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CAVITATING VENTURI AS A MASS FLOW CONTROLLER IN A DEEP THROTTLING LIQUID ROCKET ENGINE

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Abstract

The most common solutions for rocket engines are the single operation point (thrust level) units. Oxidiser and fuel mass flow rates and the oxidiser-to-fuel mass flow rate ratio (OFR) are some of the determinants of the thrust level. Based on these, planetary ascent and descent; space rendezvous; orbital manoeuvring, including orientation and stabilisation in space; hovering, hazard avoidance during planetary landing; and ballistic missile trajectory control propulsion systems could use throttleable liquid engines. Several engine throttling methods, such as supply pressure variation and variable injector area, can be applied. Among others, a cavitating venturi propellant regulatory valve is one of the most promising throttling method. This type of valve can provide steady mass flow, despite the downstream pressure disturbance (i.e. from the combustion chamber), which sustains a stable engine thrust as the mass flow is kept. The article presents the valve sizing method, design and prototype test results of the cavitating venturi valve that has potential for utilisation in a deep throttling rocket engine. Mass flow stability and repeatability are presented for valve operating points in the 10%–110% nominal mass flow range. Valve design optimisation, based on CFD, to sustain cavitation for a higher downstream-to-upstream pressure ratio is shown.

Keywords: cavitating venturi; throttling; regulatory valve; HTP; ethanol; green propulsion
Type of the work: research article

1. INTRODUCTION

The design range for most liquid rocket engines (LREs) covers only a few operating points. LRE throttling is defined as varying the rocket engine's thrust in reference to the 100% rated power level (RPL). Oxidiser and fuel mass flow rates and the oxidiser-to-fuel mass flow rate ratio (OFR) are some of the determinants of the thrust level. Throttling down to about a ratio of 4:1 thrust (25% RPL) is considered 'shallow throttling', while throttling beyond a 4:1 thrust ratio is considered 'deep throttling'. There are several throttling methods that can be applied [1,2], which are described in Section 3. The design of the cavitating venturi valve as a mass flow controller for a deep throttling rocket engine is described in Section 4. Valve prototype testing, design optimisation using the Computational Fluid Dynamics (CFD) model and valve testing as part of the propellant supply system for rocket engine tests are presented in Sections 5–7.

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2. STATE OF THE ART

Methods [1,2] in which throttling can be implemented in LREs will be described in the following part. There are a few physical parameters that can be varied to change the thrust of an engine. This includes the propellant types or compositions, propellant flow rates, nozzle exit area and nozzle throat area. Some of the mentioned parameters such as propellants and nozzle exit area are difficult to obtain due to physical restriction. At the same time, the nozzle throat area is difficult to vary if heat fluxes are high. As a result, varying the propellant flow rate is the simplest recourse for varying thrust. All of methods of thrust control that are presented later are based on the assumption that the propellant mass flow rate varies to adjust the thrust.

1. High-pressure drop injectors (i.e. Project Thumper -Malta Engine manufactured by U.S. Army and General electric; Project MX-794 -Engine 0073 manufactured by Willow Run Research Inst., Univ. of Michigan and U.S. Air Force) allow for achieving an adequate pressure drop at low and high thrust levels. This method also has limitations, so it is used only for shallow throttling engines. The most concerning is that at lower chamber pressures, whistling, howling, rough burning and chugging are observed (Project MX-794). Instabilities increase heat transfer rates several times greater than expected. Performance is reduced at low power levels due to poor combustion at low chamber pressures. The flow of propellants can be regulated by control valves in propellant lines, turbopumps or cavitating venturis. However, high supply pressure requirement is imposed on the pressurisation system, tankage and turbomachinery.
2. Dual- or multiple-stage injectors (i.e. XLR-129-P-1 engine manufactured by Pratt and Whitney Aircraft and Air Force Rocket Propulsion Lab.) combine into a standard structure, both oxidiser and fuel injector, with variable injection areas to achieve throttling operation. Deep throttling is achieved from a two-manifold (primary and secondary) operation at high thrust to a single-manifold (primary) operation at low thrust. The main concern is unequal flow distribution and system response delay due to the need to reprime the secondary manifold.
3. Gas injection (i.e. RL10A-1 engine manufactured by NASA Lewis Research Center and Pratt and Whitney Aircraft) into propellants, also referred to as foamed-flow or propellant aeration, is the method that reduces the bulk density of the propellants by introducing lower density fluid into the propellant flow. The main concerns of this solution include feed system instability created by the surging gas into the injector manifold and maldistribution or nonuniformity of the aerated propellant, which could cause mixture ratio variations and local hot and cold regions in the combustion chamber.
4. Multiple chamber (i.e. RD-180 engine manufactured by Glushko) throttling is performed using a single feed system and two or more combustion chambers to achieve the desired thrust by stopping the flow through one or more chambers or varying the thrust of each chamber independently. However, this solution causes difficulty in managing propellants and increases the engine weight and feed system complexity.
5. Pulse modulation (i.e. Bell model 8414 Throttleable Manoeuvring Engine manufactured by Bell Aerospace Company and NASA Marshall Space Flight Center) objective is to obtain a thrust profile by utilising pulses of various thrust levels and durations. They are predominantly used in monopropellant engines. The performance is usually lower than that of a non-pulsed or continuous operating. Main concerns are poorer mixing and atomisation during the transients lower the average performance of the pulse, shock loading on the vehicle, and ignition of each pulse can be a concern depending on the pulse rate.
6. Throat throttling (i.e. MIT Naval Supersonic Laboratory Study Research Engine manufactured by MIT Naval Supersonic Lab. and U.S. Navy) uses a variable nozzle area, realised by a cooled mechanical pintle inserted and retracted through the nozzle throat region or gas injected into

the throat. Both methods effectively change the throat area by providing some blockage into the flow field. At constant propellant pressures, the throat restriction increases the chamber pressure, which decreases the injector pressure drop and subsequently reduces propellant flow rates and thrust. Combustion instabilities are a concern at low thrust, and as a result, excessive vibrations on the pintle device can occur.

7. In movable injector components (i.e. Apollo LMDE engine manufactured by TRW inc. and NASA), a change in thrust is received by variable area injectors. It is often referred to as a pintle injector because the majority of variable area injectors contain a single central pintle feature that is moved to vary the injector orifice area. Although this solution has many advantages, there are also some disadvantages such as the requirement for a propellant control system and heat transfer to a pintle injector element.
8. Hydrodynamically dissipative injectors (i.e. Pennsylvania State University and the NASA Marshall Space Flight Center Research Engine) use fluid dynamics to improve the impedance across the injector. Swirling vortex tubes are the most common method, enabling deep throttling by altering the discharge coefficient. The main concern in this solution is poor mixing caused by a fuel oxidiser momentum imbalance.
9. Combined methods and unconventional solutions allow even deeper throttling by combining, i.e. mass flow control with injector pressure drop control. Cavitation venturi valves can be used as part of this combined throttling method.

Cavitating venturis are widely used as mass flow controllers for LREs. There are numerous studies on the nonvariable area cavitating venturis. In Ref [3], the nonvariable cavitating venturi is taken into consideration as a mass flow controller for cryogenic fluids. In Ref [4], cavitating venturi performance has been tested for different throat diameters. Only a few publications consider variable area cavitating venturis as mass flow controllers for throttling engines. The study in Ref [5] describes cavitating venturi valves used in the lunar module descent engine (LMDE). However, this valve design can work in the cavitation zone over a throttle range of 10%–65% RPL and non-cavitating from 65% to maximum thrust. Additionally, it can operate under variable inlet pressures depending on the thrust level. In the study in Ref [6], a variable throat area cavitating venturi was described, and its performance investigation for different parameters was conducted. Performance research considers changes in different parameters including inlet or outlet pressure, where only one parameter was changed during the test.

Nevertheless, the performance of the beforementioned valves is investigated on the test bench component tests [3,4,6] or are not operating in the cavitation zone in the full range of designed throttling [5]. For this reason, there is a lack of the literature regarding the cavitating venturi valve performance in real-life operating conditions. Furthermore, in this study, deep throttling of the tested engine is considered with a throttling ratio of 11:1. While throttling to as low as 10% of nominal thrust was considered in Ref [5], throttling up to a 110% RPL, keeping the valve operation in the cavitation zone, was not considered. Furthermore, using the CFD simulation with the Schnerr–Sauer cavitation model valve geometry sensitivity study was performed in the following sections. As a result, valve performance after optimisation is verified by monopropellant engine tests, where the valve plays its role as a propellant mass flow controller.

3. DESIGN

In the Throttleable Liquid Propulsion Demonstrator (TLPD) project, which is part of the European Space Agency (ESA) Future Launcher Preparatory Program (FLPP) program, the aim is to obtain throttling in the range of 10%–110% RPL. It was decided to use a combined method of throttling as follows [7–9]:

- Variable valves' throat area (both: oxidiser and fuel)–mass flow regulation
- Variable fuel injector area–fuel injection velocity control

Such combination (valves and injector control) enables deep throttling as valves' regulation controls the mass flow, and the fuel injector enables controlling the pressure drop by maintaining a sustainable pressure drop value at a low thrust level (for maintaining combustion stability). The main advantages of this solution are deep effective throttling capacity, good atomisation, high atomisation velocities, high combustion stability and low cost.

Only green propellants were considered. After trade-off concerning physical, performance, safety and management properties, high-test peroxide (HTP) and ethanol were chosen (Table 1). Mass flows of both are controlled by two venturi valves. Most of the presented results were performed for the oxidiser valve. However, a similar test campaign is simultaneously performed for the fuel valve, and some of its results are also shown in the article.

Table 1. Propellant parameters.

	Nominal inlet pressure (barA)	**Nominal mass flow (kg/s)**	**Density (kg/m^3)**	**Viscosity (mPa · s)**	**Vapour pressure (Pa)**
HTP	40	1.9	1,435	1.25	200
Ethanol	40	0.5	805.7	1.074	5,950

HTP, high-test peroxide.

Valve construction was selected as a cavitating venturi type, with the flow controlled by the position of the needle inside the venturi. A cavitating venturi was chosen due to the number of advantages. The main advantage is that the mass flow is independent of the outlet pressure variations in a specific range of outlet-to-inlet pressure ratio (up to about 0.7–0.8 pressure ratio). At the same time, this imposes a challenge as the pressure drop required to sustain cavitation influences the pressure budget of the whole system.

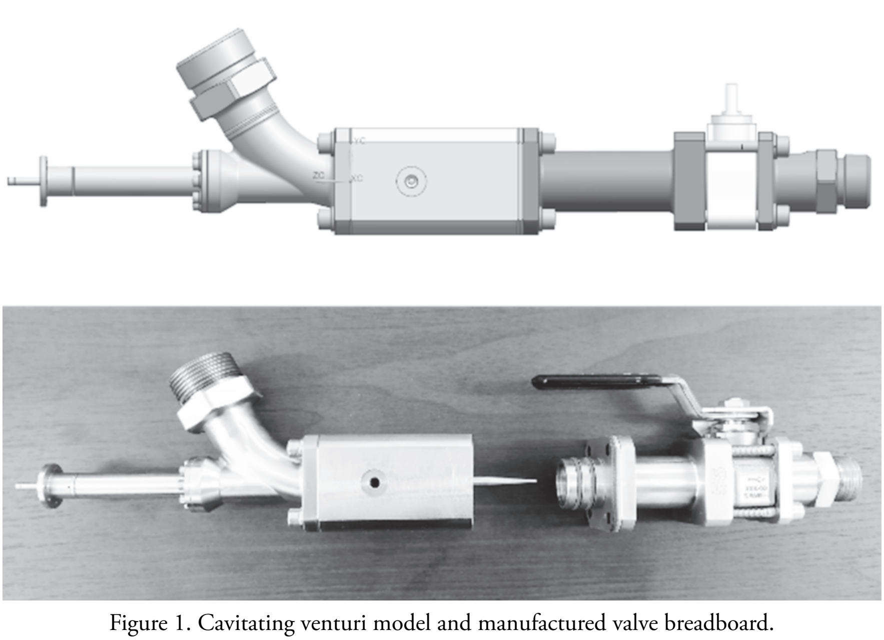

Figure 1. Cavitating venturi model and manufactured valve breadboard.

The valve design (Fig. 1). is based on numerous publications concerning venturis and cavitating venturis as mass flow controllers. General dimensioning of the venturi tube, its convergent and divergent angles and the throat length was designed, as mentioned in Ref [4,10–13]. Throttling needle design and calculation were made, as mentioned in Ref [5,6,14]. Using Bernoulli's equation, the equation of stream continuity and the mass flow equation, the required area of the throat was calculated for the full flow range (from 0% to 110%). The discharge coefficient was calculated, as mentioned in Ref [5]. Taking into consideration the required flow area in the throat and assuming that the needle is always inside the throat, despite the actual needle position, the throat diameter was assumed as 5.5 mm for HTP and 3.5 mm for ethanol. The venturi-shaped part is calculated in the way that it is always cavitation in the throat part at every mass flow level. The needle profile is calculated in the way that the mass flow is as close as possible to and linearly dependent to the needle position. The stroke is controlled by the stepper motor, which uses the threaded rod and nut to convert a rotational motion to a linear motion one.

There were two shapes of the needle compared: second-order curve (to keep the needle position concerning flow rate linearly) and the linearised curve. Due to manufacturability reasons, the second-order profile is not the preferred model. However, the dependency between the needle position and flow rate is almost linear, with excellent accuracy when the linearised shape is chosen.

The needle position is defined as the axial movement of the needle in reference to the venturi throat. 0 position or, as in the graphs, 0% position, refers to the needle touching the throat, i.e. when the valve is closed. Note that for all the following pictures, the needle position refers to the percentage of the nominal needle travel where 100% needle position corresponds to propellant nominal mass flow (nominal engine thrust) (Figs 2 and 3).

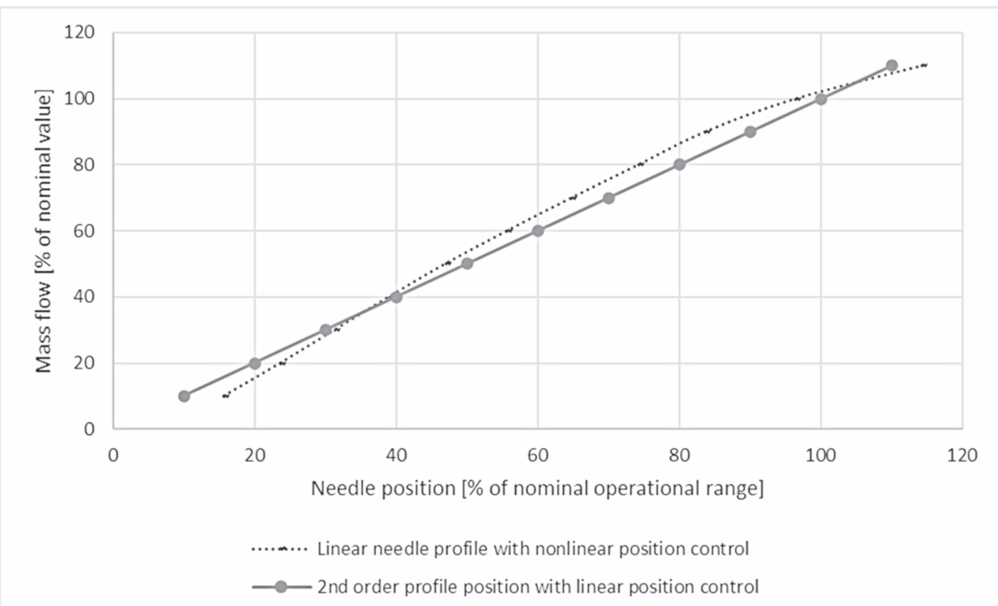

Figure 2. Needle profile calculated (second-order curve—linear position control) and linearised (as manufactured—nonlinear position control).

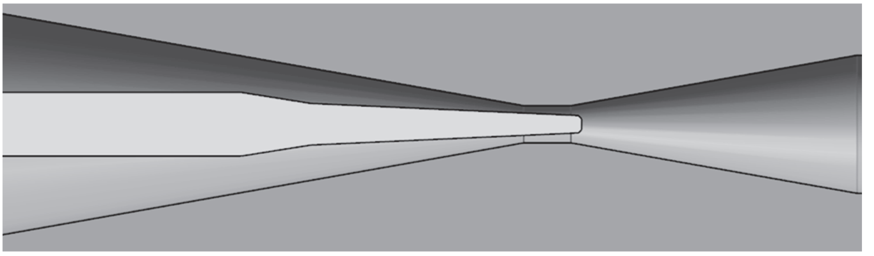

Figure 3. Venturi (dark grey) and needle (light grey) positioning in the valve.

4. VALVE PROTOTYPE TESTING

The test setup for the valve performance test is presented in Figure 4.

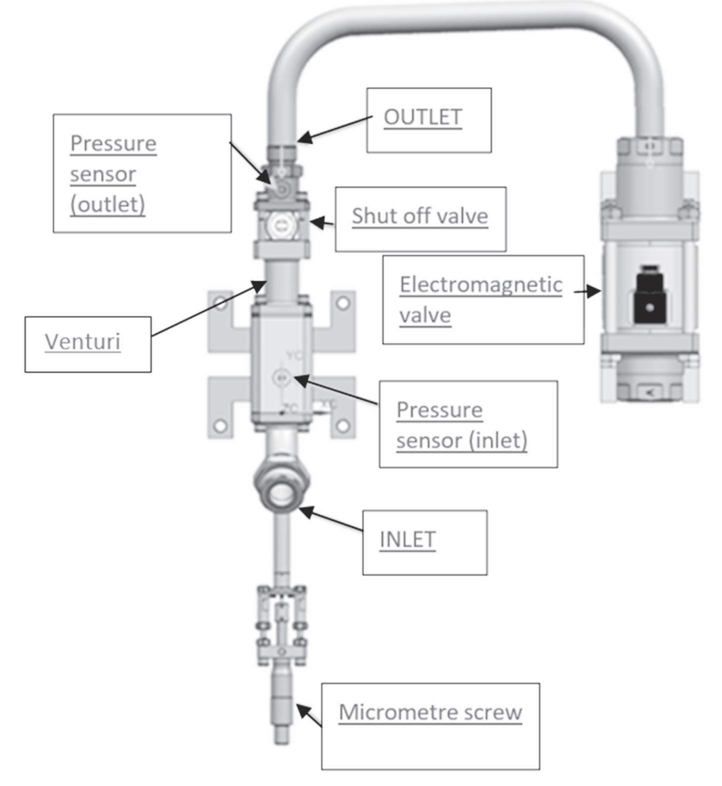

Figure 4. Test setup.

Needle position was controlled by the micrometre screw, instead of a stepper motor-based actuator, as the tests were performed in steady needle positions with no active throttling operation during the test. Downstream the valve, there was a shut-off valve for the system. It is located there to keep the valve filled with the propellant while opening, so the delay time of the valve does not include the time required for the fluid to reach the valve from the supply installation. At the end of the line, there was an off-the-shelf (OTS) electromagnetic valve that aimed to simulate the various outlet pressures; it indicated when the cavitation in the valve disappeared (pressure ratio limit). Downstream pressure regulation was performed by closing the OTS valve on the output of the tested valve. During the flow test, the OTS valve was closed at the pre-determined time. Outlet pressure was rising, and the cavitation phenomenon disappearance was observed. The flow and pressure sensors showed the boundaries for the maximum downstream pressure for the valves when the cavitation could be kept.

Inlet pressure was kept at a steady level, and after a few seconds of steady flow, the outlet pressure was increased by closing the needle damping valve (OTS) on the fuel regulatory valve outlet. As a result, mass flow vs. needle position and the cavitation limit was determined. There are a couple of cavitation limitation determinants observed. The mass flow starts to be dependent on the downstream-to-upstream pressure ratio, and at that exact moment, outlet (downstream) pressure variations rapidly decreased, and outlet pressure variations were transferred to the inlet (Fig. 5).

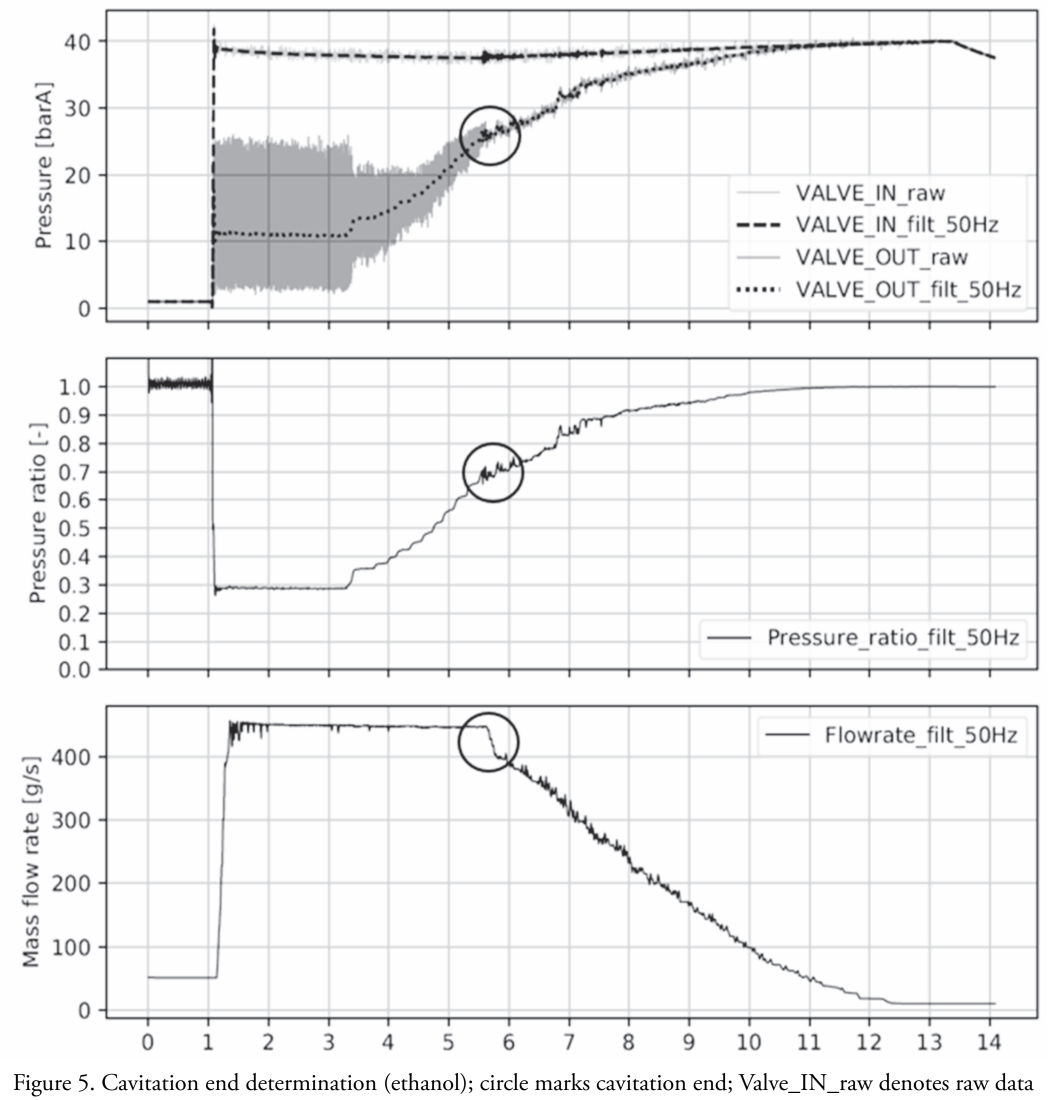

Figure 5. Cavitation end determination (ethanol); circle marks cavitation end; Valve_IN_raw denotes raw data from valve inlet; Valve_IN_filt_50Hz shows valve inlet data filtered with a 50Hz filter; Valve_OUT_raw denotes raw data from the valve outlet; Valve_out_filt_50Hz indicates valve outlet data filtered with a 50Hz filter.

All the tests were performed at least three times to determine the repeatability and eliminate anomalies from the results that could affect the tests. The most important in this test was determining the outlet pressure limit for the maximum expected mass flow. Nevertheless, the cavitation limit was determined for 10%, 30%, 60%, 100% and 110% of mass flow operating points.

Test repeatability was on a high level, with a relative standard deviation below 1% (regarding a current expected value, but not the entire span).

In Figure 6, theoretical mass flow recalculated for measured average test inlet pressure (if it was different from the theoretical supply pressure) vs. measured mass flow is presented. It can be seen that the measured mass flow is higher for low mass flow needle positions. However, this can be compensated by the needle position adjustment. What is essential is that the mass flow for the 110% position was reached with a low difference (below 1.6%) from the theoretical value. These results show that mass flow regulation in the range of 10%–110% mass flow is possible with this valve design. However, the manufacturing tolerance plays quite a significant role in the final results, which can be seen especially on the 10% mass flow point. For further development of the valve, new needles (with upgraded profile) and venturis were manufactured keeping this in mind, and the obtained results are shown in Section 7.

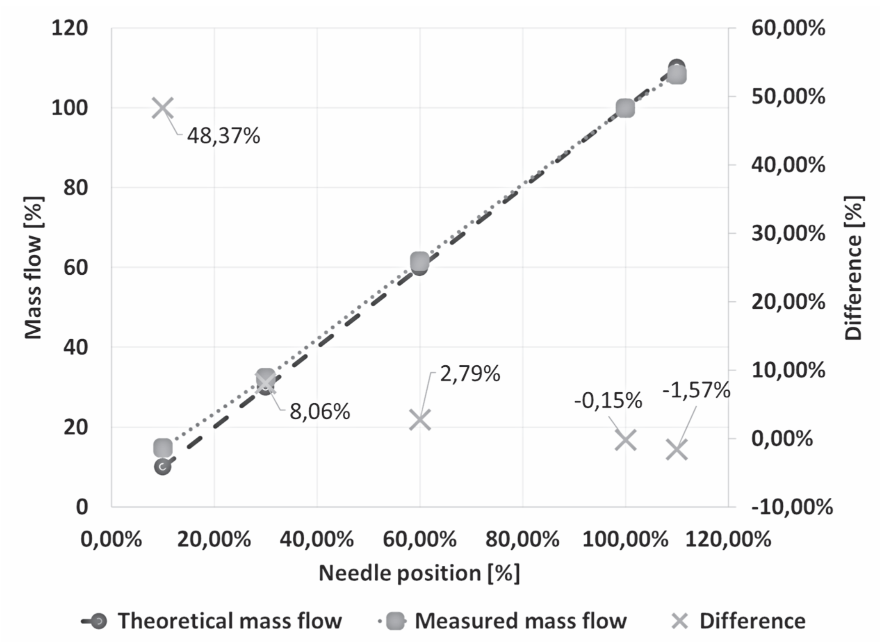

Figure 6. Calculated vs. measured mass flow (HTP); needle position as a% of nominal stroke (0% valve closed). HTP, high-test peroxide.

The cavitation end is not a single pressure ratio value, but it depends on the current valve mass flow set. This ratio is, in this case, much lower for low mass flow—about 0.3, while for high mass flows, it reaches about 0.7 for the first design (see Figs 7 and 8). In Figs 7 and 8, mass flow rate vs. outlet-to-inlet pressure ratio is shown. The grey area include the points from the flow test measurements for three different tests. Based on the measurement, the mass flow-to-pressure ratio characteristic was calculated, and it is represented as a black solid line in Figs 7 and 8.

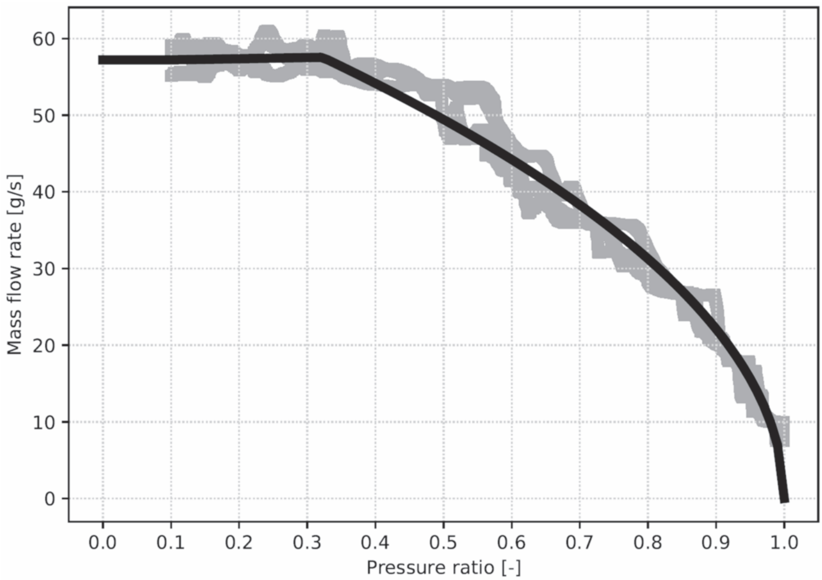

Figure 7. Mass flow rate (ethanol) vs. pressure ratio. Cavitation end determination for low mass flow; solid line is the mass flow calculated from measurement points and the grey area denotes the points measured during the test.

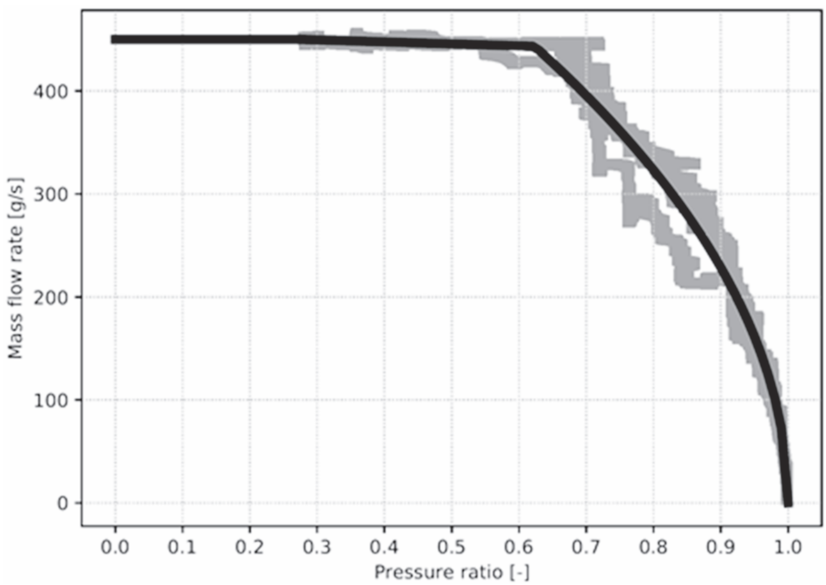

Figure 8. Mass flow rate (ethanol) vs. pressure ratio. Cavitation end determination for high mass flow; solid line is the mass flow calculated from measurement points and grey area marks the points measured during the test.

5. VENTURI OPTIMISATION

For a higher downstream pressure margin, the design's second iteration was performed using the CFD analysis of the venturi shape. Firstly, the analysis parameters were adjusted to the actual test results so that further analysis could be representative. Then, the sensitivity analysis was performed. In this analysis, the venturi and needle's geometrical parameters were considered. The idea was to determine how the shape of those two parts influences the pressure ratio at which cavitation disappears. Three parameters were identified: venturi throat length, venturi divergent angle and needle length (Table 2).

For the cavitation CFD analysis, the 2D axisymmetric model (steady calculations) was used. Liquid taken for calculation was HTP. As a solver, pressure-based coupled solver was utilised. The multiphase mixture model and k epsilon (internal flow) turbulence model was applied. CFD mesh prepared for calculation was hexahedral with 300 000 elements. All the calculation results were compared and adjusted to the real test data. As a result for the cavitation model, Schnerr–Sauer cavitation model was used with the following settings:

- Bubble number density: 1e13
- Empirical calibration coefficient of condensation: 0.2
- Empirical calibration coefficient of evaporation: 50
- Bubble radius: 10e-6 m
- Vaporisation pressure 200 Pa

For model validation, data from real valve tests were used. Geometrical parameters (needle position) from nine different tests were implemented to the model, and results of the calculation were compared to those of the experiment. The difference in the results from the model vs. the test was 2%–6%.

Fig. 9 shows results of the CFD optimisation presented. MOD1 (Modification no. 1) is only venturi divergent angle change with reference to baseline (more minor). MOD2 is needle length change only (extended). In MOD5, needle length (extended) and divergent angle (more minor) changes are combined. MOD6 and MOD7 combine MOD5 with throat length change (shortened). While MOD6 considers throat length, needle length and divergent values on the limit of the considered range, MOD7 is a bit worse in performance but easier to manufacture. MOD5 (small venturi divergent angle, 7°) was selected for the engine tests (Fig. 10). It is to confirm the correctness of CFD calculations following the principle of one parameter modification at a time.

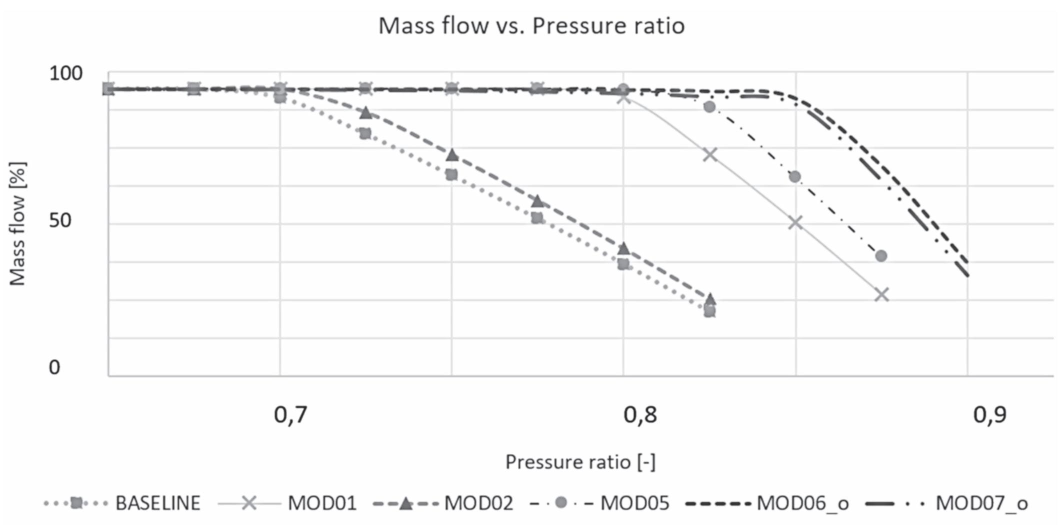

Figure 9. Comparison of different geometry modifications on the pressure ratio. When the mass flow is steady, it means that cavitation occurs.

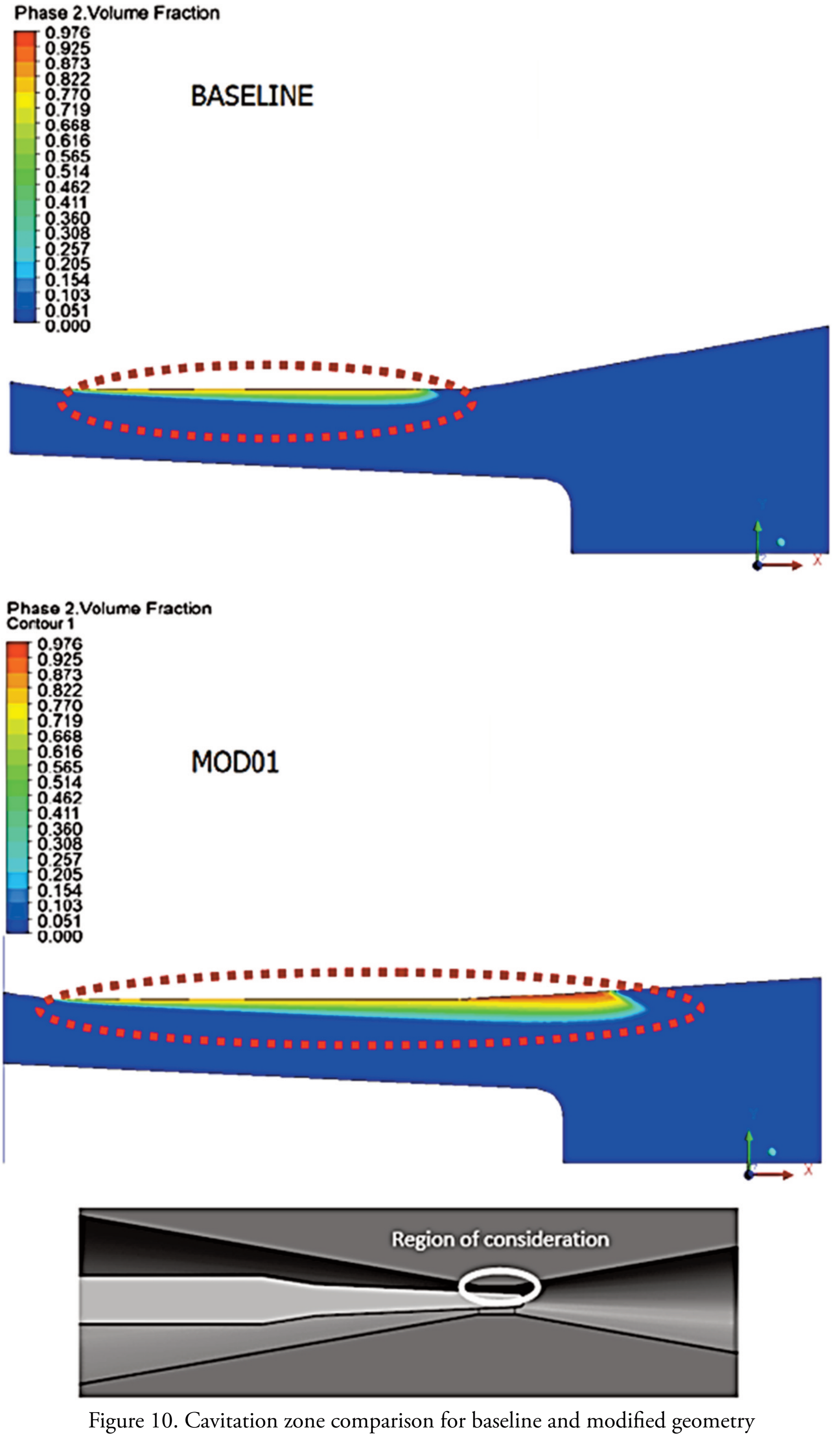

Figure 10. Cavitation zone comparison for baseline and modified geometry at the same outlet pressure.

Table 2. Cavitating venturi parameters under consideration—considered range.

Parameter		**Throat length (mm)**	**Divergent angle (°)**	**Needle extension (mm)**
Baseline		5	15	0
Considered range	Min.	0.5	6	0
	Max.	5	20	8

6. TESTS WITH ENGINE

After the optimisation, a new valve assembly was manufactured, and follow-up tests were executed. The new assembly was tested as part of an engine test, where the valve serves as a propellant mass flow controller. This test gave realistic downstream pressure variations and showed the valve behaviour in real-life conditions. The test was performed on a monopropellant engine where the HTP valve was utilised as a propellant. Based on previous flow tests, where the difference between the calculated and measured mass flow was quite significant for the low mass flow, the new needle angle and position vs. required mass flow characteristic was calculated (see Fig. 11). Only the needle angle was changed to obtain these new assumptions with the same throat diameter.

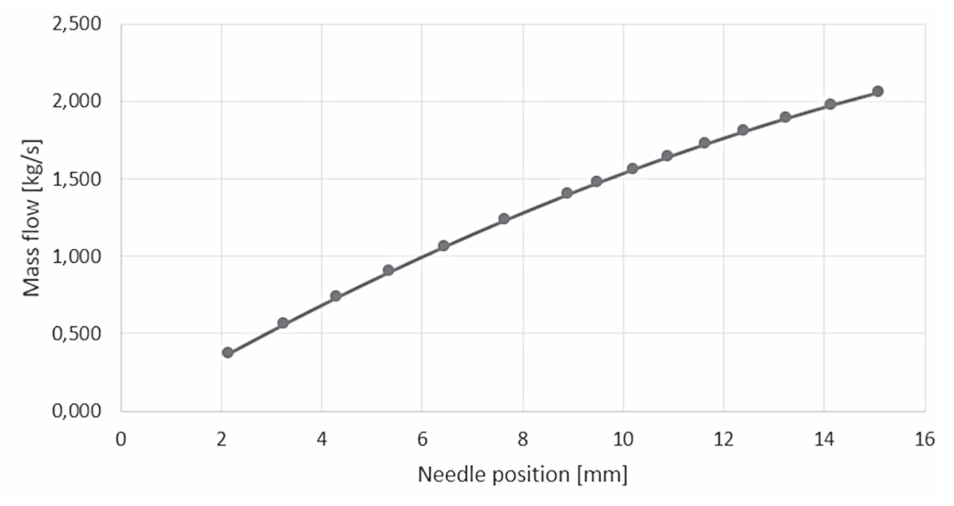

Figure 11. Mass flow vs. needle position calculated for an optimised valve design for the engine test.

A pressurised propellant from the tank was flowing through two serial flow meters towards the regulatory valve and to the engine. Two flow meters were used to obtain better accuracy as the turbine acts faster in transients, and Coriolis is more precise under steady-state operation. Additionally, propellant temperature and pressures on the regulatory valve inlet and outlet were measured.

The aims of those tests were as follows:

- To verify the mass flow vs. needle position calculation after optimisation;
- To observe the cavitation disappearance after optimisation;
- To establish if the designed valve can play its role in real-life conditions as a flow regulator for the engine.

There are some discrepancies in the mass flow, especially at both ends of the considered throttling range (for 10% and 110% of mass flow, see Fig. 12). However, the accuracy is better than that of the first design, and for this improved valve mass, flow error is not exceeding 4%.

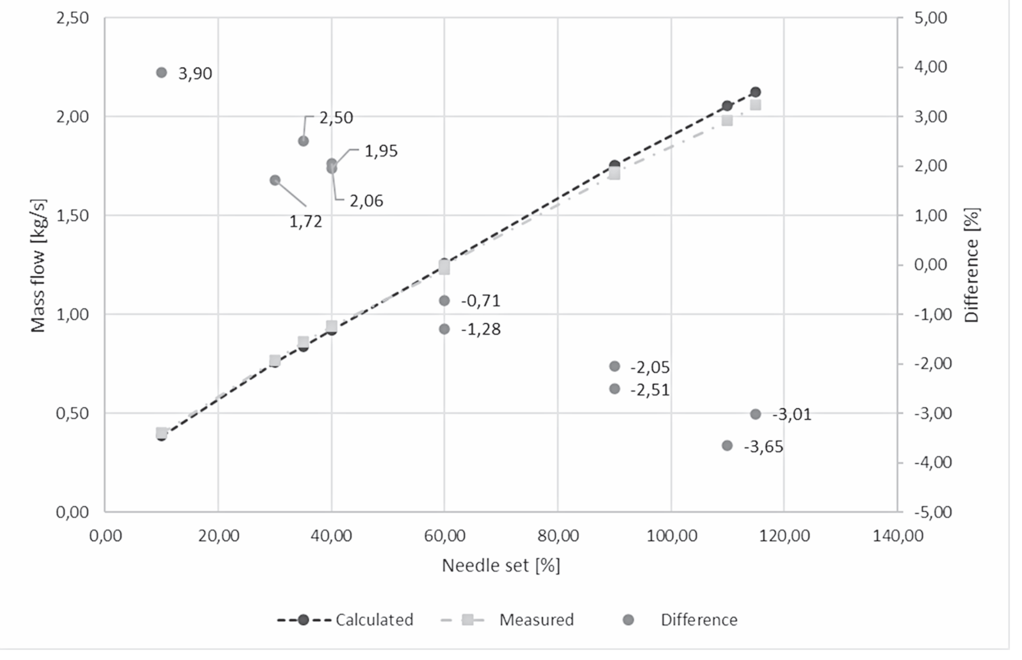

Figure 12. Mass flow calculated vs. mass flow obtained during the test.

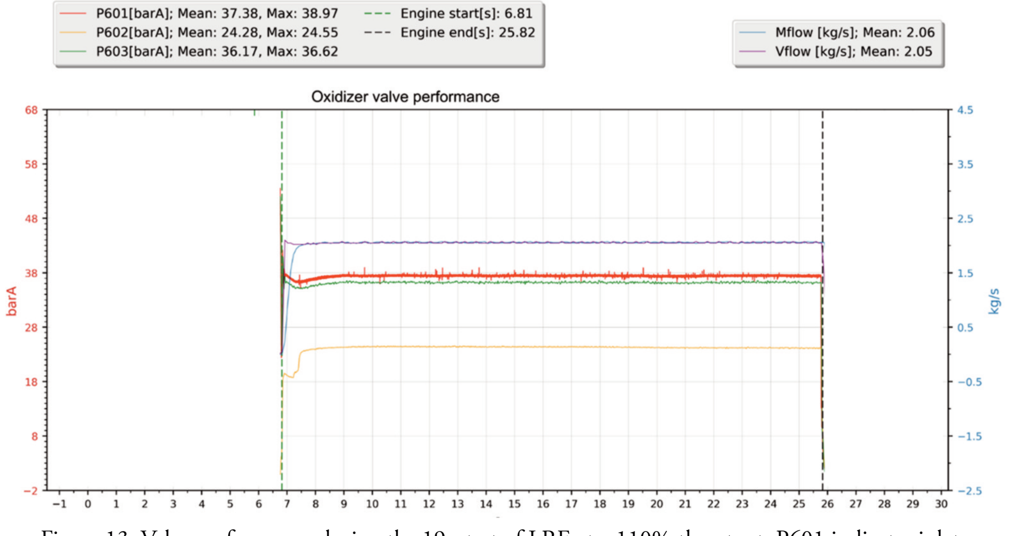

Figure 13. Valve performance during the 19 s test of LRE at a 110% thrust set; P601 indicates inlet pressure (measured by a 50 barA pressure transducer); P602 is the outlet pressure (filtered); P603 is the inlet pressure (measured by 500 barG pressure transducer); Mflow denotes the mass flow (Coriolis flowmeter); and Vflow is the mass flow (turbine flowmeter). LRE, liquid rocket engine.

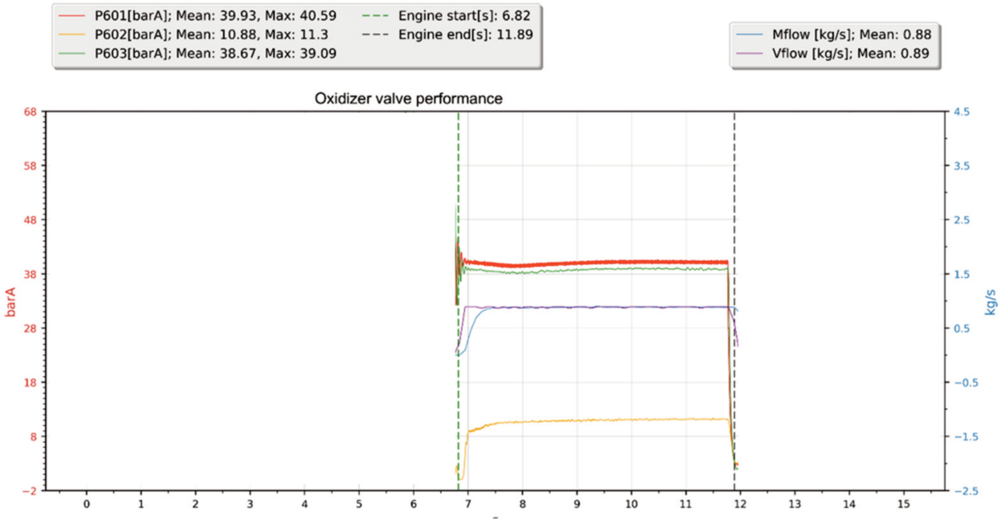

Figure 14. Valve performance during the 5 s test of LRE at 35% thrust set; P601 is the inlet pressure (measured by a 50 barA pressure transducer); P602 denotes outlet pressure (filtered); P603 is the inlet pressure (measured by a 500 barG pressure transducer); Mflow is the mass flow (Coriolis flowmeter); Vflow denotes mass flow (turbine flowmeter). LRE, liquid rocket engine.

The tests showed that the valve could operate in real-life conditions as a flow regulator for the throttleable rocket engine. The mass flow rate was as expected, with very good stability and a relative standard deviation during the test below 0.6%. This is true as long as cavitation takes place. In terms of geometrical improvements (MOD5), the cavitation limit shifted from a pressure ratio ~0.7 to as high a value as about 0.85. The results were obtained during over 25 real-life engine tests at different thrust levels and different engine operation lengths (from 5 s to 20 s of operation), but for steady thrust operation (no active throttling). Exemplary results of valve performance during tests are shown in Figs. 13 and 14.

7. CONCLUSION

This research showed that Ł-IoA (Łukasiewicz Research Network – Institute of Aviation) cavitating venturi valves with variable throat areas could be considered a perfect solution for deep throttling liquid rocket engine propellants and mass flow controllers. Mass flow control is simple and precise, and the valve showed high repeatability of the mass flow and high stability at a set position. As the engine tests proved, the mass flow is insensitive to the pressure oscillations from combustion as long as the valve operates in the cavitation range. The support of CFD analyses showed that several geometrical improvements could help optimise the operational valve range (with cavitation).

Further development of the valve will consider continuous change (throttling) in the engine thrust by the continuous change in the valve needle position (operation with an actuator). As the last step, separate component flow and hot fire engine tests with automatic valves control and thrust variations during one test run will be performed.

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