Zawisza4000 – the design of the Polish first bi-liquid rocket's propulsion system

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Abstract: AGH Space Systems stands as a student-driven organization situated within the AGH University of Krakow, Cracow, Poland. At present, the team is fully engrossed in the development of Poland's first bi-liquid propellant rocket. Named the "Turbulence" rocket, its propulsion is entrusted to the one-of-a-kind Z4000 engine, utilizing ethanol and nitrous oxide as its propellants. Drawing from their adeptness in hybrid rocket technology, the team ingeniously devised the Z4000 propulsion system, distinguished by its N_2O self-pressurization cycle, elegantly embodied through a piston-dependent pressure vessel solution. Additionally, the team incorporated a composite combustion chamber into the system's architecture. These pioneering elements, among others, firmly position this nitrous oxide-powered demonstrator as a standout contender for prospective applications within the space industry.

Keywords: rocket engine, nitrous oxide, bi-liquid, bi-propellant, design, simulation, self-pressurizing, ethanol, composite, nozzle

ZAWISZA4000 –
PROJEKT SYSTEMU NAPĘDOWEGO PIERWSZEJ POLSKIEJ RAKIETY
NA PALIWO CIEKŁE

Streszczenie: AGH Space Systems jest kołem naukowym działającym w Akademii Górniczo-Hutniczej w Krakowie. Obecnie zespół skupia swoje siły na opracowywaniu pierwszej w Polsce rakiety na paliwo ciekłe o nazwie „Turbulencja". Rakieta ta jest wyposażona w wyjątkowy silnik Z4000, wykorzystujący etanol i podtlenek azotu jako materiały pędne. Dzięki doświadczeniu nabytemu podczas konstrukcji rakiet hybrydowych zespół stworzył innowacyjny system napędowy Z4000, wyróżniający się cyklem samodoprężania N_2O, który powstał w wyniku rozdzielenia zbiornika ciśnieniowego za pomocą ruchomego tłoka. Dodatkowo do architektury systemu dodano kompozytową komorę spalania. Te i wiele innych rozwiązań decydują o innowacyjności opisywanej konstrukcji, która może konkurować z innymi kandydatami do potencjalnych zastosowań w przemyśle kosmicznym

Słowa kluczowe: silnik rakietowy, podtlenek azotu, dwuskładnikowe paliwo ciekłe, projekt, symulacja, cykl samodoprężania, etanol, kompozyt, dysza

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1. Introduction

AGH Space Systems is an interdisciplinary, non-profit, student engineering team designing and constructing sounding rockets, planetary rovers and stratospheric balloons' payloads. The team operates at the AGH University of Krakow and associate active members from the wide range of faculties and scientific disciplines.

The team specializes in building hybrid and liquid propellant rocket engines which power their sounding rockets that compete for victory in rocketry competitions against other teams from around the world. Recently, the team acquired the 4th place with their N_2O based hybrid rocket 3-TTK+ on the Spaceport America Cup 2023, taking place in the desert in New Mexico, USA.

Now, AGH Space Systems works on developing the first polish bi-liquid rocket built by university students. The rocket – Turbulence – is designed to break the altitude record for liquid propellant student rockets with estimated apogee of 9 km. The launch is planned for 2024 – the months before the debut of the Turbulence are intended for intensive engine test campaign.

The Turbulence's propulsion system utilizes unique solutions based on the team traditional choice of N_2O as an oxidizer and its self-pressurization properties. The Z4000 engine being currently in development will be a demonstrator of the usefulness of the nitrous oxide based bi-liquid rocket propulsion for the space industry.

2. Z4000 propulsion system overview

The Z4000 propulsion system consists of the pressure vessel, venting and feed system and the engine itself (as seen on Fig. 1). The following description will unfold all its elements in detail.

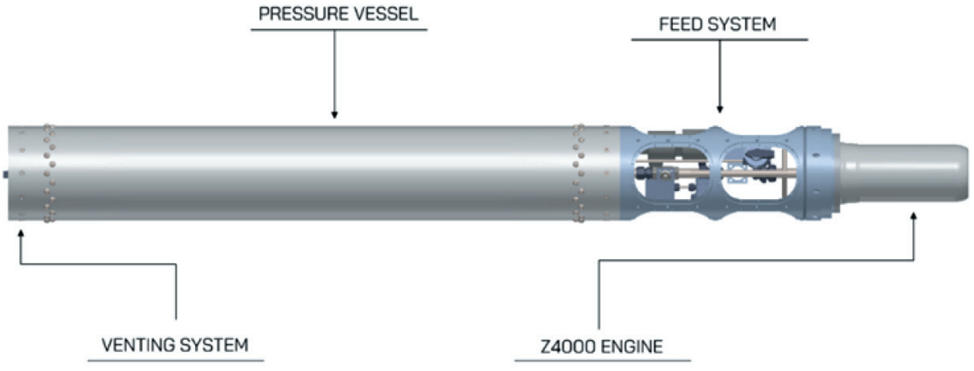

Fig. 1. Z4000 propulsion system schematic

2.1. Preliminary design

The Z4000 engine uses ethanol and nitrous oxide as the rocket propellants in a self-pressurization cycle. The propulsion system was designed to provide 4 kN of nominal thrust and 40 kNs of total impulse. The nitrous oxide has been chosen as an oxidizer – firstly because of the previous team's experience of handling it in hybrid rocket propulsion systems and secondly because of its high vapor pressure, which is the core factor in a utilized pressurization system. Although N_2O is not a common choice for bi-liquid engines, it has some advantages against other oxidizers (such as liquid oxygen or hydrogen peroxide) mainly due to its low toxicity and ease of liquefying in room temperature, therefore, safe and easy storage.

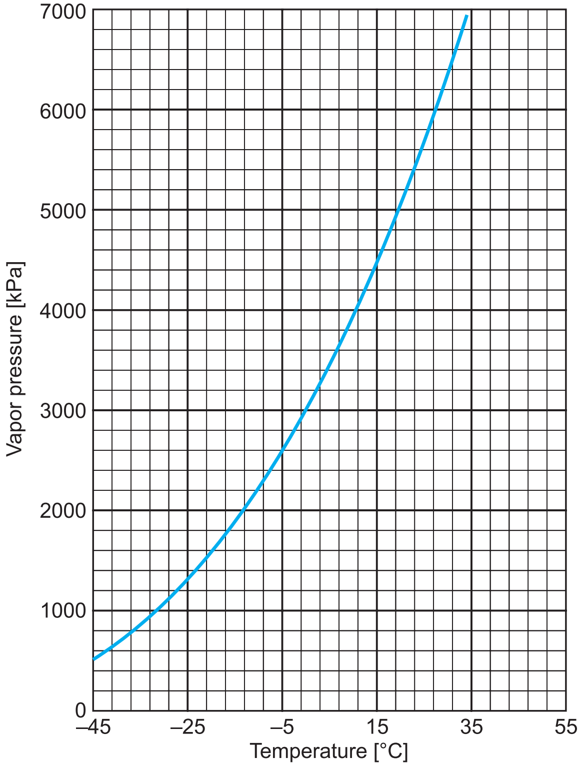

Fig. 2. Vapor pressure of nitrous oxide
Source: based on Palacz (2017)

The choice of ethanol as the fuel was dictated mainly by its price and availability. Since the oxidizer-to-fuel ratio usually oscillates around the factor of 4, the choice of the fuel becomes less crucial for engine overall performance. It was evaluated that various propellants mixed with N_2O give only slight changes in the specific impulse.

By using the NASA CEA software for thermodynamic calculations, it was estimated that the optimal O/F ratio for the Z4000 was 4.2. Due to the lack of any thermal insulation for the pressure tank containing the propellants, the nominal pressure of the system was decided using the team experience with launching rockets in the desert where the average temperature ranges between 35 to 40°C which corresponds to about 60 bars of nominal pressure of the nitrous oxide (see Fig. 2) which was chosen as a nominal value for the propulsion system calculations.

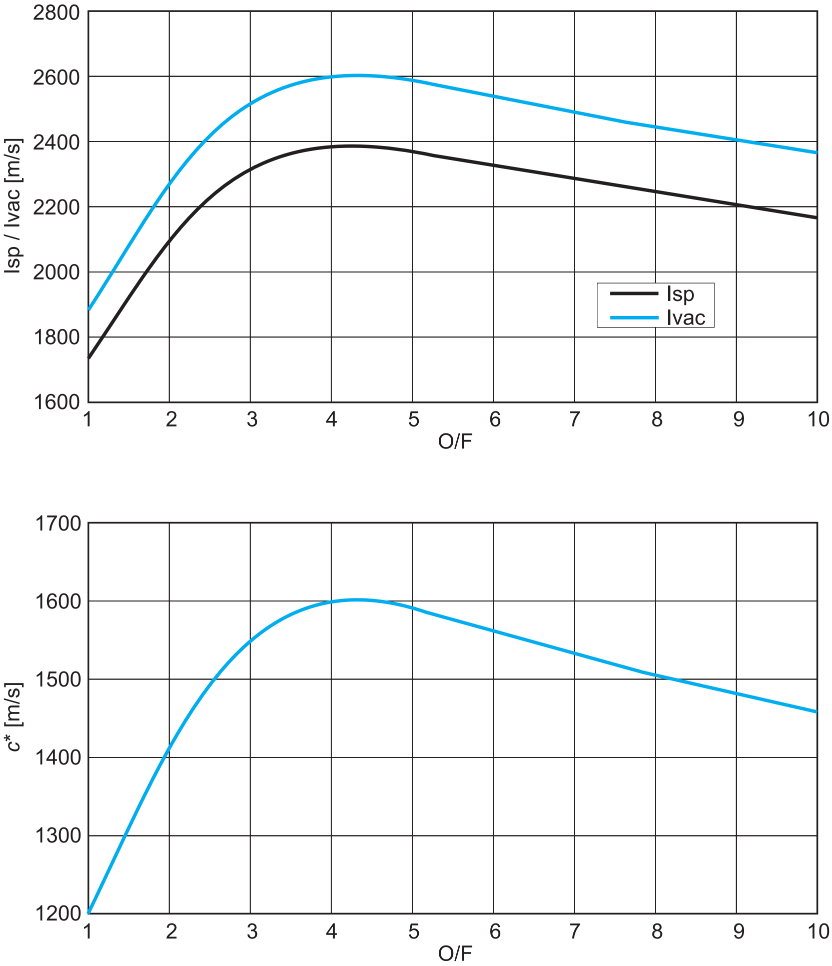

Fig. 3. Specific impulse and c^* as a function of oxidizer-to-fuel ratio

The nominal pressure of 40 bars in the combustion chamber was decided in order to provide sufficient conditions for stable combustion and to ensure a safe pressure drop between the combustion chamber and the feed system in the injector.

Using Equation (1) (Sutton and Biblarz 2001) and data gained from NASA CEA software:

$$I_s = \frac{c^* C_f}{g} \tag{1}$$

it is possible to determine that the specific impulse value is around 243 s. For the engine calculations, the efficiency was established to be 90% in order to give an additional margin for the other propulsion system parameters.

Using Equation (2) (Sutton and Biblarz 2001):

$$\dot{m} = \frac{F}{g I_s} \tag{2}$$

the required mass flow rate can be established to be 1.86 kg/s.

2.2. Pressure vessel

In the previous iterations of the Zawisza engine series developed in AGH Space Systems, where the nitrous oxide tank was pressurized using its self-pressurizing properties and the ethanol tanks used external pressurization with nitrogen, there was a significant issue concerning different pressure drops during engine operation. This led to the essential change in the O/F ratio and made the combustion fuel rich – with a loss on the performance in the outcome. In order to solve this problem and provide synchronous pressure curve, a movable sealed piston was implemented.

The Turbulence's pressure vessel contains both fuel and oxidizer in two compartments, which are separated with a movable piston (Fig. 4). The tank made out of 2017A aluminum alloy is enclosed with two domes screwed into the main tube. With the aim of not mixing those propellants in the tank, o-ring seals were provided on the piston. To prevent the skewing of the piston and to ensure smooth motion along the tank, special PTFE sleeves were designed (Fig. 5). The device itself uses two precise 316L stainless steel tubes going to the outlet of the tank (one is the fuel pipe and the second contains wires passing to the upper part of the rocket) as its guides. The pipes are covered with PTFE layer. Teflon is a great choice mainly because of its self-lubricating properties and excellent chemical compatibility with both nitrous oxide and ethanol.

Fig. 4. A cross-sectional view of the pressure vessel in a CAD program

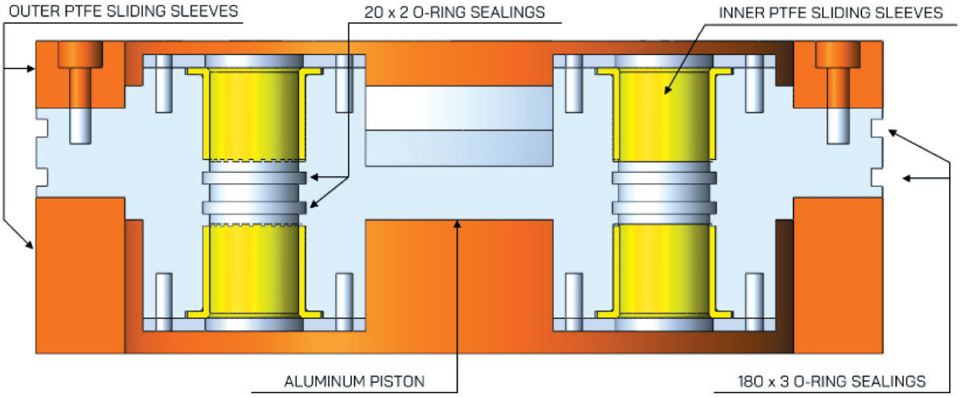

Fig. 5. A diagram of the sealed piston in a cross-sectional view

The pressurization system can be described as blowdown. In the bottom compartment, the nitrous oxide is being refueled. The refueling process starts with ethanol being pumped into the upper compartment. Then the nitrous oxide is being let into the lower compartment and because of its high pressure of around 40 bars it pushes the ethanol out of the tank. The refueling of the N_2O stops when the piston is located in the desired location in order to provide the correct O/F ratio. The process requires leaving a reservoir of vaporous nitrous oxide just beneath the piston. After the procedure is complete, the N_2O is being heat up to the temperature of 30 degrees Celsius using infrared radiators from the outside. The rise in temperature causes a raise in pressure to the nominal 60 bars. Because the gaseous oxidizer acts with this pressure on the piston, the piston itself acts with the same pressure on the ethanol, which provides the propulsion system with the synchronous pressurization of the oxidizer and fuel. Another advantage of the choice of nitrous oxide is that because of its high vapor pressure, the pressure drop during the engine operation is very slow during the majority of the engine burn time.

The position of the sealed piston is measured with a special array of 11 magnetic sensors located along the tank in one of the inner precise tubes. The piston itself is equipped with a small magnet. Its location is being determined by an algorithm that compares readings on all sensors and finds the maximum of the magnetic field strength in real time. The pressure in the tank is monitored by two pressure transducers located on the both sides of the vessel.

2.3. Feed system

The feed system of a rocket engine plays a critical role in ensuring the precise delivery and controlled mixing of propellants for efficient combustion. It was designed to ensure the 5 bars pressure drop across the piping. Five valves in the Turbulence system that are controlled by servomechanisms are responsible for creating flow through the currently needed line.

The feed system of Turbulence consists of six lines (Fig. 6). The main oxidizer feed line delivers nitrous oxide to the manifold. At the end of the line, brass piston with EPDM o-ring seals is placed. This setup ensures load transfer through the feed system cage and distributes oxidizer above the back injector plate. The main fuel feed line supplies ethanol to the manifold. The valve is fixed in a brass piston with EPDM o-ring seals, connected to a pipe that splits into two curved pipes guided into the manifold. This distribution method supplies fuel to the manifold envelope that feeds the injector from the side.

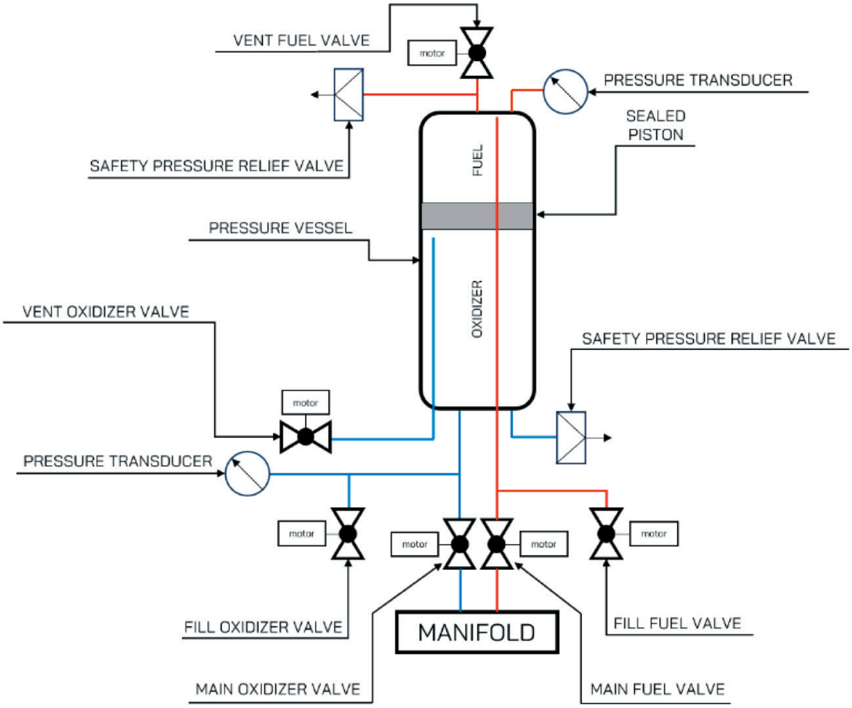

Fig. 6. A schematic of the Z4000 feed system

The fill oxidizer line refills nitrous oxide and the fill fuel line refills ethanol into the pressure vessel. Both of them start in their main propellant line in front of the valves. The lines then exit the feed system cage and terminate with a quick coupler.

The vent oxidizer line allows the excessive gaseous nitrous oxide to escape the system. A PTFE flexible pipe is introduced because vapor forms just under the sealed piston during rocket operation. One end is attached to the piston's base, the other is connected to the pressure vessel's dome. The gaseous nitrous oxide is then released outside the feed system cage. The vent fuel line purges the excess of gaseous ethanol from the system. Unlike a nitrous oxide venting system, that one does not require a flexible solution because of the static nature of the problem. It starts at the orifice in the pressure vessel's upper dome and terminates with an outlet in the rocket's fuselage.

The valves are operated with steel gears designed with greater torque than is needed in order to open the valve under nominal pressure. The servomechanisms are connected to the flight computer through wires routed through the secondary pressure vessel's pipe, ending in the electronics bay.

The Turbulence hydraulic system is also equipped with two safety pressure relief valves. One valve is attached to the pressure vessel's lower dome, and the second is connected to the vent fuel line's tube using a pipe tee. Two pressure transducers are integrated into the design: one in the pressure vessel's upper dome and the other in the main oxidizer feed line's pipe.

The entire feed system is situated within an aluminum cage, exhibiting a structured configuration featuring eight apertures. Each of these apertures is fitted with a transparent polycarbonate fairing, seamlessly enclosing the cylindrical framework of the cage.

2.4. Z4000 engine

The Z4000 engine as all standard bi-liquid rocket engines has an injector placed in the manifold, combustion chamber and a nozzle (as seen on Figure 7). It is crucial that each of these components are calculated and designed carefully in order to obtain the nominal efficiency. The following is a description and explanation of the design of the Z4000 engine.

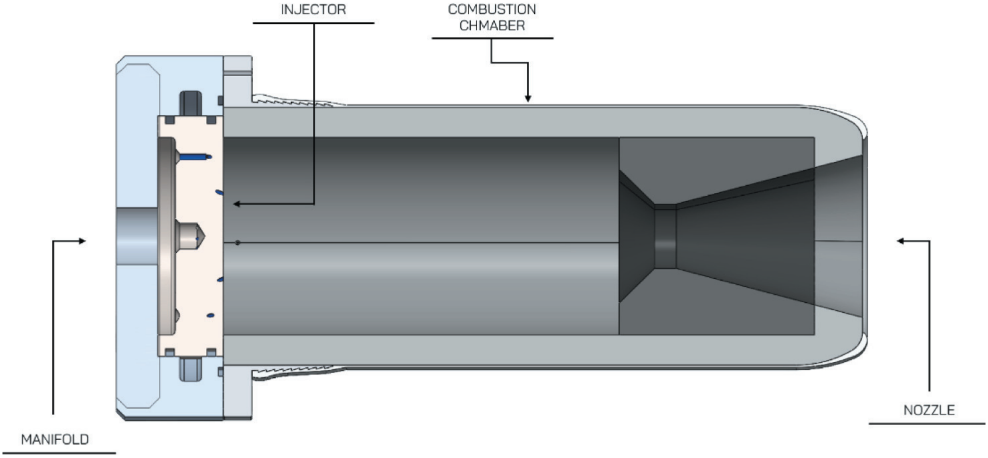

Fig. 7. Z4000 engine schematic

Injector

The Z4000 propulsion system features a cross-impinging injector disk, designed with the intention of achieving efficient mixing of propellants by intersecting oxidizer and fuel streams. The choice to employ an impinging injector design is driven by its natural ability to enhance propellant mixing, which is especially relevant considering the dual-phase characteristics of nitrous oxide and the compressible single-phase properties exhibited by ethanol. The injector's geometric specifications were established through analytical calculations that encompassed the homogeneous equilibrium model for nitrous oxide and the compressible single-phase model for ethanol. This injector arrangement is characterized by a configuration of triplet ports, involving two oxidizer ports and one fuel port, meticulously arranged within the outer ring of seven ports. In addition, the inner ring accommodates seven quadruplet ports, each comprising three oxidizer ports and one fuel port (Fig. 8). This intricate layout contributes to an exhaust composition favoring a fuel-rich mixture in close proximity to the combustion chamber walls, effectively alleviating the thermal stress experienced by these integral components.

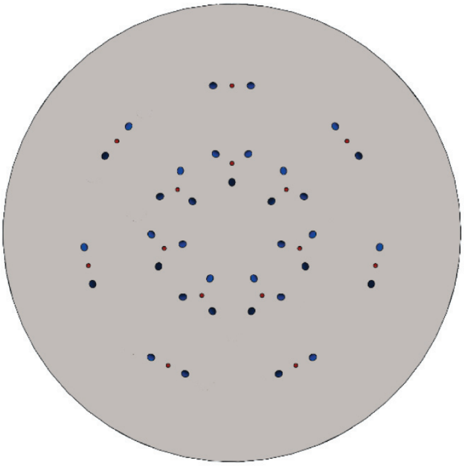

Fig. 8. The injector's plate

The injector, integral to the system's architecture, resides within the manifold. This positioning is reinforced through a joint interconnecting the manifold and the combustion chamber, the internal diameter of which is intentionally designed to be lesser than that of the injector itself, as elucidated in the Z4000 engine schematic. The injector functions as a receptacle for oxidizer, drawn from the upper section of the manifold, and fuel, sourced from lateral inlets. In order to ensure a robust and hermetic seal, the ingress points for the fuel and oxidizer are sealed through the implementation of a pair of PTFE o-ring seals, ensconced between the injector and the manifold.

The composition of the injector disk warrants attention, being precision-machined from aluminum. This decision is rooted in the team's empirical insights gleaned from prior experiences with aluminum injectors in the context of hybrid rockets.

Combustion chamber

In order to properly design the combustion chamber, both structural and thermal analysis is needed. The previous iteration of the Zawisza engine cycle utilized steel as the primary material for the combustion chamber due to its durability and easy access. The new combustion chamber consists of three main parts: aluminum flange, a thick layer of phenolic resin composite and a quite thin layer of carbon fiber with epoxy resin composite. During the burn, the ablative layer ablates and takes heat away from the structural layer. Additionally, an ablative layer serves as a nozzle extension of the nozzle. The carbon fiber-based composites were chosen for the structural layer due to their high strength, low mass, and ability to easily bond with the composite ablative layer. It is secured by the flange ring and inside of it there is a pressure sensor reading pressure from the combustion chamber during ground testing.

Nozzle

Nowadays, a use of bell-shaped CD nozzles in rocket engines is a common practice. Although those nozzles are designed in order to reduce the shockwaves, formed when the hot gas flow is passing by a flexion at the outlet of the throat, so the flow remains uniform and to direct the flow axially and to reduce overall mass – they are difficult and expensive to manufacture. In comparison, relative performance of the conical nozzle is estimated to be 0.98 of the thrust (with opening angle of 15°) and a 80% bell-shaped nozzle is 0.99. In respect to the costs, the trade-off between these two types takes advantage for the conical.

Gaining necessary data for nozzle calculations from NASA CEA thermodynamic calculations the geometry was established. Using Equation (3) (Sutton and Biblarz 2001):

$$\frac{1}{\varepsilon}=\frac{A_t}{A_2}=\left(\frac{\gamma+1}{2}\right)^{\frac{1}{\gamma-1}}\left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}}\sqrt{\frac{\gamma+1}{\gamma-1}\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{3}$$

The nozzle area ratio was calculated to be 5.52 for the sea level ambient pressure. Using Equations (4) and (5) (Sutton and Biblarz 2001):

$$A_t=\frac{\dot{m}}{p_1}\sqrt{\frac{R'T_1}{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}} \tag{4}$$

$$D_t=2\sqrt{\frac{A_t}{\pi}} \tag{5}$$

The critical diameter of the throat was set to 31 mm. The exit diameter, therefore, is 72.6 mm. The divergence and convergence angles were set to standard 15 and 45 degrees respectively (Huzel and Huang 1992). Nozzle throat length was designed in order to minimize any potential shockwaves and turbulences with length-to-diameter ratio of around 0.15 (Tolentino and Mirez 2022), that is 5 mm of length. In order to primarily evaluate the design of the nozzle a CFD simulation was performed and resulted in satisfactory velocity values (Fig. 9). Although the design needs to be evaluated in engine hot fire test.

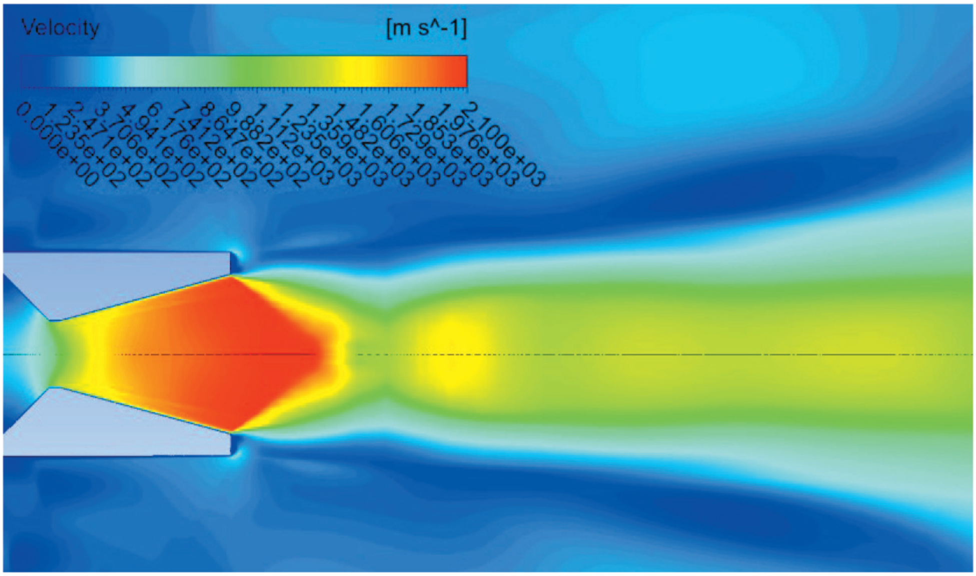

Fig. 9. CFD simulation of the Z4000 nozzle

Since the temperatures in the rocket nozzle – especially in the throat section – reach values up to 2500 K, which exceed most of the available materials' temperature strength in such duration of influence, a cooling solution shall be applied. It was decided that an ablative cooling system would be sufficient to withstand such extreme conditions. Ablative cooling consists in carbonization or graphitization of the coolant surfaces subjected to hot gas flow. For this purpose, a graphite nozzle insert was designed which rests on the nozzle extension in the combustion chamber.

Ignition system

The ignition system for this engine features a pyrotechnic mixture encased in a conical envelope, initiated using an e-match. This design characteristic facilitates a slow and sustained release of flames, which in turn serves as the ignition source for the propellant vapors. The ignition assembly is inserted through the nozzle into the combustion chamber, utilizing an extending arm, while the arm itself is securely affixed to the launch platform.

3. Tests and development

Zawisza4000 engine is currently undergoing numerous tests for empirical verification of the design and analytical approach. There are two types of tests – cold flow and hot flow. The cold flow test verifies if the pressure drop in the injector and mass flow rate is correct. In order to ensure safety during tests, CO_2 and water are used as propellants since they are good substitutions for nitrous oxide and ethanol (Waxman et al. 2013). The hot flow tests essentially verify the engine operation, therefore, generated thrust, pressure in the combustion chamber and pressure in the pressure vessel. Those tests are usually conducted with stronger substitutes of the final structure of the rocket. Both of these tests are performed on a vertical test stand in order to satisfy gravitational based design of the pressurization system. The thrust is measured with tensometer on which the engine is hanging, and the pressure is monitored with mentioned before pressure transducers. Now, the propulsion system is undergoing hard-bitten iteration process in purpose of ensuring the greatest performance and reliability.

4. Conclusion

The Turbulence's propulsion system is a promising design which can demonstrate a nitrous oxide-based application for liquid propellant space propulsion. Although N_2O is not as dense and energetic oxidizer as other, commonly used in the space industry, it has a potential of finding its usefulness in low-cost rocket and space propulsion systems. Nowadays, a great popularity in this oxidizer among student rocketry constructions can be seen, which demonstrates the possibility of becoming an alternative for the space industry. Nevertheless, further researches have to be conducted in order to improve the database of the specific values for N_2O rocket engine designs and to designate a way of commercialization.

Acknowledgments

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Nomenclature

A_2 – nozzle exit area [m^2]
A_t – nozzle throat area [m^2]
c^* – characteristic velocity [m/s]
C_f – thrust coefficient
D_t – nozzle throat diameter [m]
F – nominal thrust [N]
g – gravitational acceleration [$\mathrm{m/s}^2$]
I_s – specific impulse [s]
$\dot{m}$ – mass flow rate [kg/s]
p_1 – combustion chamber pressure [Pa]
p_2 – nozzle exit pressure [Pa]
R' – specific gas constant [J/(kg·K)]
T_1 – chamber temperature [K]
γ – specific heat ratio
ε – nozzle area ratio

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