DEVELOPMENT OF A HIGH-PRECISION CRYOGENIC E-MOTOR REGULATION VALVE

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Abstract

Cryogenic fluids, such as liquid oxygen and liquid hydrogen, are critical to the propulsion and power systems of aerospace vehicles. Accurate and precise regulation of these fluids is essential for reliable and safe operation. In this paper, we present the development of a novel lightweight, electric motor driven regulation valve designed specifically for use with cryogenic fluids. Such regulation valves are highly relevant for the application as chamber and feed valves in liquid rocket propulsion and hydrogen aviation.

The valve presented in this paper is developed specifically for application as both chamber and feed valves for a cryogenic in-space propulsion system. The valve consists of a brushless DC motor actuator and a control system. The rotation of the motor is transformed into precise translational positioning of the valve poppet by a lubricant-free ball screw spindle gear to achieve high accuracy and resolution. The valve is capable of operating in very wide temperature ranges (20 K up to 400 K) and moderate pressures of 60bar. The control system is either an open-loop or closed-loop system that continuously monitors the position of the regulating valve and adjusts it as necessary to maintain a desired flow rate. The architecture of the valve is described in detail. An emphasis is placed on the adaptability of the design for either low-pressure high mass flow or high-pressure low mass flow applications with little design effort.

To validate the performance of single components and the entire system in the relevant conditions, a series of development tests was conducted and is presented in this paper.

In summary, this paper demonstrates the flexibility and performance of the product and electric motorized regulation valves in general for aerospace fluid systems by describing the design and development process of one product specialized for cryogenic regulation applications in aerospace.

Keywords

Cryogenic liquid aerospace propulsion, electrification, valves and regulators, tank pressurization

NOMENCLATURE

Abbreviations

BLDC	Brushless direct current
CAD	Computer aided design
CAN	Controller area network
COTS	Commercial off the shelf
ECSS	European Cooperation for Space Standardization
LHe	Liquid helium
LN2	Liquid nitrogen
LVDT	Linear variable differential transformer
MFV	Main fuel valve
MOV	Main oxidizer valve
MxV	Main feed valves (oxidizer or fuel)
NASA	National Aeronautics and Space Administration
PCB	Printed circuit board
SSME	Space Shuttle Main Engine
TEC	The Exploration Company
TLN2	Liquid nitrogen temperature (77 K)

1. INTRODUCTION

An electric regulation valve allows for flexible adjustment of flow and/or pressure parameters within a fluidic system without the need of power sources other than electric power. Consequently, electric regulation valves enable fluid system designers to tune the system towards several operational cases. At the same time, system complexity can be reduced since no supporting system is required as it would be the case for pneumatic or hydraulic regulation valves. This allows for potential mass and cost decrease of

the architecture while increasing reliability.
The most prominent use case of regulation valves in a flying vehicle is the modulation of engine thrust within a chemical or hybrid propulsion system. This can be the thrust of an aircraft during its various operational scenarios. Another case is the soft-landing procedure of a rocket stage or spacecraft. Particularly the latter one requires high precision of the valve in terms of accuracy and resolution to master the sensitive manoeuvre. Additional dimensions of complexity are added when cryogenic propellants are utilized, and the operation demands for high mass flow rates to achieve the requested levels of thrust.
This paper summarizes the development status of a cryogenic, high-pressure, high-mass flow, e-motor driven regulation valve for aeronautics and aerospace systems within the German space and deep-tech startup deltaVision GmbH. Such a product is not yet commercially available on a global scale and will potentially disrupt the domain of cryogenic flow control in aerospace. The principal application of this embedded product is the NYX moon spacecraft of the German-French start-up The Exploration Company (TEC).
In this paper, firstly, the context of the operational valve requirements will be described. Secondly, the selected product architecture to meet those requirements will be presented. Thirdly, a status on the product development and verification will be summarized, before giving an outlook on product maturation and exploitation.

2. OPERATIONAL REQUIREMENTS AND SCENARIOS

Within the NYX moon propulsion system, the outlined regulation valve will serve as the Main Valve (referred to as MxV) for both the liquid methane (MFV) and the liquid oxygen (MOV) fluidic branches. Its principal purpose is to control the flow of both propellants into the Huracan engine´s combustion chamber. One valve design shall support the operational conditions for both branches, which leads to a broad range of operational requirements. A very wide throttle range in terms of engine thrust is requested to assure spacecraft mission success. The valves will not only be crucial for throttle ability in steady state operation but also control fluid flow during the engine transients (start-up and shut-down). Complex liquid propellant engines usually have complex transients (for example the Space Shuttle main engine (SSME) [1]) that rely on the predictable and repeatable actuation of the engine regulation valves. In summary, the valves need to regulate a large mass flow in engine steady-state operation and move precisely, repeatable and quickly during engine transients. Furthermore, a regulation valve enables control of pressure transients like water hammer and allows for smooth chill-down of the fluid system before operation by opening a small fraction of the valve.

The requirements for the intended application are listed in Table 1. The temperature requirement of this application reflects the temperatures of liquid methane and oxygen. However, the valve is designed with operation with liquid hydrogen and helium in mind. The minimal operation temperature of the current design is 20 K and a design adaption for liquid helium (4 K) is in development.

TAB 1. Operational requirements of the valve

Requirement	Value	Unit
Media Temperature	90-440	K
Maximum operation pressure	60	bar
Opening and closing time	< 500	ms
Effective flow area range	0-180	mm^2
Flow coefficient range (Kv)	0-9.5	$m^3\,h^{-1}$
Internal leakage at 293 K	1E-02	$mbar\,L\,s^{-1}$ He
Internal leakage at 77 K	1E-01	$mbar\,L\,s^{-1}$ He
Life cycles (full open / close)	> 1000	-
Peak power consumption	300	W
Continuous power consumption	50	W

3. DEVELOPMENT LOGIC

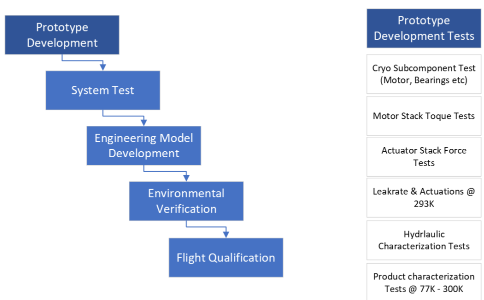

FIG 1. Visualization of the development logic (left) and the approach to development tests (right)

The regulation valve development logic follows a two-step design approach before entering into product flight certification tests. The major differences of the two model definition (prototype and engineering model) are the following:

- Upgrade of automotive graded PCB to space rated PCB
- Replacement of COTS BLDC motor to dedicated cryogenic compatible in-house design

Further improvements on sealing performance and mechanical performance are expected based on the

TAB 2. **Mass and size envelope of the valve.**

Feature	Value	Unit
Physical dimensions	133 x 68 x 68	mm^3
including electronics	148 x 104 x 96	mm^3
Valve mass	860	g
including electronics	1200	g

outcomes of the functional and environmental tests.

The development tests of the regulation valve engineering model are carried out in an agile and incremental approach. Components and subsystems (e.g. motor) are tested under the operating conditions and adjusted until adequate performance is achieved. Following this approach, risks on product level could be mitigated in the early development phase by corrective design actions. The final development tests before accomplishment of the prototype phase are assessing the full functional performance of the product before moving to engine system tests.

4. DESIGN DESCRIPTION

Figure 2 depicts the valve itself with a coin for size comparison. The size and mass envelope of the product is listed in Table 2. The available pipe interfaces are very flexible. The flange connections at the 90° fluid section allow for flexible piping interfaces adapted for any application.

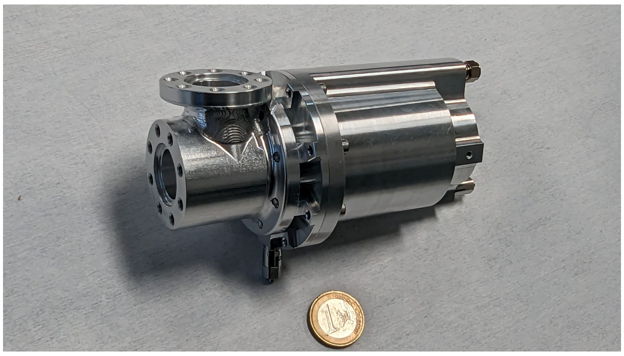

FIG 2. The product without the electronics package.

4.1. Valve architecture

The valve is a 90° poppet angle valve and is actuated by an electric motor. A schematic of the valve indicating the position of the individual components is depicted in Figure 3. A schematic of the actuator architecture including the electronics is depicted in Figure 4.
The fluid enters the valve perpendicular to its main axis and leaves parallel to its main axis. The rotation of the motor (1) is translated via a ball screw gear (5) to translation of the main shaft (8) and thus allows for continuous (stepless) regulation of the flow. The linear position of the poppet correlates directly with the effective flow area of the valve. The movement and position of the system can be measured redundantly by two sensors: A rotary resolver (3) and a linear variable differential transducer (LVDT, 4). The resolver is mounted on the same rotating shaft as the motor and allows for precise measurement (±6') of the angular position.The LVDT is mounted at the spindle of the ball screw gear, measures the displacement of the valve shaft, and can be used for direct position feedback. This architecture offers redundant position feedback of the poppet position directly through the LVDT and indirectly via the resolver and the ball screw gear.
The main rotor that holds the rotary parts of the electric motor and the resolver is supported by two angular contact ball bearings. Furthermore, assembly space is available for an optional brake. The assembly space of the bearings and the break are indicated as (2) in Figure 3. The nut of the ball screw gear is mounted on the main rotor and translates the torque of the motor into linear force to open and close the valve.
An electronics package is part of the valve flight model and can perform closed-loop control of the regulation valve in cooperation with the engine flight controller.
The fluid housing in closed position is sealed by a pressure-balanced design which allows for nearly pressure-independent operation of the regulation activities. This is achieved by a polymer main seal (7) and a pressure-supported spring-energized secondary dynamic seal (10). The motor enclosure is isolated from the fluid housing by two redundant dynamic seals (6) and a drain line (9). The motor compartment has interfaces additional fittings (11) to allow for conditioning with an inert gas (helium, nitrogen, etc.). Combined with the drain line, this ensures the motor compartment does not get in contact with the regulated media.

4.2. Actuator design

The bearings and the ball screw gear cannot use standard grease because it would freeze under cryogenic conditions. Due to the large temperature range ceramic balls that do not need lubrication are used in the two components. NASA performed tests with ceramic ball bearings for gas turbines [2] and used bearings with silicone nitride balls in the space shuttle turbo pumps [3]. They found that these assemblies have lifetime limitations at elevated temperatures which is uncritical for this product because of its short lifetime in terms of revolutions and the operation at predominantly cryogenic temperatures. One important design parameter for the actuator is the force it has to provide to move the valve. Because of the pressure-balanced design, the main force the actuator has to overcome is friction of the dynamic seals and bearings. The available force is influenced by the torque of the motor and the transmission characteristics of the ball screw (pitch, efficiency). The pitch of the ball

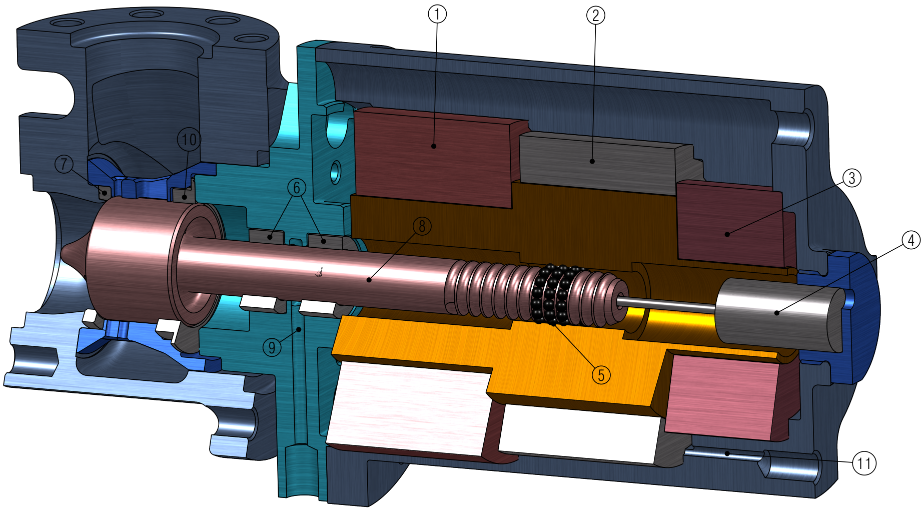

FIG 3. Schematic cut view of the valve and architecture of the actuator

TAB 3. Ball screw gear and actuator specification

Variable	Value	Unit
Nominal diameter	8	mm
Screw lead	2	mm
Forward efficiency	75	%
Max peak torque	>1	N m
Resulting max peak force	>2300	N

screw is limited by the ball diameter which in turn influences the allowable axial force of the ball screw. The force generated by the transmission is calculated by the following equation:

$$F = T * \frac{2\pi * \eta}{p} \tag{1}$$

Where F is the force in N, T is the torque in Nm, p is the screw lead in m and η is the forward efficiency of the spindle. Torque and screw lead are constant over the temperature range, but the efficiency (which depends on the friction and the geometry of the thread) may change with the temperature. The parameters of the ball screw gear with the maximum actuator force are listed in Table 3. The efficiency is calculated according to industry standards [4] adjusted for 77K with a 100 % increase in the friction coefficient between the balls and the spindle.
The calculation methods of the dynamic seal supplier [5] with adjusted friction coefficients for cryogenic operation were used to estimate the friction of the seals. With the maximum achievable torque the actuator can generate over 50 % more force than required by ECSS standards [6]. In summary, the actuator fulfils the necessary force budget requirements in worst case conditions and has 50 % additional margin to account for unexpected force anomalies that may come up during the development process or for valve upgrades that may require more opening force.

4.3. Electric motor

To accelerate the development tests of the valve, readily available commercial BLDC motors are used in the development models of the valve to assess the compatibility with the operational environment. In parallel, a custom electric motor is currently in development at deltaVision which is tailored to the special demands of this application. Since the full stroke of the valve (8mm) is achieved by four rotations of the motor, its dynamic characteristics (acceleration, deceleration) are the important design drivers for the maneuver time of the valve. Furthermore, the short time maximum stall torque to overcome initial friction is the design driver for the force budget analysis. The rated torque of the motor is mainly derived from thermal requirements and of less interest for the design due to the intermittent nature of the operation. The compatibility of the motor components with the regulated fluids and the temperature are important for the design. The polymers used in electric motors for insulation, coating, casting, or gluing must not be destroyed by repeated thermal cycling between room and cryogenic temperatures. Most polymers have increased strength at low temperatures but also become brittle [7] which can increase the susceptibility to vibration and shock loads. Special materials have to be used to address this problem. The custom motor will use an internal magnet rotor topology so that the mechanical connection between magnets

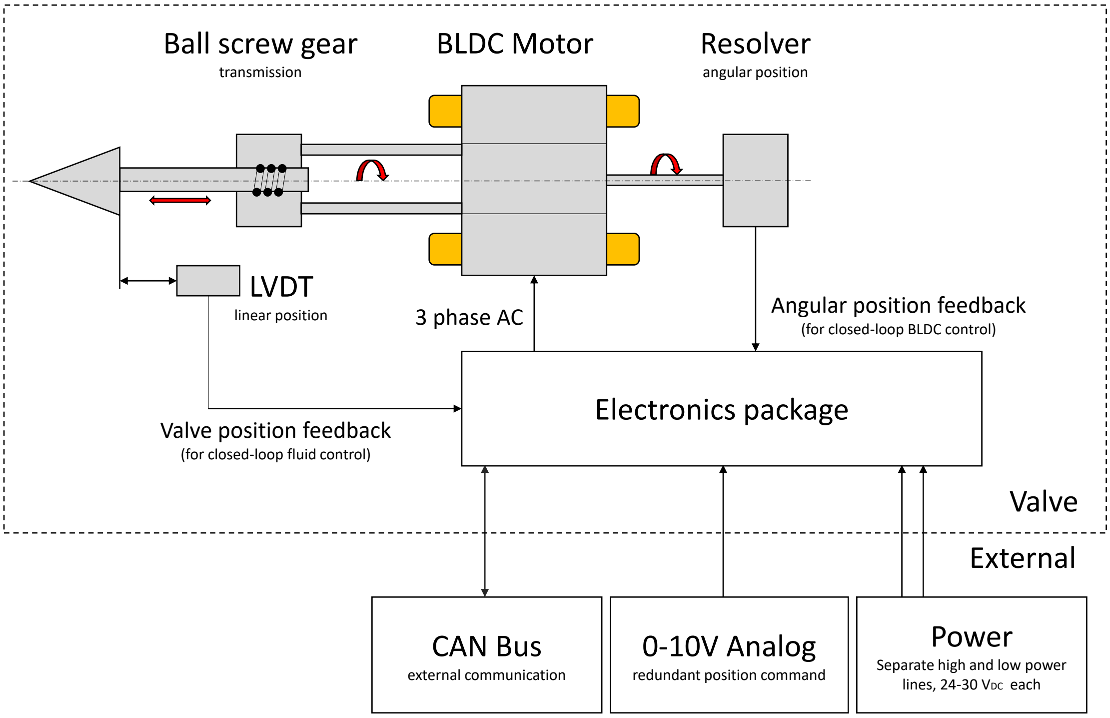

FIG 4. Architecture of the valve actuator

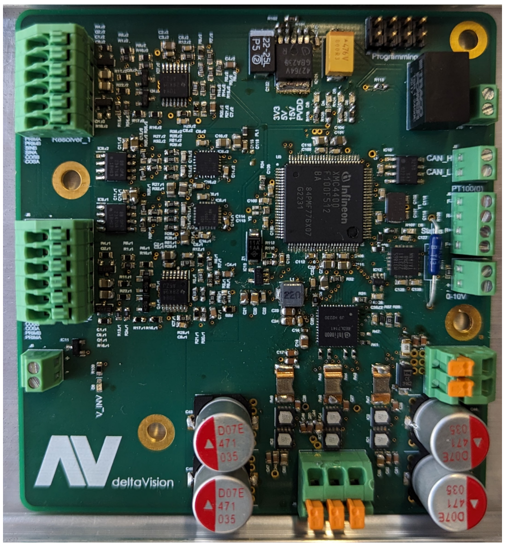

FIG 5. A picture of the custom PCB of the regulation electronics.

and rotor is not only dependent on the glued bond between the two components. Another advantage of this design is that it allows for encapsulation of the permanent magnets to protect them from corrosive media. This is especially relevant for hydrogen since SmCo [8] as well as NdFeB [9] magnet alloys are known to corrode in this environment.

4.4. Electronics and sensors

The main tasks of the custom developed electronics are the control of the electric motor and the valve position. the core of the electronics package is the micro controller XMC4400 manufactured by Infineon. Two independent position sensors are used to provide feedback for closed-loop control. The control of the motor requires angular position feedback due to the brushless design. The angular position is measured by a resolver - an inductive rotation sensor. The angular position combined with the ball screw gear can be used to derive the linear position of the valve shaft. But since the motor will perform more than one revolution for full stroke this indirect method cannot be used to measure the absolute position.
A LVDT is used for this task. The measurement principle itself is inductive as with the resolver but the LVDT can measure the linear position directly. Due to the similarity in measurement principle, two identical circuits on the PCB can be used as sensor interfaces. In general, inductive sensors are used in favor of semi-conductor based sensors such as hall probes due to the improved accuracy in cryogenic environment.
The external communication to the spacecraft avionics is redundant with a CAN Bus for two-way communication and an analog interface for position command. The power is provided separately with a high power DC line for the motor and a low power DC line for the micro controller.

4.5. Fluid design

The design of the flow channel impacts the main regulation parameters of the valve significantly. In order to achieve the required regulation characteristics, the relation between effective flow area and valve position has to be quantified during the development process. The valve can be optimized for several different parameters such as regulation accuracy or maximum

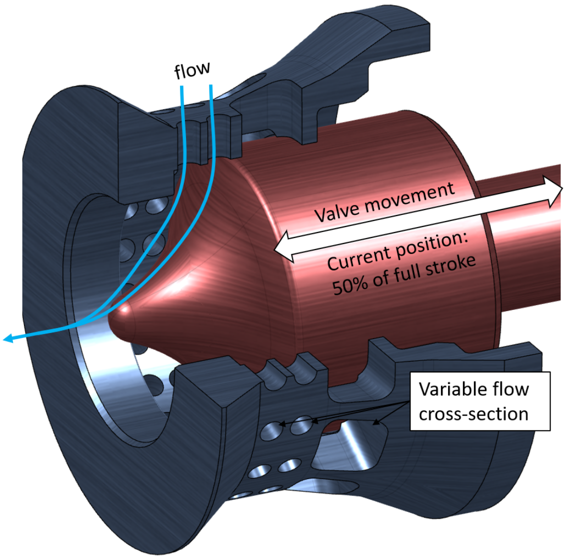

FIG 6. Detailed view of the region around the main seal at 50% of full stroke.

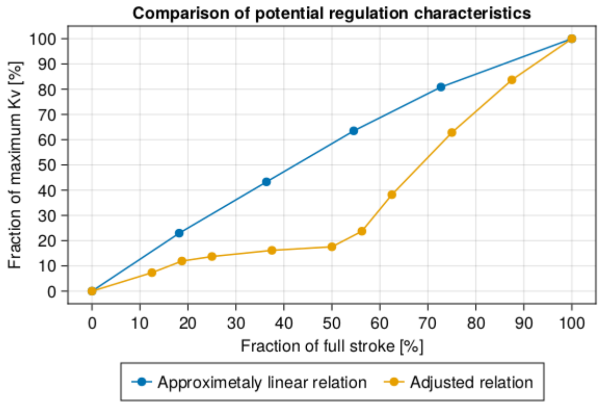

FIG 7. Comparison of flow coefficient Kv over valve position based on CFD simulations for two different sleeve configurations.

effective flow area. The flow characteristics can be altered by exchanging one single part in the valve. The openings in the sleeve surrounding the poppet (see Figure 6 for details) can be varied to define the flow cross-section relative to the valve position. The exemplary configuration depicted in Figure 6 opens a smaller fraction of the available cross-section in the first half of the valve stroke compared to the second half. This would allow for accurate regulation of smaller mass flows in the first half of the valve movement with a quick ramp-up to full flow in the second half. It enables quick an uncomplicated adaptions of the fluid flow according to specific customer requirements by exchanging the sleeve. The design of the flow channel is performed using 3D CFD software by Dassault Systémes 3DExperience. The configuration of the engineering model for full flow tests features an approximately linear relation between effective flow area and valve position to have an approximately constant accuracy in all positions.

The results of two CFD simulations for different sleeve types are depicted in Figure 7 to illustrate the potential variation in regulation characteristics. One curve shows a roughly linear relation between valve position (x-axis) and flow coefficient Kv (y-axis) while the other curve shows a characteristic with two sections as described above. For a given accuracy in linear position that the actuator and the sensors provide, one can achieve different resolutions of effective flow area. A section in Figure 7 with a low gradient corresponds with a better accuracy in flow coefficient. The CFD calculations will be verified by full-flow tests with water by the end of September 2023 as well as relevant cryogenic fluids (methane, oxygen) by the end of 2023.

5. DEVELOPMENT TESTS

5.1. Single components

Every critical single component was tested separately in liquid nitrogen (LN2, T = 77 K) early in the development process in order to identify compatibility issues with cryogenic temperatures and decide whether standard industrial parts are sufficient or custom products are necessary. The tested critical components are:

- Ball bearings
- Ball screw gear
- Resolver
- Electric motor

In general, stainless steel or other corrosion resistant materials need to be used due to condensation of moisture on the cold components after immersion into LN2. Tests at deltaVision in LN2 confirmed that the ball screw as well as the bearings with ceramic balls create minimal friction and are suitable for use in these conditions.

Tests of two standard commercial BLDC motors showed that cryogenic compatibility of the polymers and corrosion resistance of the iron cores are of high importance. The glue that bonds the permanent magnets to the rotor and the copper wire to the stator iron core can become brittle at low temperatures. This necessitates a design that either does not rely on glued bonds for mechanical integrity or the use of glue qualified for cryogenic temperatures. Minor degradation of the bond between magnets and the rotor due to material embrittlement were visible after extensive thermal cycling tests (>20 cycles 293K→77K→293K). The bond strength is still sufficient for nominal operation due to the magnetic bonding. DeltaVision is currently developing a custom electric motor with an internal magnet topology to address the gluing problem in the rotor.

The resolver showed neither visual nor functional damage after LN2 immersion tests. The functionality was tested separately and in combined operation with the motor at all relevant temperature levels.

The ball screw gear was tested separately and combined with the actuator at cryogenic conditions. The test results show a transmission efficiency of 75 % which coincides with the theoretically calculated performance.

5.2. Motor assembly and actuator

Sub-scale tests of the actuator assembly are conducted to characterize the performance of the electric motor and the friction created by the bearings at room temperature as well as 77 K. The relevant components are the motor, the resolver, the bearings and the ball screw gear. The following characteristics of the actuator are measured at room temperature and 77 K:

- Unpowered rotational resistance (cogging + friction torque) T_F
- Maximum torque generated by the motor T_M
- Valve manoeuvre time (time until 95 % of commanded position is reached) t_{95}

The friction of the bearings and the ball screw gear are in general the largest during chill-down and lowest in steady-state temperature conditions at room temperature. At steady temperature submerged into LN2, the friction is still higher than at room temperature but lower than during the transient. This can be attributed to uneven thermal shrinking of the relevant parts during the transient chill-down. For this reason, the worst-case friction torque during chill-down of the valve is given in Table 4. The manoeuvre time is measured with an average load of 1000 N provided by a spring.

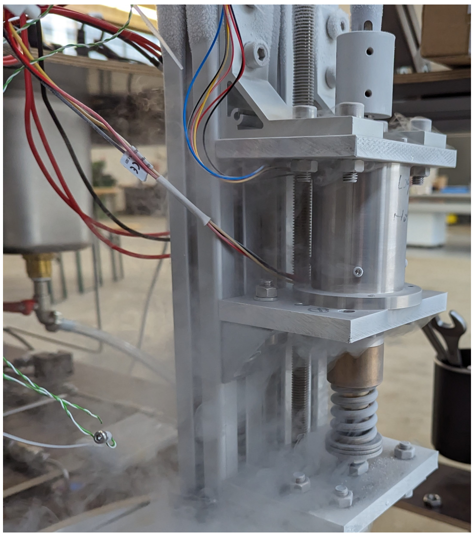

FIG 8. Actuator test configuration after liquid nitrogen immersion tests.

5.3. Valve

The leakage of the main seal and secondary main seal combined is below 1E-03 $\mathrm{mbar\,L\,s^{-1}}$ of gaseous Helium at room temperature. Results of full flow tests are not yet available at time of writing of this pre-print.

TAB 4. Results of actuator tests

Variable	Value **293** K	Value **77** K	Unit
T_F	0.04	0.3	N m
T_M	1.5	1.5	N m
t_{95}	250	250	ms

They are expected to be available at the time of the presentation.

6. OUTLOOK AND FURTHER DEVELOPMENTS

The current status of the development project is the following:

- All relevant single components were tested separately at room temperature and TLN2
- The actuator consisting of the motor, the position sensory, the bearings and the ball screw gear was tested successfully at room temperature and TLN2.
- One engineering model of the entire valve including the electronics was tested successfully for leak tightness and with water to characterize the flow characteristics.

The following activities will be performed in the near future (until the end of 2023):

- A test campaign including hot fire tests of the thrust chamber designed by TEC with this valve is scheduled for the end of 2023 / beginning of 2024 at the facilities of DLR Lampoldshausen. The valves will be tested there in relevant flight-like conditions.
- Engineering models of an in-house developed customized electric BLDC motor are currently being procured. First development tests are scheduled to begin in the end of October 2023. This motor features polymers qualified for cryogenic conditions and an internal permanent magnet topology. The 3 phase, 14 pole motor with 15 slots reaches the same mechanical performance parameters with the same form factor as the commercial BLDC motor. This ensures easy interchangeability without changes in hardware of the valve itself. A 3D CAD rendering of the motor is depicted in Figure 9.
- Currently, an upgraded version of the valve for a higher operational pressure of up to 150 bar with a reduced effective flow area (95 $\mathrm{mm^2}$) for a gaseous hydrogen aviation application is in development. Hydrogen full flow tests are panned in 2024.
- Furthermore, an adaption of the current design for lower pressure and increased effective flow area (lower pressure drop for same mass flow) as a feed valve for space propulsion is in development.

For the mid and long term (2024 and later), the following activities are planned:

- The electronics package will be miniaturized for flight operation. Furthermore, the electronics needs to be space-rated for the the flight models. Both activities are currently in development.

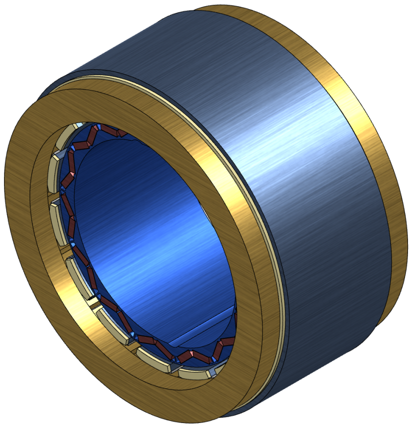

FIG 9. A CAD rendering of the in-house developed BLDC motor.

- The valves will be used on the TEC demo engine in mid 2024.
- After the development test campaign, the valve will be qualified for flight onboard a spacecraft developed by the Exploration Company.
- For applications outside mobility solutions, the valve is being adapted for temperature control with liquid helium. This necessitates a version of the valve with the same actuator but a smaller maximum effective flow area to achieve the desired accuracy. This valve will be optimized for temperature control with cryogenic media (LN2, LHe) for precise measurement machines or cooling of super conductors (e.g. fusion energy).

In addition to the operational scenarios as high mass flow control units, the valve also has the potential to act as a pressure control assembly. The actuator can provide enough force to open the valve against up to 400 bar operational pressure with a effective flow area of 12.5 mm^2 (corresponding to a nominal diameter of 4 mm). This enables the application of the valve for in-space propulsion tank pressurization systems which are currently either regulated by bang-bang systems (for example [10]) or mechanical pressure regulators. Compared to these systems, a pressure regulator derived from the design presented in this paper would be competitive in terms of mass per maximum mass flow.

7. SUMMARY

Electric motor driven regulation valves are valuable additions for (cryogenic) aerospace propulsion systems and offer high mass flow and and fluid control with competitive size, mass and power requirements. The development of a regulation valve specialized for fluid control of cryogenic media was presented. It was developed specifically for the application in cryogenic space propulsion which is the primary source of the requirements for this product. The experimental results of development tests show promising results, but not yet completed.

In summary, electric motor driven regulation valves have several advantages including:

- Consolidation of several tasks in a fluid system in one product (chill-down, regulation, shut-off, purging) .
- Health monitoring of the valve is possible by read-out and processing of data obtained by the electric motor and the position sensors (for example: mechanical resistance) during the operation. Because the valve is delivered together with the electronics, health monitoring can be added as a software service.
- An electric motor actuator features a high power density, large actuation forces and quick reaction time independent of valve stroke position.
- The presented valve and actuator concept is highly flexible and applicable in many different fluid control scenarios as presented in the previous chapter.

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