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Design And Development Of A Nitrous Oxide / Alcohol Sounding Rocket Technology Demonstrator

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Abstract

AGH Space Systems is student organization based in AGH UST in Cracow, Poland. Liquid rocket engines are being developed in AGH Space Systems since 2016. From the very beginning group has been developing unique propulsion system based on nitrous oxide in full self-pressurization cycle named Zawisza. Turbulence rocket project has been started in 2017 and its goal is to develop bi-liquid, sounding rocket technology demonstrator with Zawisza Z4000 engine. In 2018 Turbulence project took 2nd place in Spaceport America Cup's Liquid/Hybrid high altitude category for its overall design quality and unique approach to the propulsion system. In early 2019 successful hot-fire test campaign has been carried out with small-scale Z500 engine to demonstrate feasibility of the technology. Flight model has been publicly unveiled in June 2019. Next milestones are low altitude launch to 2 km in August 2019 followed by high altitude launch to 10 km in October 2019.

1. Introduction

The AGH Space Systems is an interdisciplinary, non profit, academic engineering team specializing in space industry technologies. We operate at the AGH University of Science and Technology in Krakow and associate active members from almost all faculties of the university. Since the beginning of our existence we have been dealing with projects from the wide scope of space industry, achieving numerous successes in the international arena. During 5 years of our activity we have gained valuable experience and knowledge necessary for the implementation of advanced designs in rocket technologies, autonomous planetary rovers and atmospheric probes.

The team is working on small, probing rockets, which we use to test the CanSat lander, take measurements in flight and reach higher apogee levels. The virgin flight of our first hybrid rocket took place in 2016. The next three designs were made almost entirely of glass fibre and were powered by N2O hybrid rocket engines. The test bench and infrastructure for testing small engines were constructed.

Another project developed in parallel with the hybrid rocket program was the development of rocket engine technology for liquid propellant. Finally, at the end of 2017, we obtained the first experimental liquid fuel engine generating 1000N of thrust. The infrastructure makes it possible to measure temperature and pressure at any point in the engine. Thanks to the test bench we can test the efficiency of various injectors and characterize the engine. A rocket based on a new propulsion system was built to compete in the Spaceport America Cup 2018. Despite not having finished the rocket on time, it met with great interest and was awarded 2nd place in the high altitude category of rockets self designed and built with bi-liquid.[3] The project motivation is to fill the gap of European micro launcher industry that is falling behind the world leaders.

The European needs are disposed by ESA's Future Launchers Preparatory Programme. A micro launcher can place a small satellite typically used for Earth observation, technology demonstration, education and telecoms into low orbits, starting from the ground or from an aerial platform. At Space19+ in November, ESA will propose a programme to nurture commercially viable ideas from European industry to open up new space transportation markets. The recent programme would support proposals for privately-led privately-funded space transportation services, with an initial focus on launch services based on microlaunchers. The technology described in this paper aims to pave the way for the future generations of liquid rocket engines both reliable and cheap.

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Figure 1: Flight model of an upgraded version of the rocket during unveil in June 2019

2. State-of-the-art of student built bi-liquid rockets

Liquid rocket engines have always been most complex in design, development and testing. That is why usually student rocketry teams around the world favoured solids or more commonly hybrids over liquids. To date only few teams have managed to successfully design, build and launch bi-liquid rocket. In 2015, San Diego State Univeristy launched their rocket to about 4 km, but they have used surplus engine Rocketdyne's LR-101. In 2018, UCLA have launched fully student built LOx / ethanol rocket to 3.8 km and it is thought to be world record in this category.[2] There is growing interest among such teams to launch bi-liquid what can be observed in annual Spaceport America Cup (former IREC) competition. In 2018, three teams have brought their rockets - Colorado State University, University of Michigan and our team from AGH University in Cracow. What is more, this need is also expressed by the industry, which comes up with ways to encourage the pursuit of building bi-liquids by organizing competitions like FAR-MARS Prize, which allows only liquid rockets (especially using LOX / LCH4) or more recently Base11 competition in which students build bi-liquids to over 100 km. To the best of our knowledge there have been none student launched liquid rockets in Europe so far, although there some projects to achieve that, for example Asteros rocket from France.[4]

3. Top-level system overview

Turbulence rocket consists of the following subsystems which are shown on Fig. 2:

1. Zawisza Z4000 propulsion system:
    (a) ablatively cooled thrust chamber
    (b) feed system with control valves and fill system
    (c) self-pressurized pressure vessel

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2. onboard electronics:
    (a) distributed, multi-level control CPUs with voting system
    (b) AHRS and measurement modules
    (c) redundant recovery deployment modules
    (d) power distribution and management module
    (e) telemetry avionics
    (f) communication antennas
3. aerostructures:
    (a) nosecone
    (b) fairings
    (c) fins
4. recovery system:
    (a) drogue parachute
    (b) main parachute
    (c) deployment system
5. payload module

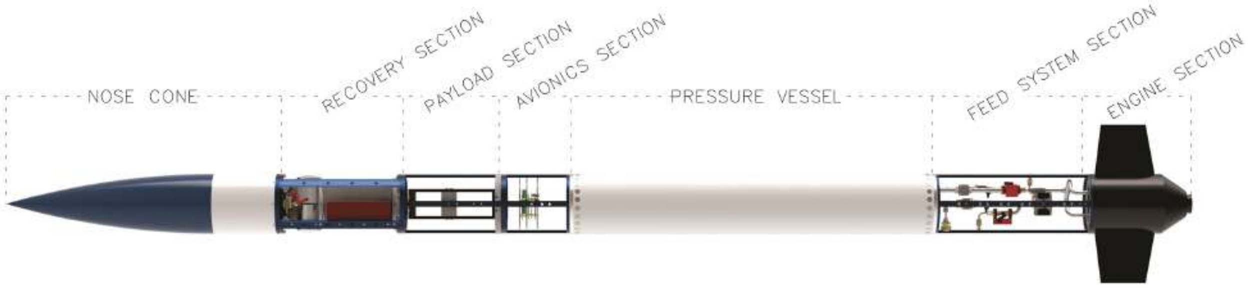

Figure 2: Overview of the Turbulence rocket subsystems

3.1 Propulsion system

3.1.1 Z4000 rocket engine

The Turbulence rocket is propelled by liquid rocket engine called Zawisza Z4000, which is developed, built and tested by members of AGH Space Systems. Nitrous oxide is used as an oxidizer, while ethyl alcohol is used as a fuel. The team decided to utilize nitrous oxide due to extensive experience with previous use in hybrid rockets engines, good availability and storability.[6] Alcohol was chosen over kerosene, because OF ratio with nitrous oxide is so high, that there is negligible performance impact of choosing kerosene over alcohol. Z4000 is designed to deliver average thrust of 4000N. Burn time is limited by ablative liner in the chamber and propellants in the tank. Thanks to its modular design it can be equipped with bigger tank, which enables longer burn, which means it its mainly limited by the liner. Key parameters of Z4000 are given in Table 1.

3.1.2 Self-pressurization cycle

Nitrous oxide can be used is self-pressurization cycle, what is often incorporated in the hybrid rocket engines. However, in bi-liquids it is possible to use this oxidizer to pressurize both itself and the fuel. Z4000 propulsion system has only one tank, which is filled with both propellants, that are separated by a moving diaphragm. Fuel is pressurized by high pressure of the nitrous oxide vapour. This eliminates need for external pressurization gas or turbopumps drastically reducing bi-liquid propulsion system complexity.[6]

Property	Value
Average thrust	4 kN
Burn time	10 s
Mass flow	2 kg/s
Chamber Pressure	40 bar
Specific impulse	240 s
Total length	2 m
Diameter	20 cm

Table 1: Key parameters of the Z4000 propulsion system for the Turbulence rocket

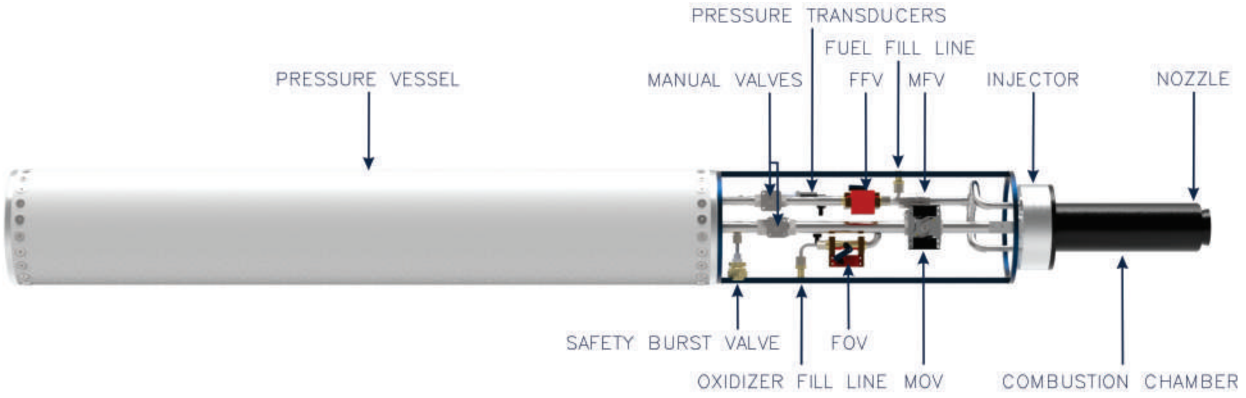

Figure 3: Z4000 propulsion system overview

3.1.3 Ignition system

Ignition of the engine is achieved with a pyrotechnic mass. Standard formulation black powder mixed with 13 wt. % 100 mesh magnesium powder was homogenized with 5 wt. % of epoxy resin, formed into an annular shape (outer diameter matching the chamber diameter) and allowed to cure. Each igniter contained approximately 40 g of the composition. An e-match taped to the igniter's surface provided initial heat source. Delay between e-match ignition and valve opening sequence was chosen individually for each test.

3.2 Recovery system

The recovery system enables the recovery of an undamaged rocket and its payload and its reuse in another launch. In addition, it provides safety for the launch site and the surrounding areas.

The use of a two-stage recovery system allows to limit the area onto which the rocket will fall. Dry mass of a rocket which is being recovered by designed parachute system is about 50 kg. The drogue chute is deployed at the apogee, while at a predetermined altitude, the main parachute is released. The main parachute allows a gentle landing. When descending with the drogue chute deployed at apogee, the rocket descends faster, which allows to reduce the effect of wind conditions that could significantly drift the rocket off the launch site. At an altitude of 10 km, as meteorological data shows, we can expect winds blowing at around 25 m/s. If such a wind blew, the entire radius of the rocket search would be about 10 km. It would make it difficult for the rocket to be found, and we could even risk losing it due to the breakdown of communication with Ground station.

The recovery system must be designed so as to:

- slow down the rocket while descending under the drogue chute so that the main parachute can be safely deployed and inflated. The difference in velocity between descending under the drogue chute and the main parachute have to be small enough, so that during inflation of the main parachute's canopy no overload on the rocket structure occurs;
- stabilize the fall. It was decided to put the recovery sections close to the front of the rocket to provide better conditions for stabilizing effect of the parachutes.

The launch and operation of recovery system occurs as follows:

1. Apogee is detected.

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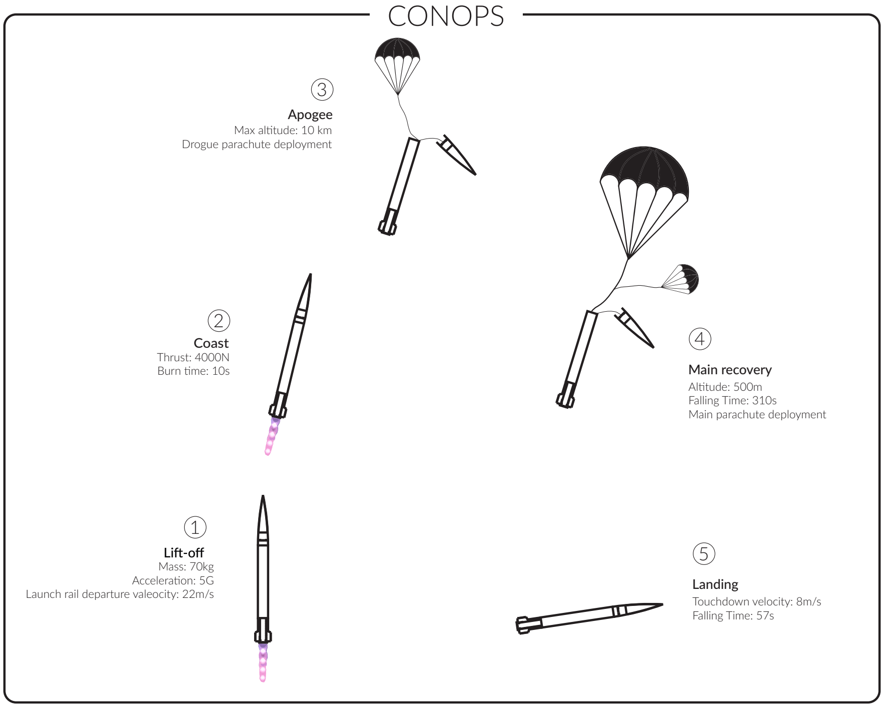

Figure 4: Concept of operation of the Turbulence rocket

2. Command is sent by recovery avionics to deploy drogue chute. Pyrotechnical deployment is activated. Nosecone is ejected from the rocket and pulls out the drogue parachute.

3. Drogue inflates and begins to stabilize and slow down the rocket.

4. On 500 m AGL command is sent by recovery avionics to deploy main parachute. Second pyrotechnical system is activated and main is released by lock-down mechanism and pulled out of the rocket by drogue chute.

5. During inflation of the main parachute shock absorbers minimizes the effect of generated force impulse.

6. With main parachute inflated rocket descents with vertical velocity of 8 m/s.

7. The rocket touchdowns and awaits retrieval.

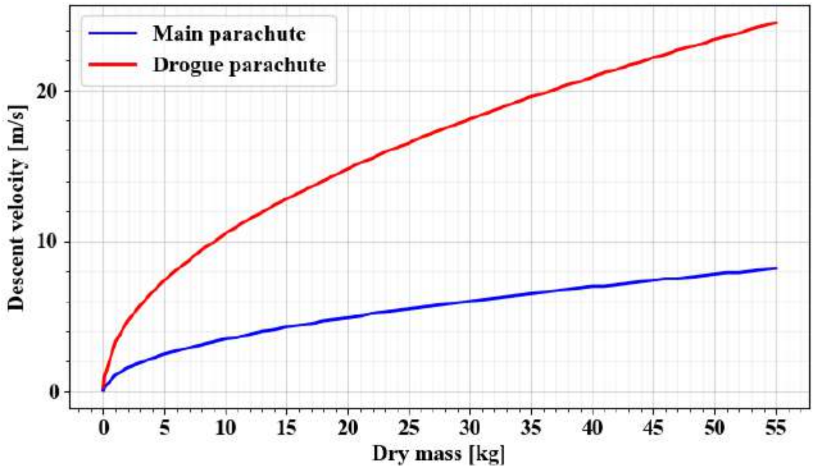

Figure 5: Descent velocity calculated for dry mass of the rocket

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Drogue parachute is designed as a hemispherical type. It is a simple type of parachute, widely used in sounding rocket recovery systems. It consists of 12 segments in the gore shape and the proper rigging. Diameter of parachute is 1.6 m. Drag coefficient of designed parachute was calculated to Cd = 0.75. Ringsail is the type of main parachute designed for the Turbulence rocket. Its main advantages are increased inflation time, what reduces impulse forces affecting the structure of the rocket during inflation and greater stability during descent, when side winds occur. Ringsail parachute has cone-shaped cross section in the upper part - ring section, and quarter-spherical cross section in the lower part - sail section. Ring section consists of 48 elements. Sail section contain 80 parts. All segments are connected using ribbon tapes and proper rigging. Diameter of parachute is 4.5 m. Drag coefficient of designed parachute was calculated to Cd = 0.85. Figure 5 gives calculation of the descent velocity for designed parachutes. For the 50 kg of dry mass of the rocket, descent velocity of drogue parachute is 23.38 m/s. Descent velocity of main parachute is 7.78 m/s. Calculated values allows for safe recovery of the rocket.

3.3 Onboard electronics

The electronics subsystem is an effect of 3 years of work. Many factors were taken into account during the preliminary engineering phase, the main emphasis was set on safety and reliability. Basing on the experience gathered from previous projects, an approach close to a distributed system was chosen. It is composed of 10 modules, which reduces the responsibilities of individual boards by splitting the tasks required for rocket operation. To ensure the system is fail-safe, each unit can operate independently.

3.3.1 Internal communication

The decentralized sensing and executive system solves the problem of redundancy required in the rocket system. It allows to carry out voting for each decision and software stage change by assigning weights to each module and making several types of conditions available for presentation in a vote. A steady and reliable connection between each module was obtained using the almost failure-free CAN protocol. This standardized communication system in terms of physical and protocol layer allows for flexible adjustment of the number and data frames needed in the sensory network. To make it even more robust, an additional CAN bus between the most crucial modules was implemented in order to preserve communication in case of the main line failure.

3.3.2 System architecture

Boards' layouts are compatible, which makes the stackable configuration possible using board to board connectors and spacers. Every microprocessor is based on Cortex M4 core family. STM32F446 processors were selected due to their wide spectrum of capabilities, reliability and good support of programming environments/software. All the microcontrollers are programmed in C, using STM32 Hardware Abstraction Layer (HAL). It provides many useful functions and drives, which simplifies the development process. The libraries for different sensors and modules are universal and used by multiple boards. To make debugging of the microcontrollers more convenient, a custom programmer based on StlinkV2 with Micromatch connector was designed.

3.3.3 Power supply

The greatest emphasis was set for the power supply reliability. Unspecified online time on launchpad, variable power consumption and multiple different voltage levels necessary imposed the idea of a design two boards that are responsible only for power management. There are 3 main power sources. Two of them are located onboard the rocket and one at the launchpad. During the preflight preparation and on rail operations, the rocket is supplied by an external battery pack, that is also charging the main battery using a passive cell balance algorithm. When the outboard supply is disconnected during lift-off (passively by the rocket), the prioritized powerpath controller swapes the power source to the main battery. In order to protect both batteries and the whole system, over and under-voltage protection was implemented. When the main battery has critical voltage level, the source is swapped to the backup battery.

3.3.4 Main Control Unit and DAQ

Staszek is an unit responsible for major launch sequence. Its analog part acquires data using 24-bit analog-to-digital converter with frequency of 4800 samples per second. It is used for gathering data from pressure transducers at combustion chamber and tank, resistance of the devices connected to power outputs and temperature of the pressure vessel. Onboard flash chip (512Mb) stores flight data, which also contains atmospheric pressure (MS5607), acceleration, magnetic field and angular velocity (MPU9250). As the main control unit, Staszek takes part in votes, such as recovery

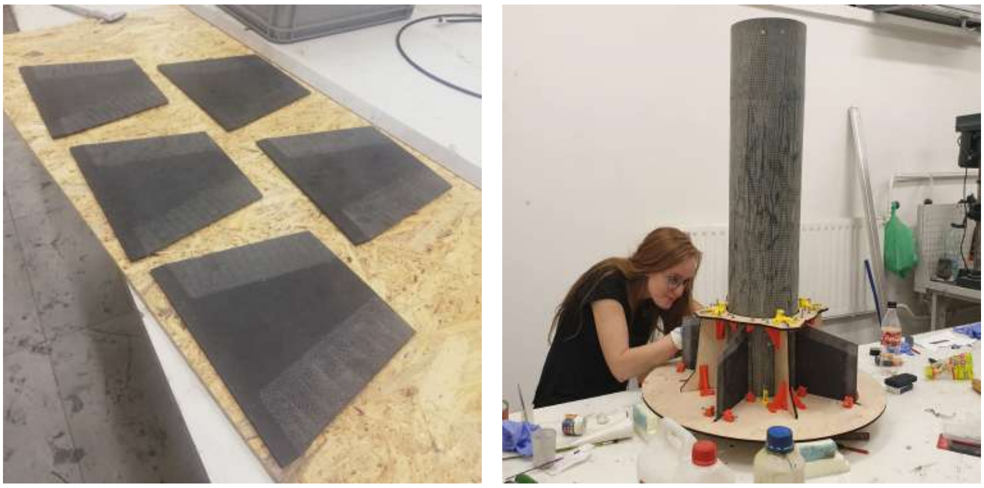
(a) Drogue parachute

(b) Main parachute

Figure 6: Inflated parachutes for the Turbulence rocket

(a) Laminating material pieces

(b) Vacuum bagging



(c) Fins milled to shape

(d) Fitting of the fins to the rocket airframe

Figure 7: Manufacturing process of the rocket fins

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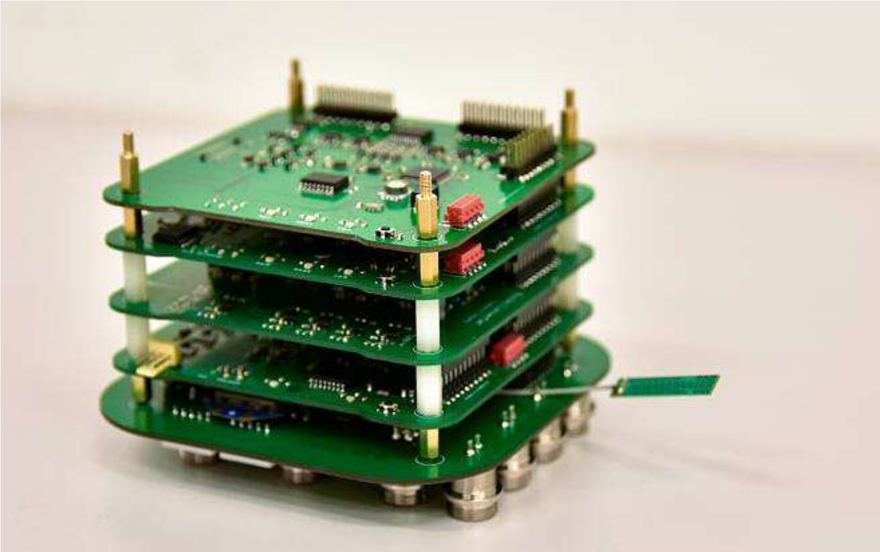

Figure 8: Onboard, stackable control electronics subsystem

events. Main control board steers the MOV, MFF and refueling valves. It is responsible for initiating the launch sequence and cutting-off the engine at proper time. It uses velocity, altitude, acceleration and rockets orientation to determine proper time for closing MOV to shutdown the engine.

3.3.5 Communication

Czapla is a comprehensive telemetry and position reporting system. It consists of u -blox GPS/GLONASS module, GSM/GPRS module and a LoRa RF transmitter. Czapla is responsible for providing real-time telemetry via the LoRa technology. The STM32 microprocessor gathers data from GPS/GLONASS module, encodes them to proper frames and transmits via the LoRa transmitter on radio frequency ISM band (868MHz for Europe, 915MHz for North America) using helical $\frac{1}{4}\lambda$ antenna. Additionally, Czapla is equipped with CAN bus capabilities, therefore other boards can command it to transmit additional data, such as altitude, pressure, rocket's orientation in space, temperature, provided through CAN bus. LoRa technology allows for transmitting data over large distances, up to 10km in rural areas and even more in line-of-sight communication, which makes it a perfect choice for this application. Position reporting is a crucial system, hence, in order to improve redundancy of the system, Czapla has been equipped with additional GSM/GPRS module. It enables the transmission of critical data, such as geographic coordinates, via cellular network and the internet.

3.4 Aerostructures

3.4.1 Fins

Fins as a crucial part for the passively stabilized rocket should meet certain requirements. In our case, a trapezoidal tapered-swept shape ensures the least drag. The size of the fin and the angle of attack were designed suitable for the rocket properties. Main concern when designing fins was to avoid flutter. To optimize its thickness and not risk reaching flutter speed, we have included Flutter Boundary Equation in our calculations.[5] To generate low drag we have decreased fins thickness and compensate it using rigid composite material. We have chosen sandwich type composite material with Nomex honeycomb core. We have manufactured composite material with carbon fiber reinforcement in the epoxy resin matrix using vacuum bagging technique. After manufacturing, we have tested fin with tensile and bending machines.

3.4.2 Airframe and nosecone

To decrease the mass all structural airframe tubes were manufactured out of composite material using carbon, fiberglass and Kevlar fibers in the matrix of epoxy resin. We have also designed internal structure to transfer significant loads, so fairing tubes have mainly aerodynamic function and to provide stiffness. All parts of the structure were produced

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in-house by our team members. Similarly, nose cone was also hand-manufactured by our team. It was designed to operate at the velocities exceeding 1 Mach.

Shape	Tangent Ogive
Length	600 mm
Wall thickness	3 mm
Material	Fiberglass-epoxy composite
Shoulder length	200 mm

Table 2: Parameters of the nosecone

4. Small-scale rocket engine tests

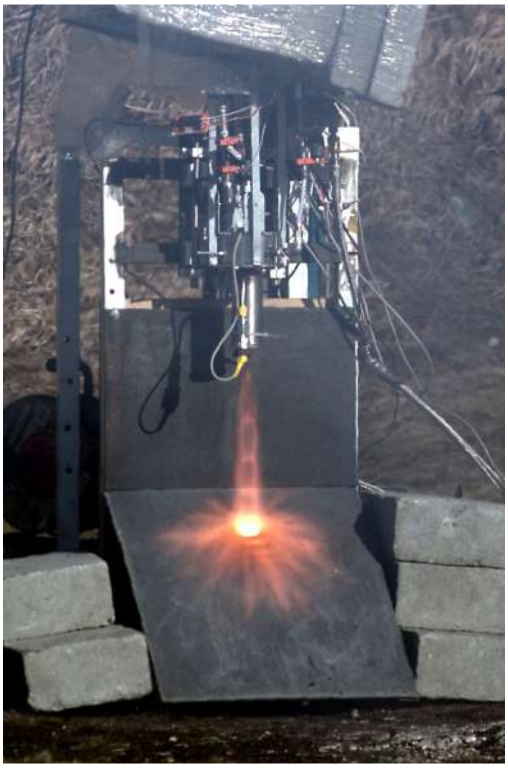

Figure 9: Small-scale Z500 rocket engine during burn

First experimental liquid rocket engine project based on nitrous oxide in AGH Space Systems was completed in 2017.[1] However, in that prototype fuel was externally pressurized by nitrogen, therefore feasibility of full self-pressurization yet needed to be proved. That is why Zawisza Z500 has been constructed. It is small, test-bench liquid rocket engine delivering about 500 N of thrust. In early 2019 hot-fire test campaign has been conducted, during which 8 burns were accomplished as summarized by Table 3.

Z500 used single tank with self-pressurization cycle for both fuel and oxidizer. The campaign started with ignition tests and low pressure in the tank to limit flow of propellants. Due to two-phase flow of the nitrous oxide in the feed system and the injector mass flow of the oxidizer was overestimated in the design resulting in serious shift in OF from optimal 4.5 to 2.75 or even less. Nevertheless, these very first tests provided insight into the startup sequence and proved full self-pressurizing cycle to be working fine. Test No. 2 with successful ignition is presented on Fig. 10. No malfunctions were noticed.

Over next tests pressure in the tank, thus propellants mass flow were increased to achieve designed working parameters. In Tests 1 - 6 fuel flow was close to nominal, while oxidizer was around 60%, which led to reduce in the performance. In tests 7 - 8 injector has been modified to increase mass flow of the nitrous oxide, which resulted in nominal flow in these tests. In few tests, especially test No. 6 given on Figure 11 serious instabilities have been registered. This was accounted to off-nominal pressure in the tank, which caused two propellants to flow in off-nominal

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Test	$\dot{m}_{ox}$ [g/s]	$\dot{m}_{fuel}$ [g/s]	OF	P_c [bar]	Tank pressure [bar]	Isp [s]	Thrust [N]
No. 1	110	40	2.75	8	30	110	150
No. 2	110	40	2.75	9	33	117	175
No. 3	110	40	2.75	9	33	117	175
No. 4	105	37	2.83	9	29	119	160
No. 5	120	38	3.15	20	36	147	210
No. 6	130	40	3.22	27	37	181	300
No. 7	190	45	4.22	45	60	241	500
No. 8	190	45	4.22	45	60	241	500

Table 3: Z500 tests performed during early 2019 campaign

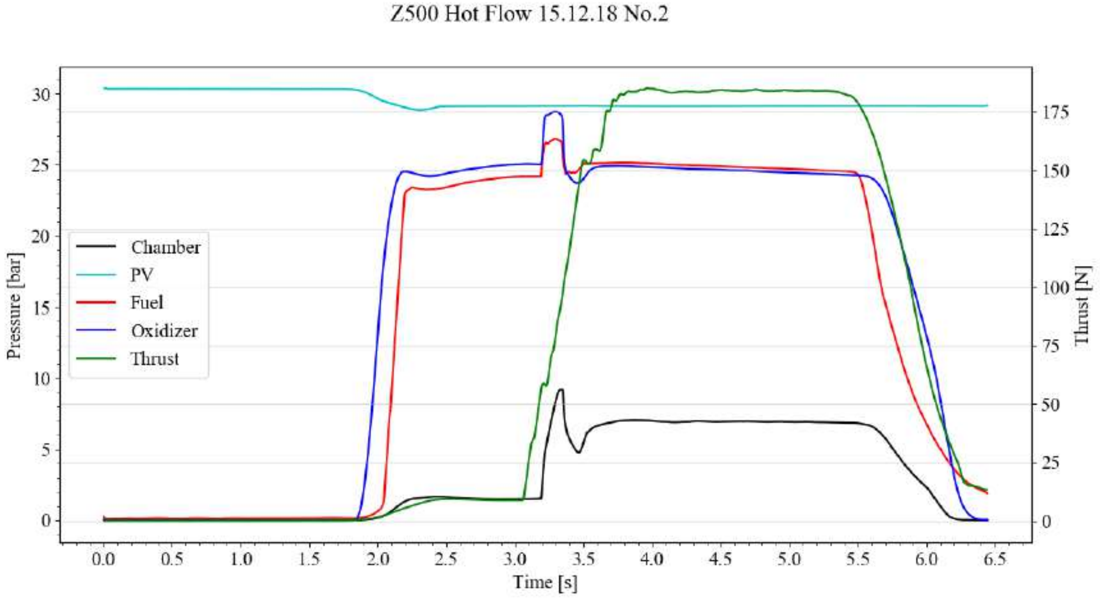

Figure 10: Test No. 2 of the Z500 small-scale rocket engine

quantity. While flow of the fuel depends solely on the pressure drop (which was close to nominal), nitrous oxide needs high vapour pressure to achieve calculated values. This difference favored fuel over oxidizer, when pressure in the tank was around 35 - 40 bar. It was decided to raise tank pressure to the nominal value (60 bar) in the next tests along with mentioned injector modification. This removed the problem. Still this dynamic behaviour needs further investigation. These campaign along with preceding cold-flow tests highlighted complex issue with estimating mass flow of the oxidizer. When used in self-pressurization mode, nitrous oxide flows in two-phases in feed system and the injector due to its high vapour pressure. Additionally, its compressibility in both phases is relatively high. All this accounts for unpredictable flow, when using traditional models like single, in-compressible flow model or SPI, which can easily by applied to most of propellants like LOX or kerosene. This problem is not this prominent in hybrids, because they are less vulnerable to changes in oxidizer mass flow. Few models have been used to estimate flow and validated with measured values during cold-flow tests of the injector. Results were confusing as it turned out that flow of nitrous oxide depends not only on pressure drop (which is high during cold flows), but also one vapour pressure. To study this problem thoroughly experimental apparatus has been built, which can simulate combustion chamber and set vapour pressure to given value. It turned out that some models like HEM (Homogeneous Equilibrium Model) are correct for high L/D ratio of the injector orifices, while SPI are much better at estimating for low values of L/D. This behaviour of high vapour pressure, two-phase liquid is subject of another paper.

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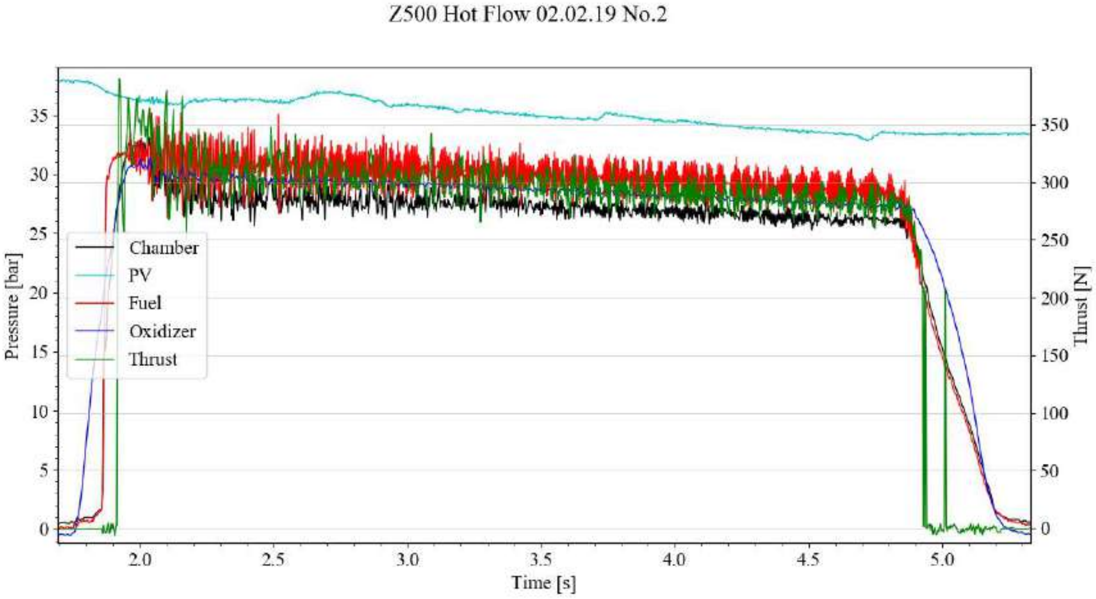

Figure 11: Test No. 6 of the Z500 small-scale rocket engine showing serious instabilities

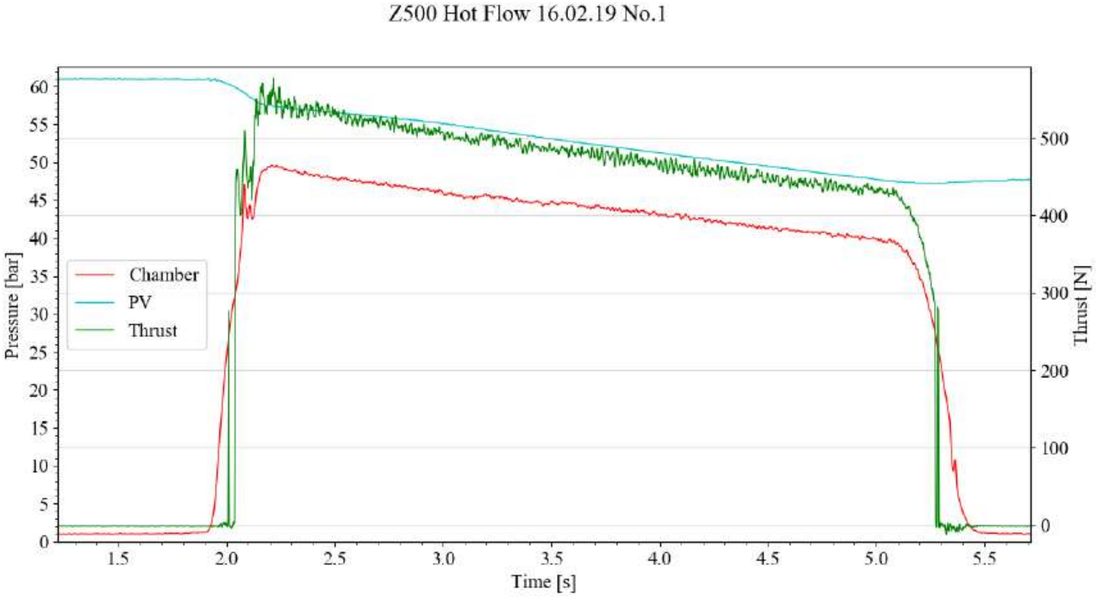

Figure 12: Test No. 7 of the Z500 small-scale rocket engine showing flawless ignition and burn

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Figure 13: Engineering model of the Turbulence during Spaceport America Cup 2018 in New Mexico, USA

5. Conclusions

The Turbulence rocket, which started in 2017 is going to be launched in 2019. This rapid development was possible thanks to hard work and dedication of over 20 students and huge amount of support from the university and the partners. Participating in this project is amazing opportunity for students, because they can gain hands-on experience with advanced rocket technology. Although this project is far from being finished it has already demonstrated unique technology developed by students, namely full self-pressurization cycle for nitrous oxide bi-liquid rocket with small-scale Z500 rocket engine. What is more, the overall design was awarded with 2nd place on Spaceport America Cup 2018 in 30k hybrid / liquid category. If launched it can be first Polish liquid rocket and first student European liquid rocket. Also, with current world record in this category being 3.8 km, the Turbulence can easily beat that altitude going to its maximum altitude of 10 km.

6. Acknowledgments

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