

## Applications of the continuously rotating detonation to combustion engines at the Łukasiewicz – Institute of Aviation

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*In the paper short information about advantages of introduction of detonation combustion to propulsion systems is briefly discussed and then research conducted at the Łukasiewicz – Institute of Aviation on development of the rotating detonation engines (RDE) is presented. Special attention is focused on continuously rotating detonation (CRD), since it offers significant advantages over pulsed detonation (PD). Basic aspects of initiation and stability of the CRD are discussed. Examples of applications of the CRD to gas turbine and rocket engines are presented and a combine cycle engine utilizing CRD are also evaluated. The world's first rocket flight powered by liquid propellant detonation engine is also described.*

**Key words:** *detonation, detonation engines, RDE, experimental rocket*

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### 1. Introduction

The first idea concerning possibility of increasing efficiency of engines due to applications of detonative combustion came from Zeldovich [1], but at that time no one was interested in this idea. At the end of fifties and beginning of sixties of the last century continuously rotating spinning detonation was discovered in Institute of Hydrodynamics of the Soviet Academy of Sciences in Novosibirsk and was described in a few publications [2–4]. At the same time at the University of Michigan Nicholls et al. [5] was tested laboratory model of the Pulsed Detonation Engine (PDE) and a few years later research were undertaken on applications of CRD to rocket engines, but unfortunately at that time they been unable to succeed. Adamson et al. was only able to perform theoretical analysis of CRD structure in combustion chamber of rocket engines [6, 7]. Since that time research on application of the CRD to propulsion system was abounded for many years. Research on application of detonation to the PDE were reinitiated at the end of the last century by Edelman et al. [8, 9], and dominated the research on the applications of detonation to propulsion system up to beginning of twenty first century. More information about such research could be also find on survey paper devoted to the PDE [10–12]. Only at the end of last century and the beginning of this one research on the possible application of the CRD to propulsion system was nearly simultaneously reinitiated in Russia, France, Poland and Japan then exponential interest on such system was significantly increased [13–15]. Since that time many initiatives were undertaken to better understand nature of detonative propulsion and to develop engines based on detonation. The rate of increase publications devoted to RDE at the beginning of XXI century is shown in Fig. 1.

The aim of the article is to discuss the latest works related to the issue of rotating detonation carried out at Łukasiewicz – Institute Aviation.

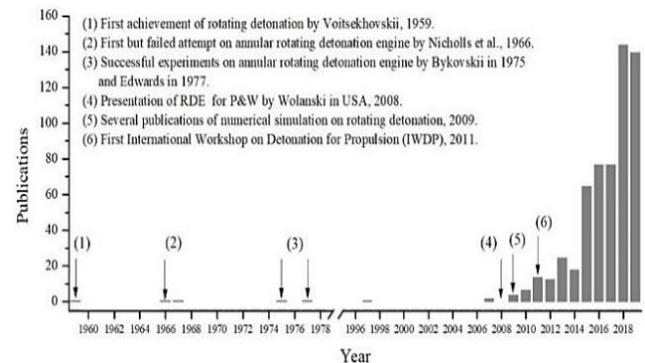


Fig. 1. Graphical illustration of numbers of publication related to RDE research from time of first experimental obtainment of the continuously rotating detonation up to recent time (2019) (Courtesy of Bing Wang) [16]

### 2. Detonation versus deflagration

It is well known that combustion of gaseous mixtures can happen at two different modes: deflagration and detonation. During deflagration, combustion is usually slow and flame velocity is always subsonic, while for detonative mode flame propagate with supersonic velocity. For deflagrative combustion pressure at the end of combustion always decrease, while for detonative combustion is always increased. Typically for detonation of fuel air mixtures pressure can be increased about 15 times, while detonation of fuels with gaseous oxygen can increase more than 30 times. Details of the detonative combustion of gaseous mixtures can be found in many publications [14–17]. Because combustion of the same mixture can result in very different parameters depending on the deflagrative or detonative mode, application of different modes of combustion to a propulsion system can also result in different performance of the propulsion system. It was shown already in many publications that application of detonative combustion to engines can result in significant increase of engine efficiency. For example, if detonative combustion is applied to the turbojet engine, theoretical engine efficiency could be even increased more than 30% [14], but even if in reality



mixture supply to the chamber [29–31]. If all necessary conditions of mixture supply are fulfilled and sufficient energy of initiation is released, then in a short time a stable continuously rotating detonation in the chamber will be achieved. Pressure record of stable detonation in the annular chamber is shown in Fig.5. and numerically calculated structure of stable detonation is shown in Fig.6. In this case two detonation waves are propagating in the same direction, but generally many different conditions of waves propagation in detonation chambers are observed.

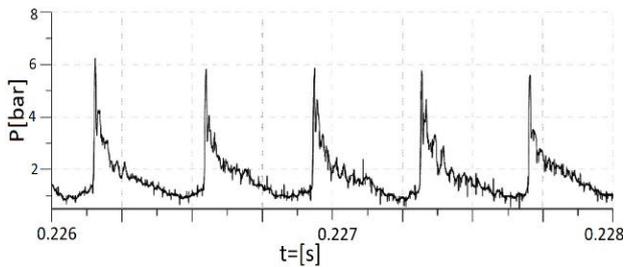


Fig. 5. Pressure variations of stable detonation in the annular chamber [14]

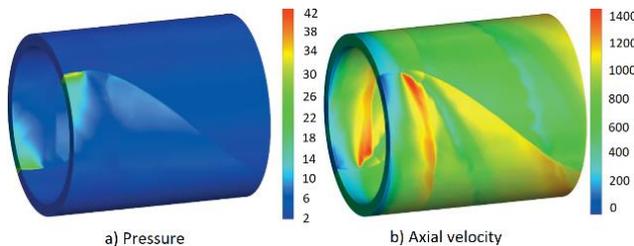


Fig. 6. Numerically calculated 3-D flowfield of the two waves stable rotating detonation structure in annular detonation chamber [32]

Stabilization of direction of rotating detonation wave was studied by Kawalec et al. [33], which show that direction of rotation could be controlled by small eccentricity synchronized with selected initiation place.

CRD could be initiated also in different shape of the chambers, such as presented by Bykovskii et al. – Fig. 7. [34], but also con-shaped and successfully tested by Kawalec et al. [33]. There are also other geometries already tested, such as cylindrical chamber with short insert and hollow

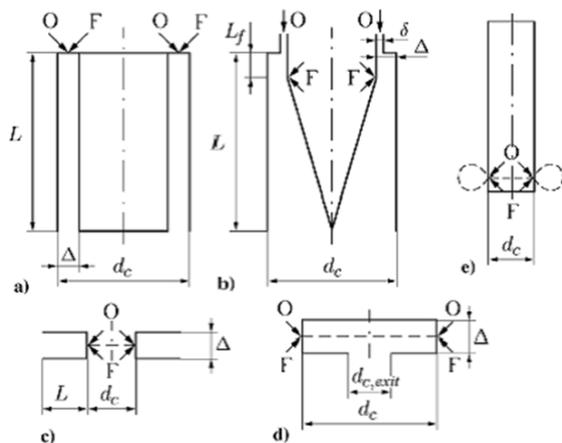


Fig. 7. Geometries of detonation chambers tested by Bykovskii et al. a) annular chamber, b) partially annular with inner cone, c) open space inner disc, d) disc chamber, e) open space external disc [34]

chamber and disk-shaped connected to the nozzle and other [24–27, 35–41].

#### 4. Research on application of the CRD to propulsion systems at the Łukasiewicz – Institute of Aviation

Research on the application of the CRD to propulsion system is carried out at the Institute of Aviation for more than 10 years. During that time a few systems with CRD were developed, such as GTD-350 with detonation chamber, special system of mixture preparation which guarantee stable operation in annular/cylindrical chambers working on liquid fuels, control of directions of rotating of detonation wave in the annular chamber, development of disk and con shaped detonation chambers working on liquid propellants with regenerative cooling and designing and launching of first in the world rocket powered by disk-shaped detonation liquid rocket engine. We will briefly mention first two systems, which are already described in the publications [27, 42–43], but more details will be presented on the development of rocket and rocket-ramjet engine as well as a very successful flight of experimental rocket powered by disk-shaped liquid rocket engine utilizing CRD.

##### 4.1. Research on applications of the CRD to the air-breathing propulsion

During 2010–2015 development of gas turbine engine with detonation combustion chamber was carried out at our Institute under the project UDA-POIG.01.03.01-14-071 “Gas turbine with detonative combustion chamber” supported by EU and Ministry of Regional Development of Poland. During this project many problems were studied, such as: mixture formation, development of proper geometry of detonation chamber, detonation initiation as well as the operation of this engine with detonation chamber. Engine was tested on the following fuels: Jet-A, Jet-A with additions of gaseous hydrogen and on gaseous hydrogen only. It was found that engine operating on gaseous hydrogen demonstrated increased thermal efficiency by 5–7%, as compared to the based engine operating on conventional fuel with the classical combustion chamber. Details of this research can be found in [27, 42, 43]. It must be also added that recent initiatives of the Airbus company to develop aircraft powered by hydrogen fuel will also open a way for the introduction of turbojet engine with detonative combustion chamber, since it was already proved, much higher efficiency can be achieved with applications of the turbojet engines utilizing CRD in engine’s combustion chamber [44, 45].

Another research which was continued, after the above project was completed, was focused on development of the new system of preparation of liquid jet fuels for combustion in annular detonation chamber. Development of such system for air-breathing engines utilizing CRD will improving engine efficiency and thus results in fuel saving. This research concerns development of system which could allow preparation of liquid fuel-air mixture which can support stable CRD in annular chamber [24]. Schematic diagram of such system is presented in Fig. 8a and typical recorded pressure signals of detonation in Fig. 8b.

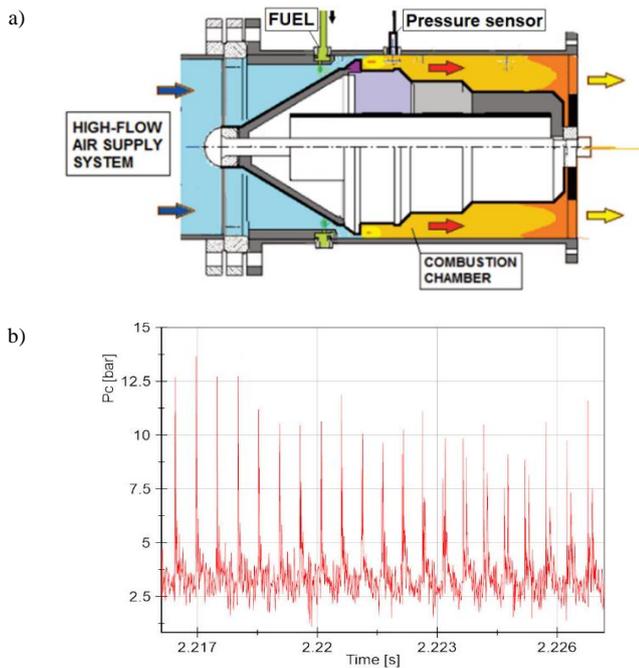


Fig. 8. Schematic diagram of the annular detonation chamber (a) and recorded pressure of the CRD for Jat-A – air mixture (b)

#### 4.2. Research on applications of the CRD to rocket engines

For the last few years in the Institute research on application of the CRD to rockets engines were initiated. Initiation of those research came from US Air Force Research Laboratory with granted the project related to development of the methods of wave direction control in rocket engine. The main goal of this research was to find effective way of control direction of wave rotation in detonation engine. Tests were carried out for gaseous mixtures such as hydrogen-air and methane-oxygen. A few different methods were tested to control direction of wave motion, but it was found that applying small eccentricity such control could be achieved (see Fig. 9).

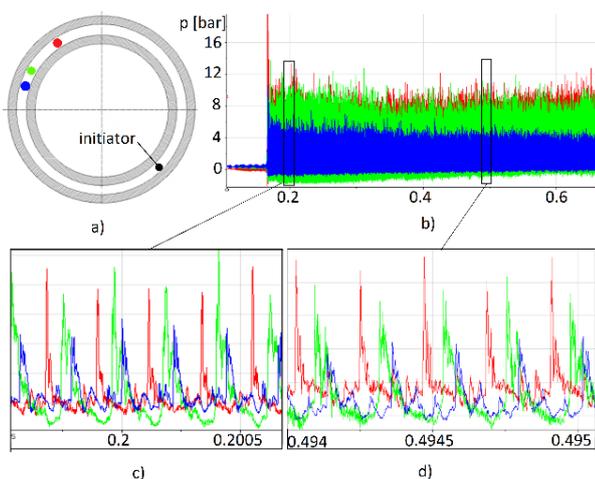


Fig. 9. The example of an experiment with the use of the initiator close to the small eccentricity, a) schematic of the cross section of the annular detonation chamber with colored points of located pressure transducers and indication of the position of the initiator, b) recorded pressure by the three transducers, c, d) enlarged randomly selected pressure records. More detailed description of this research can be found in [33]

Another research was directed in development of the liquid propellant rocket engine which utilize CRD. As a propellants liquid propane ( $C_3H_8$ ) and liquid nitrous oxide ( $N_2O$ ) were used. The tests were carried out in an engines with an annular, a disc-shaped and a cone-shaped detonation chambers. Pictures of the tested engines can be seen in Fig. 10. The specific impulse obtained of the disk-shaped engine was equal to 1600 m/s, about 80% of theoretical value. For con-shaped engine with regenerative cooling, the specific impulse increased to 2005 m/s.

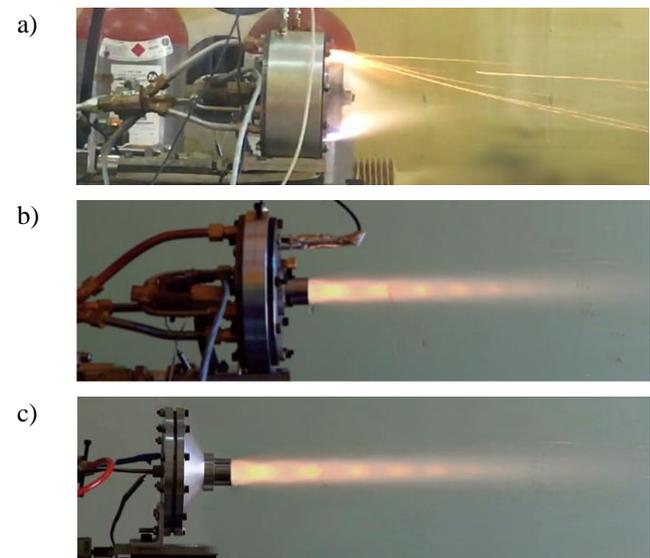


Fig. 10. Rocket RDE: with annular cylindrical detonation chamber (a), with disc-shaped detonation chamber (b) and with con-shaped detonation chamber (c) [21]

Also the first research on possibility of using combined cycle rotating detonation in rocket-ramjet engine was conducted. For this case rocket engine was operating on fuel rich conditions. This allow afterburning of hot, not completely reacted products from the rocket engine, which was burning with air passing through ramjets subsonic combustion chamber and generate extra thrust. It was shown that such combined cycle Rocket-Ramjet can, in optimum operating condition exhibit 25% increase of efficiency as compare to rocket itself operating in similar conditions. Picture of the rocket-ramjet engine during test at the experimental stand at our Institute is shown in Fig. 11.



Fig. 11. Test of the rocket-ramjet engine at the experimental test stand at Lukasiewicz – Institute of Aviation [33]

#### 4.3. Development of experimental rocket powered by liquid fueled rocket engine utilizing CRD

Since the liquid rocket engines utilizing CRD were developed at our Institute, the next logical step was to apply one of the engine to propel the experimental rocket. The cone-shaped engine was chosen as the propulsion system for the rocket. Before installing it on the rocket, special

validation tests were carried out in the laboratory. As it was already mentioned, as propellants liquid Propane and liquid Nitrous Oxide were used. To ensure a few seconds work, engine was design in such a way that both liquid components were used for cooling engine's walls. Engine was first tested at the research stand in horizontal conditions, but after completion of such tests engine was integrated with the rocket and was also tested in vertical condition and with supply of both propellants from the rocket tanks. Both propellant tanks were pressurized before experiment by gaseous helium. This guaranteed nearly constant rate of feeding of engine with both propellants. Only after such successful static tests of the engine integrated with the rocket, the experiments was conducted at the military test range outside Warsaw at WITU in Zielonka On September 15, 2021 at 9:29 rocket was successfully launched and reached the altitude of 450 m.



Fig.12. Launch of the experimental rocket power by liquid fueled RDE which utilize CRD at the military test range in WITU, Zielonka

Picture of the liftoff of the rocket is shown in Fig.12. The rocket engine, according to the plan, worked for 3.2 s, accelerating the rocket to a speed of 93 m/s, which allowed the rocket to reach an altitude of 450 m. It was the world's first attempt to use a detonation engine powered by liquid propellants (liquid propane and liquid nitrous oxide) to propel a rocket. It was also world's first detonation engine that achieved flight under its own power.

## 5. Conclusions

Łukasiewicz – Institute of Aviation is engaged in research on application of CRD for different propulsion system for more the 10 years. The most important achievements in this field are:

1. Development of the detonation combustion chamber for GTD-350 engine, which working on gaseous hydrogen fuel shows improvements of engines efficiency by 5–7% as compare to base engine supply by Jet-A fuel.
2. Development of effective mixture preparation system which allow to achieve stable sustainable operation of CRD in the annular detonation chamber for the Jet-A – air mixture.
3. Development of effective way of control of detonation wave rotation in the model of rocket engine combustion chamber.
4. Development of the liquid propellant disc-shaped and cone-shaped rocket engines with regenerative cooling by liquid propellants.
5. Development the combine cycle rocket-ramjet engine working on liquid propellants.
6. Development of the experimental rocket which utilized RDE cooled by liquid propellants and perform its successful flight test. It's the world's first detonation engine that achieved flight under its own power.

Due to this activities and achievements Institute will be more engaged in further development of this very promising research and hopefully will widen international cooperation in this field.

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