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SMART ROCKETS: DEVELOPMENT OF A 500 N LOX/ETHANOL-SOUNDING ROCKET FOR THE DLR STERN PROGRAMME

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Abstract

Embedded within the DLR STERN programme, the SMART Rockets Project is a student mission with the aim to develop and launch a 500 N ethanol / LOX driven sounding rocket. It is right now in an early phase B project status. The constructed test bench is a cornerstone for the whole project and hence described in detail. On this basis an overview of recent test activities is given with an emphasis on the development of a first injector model. In addition to the presentation of first measurement results an analysis of the combustion chamber parameters is depicted. The final launch is envisaged for late 2015.

1. INTRODUCTION

The SMART Rockets Project[5] (SRP) at the Technische Universität Dresden (TU Dresden) is a project integrated within the nationwide STERN programme (Studentische Experimental-Raketen) which is initiated and conducted by the German Space Administration (DLR) and funded by the Federal Ministry of Economics and Technology (BMWi). The primary objective of this programme is the promotion of young professionals for launcher systems and a practical education of students in the field of aerospace engineering. At the TU Dresden, we set us the ambitious goal of developing a sounding rocket propelled with liquid oxygen (LOX) and ethanol. This development, which consists of the design, building and flight of the rocket, is conducted mainly by students. [1]

As a project for student education, the SMART Rockets Project is embedded within the teaching at the Institute for Aerospace Engineering. With the knowledge gained by lectures and practical education, the students are qualified to carry out nearly all necessary steps for the rocket development, starting from first design analyses until testing and parameterisation of the fabricated part. While the theoretical work of the project is conducted with diploma theses and research papers, the practical work is realised by a number of student assistants. The administration is done by the project manager and initiator Dr.-Ing. Olaf Przybilski and two PhD students. The duration is projected for a three year time span. [2]

As mentioned before, we decided to use liquid propellants for our rocket. This aspect is a distinctiveness of the SMART Rockets Project compared the other university teams participating in the STERN programme, who use hybrid, hot water or solid rocket motors. The use of ethanol and LOX as propellants provides the opportunity to learn the handling of cryogenic propellants and to be close to the fuel systems of current launcher systems. The advantage of ethanol lies in the possibility of being thinned with water in order to control the combustion process, while the handling of ethanol is relatively modest.

The current design of our rocket is shown in FIG 1. It shows the coaxial interleaved LOX and ethanol tanks right above the rocket engine, covered by manometers and control valves. The upper part of the rocket is equipped with a high pressure gas tank for tank pressurisation and a two staged recovery system. Right underneath the nose cone the payload, sensor and telemetry unit is located. This first design is designated to realize the requirements imposed by the DLR: reach the speed of sound, reach an apogee of at least 3 km, transmit the current rocket position and ensure a safe recovery. [1]

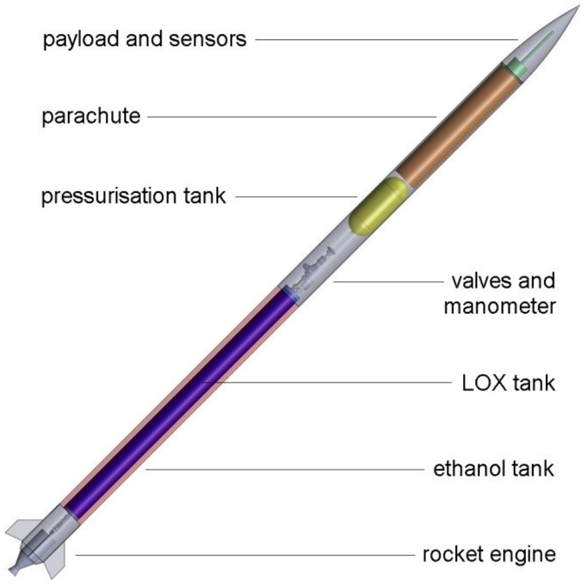

FIG 1 Rocket structure

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While a complete overview has been presented in previous work [3], the scope of this paper is to present recent developments of the SRP in detail. In chapter 2, the test bench is presented. Its development is nearly completed and the full operational state is expected within the next months. The following chapter 3 displays the current state of a first test injector, which is a coaxial swirl injector. Besides a design description, first measurement results are shown. An analysis of the combustion chamber parameters is given in chapter 4. Chapter 5 finalizes this paper with an outline of our future perspectives.

2. TEST BENCH

As one of the most crucial fields, the development, qualification and operation of the test bench is fundamental for the SRP and potentially upcoming projects. It is an accurate functional model of the rocket propulsion system. Of course all system parameters like pressures, temperatures and mass flows can be acquired, monitored and documented.

Every endeavour has been made to set up the test bench and guarantee its safe and reliable function. First tests, which will be presented in chapter 3, have been performed and the layout and procedures have recently been optimized. Currently the test bench is under preparation for a review in cooperation with the Cryogenic Institute at TU Dresden and experts at DLR Lampoldshausen. This chapter will give a detailed overview of the tasks, requirements, design and the test program itself.

FIG 2 – Test bench with ethanol (left) and LOX pipeline (right)

2.1. Tasks and objectives

The purpose of the test bench is not only the verification and validation of the rockets propulsion system. Besides the optimization of system parameters, the preparation, conduction and also the documentation of test procedures is of high interest for the student project.

The modular and variable test bench, which will be precisely described in the following section, allows the students to gradually cope with the challenges of handling cryogenic, oxidizing liquids. Due to the hazardousness of these materials and the criticality of the processes, safety is the top priority. Therefore redundancy plays an important role, especially in case of emergency shut-downs.

Also numerous requirements regarding the technical compatibility of components must be considered. Particularly vital is the selection and layout of sensor and actuator elements for cryogenic temperatures and a high number of test cycles.

2.2. Setup and functionality

The mobile test bench consists basically of the LOX and ethanol pipelines, the nitrogen pipeline, the control box, an engine rack, the sensor system and the control computer. FIG 2 shows the main part of the test bed with the whole pipeline system and the control box. Elementary schematics to all parts can be found in the appendix.

2.2.1. Nitrogen Supply

Just as later in the rocket, pressurized nitrogen is used to drive the propellants out of their tanks. This is already the first essential step to be taken in order to establish a stable combustion, for which the controlled and balanced delivery of the fluids is mandatory.

The nitrogen is provided in a customary gas cylinder and flows through a pressure reducing valve to the control box, where the mass flow is divided to different pipelines: the LOX tank pressurisation pipeline, the ethanol pressurisation pipeline, the pressurisation pipelines for the pneumatic main control valves and the flushing pipes. The latter are important to clean and even more to flood the pipelines and, if mounted, the combustion chamber in an emergency scenario.

2.2.2. Control Box

The control box displayed in FIG 3 is the central part of the test bench and consists of a solid and robust housing which contains all required electronics and magnetic valves to control the tank pressurization. It also serves as the interface to the measuring computer, while the housing, which is mountable to the framework of the test bench, creates a barrier between the electrical components and the rest of the test bench.

On the left side of FIG 3 you can see the interface for the several sensors and the one to the measuring computer. The lower part contains the electrical components, which are further described in section 2.2.5. Here the commands from the computer are transferred to the different valves in the centre, which are in each case the tank pressurization, the main control valve and the flushing pipe for the ethanol and LOX side of the test bed. The power supply is situated on the right.

FIG 3 - Control box

2.2.3. Ethanol Pipeline

The ethanol supply starts from an aluminium tank that contains the ethanol and which is pressurized by the nitrogen. On the upper side of the tank, an adapter is installed, to which different controls and instruments can be mounted (see FIG 4). By now there are a connection for the pressurisation, which is secured with a back-pressure valve, a pressure sensor, a manometer and a pressure control valve, which also can be opened manually. The ethanol is filled in also through the adapter.

To the bottom side of the tank, the fluid track is mounted via a further adapter. The first element in flow direction is another back-pressure valve. Prior to the miscellaneous sensors, a filter makes sure that no impurities can affect the measurements.

This filter is followed by a flow measuring device, a cut-off cock and the pneumatic main valve. Behind the main valve, the flushing pipe is connected via another back-pressure valve. A further pressure sensor completes the ethanol pipeline.

FIG 4 – The adapter for the ethanol tank with the mounted instruments and the LOX tank adapter in the background.

2.2.4. LOX Pipeline

The LOX supply is constructed very similar to the ethanol pipeline. The mountings on the LOX tank, which is equal to the ethanol tank, are nearly the same as described above. Only the pressure control valve cannot be opened manually like the one for the ethanol tank. Therefore an additional bleed valve is installed.

The tank outlet adapter on the bottom side of the LOX tank is followed by a filter, alike the ethanol pipeline. A Venturi tube, which is installed behind the filter, is used to estimate the LOX mass flow. The LOX supply is completed by the pneumatic main valve, which has also the function of a back-pressure valve, the secured connector for the flushing pipe and a pressure sensor.

2.2.5. Electronics and controls

The control box serves as an interface between the mechanical and electronic parts of the test bench. The applied AC power supply voltage is converted by two mains adapters into a 12 V DC switching voltage for the relays and a 24 V DC supply voltage for the magnetic valves and sensors.

As already mentioned in section 2.2.2, the relay board switches the magnetic valves in the following way: an incoming digital high-signal leads to the switching of the corresponding transistor, which applies a voltage to the relay. Thereupon the relay switches an according voltage, which opens the magnetic valve. Should a power shutdown occur, for instance in an emergency case, the current would break down and the valve would close instantly.

The several sensors of the measuring track are lead through the control box to the measuring board, where they are conditioned to monitor the according system parameters on the measuring computer. The control and data acquisition programme developed by Schubert [4] is based on LabVIEW and is designed to intervene automatically if any specific value should be critical. Manual access is of course also guaranteed at all times. The LabVIEW programme can be easily appropriated by the students and on-going optimizations are simple to implement.

2.2.6. Further elements

Further elements necessary for the test programme are particularly an engine rack and an ignition system. The engine rack is designed with a main focus on variability. The injector plate, the injector, the combustion chamber and the ignition system can be mounted to it. Moreover it is constructed to enable the testing of different engines in a thrust range from 100 to at least 3000 N by using elementary lever principles. Thereby an exchange of the force sensor is not required.

The ignition system developed by Brandt [5] is construed especially for a high number of test cycles and therefore much heavier than the flight model will be. Since a powerful and dependable igniting flame is obligatory and a malfunction of the igniter could lead to an oxygenated atmosphere, which presents an enormous explosion danger, the development of the ignition system is a key aspect of the project. The reusable and variable igniter is based on propane and oxygen, which are injected into a central mixing chamber and ignited by a micro-processor controlled sparking plug.

2.3. Test programme

The projected test programme ranges from the verification and validation of the test bench itself to the optimization of the rocket propulsion system. Already conducted tests cover:

- leakage tightness tests of the nitrogen, ethanol and LOX pipeline
- basic flow tests of the ethanol and LOX pipeline with water as replacement fluid
- flow test of the ethanol pipeline with pure ethanol
- cold flow tests of the test injector with water (ethanol and LOX nozzle, see chapter 3)
- cold flow test of the test injector ethanol nozzle with ethanol (see chapter 3)
- leakage tests of the ignition system

Further scheduled tests:

- leakage tests of the first test model LOX tank
- pressure test of the first test model LOX tank
- functional test of the ignition system
- cold flow test of the LOX pipeline with liquid nitrogen
- cold flow test of the LOX pipeline with LOX
- several nebulization and mixing tests of the injector
- cold flow test of the injector plate with mounted test injector (with water, ethanol, liquid nitrogen and LOX)
- verification and validation of the engine rack
- open combustion test without an combustion chamber
- pressure test of the combustion chamber
- full combustion test

3. INJECTOR

One key element in a liquid propelled combustion chamber is the injector. The main functions of the injector are: inducing the propellants into the combustion chamber, their proper mixing and the decoupling of the feeding system from combustion chamber vibrations. Following several theoretical works concerning mixing and flow characteristics (Wagner [6], Sieder [7]), a first coaxial swirl test injector has been designed and built (Voigt [8]). A coaxial swirl injector offers the possibility of mixing the propellants fully or partially already within the injector and therefore allows a length reduction of the chamber compared to most other designs such as impinging or shear injectors.

3.1. Injector design

The current test injector is designed for a nominal thrust of 100 N with the combustion chamber parameters described in chapter 4. The corresponding design parameters for the injector are displayed in TAB 1. FIG 5 shows a computer aided design (CAD) model. The distinctiveness of this test injector is the relocatable inner LOX nozzle (grey/bright in CAD model) with respect to the outer ethanol nozzle (green/dark). This feature is used to find the right recession of the LOX nozzle for optimal propellant mixing. First investigations of the mixing process have been realized with water as replacement fluids. The results vary from two separate spray cones (LOX nozzle at its lowest position) to full intermixture with the LOX nozzle at its highest position. A detailed mixture and spraying analysis is currently realized in a diploma thesis. For the design process, water thinned ethanol with a volumetric ethanol fraction of 70 % (Eth70) is used.

parameter	value
mass mixture ratio LOX/Eth70	1:1
pressure drop over the injector	5 bar
nominal thrust	100 N
total mass flow	47 g/s

TAB 1 – Design parameters for the first test injector

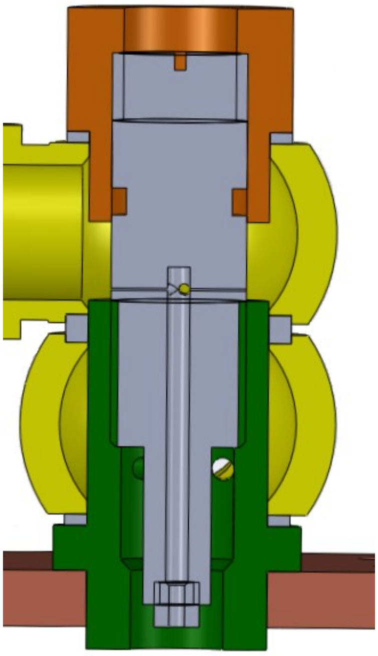

FIG 5 – CAD model of the test injector

3.2. Measurement results

First measurements have been conducted with the 100 N test injector and water has been used as a replacement fluid. Both nozzles have been measured separately using the ethanol pipeline of the test bench due to the installed calibrated volume flow meter. In addition to the volume flow, the gauge pressure right before injector is measured, providing the pressure drop of the injector, since the fluids were sprayed into ambiance. The mass flow $\dot{m}$ is calculated from the volume flow $\dot{V}$ with:

$$\dot{m} = \rho \cdot \dot{V} \tag{1}$$

The densities ρ of the used fluids are listed in TAB 2. At the first stage, the assumption was made that the volume flow is only depending on the pressure drop over the injector, not on fluid characteristics such as viscosity.

fluid	density ρ [kg/m^3]
water	998
pure ethanol	789
Eth70	885
LOX (93 K, 20 bar)	1130

TAB 2 – Densities of fluids

The measurements are evaluated as follows: The mass flow is rounded to an accuracy of a half gram per second and the corresponding pressure drop averaged. A discussion of the measurements follows.

3.2.1. Ethanol nozzle

With the ethanol nozzle, three measurements have been realized so far. One has been conducted with denatured ethanol and a reasonably constant tank pressure, resulting in an almost constant pressure drop over the ethanol nozzle of the injector. The other two measurements have been realized with water and a falling tank pressure, therefore a falling pressure drop.

FIG 6 shows the measurement results with the mass flow calculated for the projected Eth70. These first measurements support the assumption that water and ethanol behave similar regarding their volume flow within the injector. The measured pressure drop for the necessary mass flow of 23.5 g/s ranges from 5.36 to 5.56 bars, which is up to eleven per cent above the design parameter. These first results have to be extended by further measurements to ensure a well substantiated design. The spray cone of an ethanol nozzle test is shown in FIG 7.

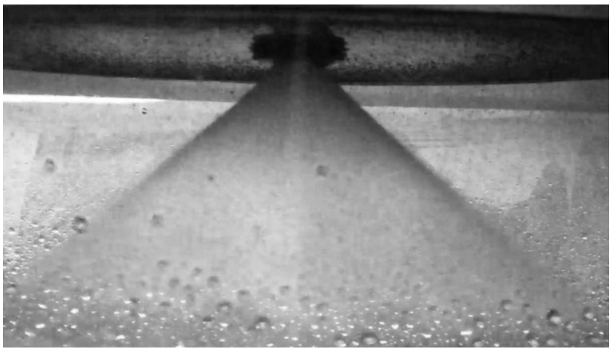

FIG 7 – Spray cone of the ethanol nozzle

3.2.2. LOX nozzle

Three water tests have been conducted with the LOX nozzle so far, again one with a constant tank pressure, two with falling tank pressures.

FIG 8 shows the pressure drop – mass flow correlation for the measurements assuming again an equal volume flow of LOX and water at a certain pressure drop. In the present results it can be seen that the pressure drop of a certain mass flow while having a constant tank pressure (solid circles) is higher than during a measurement with falling tank pressure (cross markers). This could be a result of higher dynamic influences due to the narrower flow channel in the LOX nozzle. With these measurements a pressure drop of 4.71 to 5.15 bars is necessary for a LOX mass flow of 23.5 g/s. FIG 9 shows the water spray cone of the LOX nozzle.

At this point it should be mentioned that a cryogenic fluid behaves different compared to water and ethanol, therefore the measurements have to continue e.g. with liquid nitrogen as a proper replacement for LOX. Additionally the influence of a falling tank pressure versus a constant tank pressure has to be further investigated.

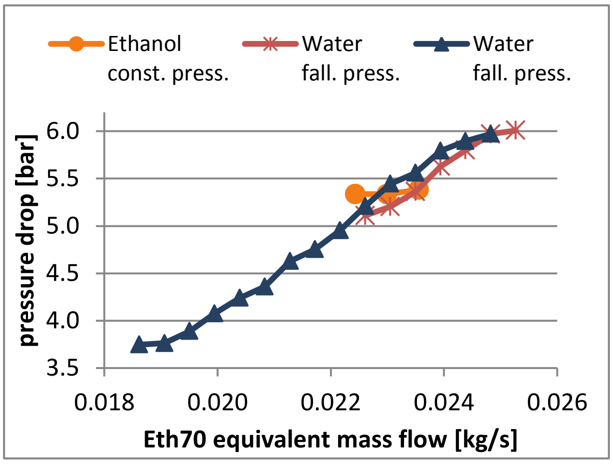

FIG 6 – Measurement results with the ethanol nozzle

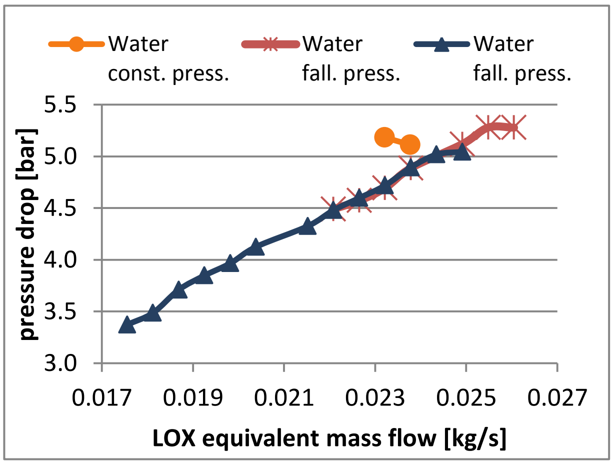

FIG 8 – Measurement results with the LOX nozzle

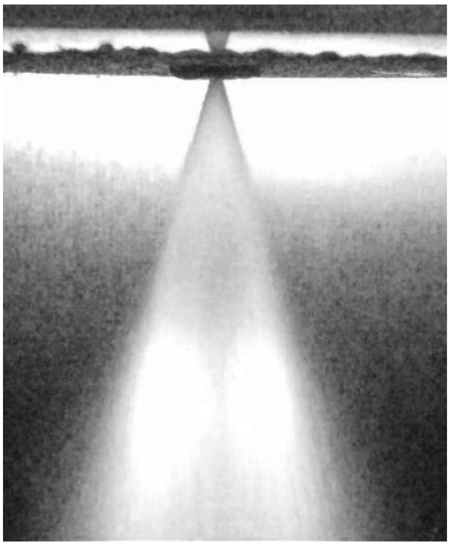

FIG 9 – Spray cone of the LOX nozzle

4. ROCKET ENGINE

The combustion chamber is the heart of every rocket, since this device produces the thrust necessary to get the rocket into the air. Here, the stored energy within the propellants is released through chemical reactions and converted into thermal energy. A portion of this thermal energy is then converted into kinetic energy during the flow of hot gasses through the convergent and divergent part of the chamber nozzle.

As mentioned before, our rocket will be propelled with liquid oxygen and ethanol, which might be thinned with water. First design and problem analyses have been done in several theses. Design and flow analyses have been realised by Wagner [6], Eckhardt [10] and Nowosielski [11]. Hessel [12] investigated the problems of regenerative, Winter [13] the field of radiation cooling. Also a survey of coating materials was done by Schümann [14].

4.1. Current working point

At the beginning of the SRP, a set of parameters for the combustion chamber were chosen, which are oriented on historic rocket engine data using the same propellants. Here, the nominal thrust F, the combustion chamber pressure $\mathrm{p_c}$, the mass flow ratio and the use of water thinned ethanol (70 %-vol.) were defined as set points.

First performance data of the projected rocket engine were obtained with the free software tool “Rocket Propulsion Analyses v.1.2 Lite Edition”, based on the original code of Gordon and McBride [15]. TAB 3 shows the currently used parameters and derived performance results.

parameter	value
nominal thrust F	500 N
chamber pressure $\mathrm{p_c}$	15 bar
mass flow ratio LOX/Eth70	1:1
combustion chamber temperature $\mathrm{T_c}$	2757 K
area ratio ϵ	3
char. velocity c^*	1535 m/s
specific impulse $\mathrm{I_{sp}}$	205 s
mass flow $\dot{\mathrm{m}}$	250 g/s
burn time $\mathrm{t_b}$	20 s

TAB 3 – Parameters and performance of the combustion chamber design at the current working point

4.2. Propellant parameter variations

For further investigation of the performance potential of the rocket engine, a variation analysis of the fuel configuration has been done, again by using the “Rocket Propulsion Analysis” tool. For this analysis, the oxidizer fuel ratio has been varied from 0.4 to 2.4 and the ethanol mass portion within the fuel from 50 % to 100 %.

One of the key performance values of the rocket engine is the generated thrust. E.g. in [16], the following thrust equation can be found:

$$\mathrm{F} = \dot{\mathrm{m}} \cdot \mathrm{C_F} \cdot \mathrm{c}^* \tag{2}$$

It shows that we have to increase the thrust coefficient $\mathrm{C_F}$ and the characteristic velocity c^* in order to minimize the propellant mass flow $\dot{\mathrm{m}}$ for a certain thrust F. The thrust coefficient, which relates the generated thrust to the product of chamber pressure and throat area $\mathrm{A_t}$, is calculated for an ambient pressure matched expansion nozzle as follows [16],[17]:

$$\mathrm{C_F} = \frac{\mathrm{F}}{\mathrm{p_c} \cdot \mathrm{A_t}} = \left\{ \frac{2\,\kappa^2}{\kappa - 1} \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa+1}{\kappa-1}} \left[1 - \left(\frac{\mathrm{p_e}}{\mathrm{p_c}} \right)^{\frac{\kappa-1}{\kappa}} \right] \right\}^{1/2} \tag{3}$$

Hence, it is obvious that the thrust coefficient depends only on the gas type in form of the isentropic exponent κ and the pressure ratio $\mathrm{p_e}/\mathrm{p_c}$ between the pressure of the gas flow at the nozzle exit $\mathrm{p_e}$ and the combustion chamber pressure $\mathrm{p_c}$. Since there is no variation in the pressure ratio and the resulting gas has a minor influence, the thrust coefficient remains nearly constant through the analysis procedure, ranging from 1.35 to 1.37. So the key feature of a performance increase would be the characteristic velocity, which is a measurement of the combustion efficiency [16] and is defined by:

$$\mathrm{c}^* = \left[\frac{1}{\kappa} \left(\frac{\kappa + 1}{2} \right)^{\frac{\kappa+1}{\kappa-1}} \frac{\mathrm{R\,T_c}}{\mathrm{M}} \right]^{1/2} \tag{4}$$

It can be seen that the characteristic velocity is a function of the chamber temperature $\mathrm{T_c}$, the universal gas constant R and the propellant dependent molecular weight M and isentropic exponent κ.

For the reason of completeness, the definition of the specific impulse, which is a hot gas weight flow weighed thrust coefficient, is given with:

(5) $$I_{sp} = \frac{F}{\dot{m} \cdot g_0} = \frac{C_F \cdot c^*}{g_0}$$

With this equation it is obvious that an increase of the characteristic velocity results directly in an increase of the specific impulse, which means a decrease of the necessary mass flow of propellant in order to obtain the desired thrust.

FIG 10 and 11 show the characteristic velocities and the combustion chamber temperatures for the investigated points of the mixture ratio and the ethanol portion within the fuel. It shall be mentioned that fuel with an ethanol volume portion of 70 % has an ethanol mass portion of 62.44 %.

By evaluating the data, it becomes obvious that the characteristic velocity is nearly constant for the investigated values of ethanol concentration within the fuel and a mass ratio of 1:1. It ranges from 1491 to 1539 m/s and is about 90 % of the maximum (1661 m/s) realizable with pure ethanol and a mixture ratio of 1.6 : 1.

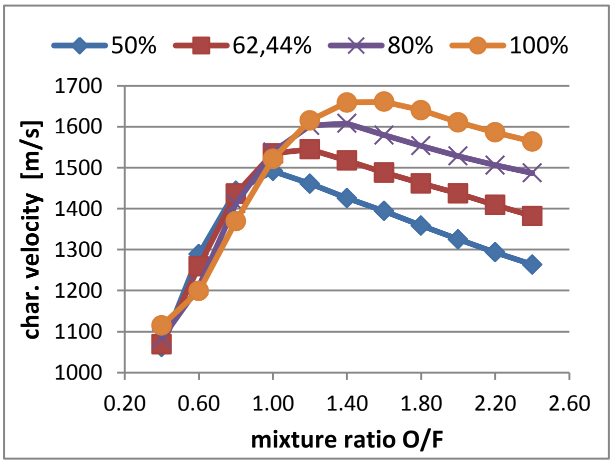

FIG 10 – Characteristic velocity c^* as a function of mixture ratio O/F and ethanol portion

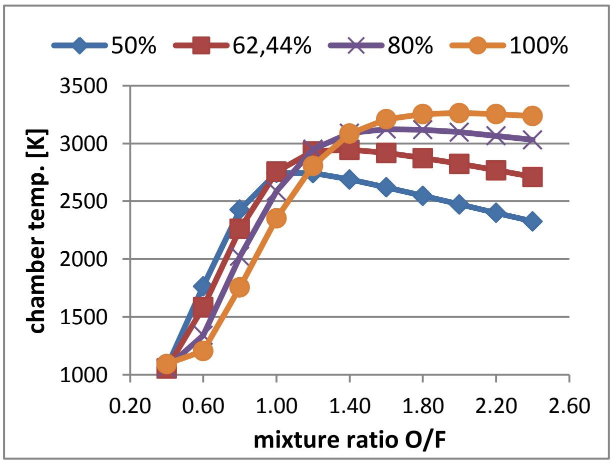

FIG 11 – Combustion chamber temperature T_c as a function of mixture ratio O/F and ethanol portion

On the other hand, the combustion chamber temperature is important. In order to keep the cooling effort as low as possible, the chamber temperature shall be kept lower. Here, for the mixture ratio of 1:1, the temperature can be significantly lowered from 2757 K to 2352 K by using pure ethanol instead of water thinned ethanol. So the temperature could be lowered to 72 % of the maximum chamber temperature (3263 K) obtained with a mixture ratio of 2 : 1 and pure ethanol.

This non intuitive effect of lowering the chamber temperature by using less water within the fuel can be explained with the composition of the hot gasses. During the combustion of Eth70 with LOX in the mixture of 1:1, the hot gas mass consists of 37 % carbon dioxide (CO_2), 15 % carbon monoxide (CO) 48 % water (H_2O) and residues. Using pure ethanol, the combustion gas mass is distributed as follows: 26 % CO_2, 44 % CO, 26 % H_2O and residues. During the combustion process, the formation of CO_2 releases more energy than the formation of CO. Therefore, the combustion with Eth70 converts more chemical into thermal energy than with pure ethanol.

Depending on the thermal strength of the combustion chamber, the current working point will be revised and might be switched to a higher performance working point. This could be done by a change of the ethanol concentration in the fuel as well as the LOX / fuel mixture ratio.

5. OUTLOOK

The upcoming tasks within the SMART Rockets Project are concentrated on a successful Preliminary Design Review (PDR) projected for the second quarter of 2014. The first step will be the achievement of a full operational test bench service to enable the successive execution of the planned test programme described in section 2.3.

Simultaneously the design of the rocket will become more detailed and adapted and the associated infrastructure circumscribed with Ground Support Equipment (GSE) will be finalized and fabricated. Especially, the detailing of components for the propulsion system, the recovery and sensor system, the launch pad and the service tower will be advanced.

Subject to a successful launch campaign of the 500 N rocket, further projects could aim for a realisation of heavier and more powerful versions of the actual rocket. With the gained knowledge most of the existing components could be up-scaled, so that efforts could be stepped up to provide more technical capabilities.

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APPENDIX

Pos.	Description
1	Pressure Regulator
2	Carbon Steel Gasket
3	Tube Fitting, Male Connector
4	Multi-Purpose Push-On Hose End Connection
5	Multi-Purpose Push-On Hose
6	Tube Fitting, Bulkhead Union
7	Tube Fitting, Union Cross
8	Tube Fitting, Union Elbow
9	Copper Gasket
10	2/2-Way solenoid control valve
11	Pressure Regulator
12	Tube Fitting, Union Tee
13	2/2-Way solenoid control valve
14	3/2-Way solenoid control valve
15	Tube Fitting, Male Connector
16	PTFE Tape Thread Sealant
17	3/2-Way solenoid control valve
18	tank inlet adapter ethanol
19	aluminium tank
20	tank outlet adapter
21	Brass Poppet Check Valve
22	Tube Fitting, Female Connector
23	Pressure Sensor
24	Industrial Pressure Gauge
25	SS High-Pressure Proportional Relief Valve, Manual Override Handle
25-A	Fork for Manual Override
26	Blank Plug
27	PTFE-Seal 21x27
28	Tube Fitting, Male Connector
29	Tube Fitting, Female Connector
30	1-Piece Poppet Check Valve, Fixed Pressure
31	Brass Tee-Type Particulate Filter
32	Flow Meter
33	1-Piece 40 Series Ball Valve
34	SS Bellows-Sealed Valve, Gasketed
35	Tube Fitting, Male Connector
36	Tube Fitting, Union Tee
37	Reducer Connector
38	Tank Inlet Adapter LOX
39	Poppet Check Valve, Fixed Pressure
40	Tube Fitting, Port Connector
41	Tube Fitting, Female Connector
42	Cryogenic Safety Valves, angle type
43	SS 1-Piece 40 Series Ball Valve
44	Copper Gasket
45	Cryogenic Filter
46	Tube Fitting, Port Connector
47	Tube Fitting, Union
48	Venturi Tube
49	Wet/Wet Differential Pressure Transducer
50	Cryogenic-Control Valves w. Pneumatic Actuator
51	Tube Fitting, Reducing Union
52	Reducing Union
53	Tube Fitting, Female Connector
54	Tube Fitting, Union
-	1/4 in. Copper Tube
-	1/2 in. Copper Tube

TAB 4 – List of test bench parts

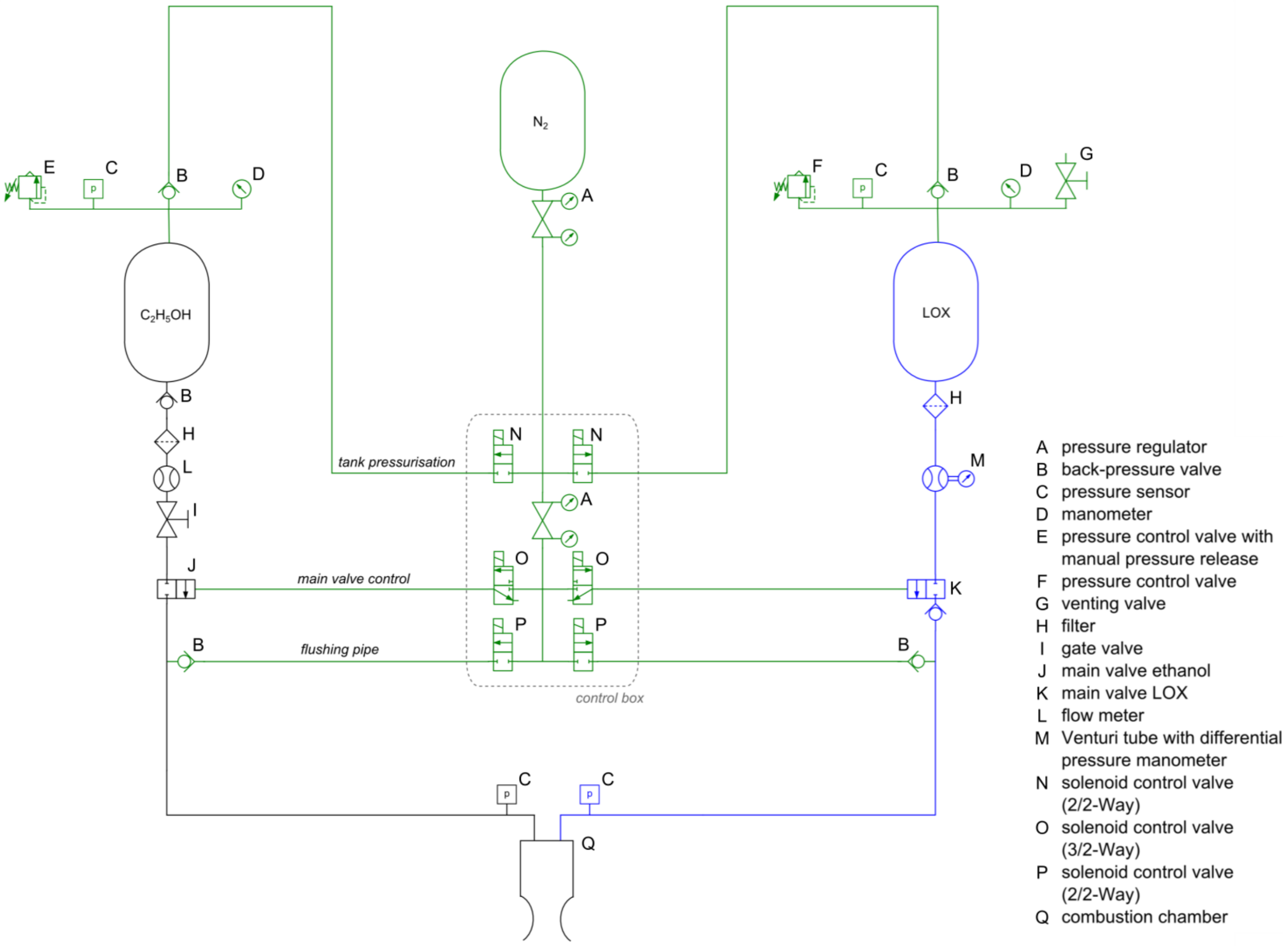


FIG 12 – Schematic diagram of the test bench

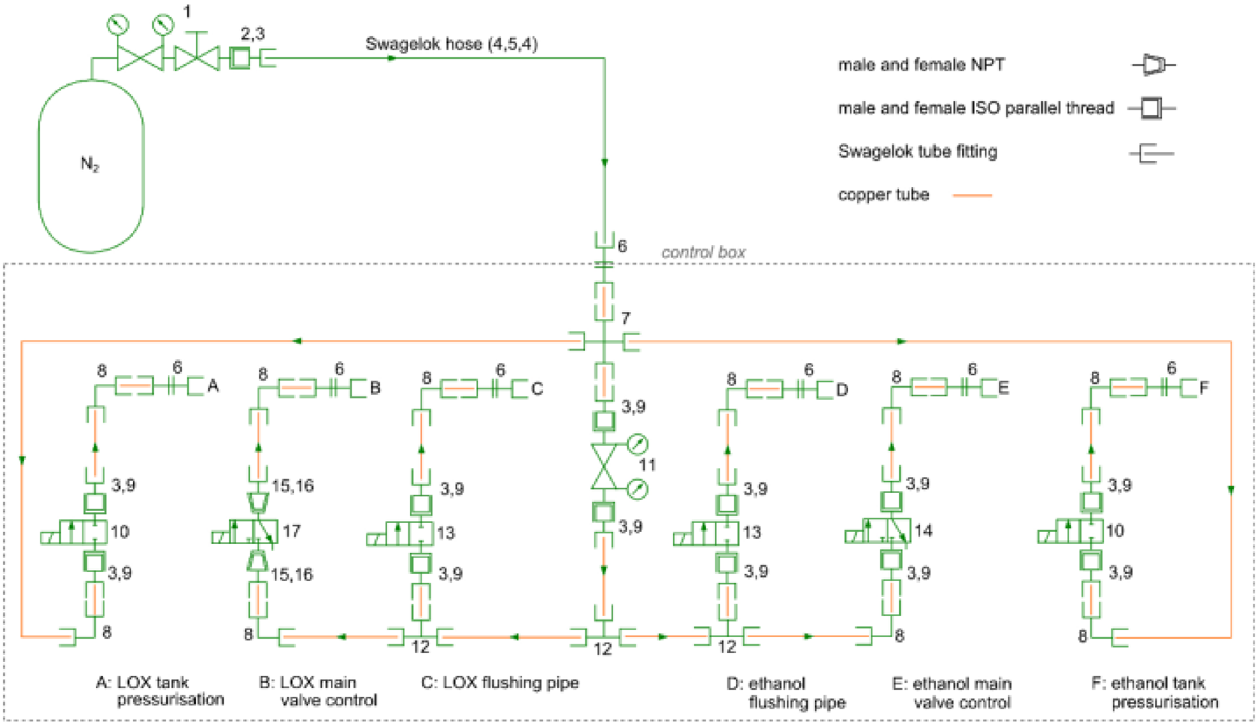
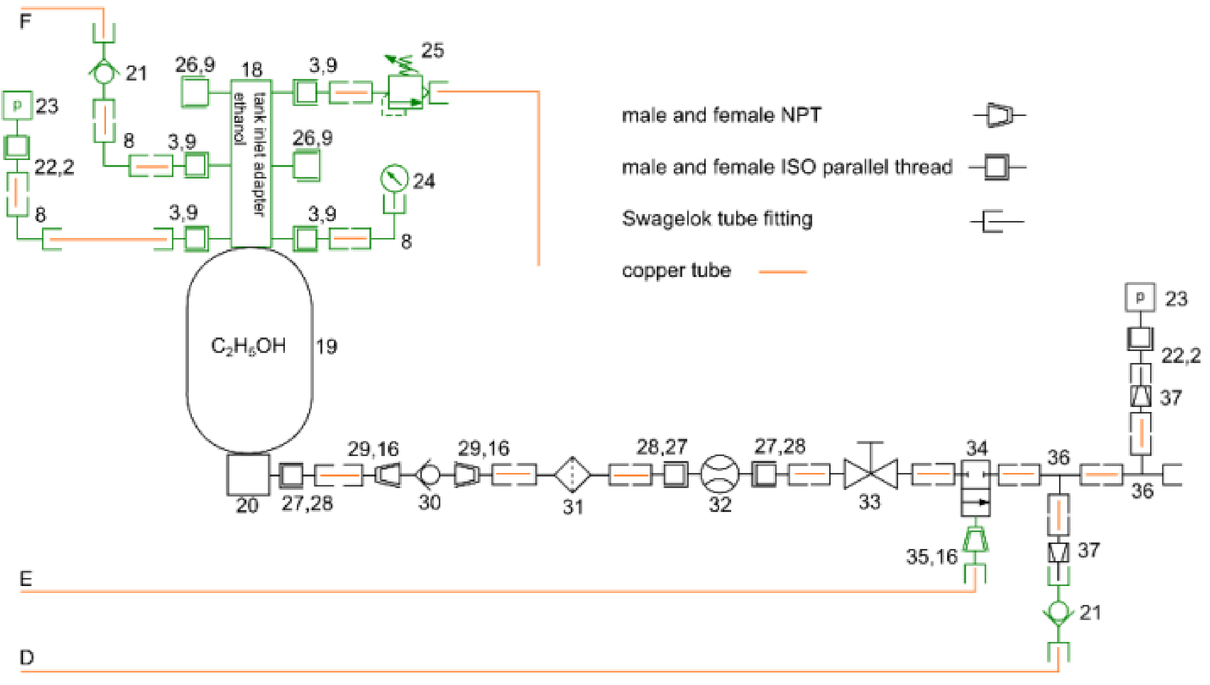
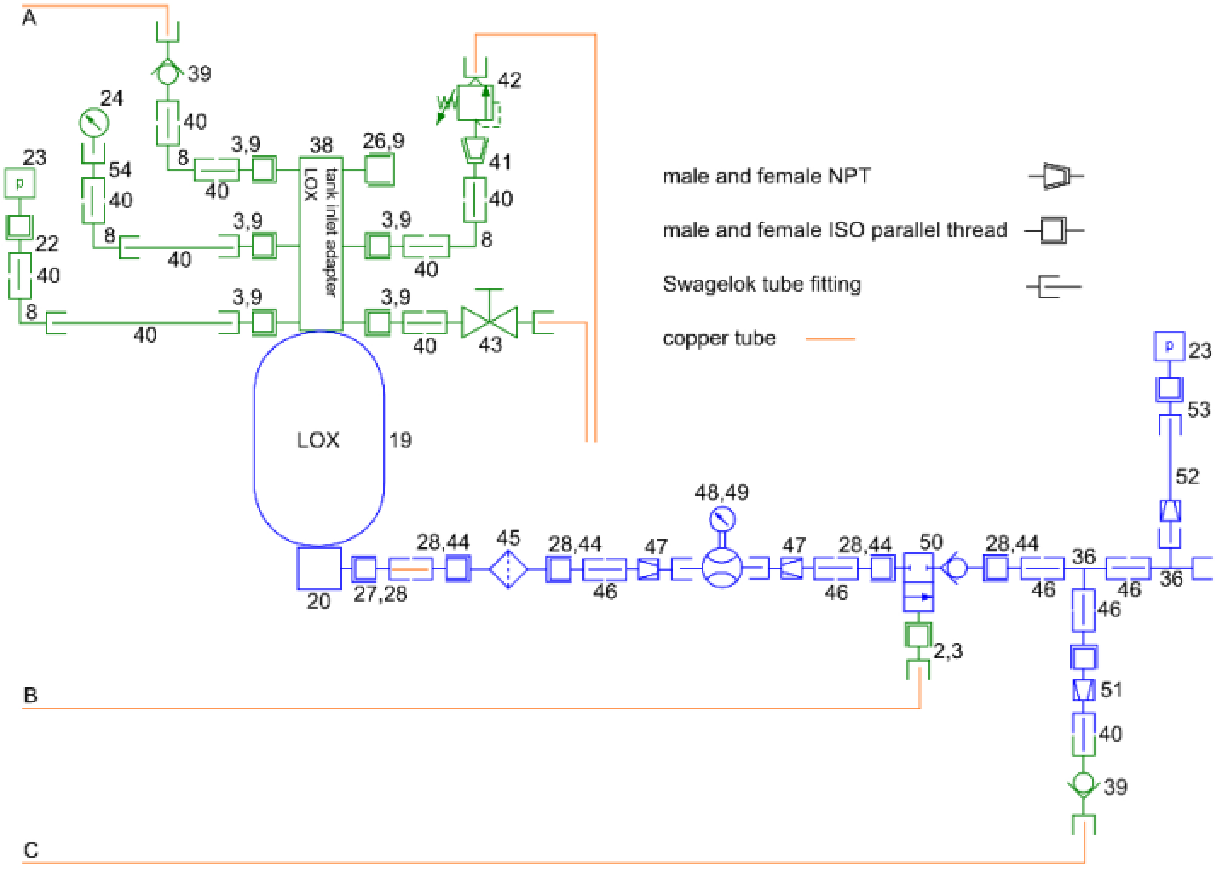


FIG 13 – Schematic diagram of the nitrogen supply pipeline (cf. TAB 4)



D: ethanol flushing pipe E: ethanol main valve control F: ethanol tank pressurisation

FIG 14 – Schematic diagram of the ethanol supply pipeline (cf. TAB 4)



A: LOX tank pressurisation B: LOX main valve control C: LOX flushing pipe

FIG 15 – Schematic diagram of the LOX supply pipeline (cf. TAB 4)