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Development of Rocket Engine with Continuously Rotating Detonation supplied by Liquid Propellants

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Abstract

In the paper laboratory research focused on the development of rocket engine with continuously rotating detonation (CRD) supplied by green storable liquid propellants is described. Initial research was focused on the tests of different engines geometry as well as on evaluating conditions under which such engines were operating in a stable conditions. Three different geometries of the detonation engine's chambers were tested: annular, disk and cone chamber. For all engines configuration trust was measured and specific impulse was evaluated. Based on those experiments optimum geometry of the engine's detonation chamber was selected. It was found that biggest specific impulse was obtained for cone geometry. To insure sufficient working time, cone engine was designed with regenerative cooling system, which used both liquid propellants for cooling of both engine walls. Then the special light weight feeding system was designed and tested in laboratory conditions. Such system was then integrated with the rocket and additionally tested in laboratory conditions before flight. After those tests experimental flight of the rocket was conducted on the Military Test Range in Zielonka near Warsaw. During this test the rocket reached an altitude of nearly 500m. To our knowledge it was the World's first experimental flight of a rocket powered by detonation engine splayed by green storable liquid propellants.

Key words: detonation, continuously rotating detonation (CRD), green liquid propellants, nitrous oxide, propane, rocket engine, experimental rocket,

Introduction

Detonation is a very fast process of combustion propagating with velocity of order of km/s or even faster and during detonation pressure always rises significantly. Unlike in detonation in deflagration combustion velocity is always subsonic and additionally if deflagration propagates in channels, like in combustion chambers of turbine, ramjet or rocket engines, pressure always drops. Since pressure in detonation is always significantly increased application of detonation to jet engines offers significant improvements of efficiency and for this reason research on detonation engines was undertaken many years ago. The first research of application of detonation to jet engines was undertaken more than half century ago at the University of Michigan, where theoretical analyses of ramjet engine with standing detonation wave as well as first experimental research of pulsed detonation engine were undertaken [1-2]. At the same time in Novosibirsk the continuously rotating detonation (CRD) was discovered [3] and very soon later also at the University of Michigan, research on application of that kind of detonation to propulsion systems was undertaken but unfortunately they were not successful [4]. Since that time many theoretical and experimental attempts were undertaken and many papers were already published on this subject, so detailed description of theory, numerical simulations as well as experimental research of such engine can be found in many publications [5-10]. In addition the extensive survey of recent CRD research can be found in [11-13]. Most of this research concerns use of gaseous propellants but there is a growing number of research on application of the CRD for liquid fuels with air or oxygen mixtures. A lot of research on applications of the CRD

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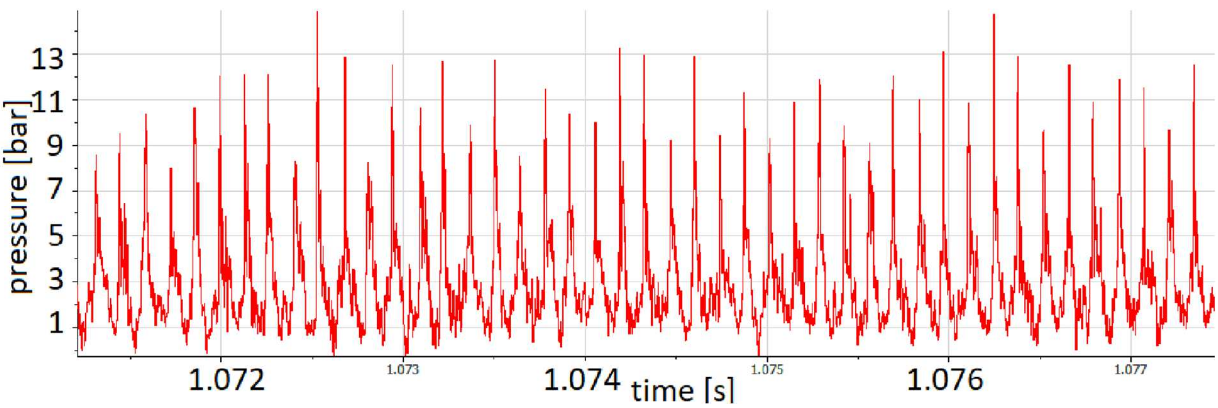
with utilization of the CRD of liquid fuels to different engines was already successfully conducted at the Łukasiewicz-Institute of Aviation and detailed description of those works can be found in many publications [13-15]. So in this paper we will only focus on development of the rocket engine which utilizes CRD of liquid fuels with liquid oxidizer.

Research of the CRD liquid propellants Rocket Engine

Recently at the Łukasiewicz-Institute of Aviation in Warsaw research was conducted on utilizing liquid propellants for small size rocket engines with utilize CRD. As a propellants liquid Nitrous Oxide (N2O) and liquid Propane (C3H8) were used. Initial, short duration tests, were carried out in annular combustion chamber equipped with slit nozzle as well as a disc shape combustion chamber equipped with classical cone shaped nozzle. The test stand was equipped with pressure sensors for measuring fast changing pressure as well as for measuring average pressure in combustion chamber. Detailed description of those experiments can be found in [13,16]. Pictures of engines working on such propellants are shown in Fig.1, while records of quick changing pressures and average pressure in the chamber are shown in Fig.2. Records provided by high frequency sensor allow to assess stability of the detonation process (Fig.2a). The best indicator of detonative combustion in engines chamber are those pressure records, however, additional strong indication of detonation combustion in the engine is very short exhaust plume from the engine as well as thrust measurements. In some cases when detonation was not initiated in the rocket chamber the measured thrust was nearly zero and plums from the engine was very long with strong indication of diffusion flame (no Mach disk visible). It should be also mentioned that in all cases pyrotechnic igniter was used and before ignition the engine was warmed up by electrical heater. During those tests thrust was also measured and specific impulse was calculated. Disc shaped combustion chamber was much shorter, lighter and more compact than an annular one.

a)

Fig.1 Pictures of short duration tests of the small rocket engines supplied by liquid Nitrous Oxide and Liquid Propane with: a-annular chamber, b-disk chamber.



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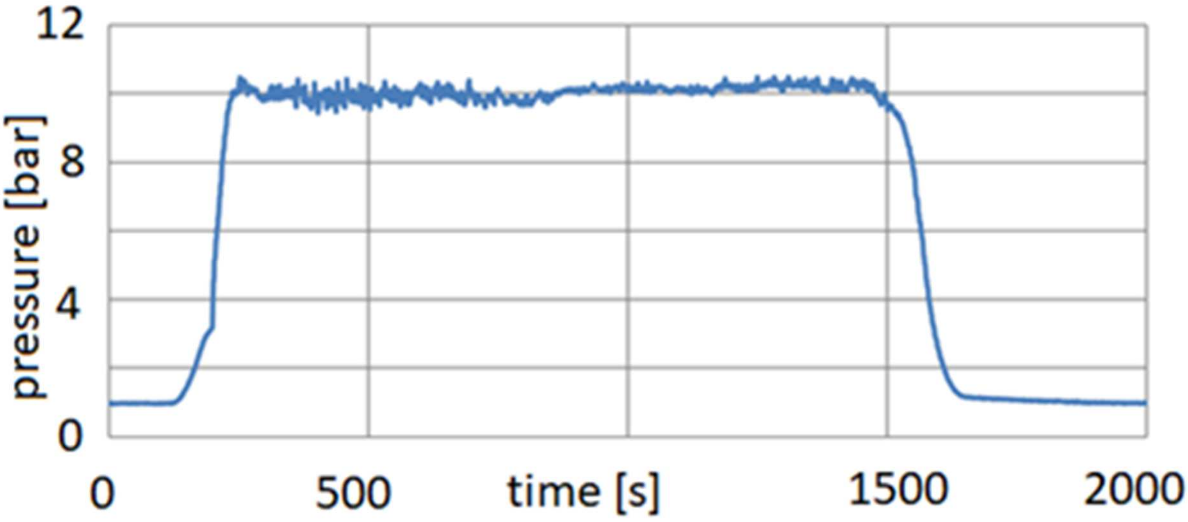
a)



b)

Fig.2. Typical pressure record inside detonative cone chamber for the case of stable CRD, a- part of pressure record by high frequency pressure sensor, b-pressure record by low frequency pressure sensor (average pressure in the chamber).

For given propellants stability of CRD depends strongly on chamber size and mass flow rate. For low mass flow rate only deflagration combustion is observed. If flow rate increases than initially unstable detonation, similar to galloping detonation, is observed, and as mass flow of propellants increases farther, stable detonation is observed. Detailed analyses of CRD stability can be found in [12,13,17].

During our research stable detonation process was achieved for a wide spectrum of mixture composition. The influence of the mass flow ratio was also checked for both chambers, annular and disk. However the velocity of the detonation waves and values of the pressures was similar for both annular and disk combustion chamber. For all test thrust and mass flow rate was measured and on this based specific impulse (Isp) was calculated. The performance (Isp) of the disc chamber exceeded the annular one and reached 85% of the theoretical value of the Isp and only 66% of theoretical value was obtained for the annular detonation chamber with a slot nozzle. It should be mentioned that both engines were not cooled, and utilized only heat sink protection from high temperature detonation products. This however, removed a significant amount of energy, and as results decreased measured value of specific impulse. Also for uncooled engines duration of operations was limited to only 0.5s, since for longer operation time (0.8s) wall of the engine was burned through.

As a results of those initial tests the new laboratory rocket engine was built and tested. The shape of the disc chamber was slightly changed to a conical one with a small cone angle and the same conical nozzle was kept. It was ten necessary to design cooled system for the engine to allow longer operation time. The idea of engine with accumulation cooled (heat sink to heavy cupper structure) was ruled out since the mass of the engine will be too large and it will even will not able to lift itself. It was then decided to design cone engine with the regenerative cooling by both liquid propellants. Schematic diagram of coolant flow in such engine is presented in Fig.3. More details of such design will be published later after we will obtain patent on the most sensitive elements of this engine. Such engine was tested few times and measured thrust for given mass flow rate of both propellants allow to calculate real value of specific impulse. The trust measured in the laboratory conditions for regenerated cone detonation chamber was 250-270 N with Isp

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of about 200 s which was about 95% of theoretical value calculated by NASA CEA Code with assumption of mean measured pressure of 10 bar [19]. This engine, with mass equal to 0,8 kg, was qualified to be used as a propulsion for a small liquid fueled research rocket.

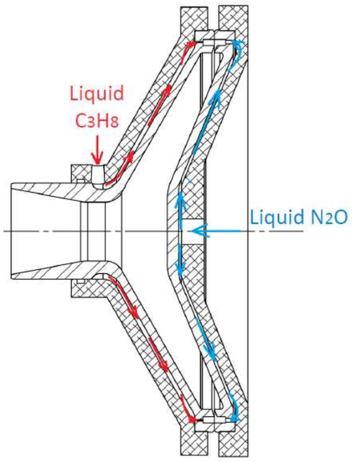

Fig.3. Schematic diagram of cone rocket engine with regenerative cooling system by both liquid propellants (please note that geometry of the engine are only approximate).

Fig.4. Test of the regenerative cooled cone detonation rocket engine supplied by liquid Nitrous Oxide and Liquid Propane.

Rocket design

The main idea of design of the rocket was to prove that detonation engine could be effectively used for practical applications. As it was already mentioned many times that engines which use CRD will have not only smaller mass and will be also smaller than classical engine which deflagrative combustion. The major challenges for rocket design were: small size and small mass of the rocket engine as well small budget allocated to such development, as well as design of small, but effective pressure propellants fed system. For this size of the rocket applications of special valves which will control value of feeding pressure was not considered, due to mass of such valves, not to mention the price of very small and very precise valves. So to design such light supply system the idea of two separate tanks for fuel and oxidizer with direct pressurization of both tanks was chosen. Both tanks should have different pressurization, since each liquid has different vapor pressure at ambient conditions. The necessary volume of each tank was calculated and the pressurization system should guarantee supply of both propellants in liquid state to the engine injection system. Additionally, to guarantee proper mixing ratio, the injection

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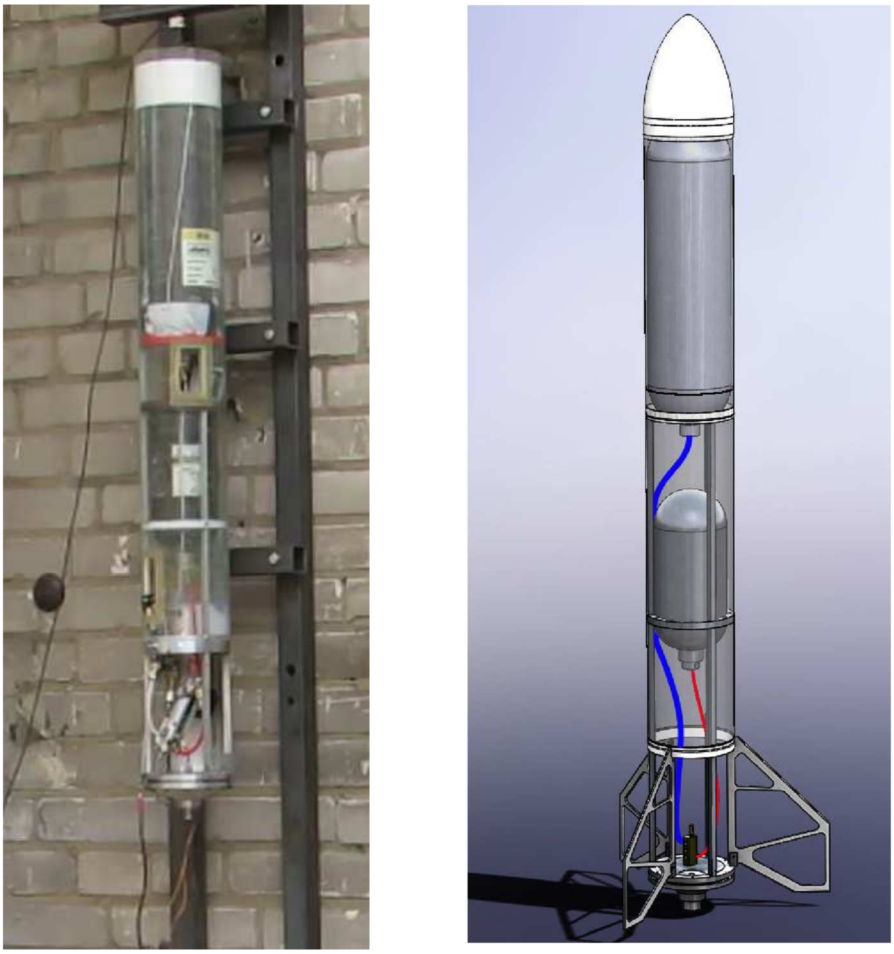
pressure for both components should be nearly the same. To achieve this, the special calibrated orifices were installed before servo valves which control supply of propellants to the rocket engine. Also on board of the rocket a special microcomputer was installed which not only operated opening of propellants valves, but was also designed to record all flight data. Picture of the rocket attached to the laboratory wall, before qualification test is presented in Fig.5a, and schematic diagram of rocket is presented in Fig.5b.



a) b)

Fig.5. a- picture of the rocket tested on the laboratory wall, prepared for the final qualification test of the system before flight and b- schematic diagram of assembled rocket .

Experimental flight

The launch of the rocket was conducted on 15 September at the Military Test Range outside Warsaw in Zielonka. Rocket was placed on the launcher rail guide of about 4,9m length. Calculated rocket acceleration of 3g should provide a sufficient velocity for aerodynamic fines fins attached to the end of the rocket to stabilize the free flight of the rocket after leaving launcher. After the rocket was attached and temporary fixed to the launcher rail guide, both tanks were filled with appropriate mass of propellants: 460 g of liquid N_2O and 70 g of liquid C_3H_8. Then both oxidizer and fuel tanks were pressurized with gaseous helium to the pressure of 73 bar for oxidizer and 16.5 bar for fuel which add about 200 g of He to initial mass of the rocket.

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The rocket before launch had a total mass of 5,55 kg. After this rocket engine was heated electrically to the temperature of about 80 C, and pyrotechnic ignition system was placed in rocket engine chamber. Then on board processor was activated and temporary fixing system of rocket to the launch guide rails was relished, pyrotechnic igniter was initiated (pyrotechnic igniter was designed to work for about 4s) and the launch team left the launcher site. When the launch team was in safe place the onboard control system raised servo valves and both liquid fuel and liquid oxidizer started to flow into the rocket chamber and the created mixture was ignited. As it was detected from the video records, detonation was initiated about 0.1s after servo valves were open and on 0.6s rocket left launch guides rails with velocity of about 18 m/s, which provided sufficient stabilization of rocket flight by aerodynamic fins. Unfortunately parachute was not opened and rocket crashed. It was estimated from the video records the total flight duration was equal 20.3 ± 0.3 s and the engine was working for duration of 3.3 ± 0.2 s. It was estimated the maximum velocity of the rocket was about 95 m/s and estimated maximum altitude was about 450 ± 10m. Picture of launch is presented on the Fig.6, and video records of that launch can be found on Łukasiewicz-Institute of Aviation web site [20].

Fig.6. Picture of the launch of the first World's rocket powered by liquid propellants detonation engine.

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Summary and conclusions

Extensive research on CRD has been carried out at the Lukasiewicz - Institute of Aviation for nearly 15 years. Initially research was focused on application of the CRD to gas turbine engine but later was also focused on numerical modelling of flow and detonation structure and stability. Later research was focused on applications of liquid fuels and ways of preparing mixture which can support CRD in an annular chamber for liquid fuels mixtures with air and stable operation for Jet-A as well as gasoline were obtained. In the same time modelling research of gaseous rocket engines supplied by gaseous hydrogen and gaseous methane with oxygen was successfully conducted. Finally research was directed on application of liquid storable green propellants to rocket propulsion. As storable green propellants liquid Nitrous Oxide and Liquid Propane were selected. Initial tests were carried out in engines with annular, disk chambers, in which conditions necessary to support stable operation were evaluated. Also for all cased thrust was measured and specific impulse calculated. All the tests in uncooled engines lasted about 0.5s. Longer runs resulted in burnout of engine wall. To increase duration of engine operation special cone shaped engine with regenerative cooling system was designed. This allows extension of the engine work to nearly 4s. Such engine was then selected and used to propel small experimental rocket. For rocket structure special materials were used for both propellants tanks, since the engine has trust slightly higher than 200N, so to assure sufficient acceleration the mass of the rocket should not exceed 5 kg, to guarantee aerodynamic stabilization of the rocket at the moment of leaving launch structure. Launch of the rocket was conducted successfully and rocket reached an altitude of nearly 0,5 km. To our knowledge it was the first successful launch of the rocket propelled by detonative rocket engine supplied by liquid propellants.

Acknowledgment

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