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Development of a Cavitating Pintle for a Throttleable Hybrid Rocket Motor

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Abstract
Hybrid rocket motors have several potential advantages respect to current used propulsion systems (i.e. solids and liquids) like simplicity, safety, reliability, environmental friendliness, lower cost. A particular positive feature of hybrid rockets is the possibility to control the thrust level operating only on the oxidizer mass flow. Thanks to this it is possible to develop a relatively simple propulsion system that is throttleable on demand without the complex mixture ratio control and related hardware of a liquid system. In the past University of Padua has developed a lab-scale hybrid rocket motor that can be throttled at few different discrete levels with the use of parallel feedlines. To give the possibility of having a continuous throttling capability a new mass flow control has been developed recently. The mass flow control make use of a cavitating pintle. The cavitating pintle acts as a cavitating venturi in order to choke the mass flow and make it independent of downstream pressure. The pintle is used to change the venturi throat area and consequently varying the oxidizer mass flow keeping a constant upstream pressure. The paper presents the design of the cavitating pintle and the experimental campaign composed by cold tests followed by hot fire tests of the lab scale hybrid rocket.

1. Introduction

There has been recently a renewed interest on hybrid propulsion thanks to a stronger focus towards its advantages like affordability, safety, reliability and environmental friendliness. At the same time the research has progressed in order to overcome the inherent issues of hybrid propulsion like the low regression rate. One promising solution is the use of paraffin wax[1,2,3] . University of Padua has been working on paraffin wax based hybrids since almost 10 years ago[4,5,6,7] . Another advantage of hybrids is the possibility of throttling and is the focus of this work.

Thrust profile control in hybrid rocket motors is paramount. For launching vehicle applications this means optimizing the trajectory, hence reducing the total Δv required to reach orbit. In ascending and descending vehicles (ADV), another peculiar application for throttleable hybrid rocket motors (HRMs), the thrust control is required in order to achieve soft landing and trajectory control.

Since most rocket applications use a fixed throat nozzle, and not a variable one, throttling is generally achieved by varying the combustion chamber pressure and hence the propellant mass flow. In solid rocket motors (SRMs) the propellant grain is shaped in order to vary the burning area during the burning time, while in liquid rocket motors (LRMs), oxidizer and fuel flows are simultaneously controlled.

Of course the trust control achieved in SRMs is rigid, can be set only during the design and manufacturing phase, because directly linked to the shape of the propellant grain. The thrust control in LRMs is far more flexible, and give the chance to arbitrarily change the level of thrust during the flight, i.e. throttling.

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To throttle a HRM, the oxidizer flow is the best involved variable that can be directly controlled, while the fuel is partially linked to the latter. Using the simplified form of the Marxman power law model the fuel mass flow is proportional to $\rho_{fuel}\ A_b\ a\ G_{ox}^n$. Unfortunately this kind of control implies a o/f shift that inevitably leads to a characteristic velocity loss, while in liquid and solid rocket motors the ratio between the reactant is kept constant allowing to work always at the maximum specific impulse. This is the main drawback in hybrid rocket motors. Furthermore, since throat erosion has been demonstrated to be particularly severe in hybrid rocket motors (HRMs),[9] the ability to control the oxidizer flow to the combustion chamber is required in order to compensate the force coefficient reduction due to throat erosion in any application where this degrading contribute is not acceptable.

On the other hand the main advantage of throttling hybrid rocket motors is the simplicity of the control. In fact the control of just a single feeding line is needed and in order to do this a single dedicated flow control valve is required. Taking the Lunar Module Descent Engine (LMDE) as an example it was realized with two identical flow control valves, and since the required mass flows and operating fluids were different it used a positioning link from a single actuator to grant the correct ratio between the mass flows. Of course the complexity and probability of failure of the assembly increase with the number of movable parts. So HRMs are less expensive and more reliable also from the throttling point of view with respect to LRMs.

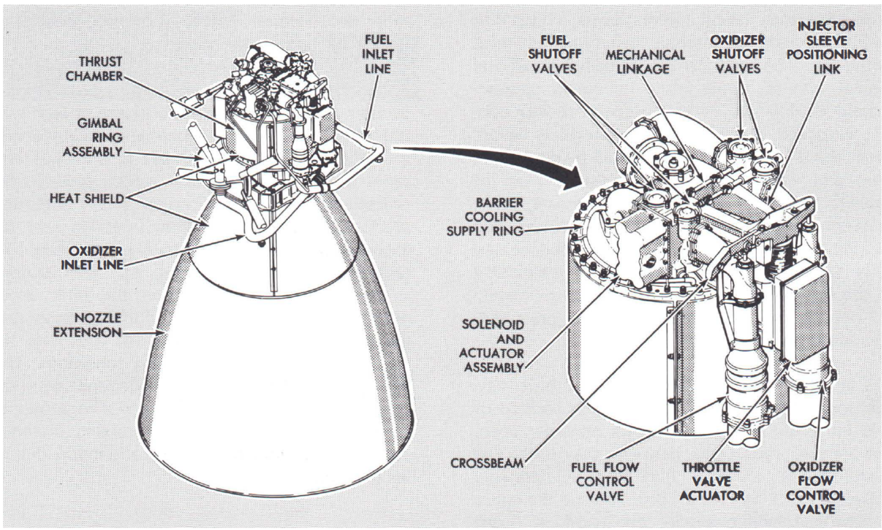

Figure 1: LMDE flow control assembly

Continuing downstream of the FCVs in the descent engine there is a variable area injector which uses a moving sleeve to vary the injection area of both fuel and oxidizer so to obtain the optimal atomization for all the operative mass fluxes.[8] This device would be required also in a HRM, and in this case it would be slightly simpler, but if the oxidizer used is a mono-propellant, such as HTP or N_2O, with the appropriate catalytic bed it is possible to have a gaseous injection for a wide range of mass fluxes and so further reducing the complexity of the throttling apparatus. This approach is possible also with LRMs but few are the fuel/oxidizer combinations in which both the reactants act as mono-propellant.

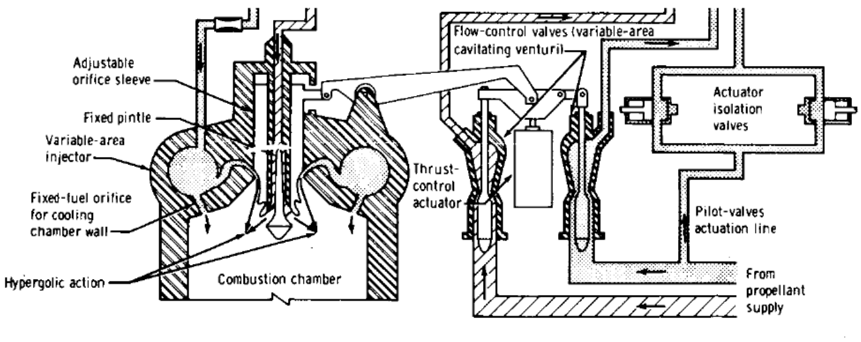

Figure 2: LMDE flow control scheme

Currently at the University of Padova we are studying a HTP fed Hybrid Rocket Motor which merge all the

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technical advantages described before and so it is well suited for throttling. HTP has a high density, is green, can be stored at room temperature, is very versatile and has a low temperature sensitivity that makes it particularly well suited for throttling applications.[7] This article describes the design and static-characterization of a flow control valve based on the principle of the cavitating venturi to be applied on the motor under study. Before this description, a section is presented, in which the theoretical limits of HRMs throttleablity are analyzed. The final section of the article presents the results of a preliminary test campaign focused on characterizing the motor behavior for a wider range of oxidizer mass flows than the one used in the test motor up to now.

2. Characteristic velocity penalty and throttleability accuracy in HRMs

Considering a throttleable Hybrid Rocket Engine in which we vary the oxidizer mass flow to control the thrust, and assuming a cylindrical port fuel grain that is consumed exclusively in the port, we can describe the fuel mass flow as using the simplified form of the Marxman power law. As said before this lead to a oxidizer to fuel ratio shift while throttling:

$$o/f = \frac{\dot{m}_{ox}}{\dot{m}_{fuel}} = \frac{\dot{m}_{ox}}{\rho_{fuel}\, A_b\, a\, G_{ox}^{n}} = \frac{\dot{m}_{ox}}{\rho_{fuel}\, \pi\, D_p\, L_p\, a\, \left(\frac{\dot{m}_{ox}}{\pi\, D_p^2/4}\right)^{n}} = \frac{\dot{m}_{ox}^{1-n}\, D_p^{2n-1}}{4^n\, \pi^{1-n}\, a\, \rho_{fuel}\, L_p} \tag{1}$$

where A_b is the burning area, a and n are the Marxman power low coefficient and exponents respectively, D_p and L_p are port diameter and length. It is worth noting that to reduce the effect due to a port diameter change it is desirable to have n as close to 0.5 as possible while to reduce the effect due to throttling, i.e. a change of the oxidizer mass flow, n should be toward 1. Practically the power law exponent ranges from 0.45 to 0.8. Of course a change in oxidizer to fuel ratio imply a variation of the characteristic velocity, and since, via throttling, we can not operate at the optimum point this always result in a c^* penalty. Another important consideration is how the characteristic velocity for the propellant formulation changes with the o/f. Figure 3 show the frozen c^* trends for paraffin and the currently most used oxidizers (90% HTP, N_2O and LOX) obtained using CEA.[10] As you can see the LOX trend is quite steep, while the HTP and N_2O are flatter.

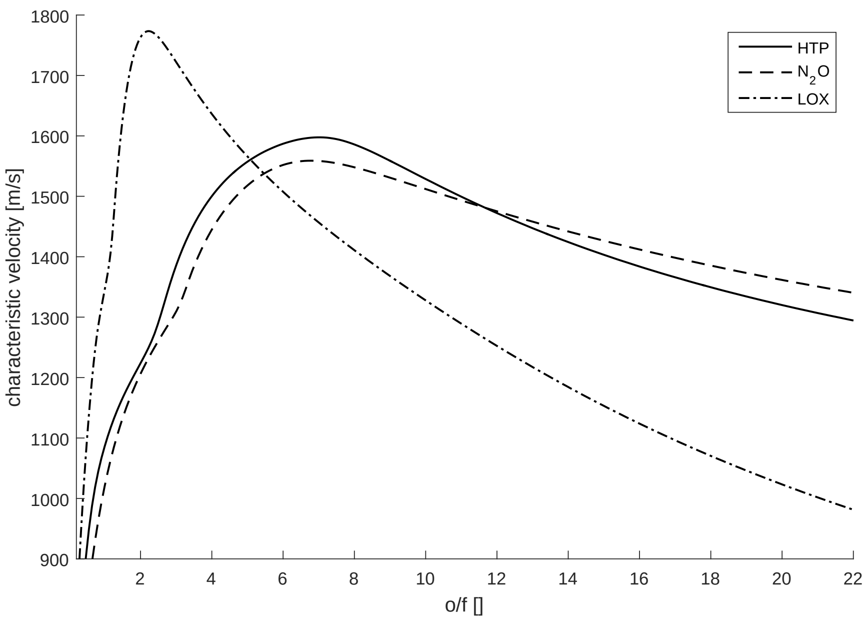

Figure 3: Characteristic velocity trends with the oxidizer to fuel ratio for paraffin (different oxidizers)

Table 1 reports the maximum values of c^* and c^* sensitivity [1] as well as two information about the c^* penalty which incur with a throttling ratio of 5 and 10. In the first case (balanced), the throttling take place around the o/f at which the maximum c^* is achieved and ranges in both the oxidizer rich and fuel rich regions, in the second case the motor operates only in the fuel rich region, starting from the optimal mixture ratio. There are two main reasons why

[1]Where c^* sensitivity means the second derivative of the trends around the maximum point.

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the second c^* penalty is reported, first the quantity of total impulse associated with the low thrust is smaller if compared with the high thrust, and considering LMDE duty cycle, applicable for a soft landing ADV in general, the motor spend less time at the lower thrust. Secondly, in the fuel rich region the drop in $c*$ is partially compensated by the relative increase of consumed fuel mass and so the motor behavior results more linear than the one achieved in the oxidizer rich region. A linear motor would facilitate the throttling control loop, especially if open.

Table 1: Characteristic velocity maximum, sensitivity and losses

	HTP	N_2O	LOX
Maximum c^* [m/s]	1598	1559	1773
c^* Sensitivity [m/s]	−22.4	−16.3	−369.9
c^* Penalty TR=5 (balanced)	95.3%	95.9%	96.2%
c^* Penalty TR=5 (fuel rich)	88.0%	84.5%	82.7%
c^* Penalty TR=10 (balanced)	91.6%	92.8%	93.2%
c^* Penalty TR=10 (fuel rich)	78.3%	78.5%	75.4%

The power law exponents n used to obtain the data presented in table 1 were 0.5, 0.5 and 0.65 for HTP, N_2O and LOX respectively. As we can see the advantage of having an higher exponent for the *paraffin-LOX* formulation and hence a lower o/f shift associated with throttling is neglected by the high sensitivity of the propellant, for the maximum achievable characteristic velocity efficiency is comparable with the one for HTP and N_2O.

This being taken into account it is worth evaluate the advantages of having a power law exponent equal to 0.5 which is actually true for the *paraffin-*N_2O and HTP propellant formulation. First of all this imply that there is no o/f shift for a port diameter variation, as explained in equation 1. This means that there is no o/f shift for a constant oxidizer mass flow but it also means that, as consequence of throttling, the return to the previous combustion chamber pressure is granted with the same exactly oxidizer mass flow thus not requiring for the flow control system to know the port diameter history. For sake of clarity let's consider the following example:

Figure 4 shows the results of a simplified quasi-stationary numerical simulation using a lumped parameter model. In figure 4a the three different normalized oxidizer mass flow profiles are presented, these curves are input for the simulations. The results reported in figure 4b and figure 4c show the difference in the output normalized pressure profiles. In particular after a variation from the nominal oxidizer mass flow and the consequent restore of the nominal conditions there is a difference in the restored pressure, which is also dependent on duration and intensity of the throttle down. Figure 4b shows how this is not the case with an n exponent equal to 0.5, and of course this simplifies a lot the thrust control, because it guarantees a one-to-one relation between oxidizer mass flow and pressure. Therefore the 0.5 exponent provides the best accuracy for a throttleable hybrid in open loop, accepting, anyway, a slightly higher $c**$ penalty compared to a higher n.

It is important to note that all this considerations were made under the assumption of cylindrical fuel grain consumption following the simplified Marxman power law. However there are possibility available to reduce the negative effects of throttling on the characteristic velocity such as the implementation of consumable fuel thermal protections and tayloring the post combustion chamber design.

3. FCV design

There are many options in realizing a flow control valve, in practice every valve in which it is possible to control the position of the port, can act as a dissipative mean to control the flow, unfortunately somtimes this kind of valves can be strongly non linear. Variable area cavitating venturis (VACV) are a particular kind of flow control valves in which the flow is controlled due to the cavitation taking place at the venturi throat, in these condition the flow is said "chocked". It has been demonstrated[12,15] that if the ratio between downstream and upstream pressures is lower than 0.8,0.9 depending on the operating fluid and venturi design the flow is chocked, in this conditions the mass flow through the cavitating venturi is equal to:

$$\dot{m} = C_D\, A_{th} \sqrt{2\, \rho \left(p_{0,up} - p_{sat}\right)} \tag{2}$$

where A_{th} is the device throat area, C_D is the discharge coefficient, ρ is the operating fluid density and $p_{0,up}$ and p_{sat} are the total upstream pressure and saturation pressure of fluid. So the flow through a cavitating venturi depends exclusively from the upstream total pressure and not the pressure difference between the valve gauge as in a common dissipative valve. Furthermore the flow can be easily controlled by varying the venturi throat area, equation 2 shows a

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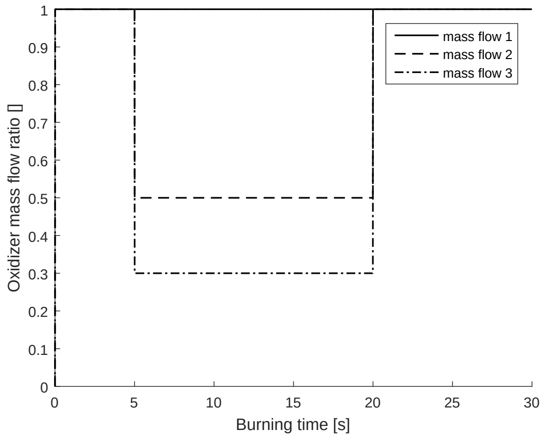
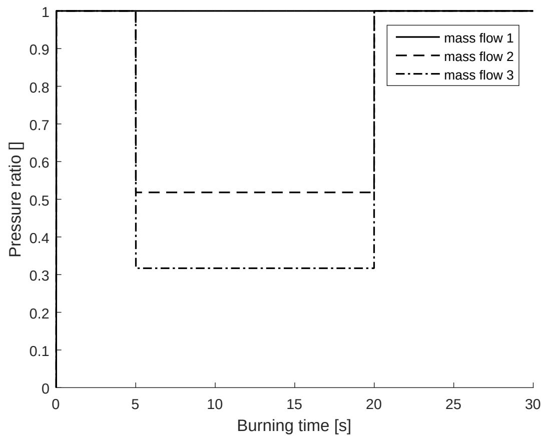


(a)



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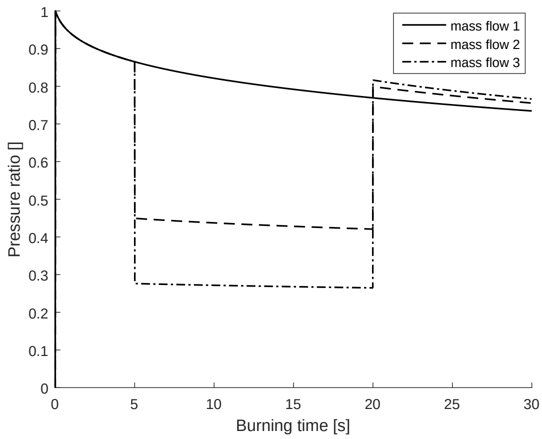

(c)

Figure 4: Difference between pressure profiles after an arbitrary variation of the oxidizer mass flow for $n = 0.5$ and $n = 0.8$

linear dependence between the two variables, even if, this liner dependence can be mined by the discharge coefficient. The easiest way to reduce the throat area is to use a linearly actuated pintle or sleeve.

The hybrid rocket laboratory at University of Padova have been using fixed throat cavitating venturi for a long time, and also performed throttling tests with discrete levels of oxidizer mass flow using parallel feeding lines. But right now we are willing to improve our test capabilities and characterize throttleable hybrid rocket motors, and in order to do this a variable area cavitating venturi based flow control valve has been designed and characterized .

In this article a variable area cavitating venturi is presented as a flow control valve. This device is not new in rocket applications, in,[12] Randall describes comprehensively the fixed area cavitating venturi he was adopting at Curtiss-Wright Corporation as well as a VACV design using a pintle to vary the throat area. In[12] Randall also describes the good practice guidelines in designing a VACV. Afterward TRW Systems developed a series of throttleable liquid rocket motors adopting a variable area cavitating venturi as a flow control valve, among them the famous Lunar Module Descent Engine.[11] In recent times when a renewed interest started to gather around hybrid rocket motors, VACV started to be applied to this propulsive technology as well. During the SPARTAN program, focused on the development of a descending vehicle employing throttleable hybrid rockets,[13] MOOG-Bradford realized a VACV based flow control valve to be applied to the rocket engine. The University of Padova was entrusted to characterize this FCV.[14] Short after the Beihang University developed and realized their own VACV,[15] this valve is used in their test bed to study and characterize throttleable hybrid rocket motors.

Figure 5a shows the VACV design. For sake of simplicity in manufacturing and quality control the pintle was designed to have a conical shaped end, the pintle was helically moved toward the venturi throat by mean of a drivescrew machined in the main body. An O-ring sealing was used to separate the wet region of the flow control valve from the

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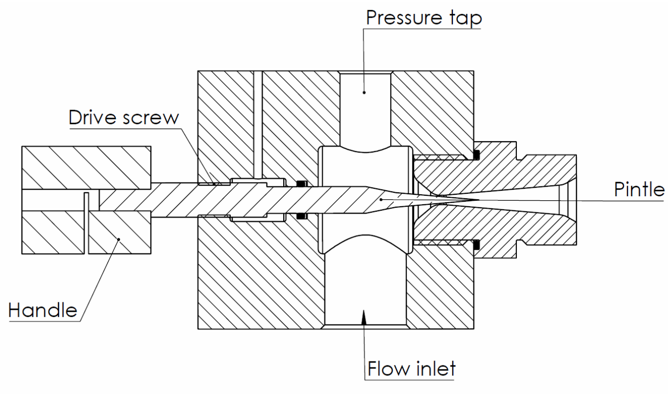
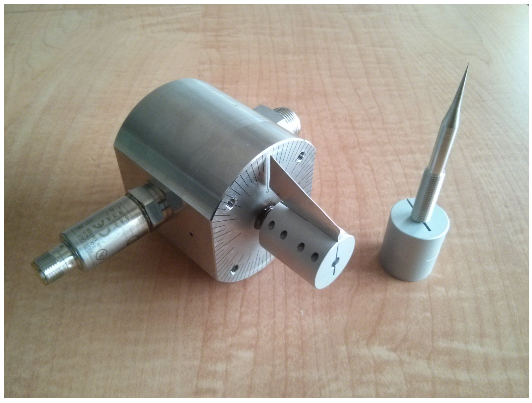
drivescrew, and in order to relief the pressure caused by a movement of the pintle a venting hole was machined in the main body. The venturi body, which resemble a nipple like fitting, is screwed in the main body, the sealing is granted by the O-ring placed in the groove at the end of the thread. This type of connection aside from providing an effective sealing also grants the precise and reproducible positioning of the venturi in the main body, which is necessary in order to reduce position uncertainties. The mass flow enters with an angle of 90° with respect to the pintle axis and port. On the opposite side of the entering bore there is a pressure tap to be used with a trasducer.



(a)



(b)

Figure 5: Variable area cavitating venturi scheme and photo

For a conical shaped pintle the throat area can be assumed as the lateral area of the troncated cone which generatrix is perpendicular to the pintle surface at the frustum. Under this condition the throat area function with the pintle stroke is:

$$A_{th}(x) = \pi \left(2 \frac{\tan\alpha}{\cos\alpha} \left(R_{th} + R_{up} (1 - \cos\alpha) \right) x - \frac{\tan^2\alpha}{\cos\alpha} x^2 \right) \quad (3)$$

where α is the apex half angle, R_{th} is the throat radius, R_{up} is the upstream throat radius (in the sagittal plane) and x is the pintle stroke, from the position in which the pintle touches the venturi. A comprehensive demonstration to this equation can be found in.[15]

Equation 3 shows how for a conical shaped pintle the throat area function is non linear with the stroke, in particular it is quadratic. The non-linearity term can be reduced by decreasing the apex angle since $\tan^2\alpha/\cos\alpha$ tends toward 0 faster than $\tan\alpha/\cos\alpha$ for $\alpha \to 0$. But, since there are mechanical limits and the maximum pintle stroke increase for a lower apex angle, making the pintle slender, in practice the VACV is slightly oversized, meaning having a bigger throat diameter than necessary, so that the operating pintle stroke must be smaller and hence reducing the effects of the non linear part of equation 3.

The designed VACV has the following requirement and characteristics:

Table 2: Variable area cavitating venturi properties

Minimum mass flow range	30 $[g/s]$
Maximum mass flow range	300 $[g/s]$
Maximum operating pressure	80 $[bar]$
Venturi throat diameter	2.2 $[mm]$
Upstream throat radius	3.3 $[mm]$
Venturi divergence angle	10 $[deg]$
Pintle apex angle	10 $[deg]$
Maximum pintle stroke	11 $[mm]$
Useful pintle stroke	7 $[mm]$

Of course all the geometrical parameters were turned in to quotes on drawings, quotes associated with tolerances. Because of these tolerances an uncertainty on the throat area exists. Figure 6a shows the trend of the throat area with the pintle stroke as well as its uncertainty due to the manufacturing and assembly tolerances. Figure 6b shows how the throat area uncertainty becomes relevant for low pintle strokes where the ratio between area uncertainty and area

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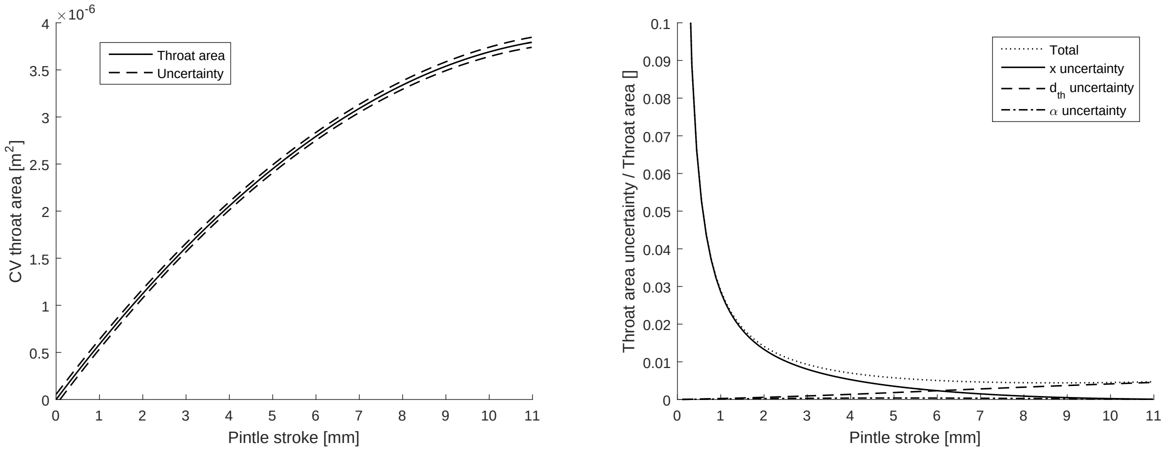
explodes. In figure 6b are also displayed the different contributors to the total uncertainty, in our design the most evident is the pintle stroke uncertainty.



(a) (b)

Figure 6: VACV throat area and throat area uncertainty trends with the pintle stroke

The major contributor in the pintle stroke uncertainty are the drive-screw thread tolerances. Since their effect becomes most evident for very low pintle stokes, we decided to set, during characterization a minimum of 0.5mm to the pintle stroke at which point the uncertainty relative error is 6%

4. FCV static characterization

The characterization consisted in a series of tests to determine the mass flow varying the pintle stroke. The tests were performed with two different operating fluids, water and 91% H_2O_2 aqueous solution, and for three different pressures. Characterizing the flow control valve is important for two reasons, first we need to precisely know the needed pintle stroke to achieve the required mass flow for a given upstream pressure, secondly the VACV can be used both as flow control valve and flow meter hence having a redundant measurement in our experimental setup.

4.1 Experimental set-up

Figure 7 shows the experimental setup used to characterize the flow control valve. From upstream to downstream the components are a high pressure nitrogen tank, the pressure regulation block consisting of two pressure regulators serially connected, the tank, a series of automated ball valves and at the end, the variable area cavitating venturi. Downstream of the cavitating venturi there is a pipe which connects the valve with a collector tank.

The tank design is particular since it also allows us to measure the mass flow. It consists of a precisely manufactured cylindrical barrel with two flat bulkhead at its ends. Inside the tank two rooms are separated by a piston the above volume host the pressurant while the lower volume holds the oxidant or water, the impermeability of the piston is granted by specific sealing. Connected to the piston and directed upward there is a stem which crosses the uppermost bulkhead, the steam is connected to a linear potentiometer. Thanks to the potentiometer output both the instantaneous mass flow and cumulative mass are determined. In order to grant the accuracy of the measure before each test most of the gas and fluid in the lower volume is vacuum removed before filling up so to reduce the ullage volume during the test. This is a very good method to measure the mass flow over a wide range of values. The tank capacity is four liters.

There are three pressure sensors in the setup p_{tank} is screwed in the upper bulkhead of the tank, and hence measure the pressurant pressure, p_{up} and p_{down} are placed immediately usptream and downstream of the cavitating venturi. A thermocouple, placed at the tank outlet, measures the outflow temperature in order to compensate the density data and also for safety reasons in case of dissociation inside the tank. Valves $V05$ and V_{tank} are manually actuated before loading the tank and pressurization. Valves V_C and V_{test} are pneumatically and automatically actuated in this order during the test. Valve V_{purge} is pneumatically and remotely actuated, it allows low pressure nitrogen to flow trough the last part of the line in order to purge this last volume from any residual HTP, during fire test the valve is also used to purge the combustion chamber. The downstream volume, between V_{test} and the engine injection is kept to a

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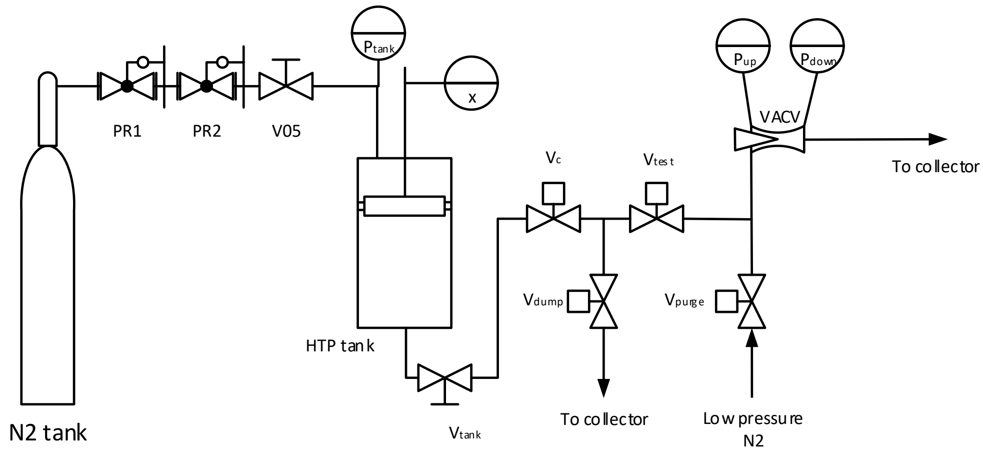
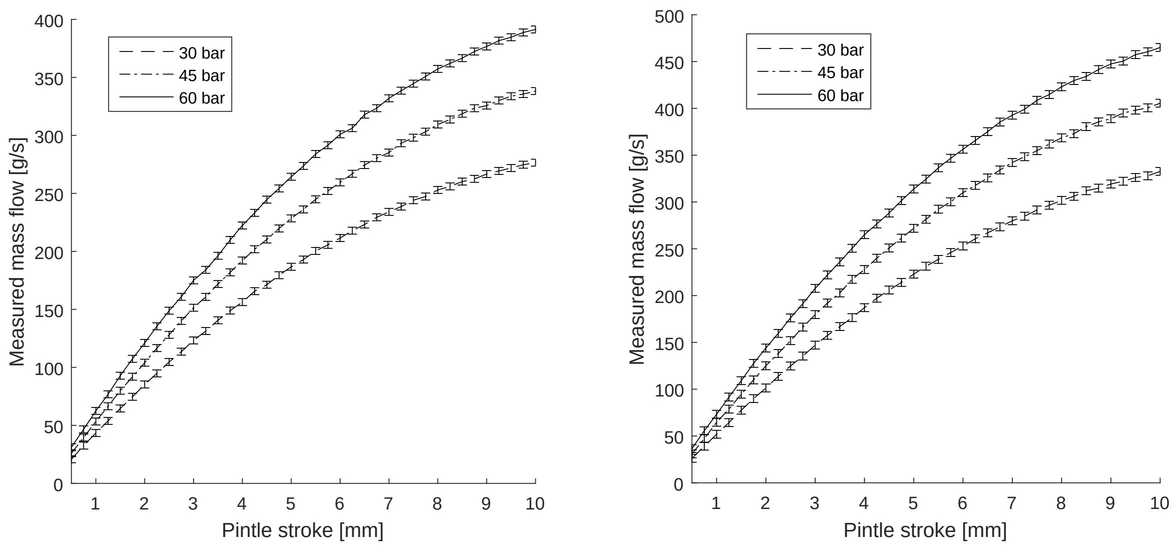


Figure 7: Experimental setup scheme

minimum. Valve V_{purge} is pneumatically and remotely actuated as well but its function is to empty and depressurize the line volume between V_C and V_{test}.

4.2 Results

The flow control valve has been characterized for three different upstream pressures, 30, 45 and 60 bar using both bi demineralized water and $91\%HTP$. The pintle stroke was varied by hand using the pintle handle and the reference goniometer on the back of the flow control valve, which are visible on figure 5b. The strokes values set ranged from 0.5 to 10mm with a resolution of 0.25mm.



(a) H_2O

(b) 91% HTP

Figure 8: Mass flow rates for different upstream pressures

The first important results of the characterization test campaign are reported in figure 8, they are the trends of the measured mass flow versus the pintle stroke. The mass flow measured with HTP results higher than the one of H_2O according to the law in equation 2.

Figure 9 shows the discharge coefficient trend computed from equation 2 using the measured mass flows and the throat area reported in equation 3 and figure 6a. The trends result similar and the data, even if scattered, are quite in the same range, suggesting no correlation with the upstream pressure. The biggest relative difference in the data are

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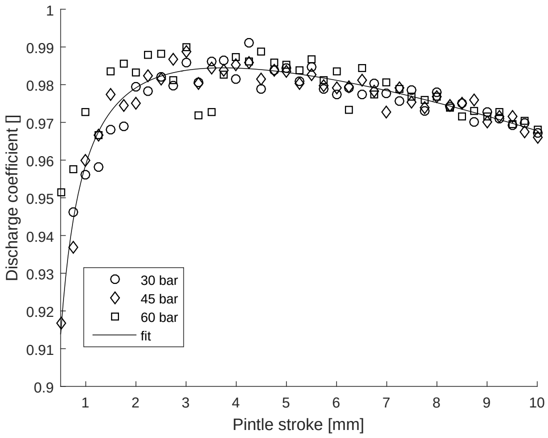
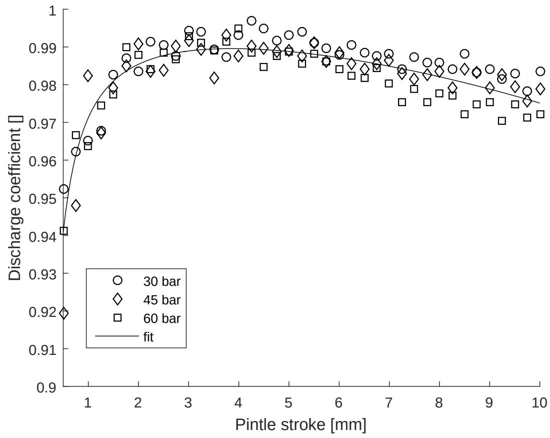


(a) H_2O



(b) 91% HTP

Figure 9: Experimental discharge coefficients and fit

for very low pintle strokes probably due to throat area uncertainty. In figure 9 are also reported the fitting functions obtained with the least square method. These functions are:

$$C_{D,H20} = 1.008 - 2.626\ x - 93.14\ x^2 - 4.643 \cdot 10^{-5}/x \tag{4}$$

$$C_{D,HTP} = 1.003 - 0.7345\ x - 174.5\ x^2 - 3.086 \cdot 10^{-5}/x \tag{5}$$

Equations 2, 3 and 5, are used to predict for a given upstream pressure the mass flow for the set pintle stroke.

5. Preliminary motor test campaign

In order to preliminary characterize the engine throttling behavior four test where performed. The tests were aimed to show how the pressure varied with the mass flow. All four times the engines performed in the fuel rich region, this was voluntary because, as said in section 2, the motor behavior is more linear due to partial compensation of characteristic velocity reduction and relative increase in consumed fuel mass. The throat was realized in refractory material which show no erosion during the four tests. A mixer was added in the combustion chamber to increase the steadiness of performance, and keeping high efficiency, with the varying mass flow. The motor was tested using four mass flows: 57, 138, 219 and $282 g/s$, achieving a maximum throttling ratio around 5. The flow control valve upstream pressure was set to $60 bar$.

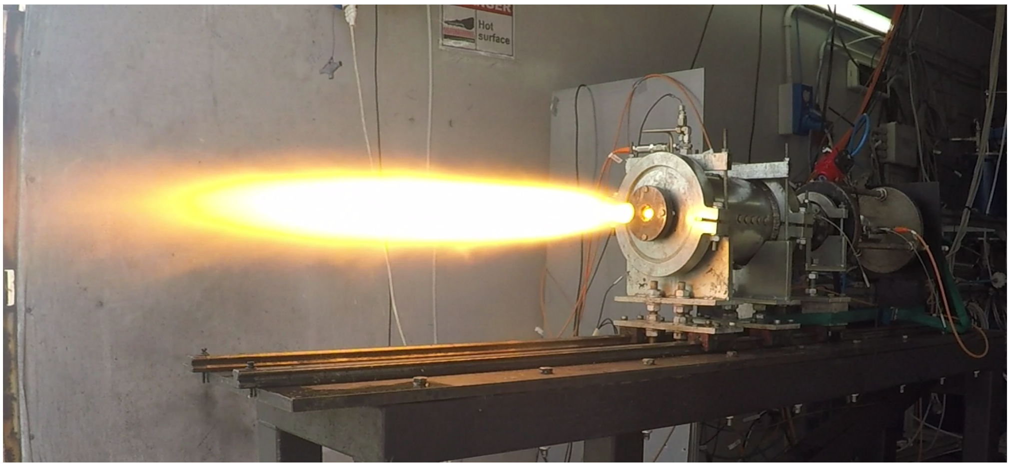


Figure 10: Test bed at experimental facility at University of Padova

Figure 10 shows the small hybrid rocket motor, currently in use at University of Padova, in particular this picture was

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taken during the forth fire test of this preliminary campaign. The flow control valve is placed immediately upstream of the catalytic bed. The setup, from the VACV upward, was the same adopted during the flow control valve characterization. In figure 11 are reported the pressure plot of post and pre combustion chamber during test number two. The flatness of the pressure profiles indicates that for paraffin-HTP propellant formulation the Marxman power law exponent is 0.5.

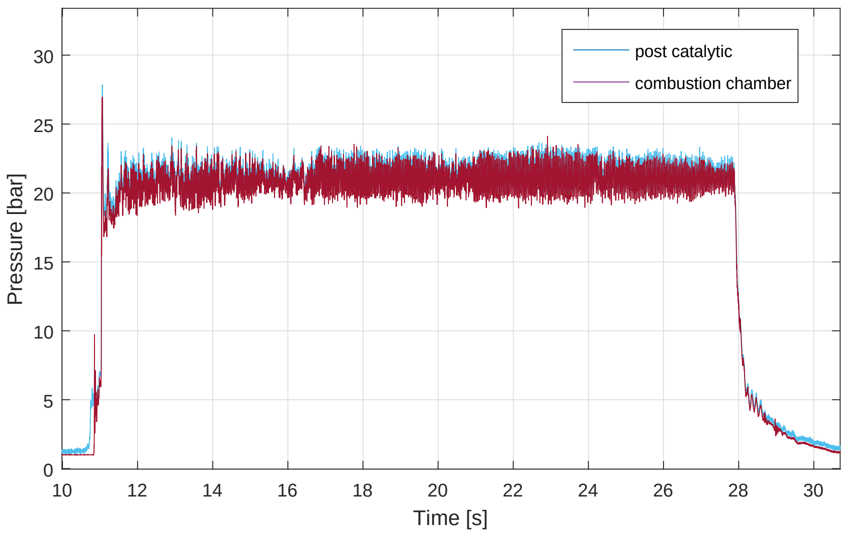

Figure 11: Pre and post combustion chamber pressure profiles during the second test at $138 g/s$

Figure 12 represents the motor behavior at different oxidizer mass flows, since the motor was performing in the fuel rich region the trend is particularly linear. This is a very desirable characteristic in order to simplify the control algorithm and improve the predictability of the thrust at various levels.

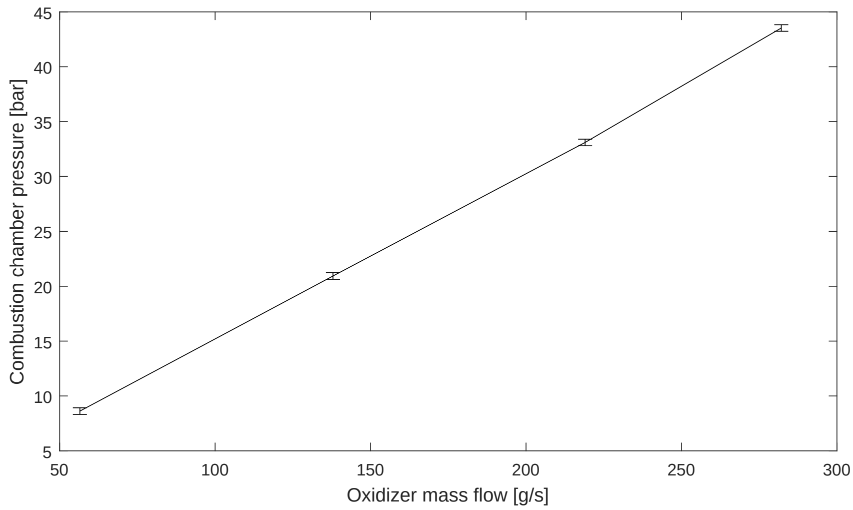

Figure 12: Average combustion chamber pressure versus oxidizer mass flow

6. Conclusion & future work

A flow control valve based on the variable area cavitating venturi was presented and characterized. Because of its peculiarity this device can both control and measure the flow. The functions presented can be used to predict the flow through the device and also measure it. The static behavior of a small hybrid motor was preliminary characterized.

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In the future some improvement will be applied at the device and the motor will be better studied and characterized for what concern throttleability. Right now the pintle is manually moved but in the future this device will be controlled by a DC motor with a position feedback loop. Since the independence between mass flow and downstream pressure was demonstrated, in the future we will measure also the limits to which this independence holds true. Since the pintle will be automatically controlled, a dynamic characterization of the flow control valve will be possible and hence the test motor can be characterized and throttling test performed.

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