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REVIEW

RDE research and development in Poland

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Abstract
A very short survey of research conducted in Poland on the development of the rotating detonation engine (RDE) is presented. Initial studies conducted in cooperation with Japanese partners lead to development of a joint patent on RDE. Then, an intensive basic and applied research was started at the Institute of Heat Engineering of the Warsaw University of Technology. One of the first achievements was the demonstration of performance of the rocket engine with an aerospike nozzle utilizing continuously rotating detonation (CRD), and research was directed into development of a small turbofan engine utilizing such a combustion regime. These activities promoted international cooperation and stimulated RDE development not only in Poland but also in other countries. A research directed to measure and calculate flow parameters as well as to analyze the use of liquid fuels was conducted. In the Institute of Aviation in Warsaw, research on the application of the CRD to turbine engines as well as rocket, ramjet, and combined cycle engines was carried out. In the paper, a special emphasis is given to international cooperation in this area with partners from many countries engaged in the development of the pressure gain combustion to propulsion systems.

Keywords Detonation · Spin detonation · RDE · Propulsion

1 Introduction

The possibility of improving the thermodynamic cycle by application of detonative combustion instead of deflagration was first proposed by Zeldovich [1], but he also pointed out difficulties in controlling such a very highly energetic and ultra-high-speed process to engine application. However, the first idea of a possible application of detonation to the propulsion system comes from the University of Michigan where Nicholls et al. [2] proposed and built the first pulsed detonation engine, which utilizes the detonation of a hydrogen–air mixture to produce propulsion impulse. Also, at the same university Adamson et al. analyzed the possibility of the application of a rotating detonation wave to improve the propulsion efficiency of rocket propulsion [3, 4]. At the time, the idea of the application of a standing detonation for propulsion systems was examined by many authors for both ramjet and rocket engines [5, 6]. Meanwhile, at the Novosibirsk Institute of Hydromechanics the so-called stationary spin detonation was successively achieved by Voitsekhovskii and his coworkers [7, 8]. Detailed research on spin detonation was also carried out at the University of Michigan [9]. Later, attempts of developing a continuously rotating detonation (CRD) for propulsion systems were undertaken also at the University of Michigan. Adamson et al. [4], using very simple computing techniques, properly predicted the basic structure of rotating detonation in a rocket engine, but experimental research carried out at that time was not successful [10], so the study of application of the CRD for propulsion was interrupted for a long time [11, 12]. Only at the end of the last century and at the beginning of the twenty first century was research on utilization of the CRD reinitiated, initially in Russia, Poland, and France, and at the end of the first decade of this century also in many other countries.

2 Basic research

Basic research in Poland on CRD was started at the Institute of Heat Engineering of Warsaw University of Technology (WUT) at the beginning of the twenty first century. Initial research was focused on studies of spin detonation in

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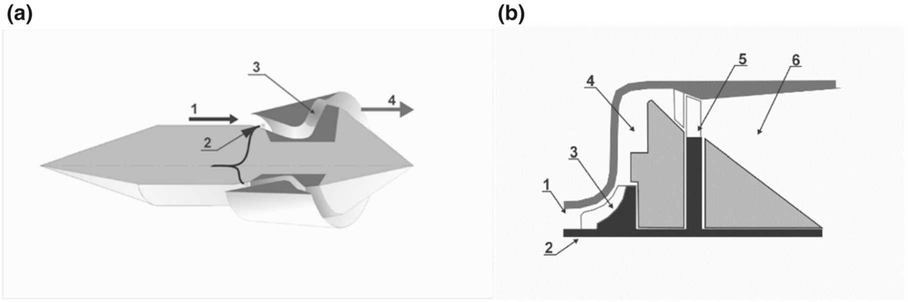


Fig. 1 **a** Schematic diagram of the RDE integrated with the fuselage (missile, rocket, aircraft, etc.): 1—inlet, 2—fuel injection, 3—tilted “ring-like detonation chamber,” 4—expansion nozzle integrated with fuselage (aerospike nozzle); **b** schematic diagram of turbocharged RDE: 1—inlet, 2—shaft, 3—impeller (compressor), 4—“ring-like detonation chamber,” 5—turbine, 6—nozzle

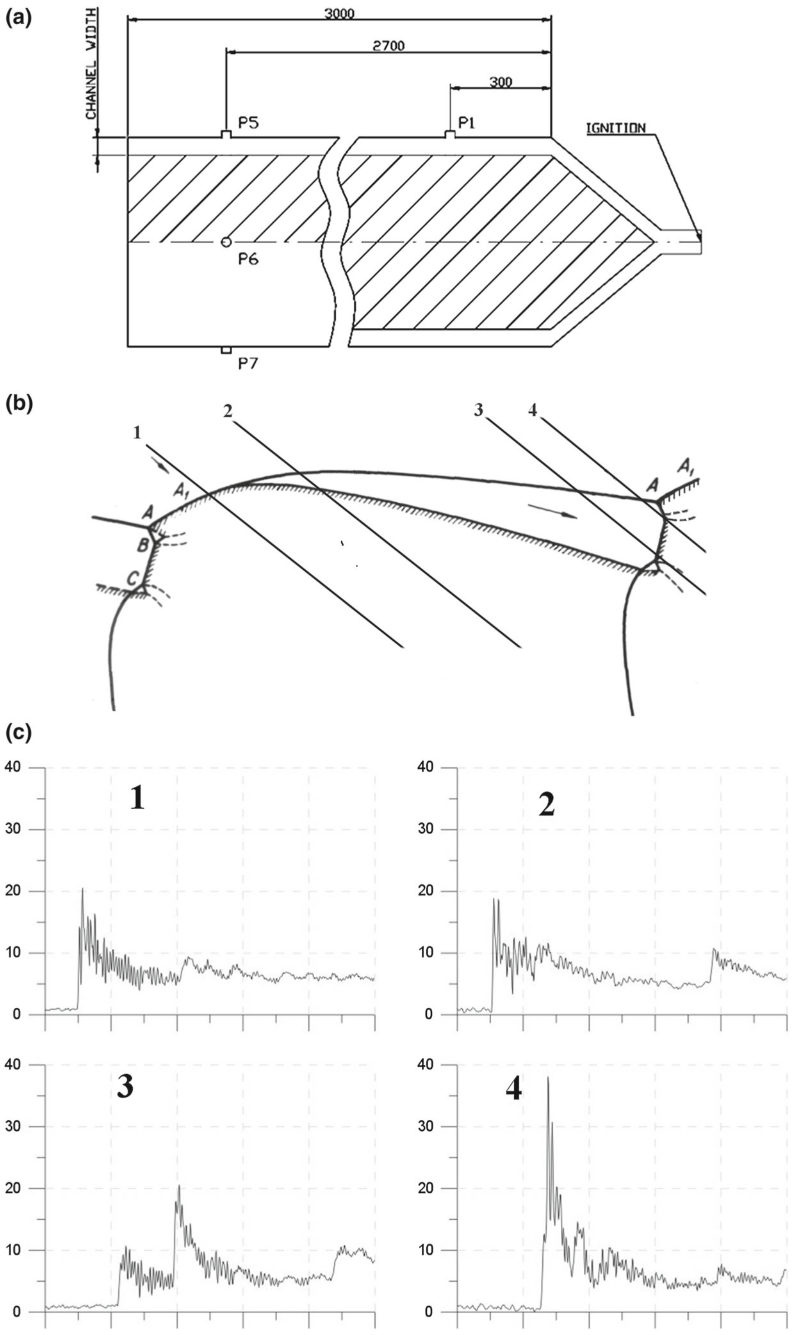
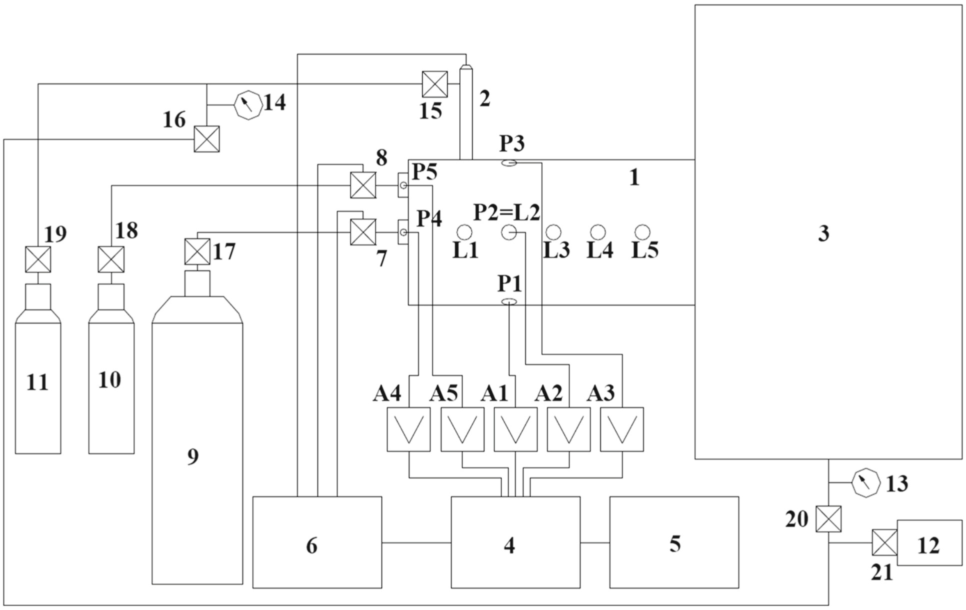


Fig. 2 Schematic diagram of the annular detonation tube **a** of diameter equal to 125 mm and a channel width, between tubes, of 10.5 mm, **b** spin detonation structure, where A–A_1 is the spin head and A–B–C is the transverse wave (arrows indicate flow direction), **c** recorded pressure variation along lines 1–4 in H2–air mixture of equivalence ratio $\Phi = 0.6$ and initial pressure in tube, po = 0.8 bar (vertical axis represents pressure variation scale in bar, while horizontal—time, sweep 25 µs/division) [22]

Fig. 3 Schematic diagram of the WUT experimental setup: 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—amplifiers, 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



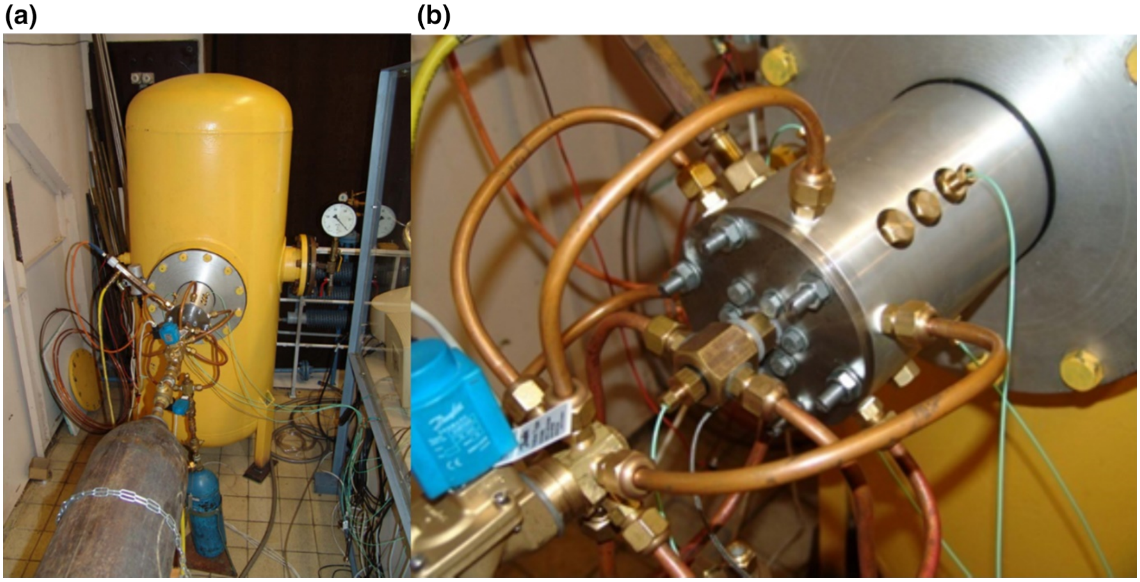


Fig. 4 View of experimental test stand with yellow dump chamber (**a**) and one of many tested detonation chambers (**b**)

gaseous mixtures, since the understanding of spin detonation structure and the mechanism of its propagation is essential in controlling CRD. Detailed studies of spin propagation are fundamental to control continuously rotating detonation, and it provides base in applying for a patent which utilizes the effect of spinning detonation in future propulsion systems [13]. At that time, the WUT cooperated closely with prof. Toshi Fujiwara from Nagoya University, who provided very good links to Mitsubishi Heavy Industry, Nagoya Guidance and Propulsion Works. Representatives of those three entities prepared the application for a patent on “Detonation engine and flying object provided therewith” which was finally issued in 2005 [13]. Schematic diagrams of proposed configurations of rotating detonation engines (RDE) are presented in Fig. 1. Other proposed configurations can be found in [13–16].

Publication of the patent opened the way to release the first joint experimental research carried out on RDE [17–19]. After this, intensive research on CRD has been carried out at the Institute of Heat Engineering of WUT for many years. First research was focused on studies of spin structure in gaseous mixtures [20–22]. A schematic diagram of the annular detonation tube used for studies of spin structure is shown in Fig. 2a, and the reconstructed structure of the spin head in a hydrogen–air mixture is presented in Fig. 2b. One can see a difference in pressure signals recorded for different

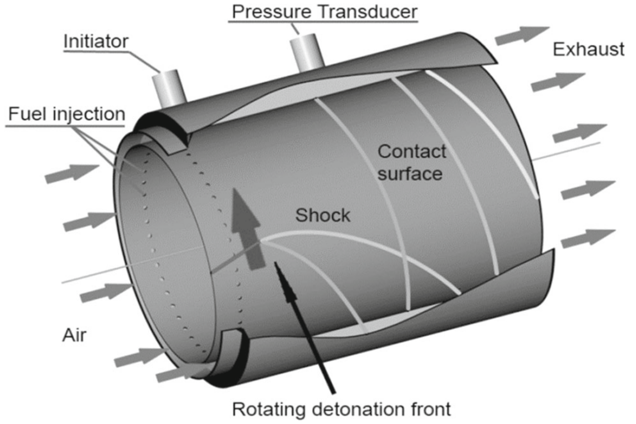


Fig. 5 Simplified scheme of typical annular detonation chamber used in experiments

segments of the spin head (Fig. 2c). For passages close to the spin head (lines 1, 2) after the initial shock, pressure is decreasing due to the chemical reaction. But for passages (3), double shocks are observed, first after the initial shock and second related to the transverse wave. The highest pressure is measured close to the triple point (4) where the maximum pressure rise is observed. This research allowed us to select a mixture composition which can support spinning detonation in the annular channels. The next task was focused on the evaluation of conditions under which spinning detonation–rotating detonation can propagate in annular detonation chambers. The research was mostly carried out in the annular chambers connected to a dump tank. Many different configurations of detonation chambers were tested. A simplified diagram of the WUT experimental setup is shown in Fig. 3, the pictures of it are shown in Fig. 4, and diagram of the annular detonation chamber used in the experiments is shown in Fig. 5. Descriptions of the operation of this test stand as well as many experimental results can be found in publications such as [17–27]. Initial research on this test stand was carried out for oxy-acetylene mixtures, but later, other kinds of gaseous mixtures with air and oxygen were tested as well. A typical variation of the pressure in the detonation chamber as a function of time is presented in Fig. 6. If conditions are selected properly, the wave form is very stable and pressure peaks are very repeatable.

At the Institute of Heat Engineering of WUT, more than ten detonation chambers were tested. The variation of chambers was not only related to different sizes but also different arrangements of mixture supply, pressure and temperature measurements, and also the location of the initiator. The basic aim of these studies was directed at finding out the optimum operation conditions at which the rotating detonation process was very stable. Typical pictures illustrating stability of such a process are shown in Figs. 7, 8.

This test stand, with a specially designed chamber, was used for tests of gaseous rocket engines with aerospike nozzles. A schematic diagram of a gaseous rocket engine with an aerospike nozzle is shown in Fig. 9. In this rocket engine, tests were performed for many gaseous propellants, such as hydrogen, methane, ethane, and propane with gaseous oxygen. During the experiments, pressure and thrust were measured. Due to the very high temperature of the detonation products, tests usually lasted for about 0.5 s. The limitation of the duration of the test was basically due to the pressure transducer's sensitivity to temperature, and for longer durations of the test the risk of damaging (very expensive) pressure transducer was too high. The time, however, was sufficient to measure pressure variation, as well as variation of thrust. This allowed us also to calculate specific impulse. Typical pressure variation and thrust measurements for the case of methane–oxygen mixture are presented in Fig. 10. The feed pressure for the gaseous components was 5 bar, and the initial pressure in the dump tank was equal to 0.02 bar. This simulated conditions of engine operation at a very high altitude. However, even during the short time of engine operation, the pressure in the dump tank was continuously increasing, so the

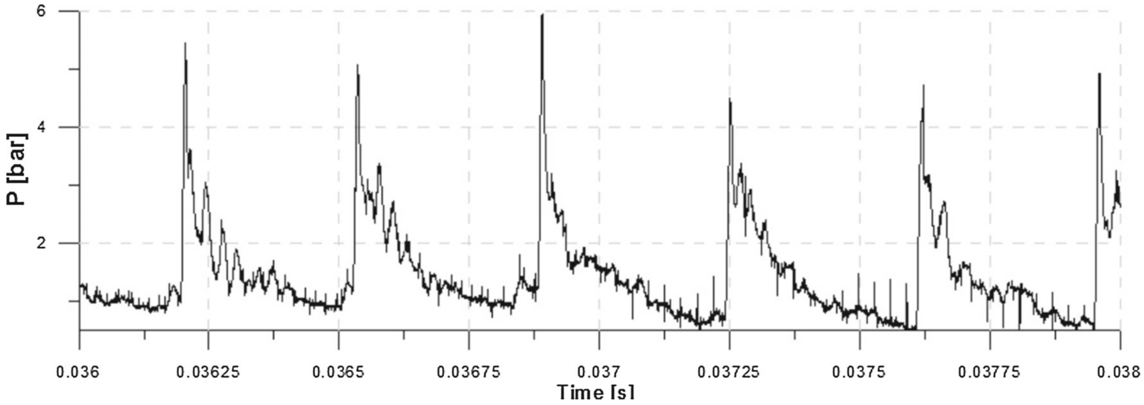


Fig. 6 Variation of the pressure at the front of stationary rotating detonation in a cylindrical chamber with inner and outer diameters of 120 mm and 150 mm, resp., in a stoichiometric hydrogen–air mixture at initial pressure 1 bar [23]

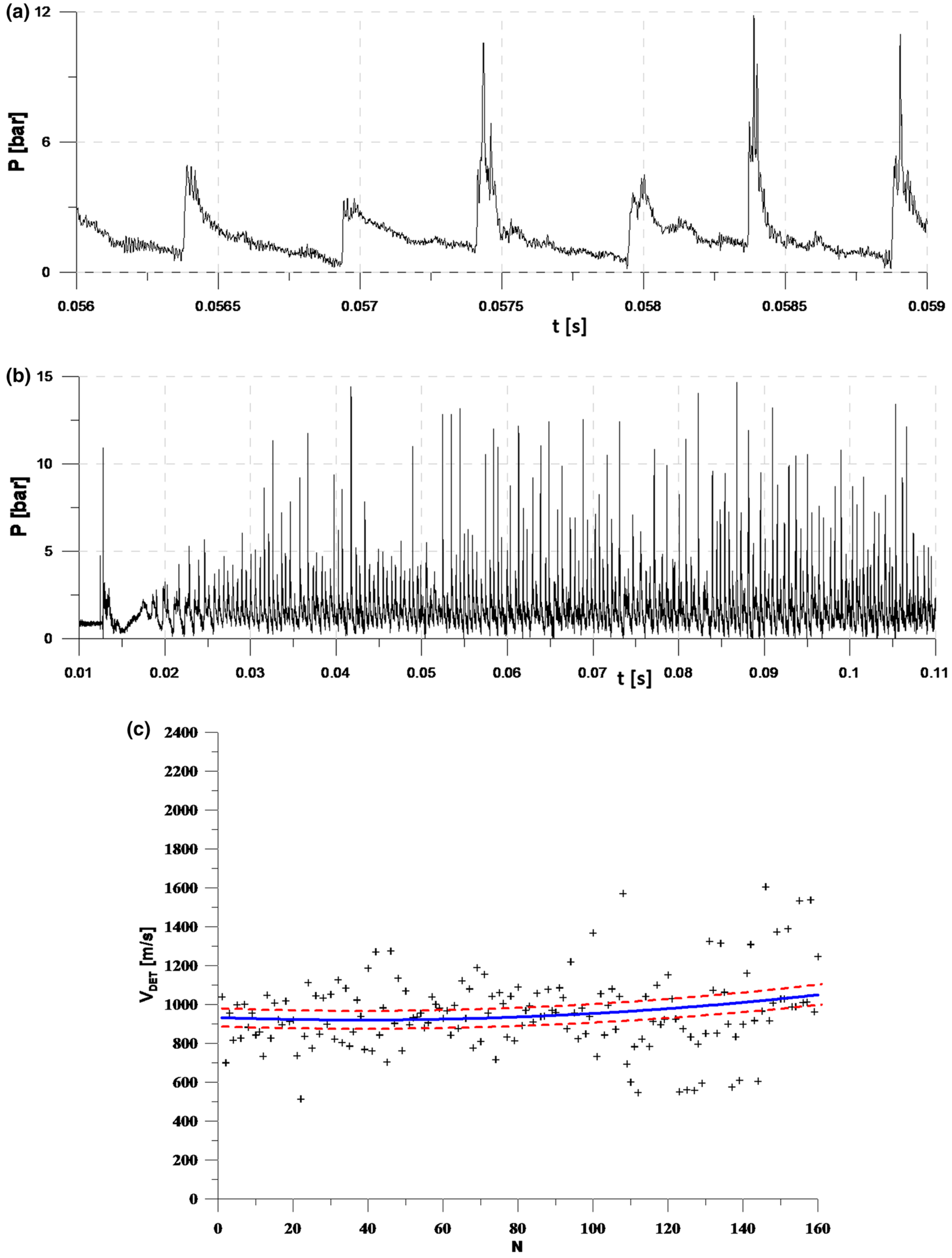


Fig. 7 Variation of pressure (**a**, **b**) and the instantaneous rotational velocity as a function of rotating wave cycle N **c** in the cylindrical detonation chamber for the acetylene–air mixture; channel dimensions are 130 mm and 150 mm for inner and outer diameters, respectively. Note **a** is enlarged section of selected segment of **b** and on **c;** blue line represents average value of measured rotating wave velocity, while red dashed lines indicate the region of +/− 5% deviation from average wave velocity

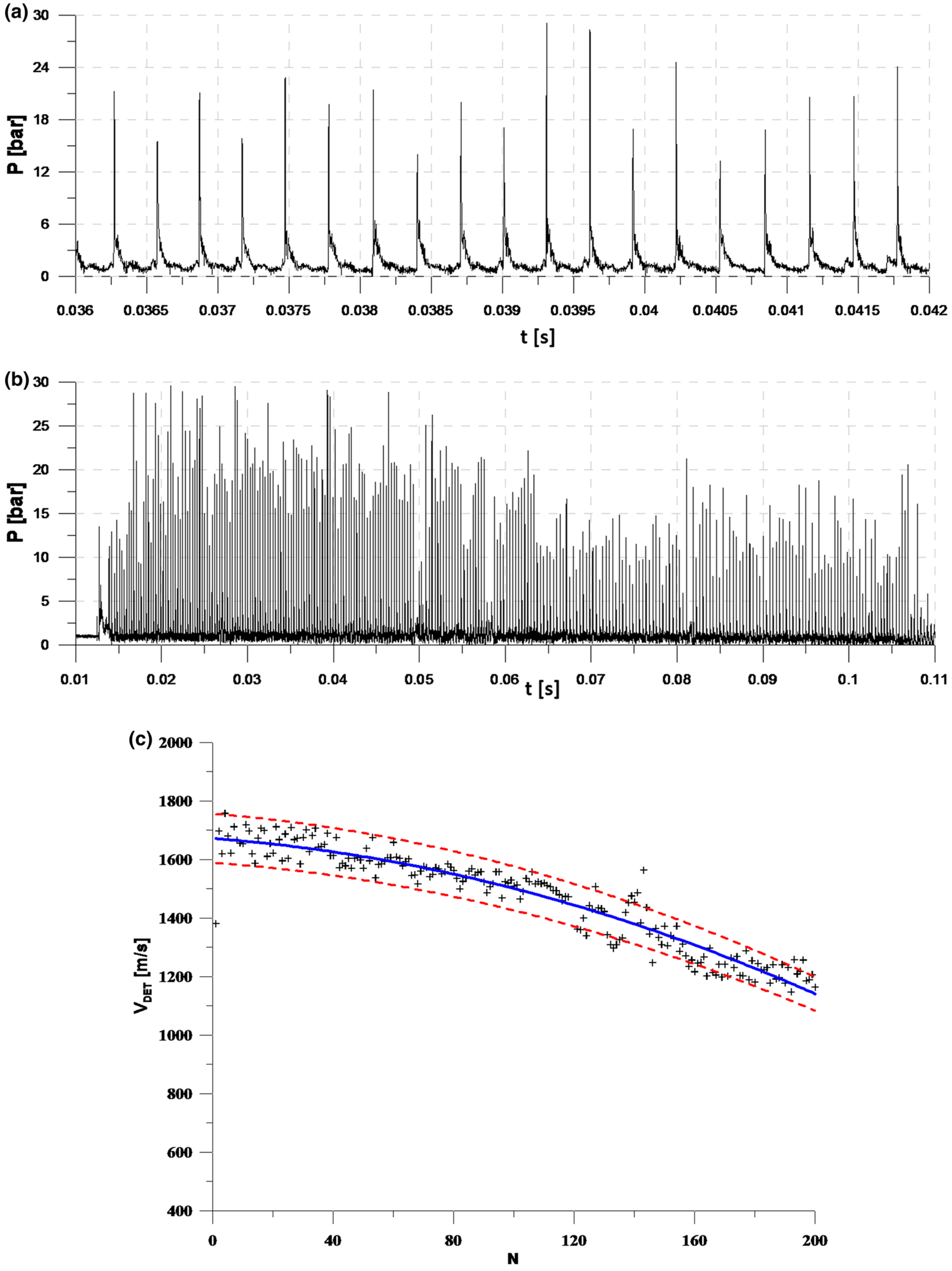


Fig. 8 Variation of pressure (**a**, **b**) and instantaneous rotational velocity as a function of rotating wave cycle N **c** in the cylindrical detonation chamber for stoichiometric hydrogen–air mixture at 1 bar. The dimensions of the channel are 130 mm and 150 mm for inner and outer diameters, respectively. Note **a** is enlarged section of selected segment of **b** and on **c;** blue line represents average value of measured rotating wave velocity, while red dashed lines indicate the region of +/− 5% deviation from average wave velocity

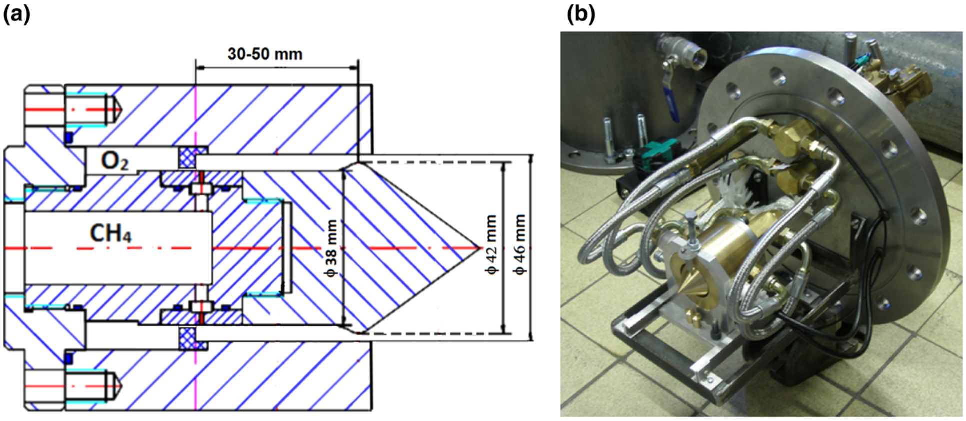


Fig. 9 Schematic diagram of rocket detonation engine (**a**) and picture of engine assembly before being connected to the dump tank (**b**)

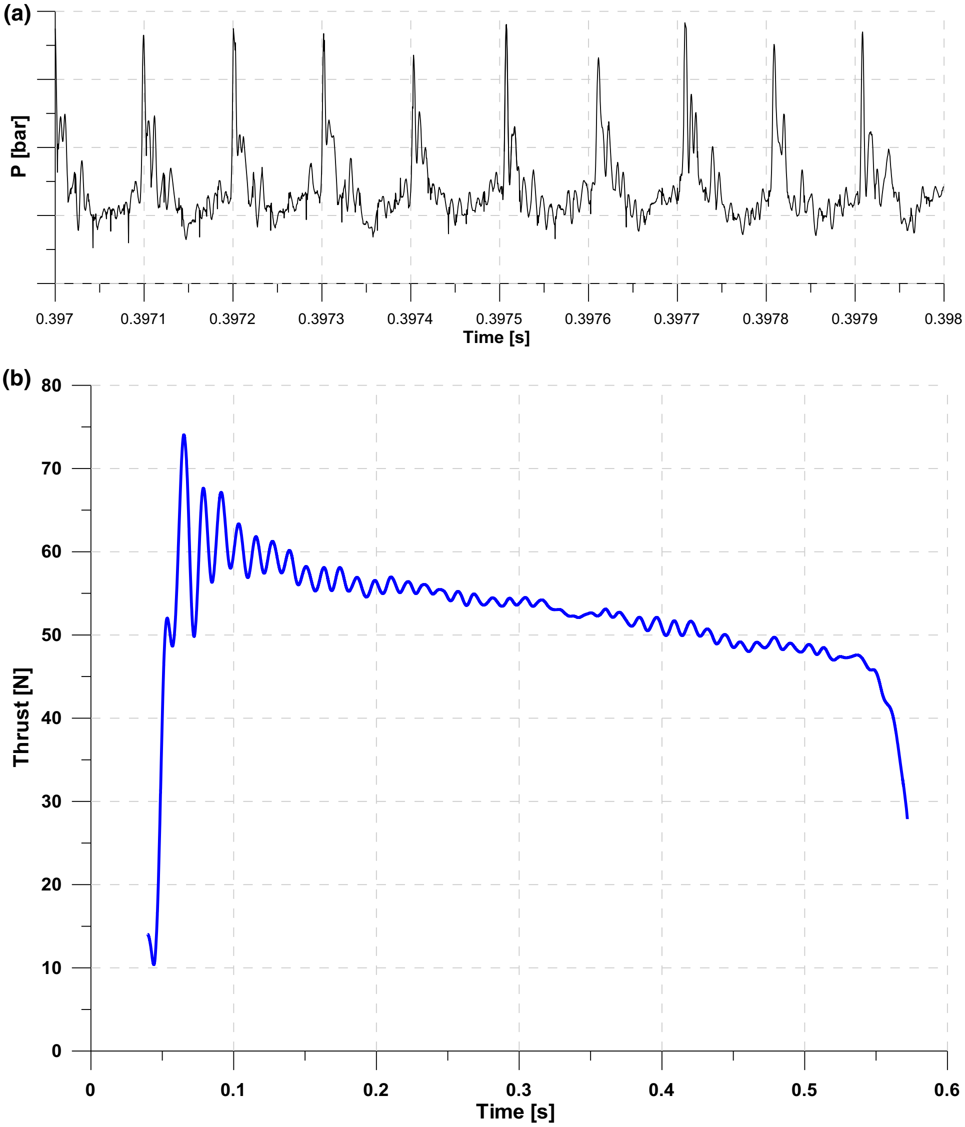


Fig. 10 Pressure (**a**) and thrust (**b**) measurement in gaseous rocket engine with aerospike nozzle

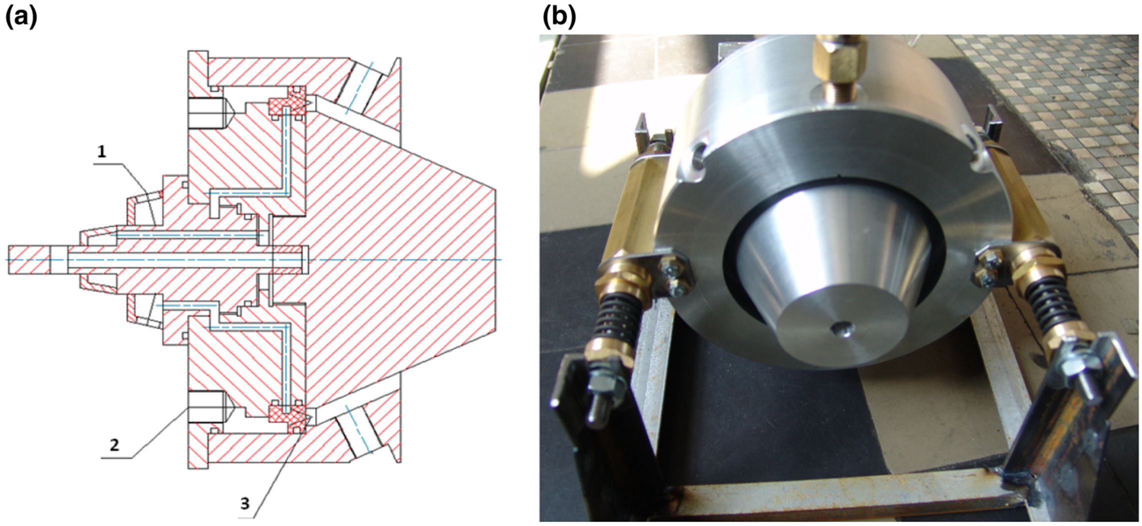


Fig. 11 Schematic diagram of the gaseous rocket engine in which rotating detonation was executed only in the expansion aerospike nozzle (**a**), supply ports for fuel (CH_4)—1 and oxygen—2, and 3–injection point of both components. The picture of this rocket engine (**b**)

thrust of the engine was decreasing, due to rising "external" pressure (in the dump tank).

The gaseous rocket engine of a bigger size was tested in a larger facility. A schematic diagram of such an engine is shown in Fig. 11. In this engine, tests were also performed to simulate high altitude, since in the dump tank the initial pressure was lower than the atmospheric pressure.

A variation of the pressure, measured thrust, and calculated specific impulse is shown in Fig. 12. The duration of the experiment was very short, about 0.3 s, for the same reason previously mentioned. During the experiment, pressure in vacuum tank was changing from 0.1 bar to about 0.5 bar. This is equivalent to an altitude changing from 16 km to about 5.5 km. One can see that the pressure in the dump tank (simulating altitude test) is initially increasing rapidly, then the rate of the pressure increase is decreasing, and finally, before switching off the engine, the operation is nearly at a steady level for a short time. This is due to condensation of the water vapors from the engine exhaust on cold walls of the dump tank, so the pressure in the dump tank (green signal) also stays nearly constant. This process is also responsible for the small pressure drop after switching off the engine. Even the number of runs in the large test facility was limited, and results proved that for a rocket engine, CRD can be obtained in an aerospike nozzle, and thus, it will facilitate a shortening of the whole rocket engine and decreasing its mass.

At the Institute of Heat Engineering of WUT, much additional research on RDE was performed such as research on the detonability range of jet fuel mixtures, measurements of the temperature field in exhaust gases, and theoretical and numerical modeling of different aspects of the RDE operation, also in cooperation with the Institute of Aviation in Warsaw [28–46].

3 International cooperation

From the very beginning, the research on the RDE at WUT was carried out with foreign partners from both universities and research centers. As it was already mentioned, first cooperating partners were from Nagoya University and the Mitsubishi Heavy Industry Nagoya Guidance and Propulsion Works. Very soon the research group from the Aoyama Gakuin University, led by prof. A.K. Hayashi, joined the team, and his contribution was focused on the numerical simulation of the RDE. In addition, a joint research project between WUT and the Institute of High Performance Computing, A-star, Singapore, was initiated [24, 47]. In all such cases, WUT provided experimental research data, and foreign partners were involved in detailed numerical calculations. In early 2008, papers on the first two-dimensional and three-dimensional detailed calculations of structure of RDE were submitted for publication [23, 24, 47–51] and opened the way for a large number of such calculations. These calculations showed for the first time the detailed structure of the rotating detonation front, as well as the existence of a secondary small cellular structure at the detonation front and the existence of instabilities generated at the contact surface, and, most importantly, the flow structure inside the RDE (Fig. 13 [23]). It was shown that despite the rotation of the detonation wave the flow inside the chamber is basically axial and that the rotational component of the flow at the exit of the detonation chamber constitutes only about 3% of the axial velocity component [23].

At the same time, WUT had close cooperation with P&W in East Hartford, USA, on developing electrical capacitance tomography (ECT) for flame visualization. During one of the visits to P&W, it was proposed to host an Invited Lec-

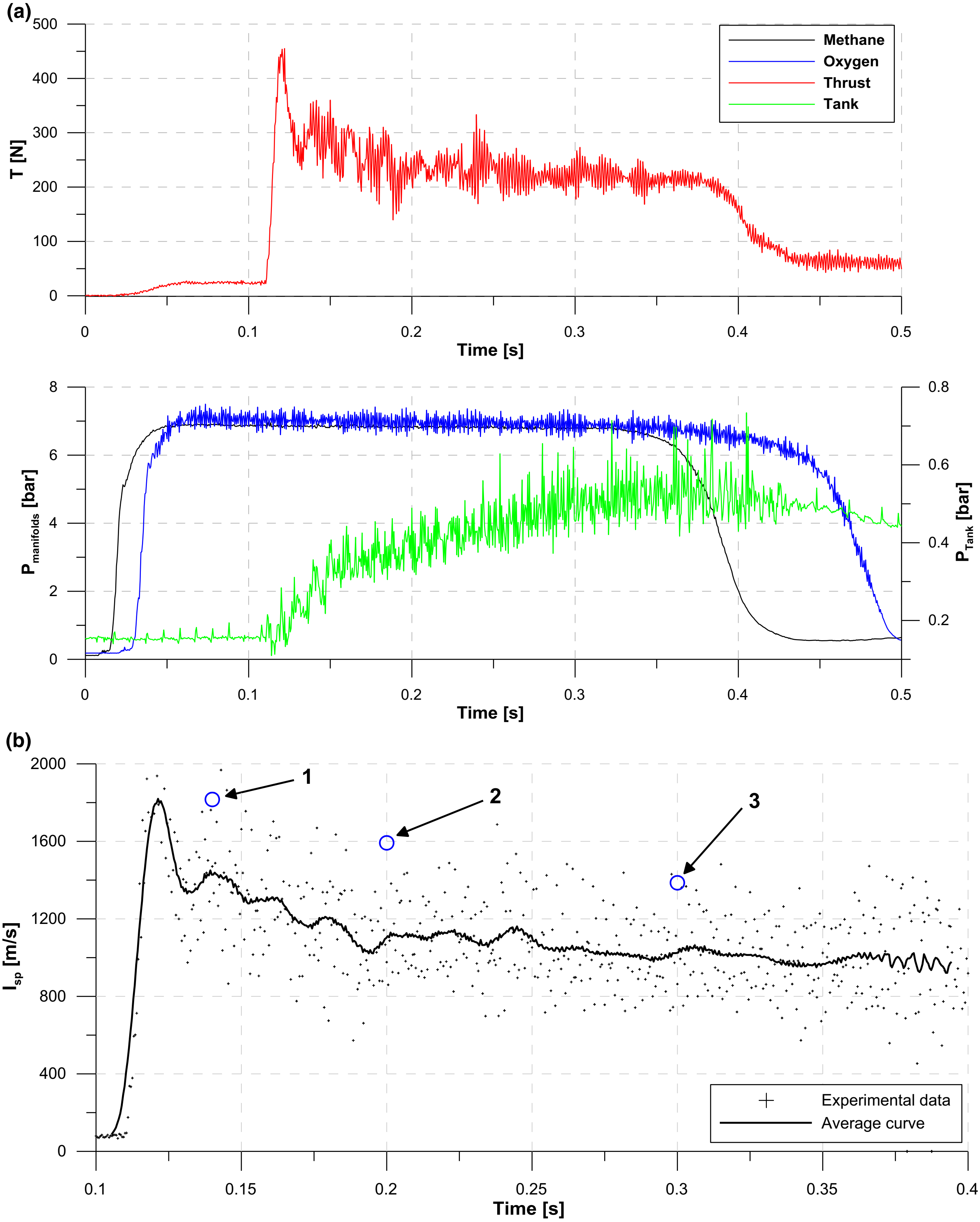


Fig. 12 **a** Measured thrust (top) and pressure in supply lines of propellants to rocket engine, as well as pressure in the dump tank (bottom), **b** average calculated specific thrust (solid line) with points of individual measurements/calculations and theoretical value of specific impulse (blue circle) calculated on the basis of real operational parameters using the NASA CEA code

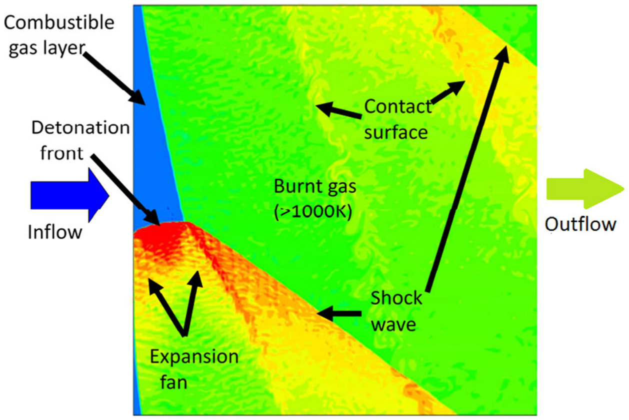


Fig. 13 Detonation wave structure in continuously rotating detonation in cylindrical chamber exposed on 2-D detonation structure (from [23])

ture on RDE development in Poland. Two days after the first lecture at East Hartford on December 9, 2008, it was also proposed to present the same lecture to P&W Rocketdyne at West Palm Beach [52]. Both presentations were transmitted live to all P&W facilities in the USA. In those presentations, all research conducted on RDE at WUT, as well as the results of our international presentation, was presented. This presentation, in my opinion, prompted research on RDE in the USA and minimized research on application of the PDE to propulsion systems.

4 Research at the Institute of Aviation

In 2010 in the Institute of Aviation in Warsaw, a new project was initiated on applications of the CRD to the gas turbine engine GTD-350. A schematic diagram of the experimental test stand used in this research is presented in Fig. 14. The main aim of this project was to show the possibility of application of detonative combustion in the gas turbine engine and demonstrate increasing engine efficiency. During this project, many important elements of such a very complex task were tested. This included fuel atomization and mixture preparation, detonation initiation in the engine combustion chamber, the condition for which stable detonation can be sustained for longer time, and finally the test of the engine with a detonative combustion chamber. Description of major tasks conducted in this research can be found in [53–62].

Although the expected performance of the engine running on the Jet-A fuel was not achieved, an improvement of engine efficiency by 5–7% was demonstrated on gaseous hydrogen fuel (Fig. 15a) [57]. Additionally significant knowledge was gained during this project, and one spinoff from it is a recent development of a new system of preparation of liquid fuel injection into the detonation chamber [57–59]. Such a system made it possible to achieve stable operation of the detonation for the Jet-A–air mixture [58, 59].

Recently, in cooperation with the US Air Force Research Laboratory, a method of controlling the direction of wave rotation in the cylindrical detonation chamber of a gaseous

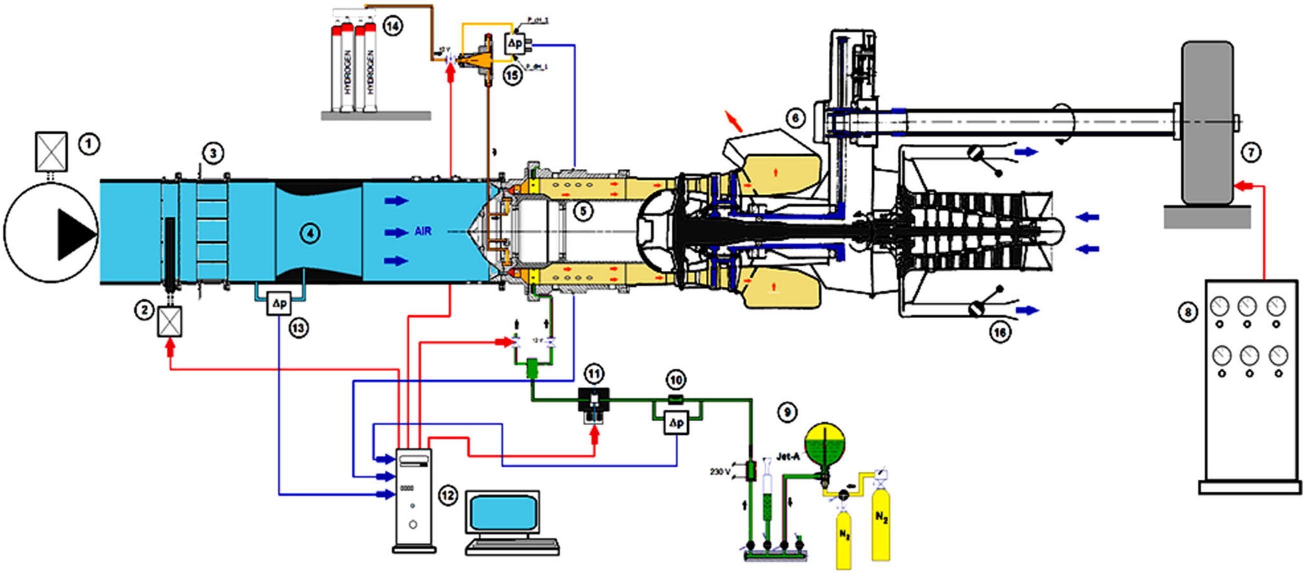


Fig. 14 Control system of the turboshaft engine with detonation combustion: 1—air compressors unit; 2—air flow controller; 3—Inlet flow equalizer grid; 4—Venturi air mass flow measurement; 5—detonation combustion chamber; 6—turboshaft engine GTD-RD; 7—brake; 8—brake controller; 9—Jet-A injection system (pressurized by nitrogen) 10—Jet-A flow meter; 11—electrohydraulic booster WLP-4; 12—management computer; 13 air flow differential pressure; 14—hydrogen supply system; 15—hydrogen flow differential sensor; 16—air exhaust with suppression valve (from [55])

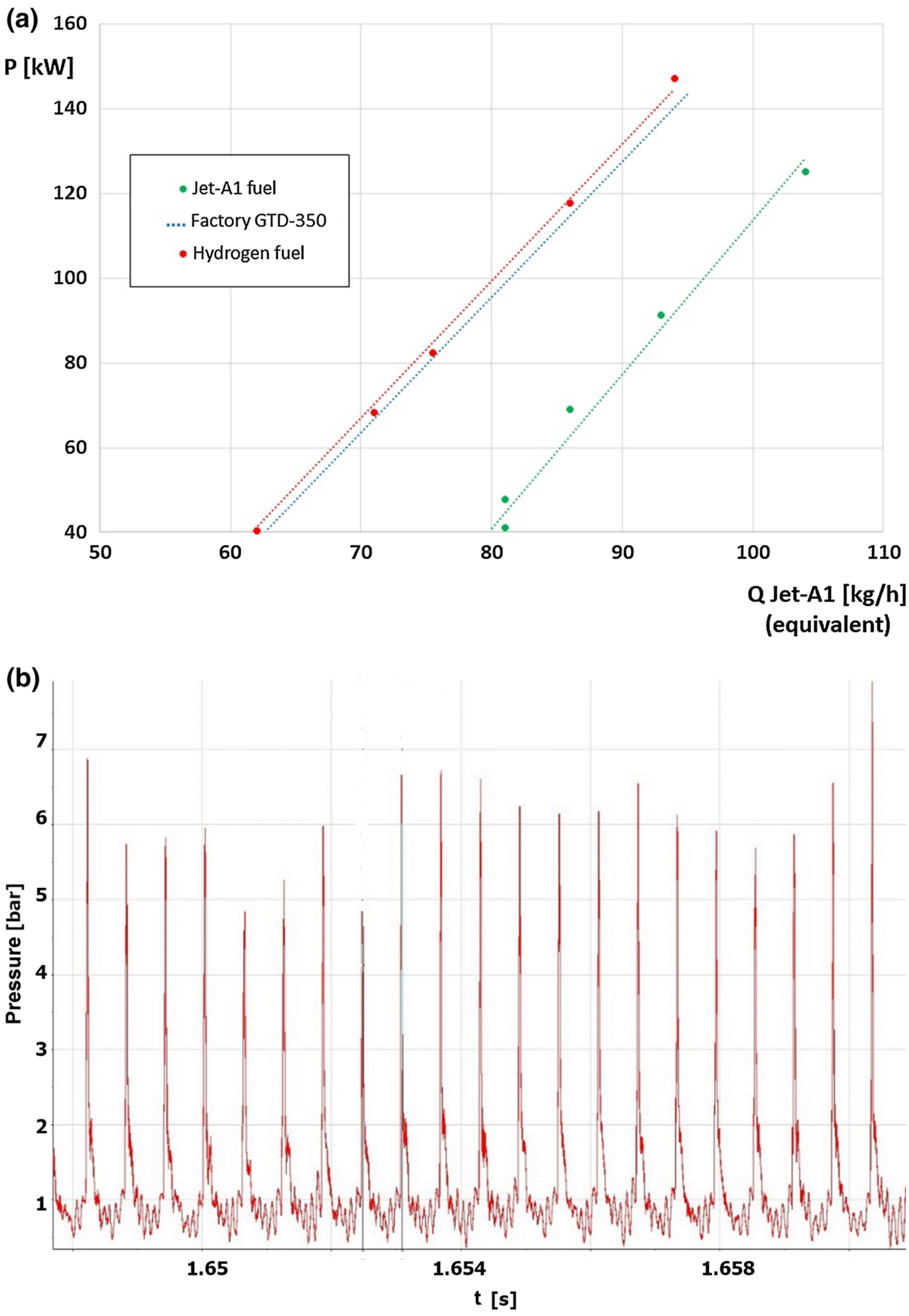


Fig. 15 **a** Comparison of fuel consumption of the GTD-350 engine with a annular detonation chamber powered by Jet-A fuel and by hydrogen (hydrogen reduced to kerosene in a ratio of 1 kg H2 is equivalent to 2.8 kg of kerosene), **b** pressure variation for stable detonation in liquid fuel–air mixture (from [56, 57])

rocket engine was successfully developed [60–62]. Also first successful laboratory tests of the operation of the subsonic combined cycle of a rocket–ramjet engine operating on gaseous propellants and utilizing CRD in the combustion chamber were performed. A schematic view of this engine and a picture from conducted experiments of the combined rocket–ramjet engine cycle are presented in Fig. 16 [62].

5 Summary and conclusions

Pioneering research focused on basic aspects and on the application of the continuously rotating detonation to propulsion systems, which was conducted in Poland, was presented in the paper. Much more research, which concerns detailed

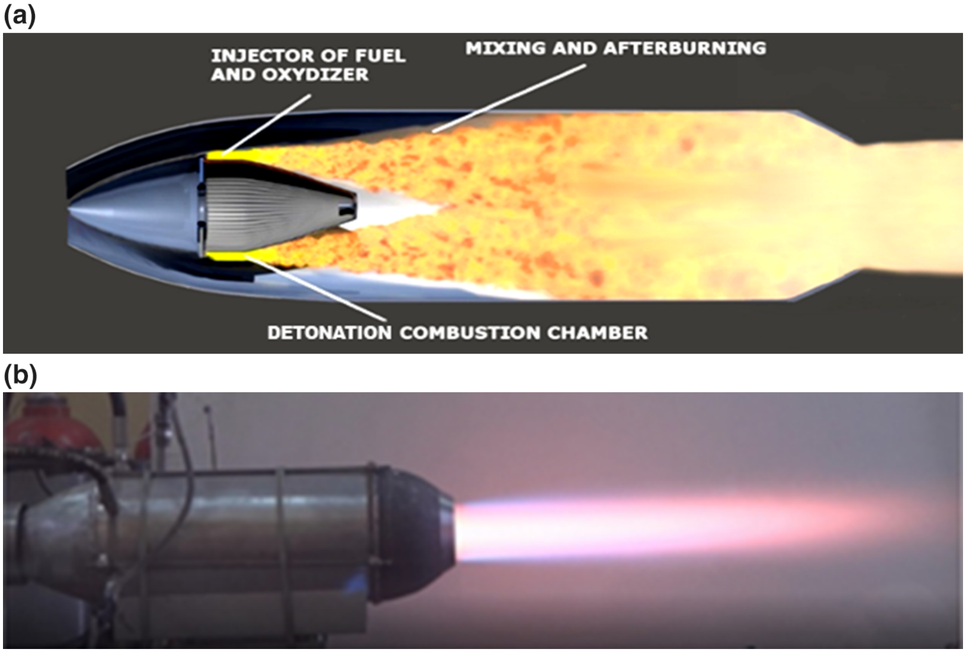


Fig. 16 **a** Schematic diagram of the rocket–ramjet engine, **b** laboratory test of subsonic rocket–ramjet engine (from [61])

problems directly related to RDE, can be found in many already published papers, and many more are still awaiting publication. It should be mentioned that the conducted research could explain many aspects of CRD, and those works have also stimulated research on RDE in numerous countries. The best example of this are joint papers prepared by international teams of authors, as well as many invitations to present our results at seminars, workshops, and conferences. Despite some confidential aspects of a large number of works, which usually accompany novel research, the international cooperation is one of the major forces moving progress in this area. I can state that without publications, nearly sixty years ago, by scientists from Novosibirsk, work on the possibility of controlling continuously rotating detonation in gaseous mixtures and then much other research, experimental and theoretical, carried out in many different countries in Asia, Europe, and USA, the development of propulsion systems based on CRD would never be possible. So, many important problems concerning development of the RDE such as minimization of the pressure losses, effective cooling, and materials which will resist long-lasting high-temperature and high-pressure loads on the detonation chamber, have to be solved before such engines will be introduced to commercial use. Let's hope that our joint efforts will soon result in overcoming those and possibly other problems and lead to the development of a more efficient and environmentally friendly propulsion system.

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