pressure Gain Combustion, Joint Propulsion Conference AIAA Paper 2018-4567,

[19] McBride B.; Gordon S.; NASA-GLENN CHEMICAL EQUILIBRIUM PROGRAM CEA2, May 21, 2004, REFS: NASA RP-1311, PART I, 1994 and NASA RP-1311, PART II, **1996**