DESIGN OF A VALVE SEGMENT FOR A HYBRID ROCKET ENGINE

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Abstract

This paper deals with the design of a valve segment for the Helios hybrid rocket engine, built by ExperimentalRaumfahrt-InteressenGemeinschaft e.V. (ERIG) for the Leonis project in cooperation with Institute of Aerospace Systems of Technische Universität Braunschweig. In the Leonis project ERIG will develope a supersonic rocket named Regulus for the Studentische Experimental-Raketen program (STERN), which is initiated by the German Aerospace Center (DLR).

Helios is based on a liquid oxidizer and a solid fuel grain. A valve segment is needed to connect the oxidizer vessel with the combustion chamber. This valve segment is responsible for some crucial features of Helios such as regulation of the mass flow from oxidizer vessel to the combustion chamber. Especially because of the high mass flow per second, the requirement for a light design and the integration of several features a new valve segment is designed. Thus different concepts of switching are compared e.g. hybrid, electromagnetical and pyrotechnical. The results of this study and the final design of the valve segment are presented in this paper.

1. INTRODUCTION

ExperimentalRaumfahrt-InteressenGemeinschaft e.V. (ERIG) student group gets professional support by Studentische Experimental-Raketen (STERN) program from German Aerospace Center (DLR). Within this program German students design and launch their own hypersonic rockets with self-made rocket engines. One objective of this program is to top the European altitude record for non-professionals of 12.55 km. ERIG e.V. is also supported by the Institute of Aerospace Systems at Technische Universität Braunschweig.

For the expansion of experience with hybrid rocket engines ERIG e.V. established the Leonis project to construct their own Helios hybrid rocket engine for their own Regulus rocket of the STERN program. Previous studys developed parts of the combustion chamber with the solid fuel grain [1][2]. Now a lightweight valve segment for the Regulus rocket is needed to fulfill the high mass flow rate supply of the combustion chamber with the liquid oxidizer. The designing process of this valve segment is described in this study. Therefore a short introduction to the design of the Regulus rocket is given at first. Afterwards the requirements to this valve segment are listed and different concepts are presented and compared. Finally the best design was chosen and described more in detail.

2. THE REGULUS ROCKET

The draft of the Regulus rocket is shown in figure 1. The Helios engine of the Regulus rocket consists of a pressure vessel, an oxidizer vessel, the valve segments between the vessels and a combustion chamber. Nitrous oxide is used as liquid oxidizer for the engine and a mixture of Hydroxyl-terminated polybutadiene (HTPB) with some metal additives as solid fuel. Due to such a combination of two different types of propellants, it offers more advantages in comparison to only solid or only liquid rocket engines. Unlike a solid engine a hybrid engine can be shut down in case of emergency by cutting off the oxidizer supply. In contrast to commonly used liquid hydrogen/oxygen engine the nitrous oxide does not need

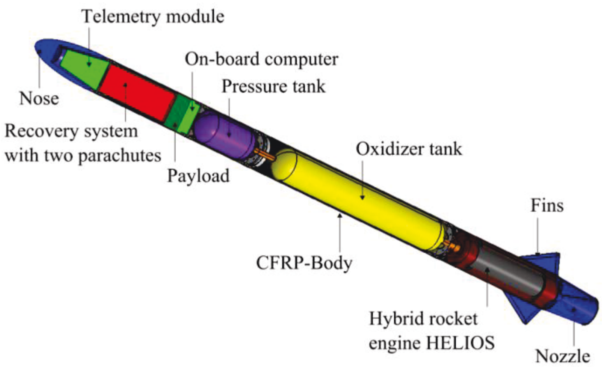

FIG 1. Draft of the Regulus rocket

a complex cryogenic storage. The development of Helios is based on gained experience by the ERIG in designing, building and hot-fire testing of the previous hybrid rocket engine series HYDRA [3]. The Leonis project began in 2012 with the development of the Regulus rocket and Helios engine. Several achievements have been made since then e.g. design of the nozzle [2], injector [1] and oxidizer vessel. Now a valve segment is developed to supply the combustion chamber with a nitrous oxide mass flow of about 2 kg/s so that the total Helios engine can perform a thrust of about 5000 N to top the European altitude record for non-professionals of 12.55 km.

3. REQUIREMENTS FOR THE DESIGN OF THE VALVE SEGMENT

The main requirements to the valve segment are listed in the following. Afterwards the two main mechanical requirements are described more in detail in different subsections.

1) Safety: An operational safety has to be guaranteed to avoid accidents and injuries to human life. Therefore an automatic opening mechanism shall be used. Furthermore a manual assembly of pyrotechnical material is prohibited.

2) Functionality: The valve should allow a mass flow of 2 kg/s of nitrous oxide. Furthermore an emergency release valve and a valve for the refilling of the oxidizer vessel is needed in addition to the switching feature for the supply of the combustion chamber.

3) Design: The design has to be simple and robust to increase reliability. An in-house production of some parts of the valve segment shall be preferred, which reduces the costs.

4) Weight and size: The structural weight has a negative impact on the maximum reachable altitude of Regulus. The higher the weight the lower is the reachable altitude as a consequence. Therefore weight should be as low as possible. According to the given objective regarding the size of Regulus the outer diameter of the valve segment may not exceed 180 mm.

5) Manufacturing costs: Manufacturing costs must be kept low without a negative impact on the quality.

3.1. Cavitation

When the static pressure of a fluid drops under its vapor pressure, the fluid begins to vaporize. Thus it creates so called cavitation bubbles, which collapse near the pipe wall and cause structural damages. This phenomenon is known as cavitation. It can occur for example in pipes, valves and turbo machineries. As mentioned in the previous chapter the valve segment will be responsible for the oxidizer supply. Therefore the focus will be on the thermophysical properties of nitrous oxide. The prevailing temperature in the valve segment can be assumed according to ERIG's experience. It will be around 273-268 K. With this evidence the vapor pressure of nitrous oxide can be determined, which will be approximately 37 bar for 273 K and 33 bar for 268 K [11]. This pressure has to be ensured throughout the valve segment to avoid cavitation. Considering the expected low pressure loss the fluid will be mostly liquid. Therefore it can be assumed that it is incompressible and thus the Bernoulli's principle [4] can be applied. In consideration of viscous losses in the pipe e.g. due to friction the equation 1 is used to calculate the resulting pressure.

(1) $p_2 = \frac{\rho}{2} \cdot v_1^2 + p_1 - \Delta p - \frac{\rho}{2} \cdot v_2^2$

3.2. Structural mechanics

The oxidizer nitrous oxide with its high pressure of about 50 bar can cause structural damages like deformation or deflection in the valve segment. These damages occur as a consequence of stress generated by the internal pressure. To avoid yielding of material a strength test is essential. The thin-walled vessel theory [5] is applied to determine the occurring stress in the valve segment, because the expected ratio of outer radius to inner radius $\frac{r_a}{r_i}$ is smaller than 1.2. Furthermore it can be assumed that the stress is constant throughout the wall-thickness. Three different kinds of stress longitudinal, radial and tangential stress appear in the cylindrical object subjected to an internal pressure. Radial stress is equivalent to the internal pressure in the inner side of the pipe and has no influence on the outer side. It is only the 1/10 of tangential stress for r_t > 10. Thus it is negligible. Equation 2 is applied for calculating the longitudinal stress and equation 3 is used for tangential stress.

(2) $\sigma_a = \frac{p \cdot r}{2 \cdot t}$

(3) $\sigma_t = \frac{p \cdot r}{t}$

4. DIFFERENT SWITCHING CONCEPTS

Three concepts for the switching of the valve segment, which meet the mentioned criteria, are described briefly as follows.

4.1. Concept A

Concept A uses two pyro actuators to open the valve. The upper pyro actuator is marked as 1 in figure 2. The incoming oxidizer is shown by red arrows has a pressure of 50 bar. Therefore it must be ensured that the valve is completely sealed. Additionally a compressed spring marked as 4 is applying a force shown as black arrows, which closes the valve. This force can be easily determined by choosing a spring with the right spring constant and the desired length. To open the valve the pyro actuators provide enough force to move the piston marked as 2, which locks down in the area marked as 3 to ensure an unrestricted flow of nitrous oxide.

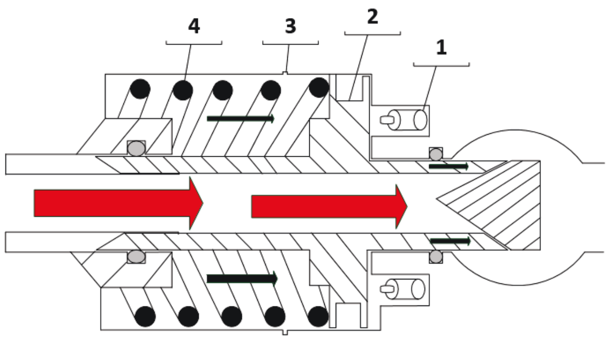

FIG 2. Pyrotechnical switching concept

4.2. Concept B

In this concept two carbon dioxide cartridges will be installed instead of pyro actuators to open the valve. The used cartridges contain carbon dioxide with a pressure of about 50 bar. This pressure will be used to move the piston and allow an unrestricted flow of nitrous oxide. An electric motor marked as 1 in figure 3 is connected with a metal sheet, which is marked as 2. This electric motor provides the driving force to move the metal sheet vertically to release the compression spring, which is marked as 3, to open the cartridges. The other parts of this design are identical to concept A.

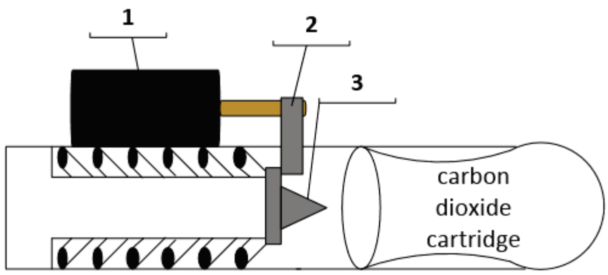

FIG 3. Hybrid switching concept

4.3. Concept C

Two electric motors will be used in this concept to open the valve. The upper electric motor is marked as 1 in figure 4. These electric motors are connected to a piston, which is marked as 2. The driving force of the electric motors will be used to move the piston and open the valve. The advantage of this concept is that the piston is arranged in a way that it just has to be moved against a small pressured surface. Thus it allows a use of a small electric motor with less power than the spring in the other concepts.

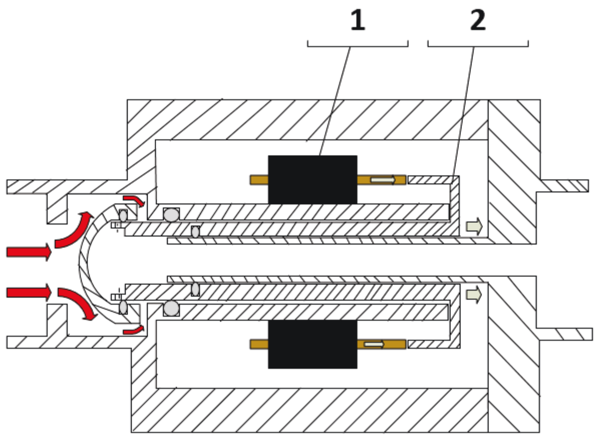

FIG 4. Electromagnetical switching concept

5. EVALUATION OF CONCEPTS

The proposed concepts will be examined so that a concept, which is most suitable, can be selected. Because of the high amount of conditions and criteria the Zangemeister Decision-matrix method [6] will be applied. Each criteria is scored with 10 points, if the concepts meets it properly. Otherwise points will be deducted. The criteria are weighted according to their priority. High energetic substances like HTPB and nitrous oxide are used in the Regulus rocket engine. As a result safety and functionality are essential. Design, weight and size are ranked second and manufacturing costs third. The table 1 shows the criteria with their weighting factor. At first each concept will be evaluated according to equation 4 to calculate the final score of the concept. The higher the score the better is the concept.

(4) $S_i = \sum_{j=1}^{k} G_i \cdot P_i$

Criteria	$G_{weighting\ factor}$	P_{points}
Safety	5	10
Functionality	5	10
Design	3	10
Weight and size	3	10
Manufacturing costs	2	10

TAB 1. Weighting of criteria for the concepts

5.1. Evaluation of concept A

1) Safety: Pyrotechnics in a rocket engine can be life-threatening in consideration of used high energetic substances. Life claiming accidents had happened in the past at launch past.

2) Functionality: The demanded opening force can be produced by the pyro actuators. Because there are several pyro actuators available with different amount of pyrogen.

3) Design: This concept has a complicated design, which will raise the manufacturing costs.

4) Weight and size: The pyro actuators are available in small size and their weight is very low.

5) Manufacturing costs: The high constructional effort will increase the manufacturing costs.

5.2. Evaluation of concept B

1) Safety: There are no safety concerns regarding the use of carbon dioxide cartridges.

2) Functionality: The carbon dioxide cartridges are available in different sizes e.g. 12 g, 18 g and 32 g. Therefore it can be guaranteed that enough pressure is produced to open the valve.

3) Design: The proposed design of this concept is relatively complicated. Drilling the holes to install the carbon dioxide cartridges will be challenging.

4) Weight and size: Due to their low weight and small size the carbon dioxide cartridges are suitable for installation in small devices such as valve.

5) Manufacturing costs: The manufacturing cost will be enormous due to the complicated design, although the cartridges are not expensive.

5.3. Evaluation of concept C

1) Safety: The use of dangerous substances is avoided in this concept. Thus there are no safety concerns.

2) Functionality: This concept has a reliable and simple functionality.

3) Design: The technical feasibility of this concept in increased by the simple design.

4) Weight and size: The electric motors have low weight and small size. Thus this criteria is met properly by the electromagnetical switching concept.

5) Manufacturing costs: The high constructional effort will increase the manufacturing costs.

The evaluation of the concepts is given in table 2.

Criteria	A	B	C
Safety	5	10	10
Functionality	10	10	10
Design	6	4	8
Weight and size	10	10	10
Manufacturing costs	6	4	8

TAB 2. Evaluation of the designed concepts

The theoretical best achievable scores are 180 points. The table 3 is showing the score of the concepts according to Zangemeister Decision-matrix method.

Concept	$S_i = \sum_{j=1}^{k} G_i \cdot P_i$
A	135
B	150
C	170

TAB 3. Final score of concepts according to Zangemeister Decision-matrix method

The electromagnetical switching concept achieved the highest score. Thus this concept is selected on the basis of advantages like simple design, technical feasibility and possibility of closure by moving the piston backward through the electric motors.

6. DETAILED DESIGN

6.1. Material

Two materials which are suitable for the valve construction are X12Cr13 and AlMgSi0.5. Other materials are either too expensive or not suitable for use of nitrous oxide under high pressure. X12Cr13 is a stainless steel with some good qualities such as good corrosion and abrasion resistance, high static and dynamic strength. Furthermore it is suitable for all common welding methods. AlMgSi0.5 is an aluminum alloy containing magnesium and silicium additives. They are used to increase the strength. This material has a high weldability and corrosion resistance.

With the evidence about the density and yield strength of the material [9] the specific strength $R_{specific} = \frac{\sigma}{\rho}$ can be calculated. $R_{specific}$ is strength per density ratio. It is important to keep the weight of Regulus low. Therefore the material of the valve segment should have a high specific strength. AlMgSi0.5 has a specific strength of 0.059 $\frac{N/mm^2}{kg/m^3}$ and X12Cr13 of about 0.058 $\frac{N/mm^2}{kg/m^3}$. The specific strength of both materials is similar. Furthermore they have good weldability and corrosion resistance. Therefore the selection of a material cannot be made at this stage. Further information e.g. roughness factor and its impact on pressure loss and friction is needed for an unambiguous decision.

6.2. Main valve

The main valve which will open or close the oxidizer mass flow is designed based on the selected concept as shown in figure 5.

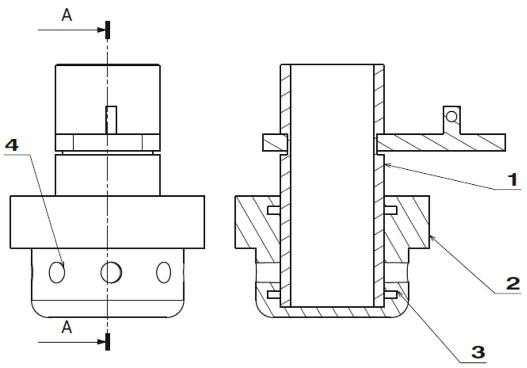

FIG 5. Design of the main valve

The pressure in a pipe flow can be calculated with Bernoulli's principle. In consideration of viscous losses in the pipe e.g. due to friction equation 1 will be applied to calculate the resulting pressure. The main valve consists of two parts, which are marked as 1 (piston) and 2 (the casing) in figure 5. The casing contains the inlet holes 4 for the oxidizer supply and the seal groove 3.

Streamline 0 → 1

Following conditions are defined for the streamline 0→1 to examine the pressure p_1 at the end of the streamline.

0: The valve is closed and as a result there is no mass flow through the holes.

1: The valve opens and the nitrous oxide begins to flow with p_1 = 50 bar through the holes as shown in figure 6.

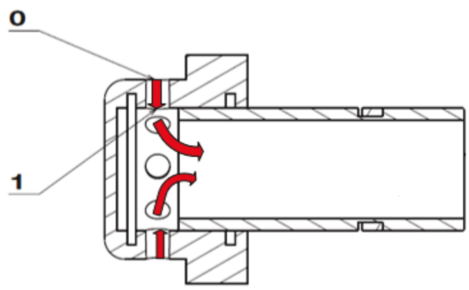

FIG 6. Streamline 0→ 1 in the main valve

The velocity v_1 is determined with the help of the mass balance in equation 5. Furthermore the number of holes is n and the relevant density of nitrous oxide is 982 kg/m³.

(5) $$v_1 = \frac{\dot{m}_1}{\rho \cdot \left(n \cdot \frac{\pi}{4} (d_1)^2\right)} = 6.6\ m/s$$

The pressure loss Δp is calculated with equation 6. The relevant velocity for equation 6 is v_1. The loss coefficient ζ is a dimensionless number which depends on the geometry of the pipe. In this case it has a sudden contraction. Thus the loss coefficient ζ is 0.2 [4]. The friction factor λ is determined with moody diagram with the evidence about Reynolds number which is about 640,000 and the roughness number k [12] of the material. AlMgSi0.5 has a k of 0.0015 mm and X12Cr13 of 0.06 mm. The friction factor λ for AlMgSi0.5 is 0.0134 and for X12Cr13 it is 0.04. The pressure loss based on the geometry is equal for the both materials. Stainless steel X12Cr13 will cause a high pressure loss considering the high roughness of this material as compared to aluminum alloy. Thus the pressure loss is only calculated for this material. The pressure p_1 for stainless steel X12Cr13 at the end of the streamline 0→ 1 is 49.7 bar.

(6) $$\Delta p_{X12Cr13} = \left(\zeta + \lambda \cdot \frac{l}{d}\right) \cdot \frac{v_1^2}{2} \cdot \rho = 0.05\ bar$$

Streamline 1 → 2

The pressure p_2 is determined through a further streamline 1 → 2 as shown in figure 7.

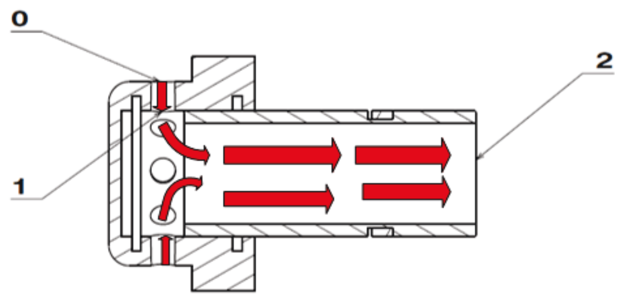

FIG 7. Streamline 1→ 2 in the main valve

The velocity v_2 is 4.5 m/s. It is determined with the evidence about conservation of quantity. The incoming mass flux $\dot{m}_1$ is equal to outgoing mass flux $\dot{m}_2$ and the density does not change. The required diameter d_2 is 24 mm. The pressure loss Δp is 0.012 bar for X12Cr13 for the length l is 70 mm, ζ is 1.1. The resulting pressure p_2 is 49.5 bar. This pressure is much higher than the required pressure for avoiding evaporation of nitrous oxide.

6.3. Seals

To prevent leakage of nitrous oxide the valve has to be sealed. An O-ring, which is the most used seal in the mechanical industry, is not suitable for the given dynamic application with high pressurized flow. Therefore a c-ring seal will be used, which consists of a high performance PTFE-compound cover and a corrosion-resistant stainless steel spring, which is integrated in cover and ensures a good sealing. Furthermore these seals have a very good chemical resistance and they can be used for dynamic applications till 500 bar and 25-633 K.

The friction caused by the seals has to be exceeded to open the valve. This friction depends on the size of the seal. Thus seals in different sizes are examined and a suitable one is selected. The following headwords are the advantages and disadvantages of both sizes.

Large seals:

1) Low manufacturing costs +
2) High material removal -
3) High friction -
4) Easy installment +

Small seals:

1) High surface quality required -
2) High manufacturing costs -
3) Low friction +
4) Low tolerance between the seal groove and seal –

Large seals offer more advantages than the small seals. But they produce high friction, which is essential for the selection of the seal, because the friction determines the required opening force. The required opening force for both material combination X12Cr13-PTFE and AlMgSi0.5-PTFE are given in table 4.

Nominal size of seals	X12Cr13-PTFE	AlMgSi0.5-PTFE
1/16”	23 N	172 N
3/32”	37 N	277 N
1/8”	50 N	375 N

TAB 4. Required opening force for a single seal

The material AlMgSi0.5 can be ruled out due to the high required opening force for the material combination AlMgSi0.5-PTFE, because the servo motor, which will be used as a driving force to open the main valve provides a force about 190 N. Other advantages for the use of stainless steel are higher yield strength $R_{p,0.2}$ [9] which is 250 N/mm² and aluminum alloy has only a yield strength of 120 N/mm², suitability for all common welding methods and lower costs.

Three seals are required to seal the main valve. As a result the seal with nominal size of 1/16" will require an opening force of F_{open} > 69 N, 3/32" needs F_{open} > 111 N and 1/8" F_{open} > 150 N. The opening safety factor S_{open} for seal with nominal size of 1/16" is 2.75, for 3/32" 1.7 and for 1/8" 1.2. The smallest seal has the highest opening safety factor. But considering the other disadvantages for the use of the seal in this size e.g. low tolerance between the seal groove and seal, higher surface quality and higher manufacturing costs the seal with nominal size of 3/32" is selected. It has a high opening safety factor of 1.7 as compared to the largest size and low manufacturing costs as compared to smallest seal.

6.4. Emergency release valve

The emergency release valve will be used to avoid unpredictable problems at the launch pad. It is designed according to the same concept as the main valve as shown in figure 8.

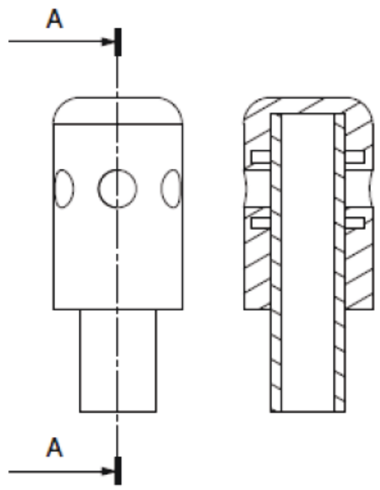

FIG 8. Design of the emergency release valve

The parameters velocity v_1, v_2, resulting pressure p_1, p_2, pressure loss Δp_1, Δp_2, are given in the table 5. The resulting pressure p_2 is much higher than the required pressure of p > 33-37 bar. The required opening force for the emergency release valve is 63 N for using two seals with a nominal size of 3/32". Thus the opening safety factor by using a servo motor is 3.0.

v_1	8.8 m/s	v_2	26 m/s
Δp_1	0.2 bar	Δp_2	0.91 bar
p_1	49.5 bar	Δp_2	45.4 bar

TAB 5. Flow characteristics in emergency release valve

6.5. Refilling connection

A further part of the valve segment is the refilling connection, which supplies the oxidizer vessel with nitrous oxide. This fueling connection is connected with a hydraulic coupling with a G 1/4" internal thread. Thus a refilling connection with a G 1/4" outer thread is designed as shown in figure 9. The side marked with 1 is connected to the hydraulic coupling and side 2 with the valve segment.

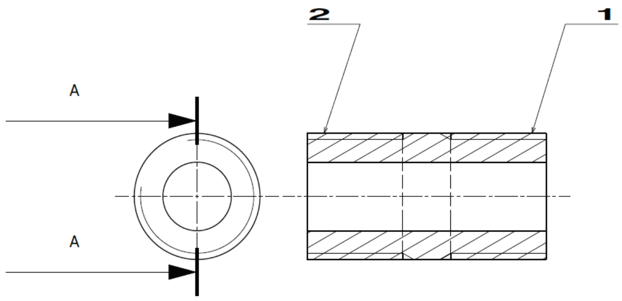

FIG 9. Design of refilling connection

6.6. Non-return valve

To prevent a back flow from the combustion chamber, in case of pressure increase after the main valve by the combustion, a non-return valve is required. To spare time and money a suitable non-return valve was searched, which should be bought. Therefore the valve coefficient C_v [13] has to be determined with equation 7. C_v is used for designing a valve. The size of the valve and the regulation of mass flow is determined with this coefficient. Calculating the right C_v is essential. Otherwise the needed performance for the particular application cannot be achieved and a too small C_v can lead to high pressure drop.

$$(7)\quad C_v = \dot{V} \cdot \sqrt{\frac{\rho}{1000 \cdot \Delta p}}$$

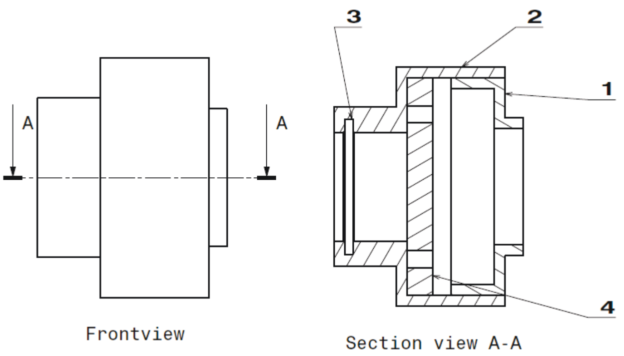

FIG 10. Design of non-return valve

The required C_v is 7.2 m³/h for the given volume flow $\dot{V}$ of $2.03 \cdot 10^{-3}$ m³/s and the pressure difference Δp of approximately 1 bar between the front and backside of the non-return valve. After an extensive search a suitable non-return valve for the required valve coefficient with low weight, small size and low cost could not be found. Thus a non-return valve as shown in figure 10 is designed. The designed non-return valve consists of three parts: combustion chamber connection 1, casing 2, which has a seal groove 3 and an internal disk 4. The functionality of the non-return valve is shown in figure 11. The non-return valve allows a mass flow of nitrous oxide through the holes of the internal disk, if the pressure p_1 is higher than the pressure p_2. In case of a pressure increase by the combustion, the mass flow is cut off through the internal disk, which contains 8 holes with a diameter of 4 mm to allow an unrestricted mass flow of 2 kg/s.

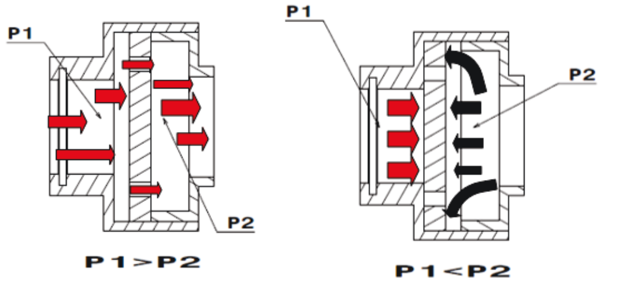

FIG 11. Functionality of the non-return valve

6.7. Assembly

Due to limited space the main valve, emergency release valve, non-return and the fueling connection are assembled in the following order as shown in figure 12.

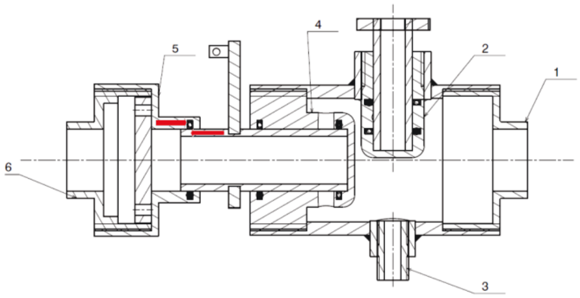

FIG 12. Assembly of the valve segment

Explanation of assembly of valve segment in figure 12:

1) Oxidizer vessel connection
2) Emergency release valve
3) Refilling connection
4) Main valve
5) Non-return valve
6) Combustion chamber connection

The outer part of the emergency release valve and the outer part of the refueling connection are welded with the casing of the valve segment as shown in figure 12. For the strength test [9] the permissible bending stress $\sigma_{w,Fb}$ and the compressive-tensile stress $\sigma_{w,Fzd}$ are calculated for the selected material X12Cr13. The equation 8 is used to determine the Mises stress [5], which consists of longitudinal σ_a and tangential stress σ_t.

$$(8)\quad \sigma_v = \sqrt{\sigma_a{}^2 + \sigma_t{}^2 - \sigma_a \cdot \sigma_t}$$

The results for the strength test with the safety factors are given in table 6.

$\sigma_{w,Fb}$	$\sigma_{w,Fzd}$	σ_v	$S_{w,Fb}$	$S_{w,Fzd}$
200 N/mm²	200 N/mm²	19 N/mm²	10	10

TAB 6. Results of the strength test

Whitworth pipe thread according to DIN EN 10226-1 is used for assembling the other parts of the valve segment as shown in figure 12.

6.8. Expansion joint

An expansion joint is used to compensate the movements in the pipelines, in particular for thermal length variations, vibrations, wall penetrations or subsidence. In the valve segment the function of the expansion joint is to avoid a double fitting of the outer CFRP rocket casing, which transmits the thrust forces to the upper part of the rocket, and the inner valve segment. To keep the design simple and reliable the piston of the main valve and the non-return valve will be used an expansion joint as shown by red arrows in figure 12.

6.9. Final design with driving system

The final design of the valve segments with all components including the two servo motors for open the main valve and emergency release valve is shown in figure 13.

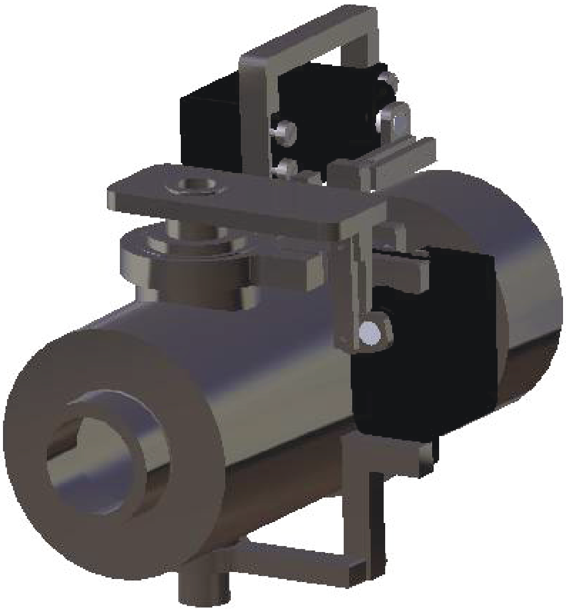

FIG 13. Valve segment with driving system

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