Recent Research on Rotating Detonation Engines supplied by liquid propellants at the Łukasiewicz – Institute of Aviation

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Abstract

The use of gaseous propellants to power Rotating Detonation Engines (RDE) is widely tested in many research centers around the world. Nevertheless, the use of liquid fuels is more promising from the point of view of aviation and space propulsion. This article describes the research of the rotating detonation process using mixtures based on liquid fuels. The results of the research on an air-breathing kerosene fueled combustion chamber are presented (a stable rotating detonation process was obtained without the use of any special admixtures). The use of rocket RDE allows to design lighter and smaller engines with lower pressures in the supply system. The development of liquid-propellants rocket RDE allowed to conduct the world's first successful rocket flight powered by RDE- only.

Introduction

Research on applications of the continuously rotating detonation (CRD) to the propulsion systems at the Lukasiewicz – Institute of Aviation (L-IoA) have been already conducted for more than 12 years. Initially development was focused on introduction of the CRD to an annular detonation chamber compatible to the GTD-350 gas turbine engine but later was focused on finding the ways to obtain stable rotating detonation for Jet fuels – air mixtures as well as on research on application of the CRD to the rocket and combined cycle propulsion systems. Since previous ICDERS (International Colloquium on the Dynamics of Explosions and Reactive Systems) significant progress was achieved both in finding the ways of organizing CRD in annular detonation chamber for the Jet-A mixture with air as well as development of the liquid propellants rocket engine with detonative chamber and performing the first in the world launch of the rocket powered by liquid propellants RDE. More detailed description of this research could be found in recently published book [1] devoted to this subject as well as other easily available publications [2-5].

Development of liquid fuel-air CRD

It is essential to develop technology which guarantee stable operation of CRD in the air-breathing engines, since such combustion allows to improve performance as well as decrees mass and size of RDE. In the L-IoA many experiments were conducted to select optimum way of preparation of the liquid fuel mixture with air which could give stable detonation of such mixtures. Initial results were already published and can be find in [1-3]. Also patent for such mixture preparation was issued in EU and in the USA [6]. The most important aspect of obtaining stable detonation of liquid fuel-air mixture is to evaporate liquid fuel before injection into detonation chambers. Typical example of a stable detonation in an annular chamber is presented in Fig.1.

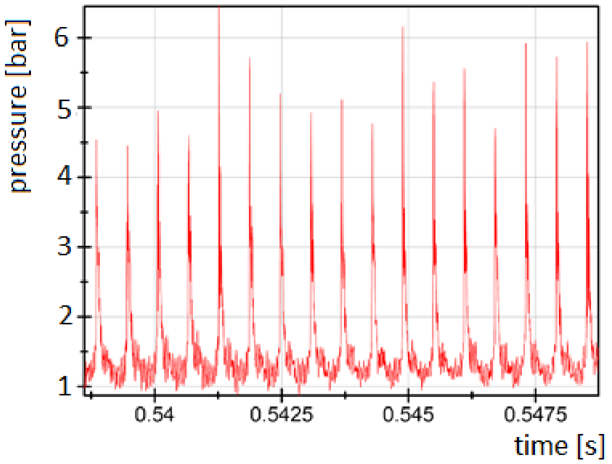

Figure 1: Selected pressure record for the fuel-air mixture with $\phi \approx 0.94$. Vd= 1160m/s.

Development of RDE fueled by the liquid propellants

The special attention was focused on the development of the liquid propelled RDE, since the real use of the CRD in engines must be associated with applications of the liquid fuels and liquid oxidizers, due to high energy storaged in a small volumes. As a first choice of propellants we selected liquid propane (C_3H_8) and nitrous oxide (N_2O) - they are both easily storable at room temperature and are non-toxic and non-corrosive as well. Since detonation of such propellants produce very high pressure and very high temperature special detonation chambers were developed. In order to guarantee stable detonation both components have to be evaporated before injection into detonation chamber. The evaporation of the propellant components before injection to the detonation chamber is also used for cooling walls of detonation engine. Initial experiments with uncooled engines were conducted only for a very short runs (without cooling, engine can basically withstand high temperature for about 0.5 s only - longer operation resulted in chamber burnout). Three types of detonation chamber were tested: annular, disc-shape and conical. Some pictures from these experiments are presented in Fig. 2. The measured pressure variation in detonation chamber is shown in Fig. 3., while calculated specific impulse is presented in Fig. 4.

Figure 2: Rocket engines with detonation combustion chambers supplied by N_2O and C_3H_8- with annular cylindrical detonation chamber and aerospike nozzle (left) and with disc-shape detonation chamber and bell nozzle (right).

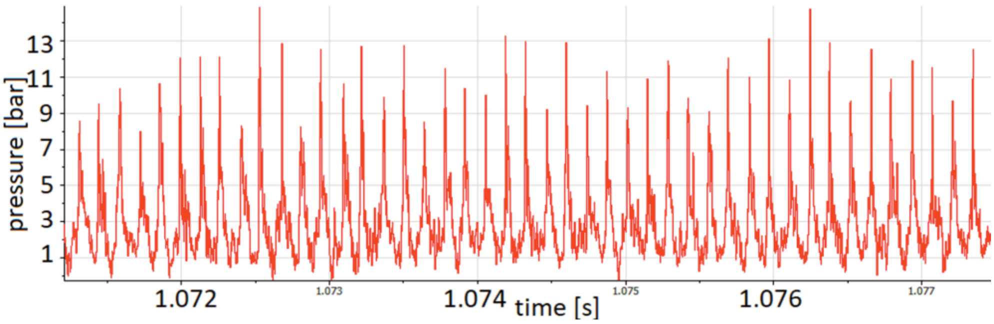

Figure3: Recorded rotating detonation pressure course for close to stoichiometric (φ=1.05) mixture in disc-shape combustion chamber. Mass flow rate – 0.15 kg/s.

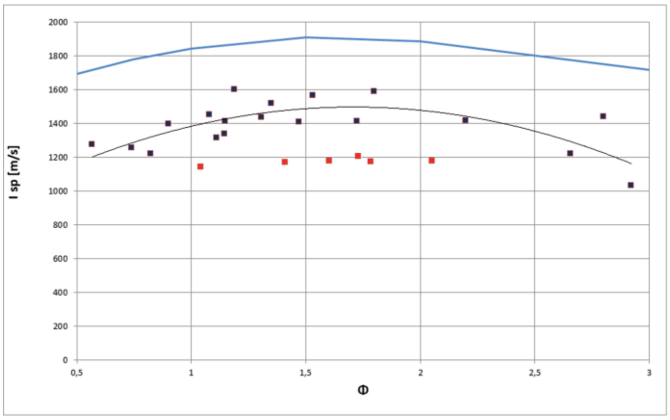

Figure 4: Specific impulse in tested detonation chambers for different mixture compositions. Black points – disc-shape combustion chamber, red points – annular combustion chamber. Blue line shows theoretical specific impulse calculated by NASA CEA Code [7]

Disc-shape chamber showed higher performance, and the next step was design and construction of a new engine with conical detonation chamber and bell nozzle. Picture of the new RDE liquid propellant engine operation is presented in Fig. 5.

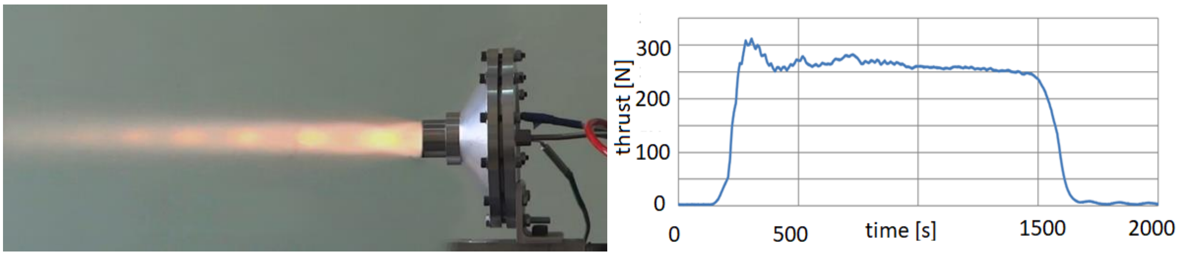

Figure 5: Rocket RDE with conical detonation chamber supplied by N_2O and C_3H_8 and a thrust of the engine.

The new rocket engine showed the best performance, so it was equipped with the regenerative cooling using both propellants. The engine could repetitively operate for about 4 s (we did not establish the limit), it have been used to power the first world's rocket with RDE which performed successful flight under its own power.

Development of first world's rocket with liquid RDE

The developed conical RDE was able to generate thrust of about 200 N for about 3 -4 s, so the rocket based on these available engine performance has been constructed. Since rocket should have lift-off acceleration of at least 3 g (to allow stable flight after rocket leaves the launcher of reasonable length), the gross weight of such rocket should be of an order of 5 kg. Since the engine itself weights 0.8 kg (0.99 kg with control valve and its servo) so the rest of the rocket (body + filled propellant tanks +

pressurization system + recovery system) should weight no more than 4 kg. Both propellant tanks are part of the rocket body and are connected by inter-tank composite section. The lower section of the rocket contains: RDE's hose, propellant supply lines, servo valves (they open propellants flow after engine igniter is initiating) and three aerodynamic fins. At the top of the rocket, under a composite cone, a parachute ejected by a spring is placed. The schematic diagram of the rocket is presented in Fig. 6.

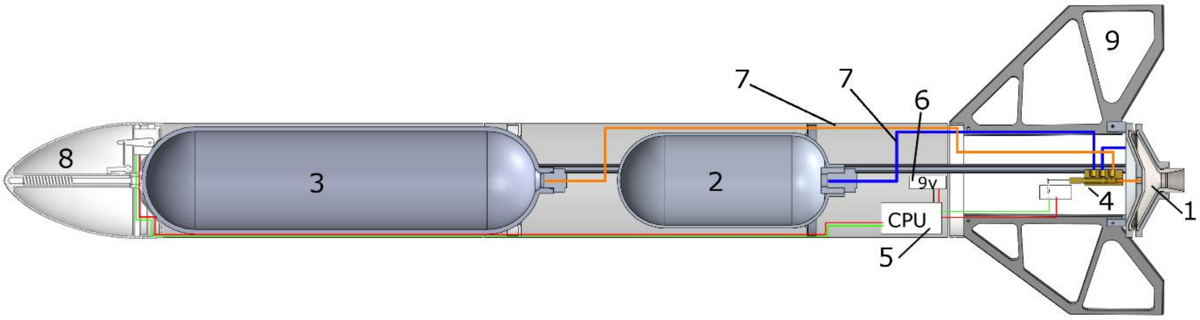

Figure 6: Schematic diagram of the rocket: 1-Rocket RDE, 2-fuel (C_3H_8) tank, 3-oxydizer (N_2O) tank, 4-main valve with servomechanism; 5–onboard computer; 6- battery; 7-propellant supply lines; 8-nose cone with parachute and spring ejector; 9- aerodynamic fins.

The electrically started pyrotechnic ignition system is not integrated with the rocket itself, but it is placed (through the nozzle) in the engine's chamber just before the launch.

Special supply system was designed, constructed and tested in laboratory with the "hot" rocket engine operation. After successful laboratory tests the first world's experimental flight of rocket powered by liquid propellants RDE was conducted at a military test range. RDE worked successfully for 3.2 s, and accelerated the rocket to the velocity of about 90 m/s (it allowed the rocket to reach the altitude of about 450 m).

a)Time= 0s   b) + 0.11 s   c)   + 0.418 s   d) + 0.69 s   e) + 0.74 s

Figure 8: Sequence of photographs showing the initial phase of the RDE rocket flight.

Conclusions

During the last 3 years successful experiments related to the development of engines which utilize CRD were conducted. New system of mixtures preparation for liquid fuels with air were tested and stable operation of CRD was achieved in annular chambers. This opens the way for the application of liquid fuels to the air-breathing engines such as gas turbine, turbojet and ramjet. Additionally the liquid propellant rocket engines which utilize CRD were developed and tested and the first world's flight of a rocket powered by RDE was successfully conducted. Further research continued at Lukasiewicz – Institute of Aviation focuses on ensuring longer operating times and improving the RDE rocket performance as well as improving the performance of the combustion chamber for air - breathing engines working on liquid fuels.

References

1. 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.
2. P. Wolański,: "RDE research and development in Poland", Shock Waves, (2021) 10.1007/s00193-021-01038-2
3. 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
4. M. Folusiak, K. Świderski, P. Wolański,: Numerical Modeling of the RDE, Transactions on Aerospace Research, 4(261) 2020, pp.13-47, DOI: 10.2478/tar-2020-0019, eISSN 2545-2835
5. M. Kawalec, W. Perkowski, B. Łukasik, A. Bilar, P. Wolański,: Applications of the continuously rotating detonation to combustion engines at the Łukasiewicz – Institute of Aviation, Combustion Engines. (2022), https://doi.org/10.19206/CE-145409
6. 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
7. McBride, B., Stanford, G.: NASA-Glenn Chemical Equilibrium Program CEA2, May 21, 2004. NASA RP-1311, Part I (1994); NASA RP-1311, Part II (1996)