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Development and verification of an oxygen mass-flow regulator under high temperature and pressure conditions

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Abstract

The oxygen pressurisation system for the main stage Ariane 6 is currently under development at Airbus Safran Launchers. The oxygen pressurisation plate, termed the PPO, will be responsible for controlling pressurisation gas mass flow to the main stage oxygen tanks and is a critical component of the oxygen pressurisation system. The flow control in this plate is made by a force-piloted electro-valve, termed PPx. The control of oxygen mass flow in high temperature, up to 440 K, and high pressure, up to 180 bar, provides a significant technical challenge from both the functional and oxygen compatibility points of view. This paper outlines the development of the PPx valve in the context of the PPO. The PPx is presented along with an overview of the development program. During the early design process three-dimensional computational fluid dynamic simulations were found to be an effective tool and lead to designs with optimised mass flow rates. Two-dimensional computational fluid dynamic simulations combined with functional modelling lead to identification of design aspects with high impact on pressure-piloted valve functionality. Additionally functional modelling allowed identification of critical operational points within the wide operational range specified by requirements and for which the PPx and PPO must displace robust functionality.

1 Introduction

The large thrust required to lift a payload from earth's surface is currently only possible with chemical rocket propulsion systems. Of the 86 launches conducted in 2015 over 50% used a rocket engine with liquid oxygen propellant (LOX) [1]. LOX provides a high specific impulse (ISP), and a low toxicity but a lower specific gravity when compared to the other widely used oxidiser nitrogen tetroxide (NTO). The cryogenic temperatures and high combustibility of materials when exposed to oxygen pose the greatest challenges when designing oxygen feed systems.

To design a safe and reliable oxygen system an analysis of the worst case operating conditions is required in addition to an evaluation of the probability and sources of ignition [2,3,4]. This analysis then needs to be considered during the system design phase whilst paying particular attention to material selection [5,6]. A number of standards exist to support the development and operation of oxygen systems [7,8,9]. However, conditions encountered in rocket systems tend to be more extreme and are less often encountered leading a to higher risk of unintended combustion. Therefore, effort needs to be expended not only to ensure that the design fulfils requirements but also that mandatory verification of oxygen capability at the required conditions must be demonstrated [10].

Oxygen supplied from the tank to the rocket engine is typically kept at cryogenic temperatures and remains in a liquid state [11]. This limits the risks associated with spontaneous reaction of oxygen with any material as a greater increase in local temperature is required to reach ignition [8]. However, in a number of cases the local mean temperature is increased, such as in a turbo pump or re-pressurisation system of the oxygen tank. Due to the higher temperatures in these systems more attention needs to be payed to material selection and to contamination mitigation methods [3,12,13]. Higher pressures also increase the risk of combustion and the pressure dependence of material combustibility needs to be taken into account [3].

The Ariane 6 launcher is currently under development at Airbus Safran Launchers. Based on the heritage from the Ariane 5 launcher, the design of the Ariane 6 is focused on reducing costs and improving reliability. The design of the Ariane 6 main stage is based on the Ariane 5 design and will use the Vulcain 2.1 engine. The supply system of the main stage will also be updated to achieve the goals of the Ariane 6 development. Specifically, the Ariane 6

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oxygen pressurisation system will be overhauled to use oxygen as the primary pressurisation gas. Previously the Ariane 5 oxygen system was pressurised with helium which provides a simplified and therefore lower risk system [11]. However, the helium blowdown system of the Ariane 5 added significantly to the structural and residual masses, decreasing the payload ratio and increasing costs. An oxygen pressurisation system using heated oxygen was selected as it improved the payload ratio therefore reducing the cost per kg of the launch. This pressurisation method has also previously been applied in other space applications, for example for the space shuttle main stage [14]. However, due the differences in fluid supply system architecture an individual solution, optimising the cost benefit for the Ariane 6, needs to be found.

This paper focuses on the development of the oxygen pressurisation plate (PPO) which is responsible for controlling the flow of heated oxygen to the oxygen tank. Valve design for aerospace applications typically must consider operating conditions far more extreme than for other industrial processes. Consequently a detailed understanding of physical processes that affect the valve as well as analysis of both the static and dynamic functional performance is required to ensure reliable operation [15]. The PPx is part of the oxygen pressurisation system following the turbo pumps and heat exchanger and as a consequence must function with high reliability for a wide range of operating conditions. The high temperatures, up to 440 K, high differential pressures, up to 180 bar, and mass flow rates, up to 3 kg/s, provide significant technical challenges in regards to oxygen compatibility as well as functionality for the electrically actuated PPx valve. This paper focuses on the design and development of the PPx valve as the critical component of the PPO. A description of the PPx valve functional concept follows the introduction with a detailed discussion on the aspects that are considered critical for robust functionality. The verification plan and current status will then be presented with a focus on risk mitigation methods regarding the valve design. The body of this work will then focus on the comparison between simulation, taken as one risk mitigation method and experimental results from the initial test investigations. Finally a short summary of lessons learned and development outlook will conclude the presented material.

2 Hardware Description

2.1 Hardware Purpose

The PPO is part of the functional propulsion system of the Ariane 6 (A6) lower liquid propulsion module (LLPM). Its main purposes are to

- Provide a mechanical link between tank and ground during tank loading and degassing
- Separate the engine loop and the oxygen tank during the tank loading
- Modulate the mass flow rate of the oxygen pressurisation system

The PPO is a component of the mixed oxygen pressurization system. Liquid oxygen flow is tapped off from the tank before being vaporized in a heat exchanger and then used to pressurize the oxygen tank. The PPO modulates the flow between the heat exchanger and the tank at the end of the pressurisation loop. It is foreseen that the PPO be operated in a ‘bang-bang’ method based on existing design heritage. Using a ‘bang-bang’ method implies that some branches remain open to provide a constant mass flow and some branches are opened by command to modulate the base mass flow rate. The following hardware description focuses on the electronically actuated valve (EV) that is the central component of the PPO mass flow regulator.

2.2 Hardware Requirements

The major challenge for the development of the PPO is the broad range of requirements. Figure 1 summarises the requirements placed on the PPx valve. The combination of high pressure, high temperature and oxygen compatibility significantly limits material choices and places significant requirements on the actuation forces. It is important to note that the broad range in temperature is primarily driven by the common use of the regulator on hydrogen and oxygen sides of the launcher. The requirements for oxygen do not decrease below 150 K.

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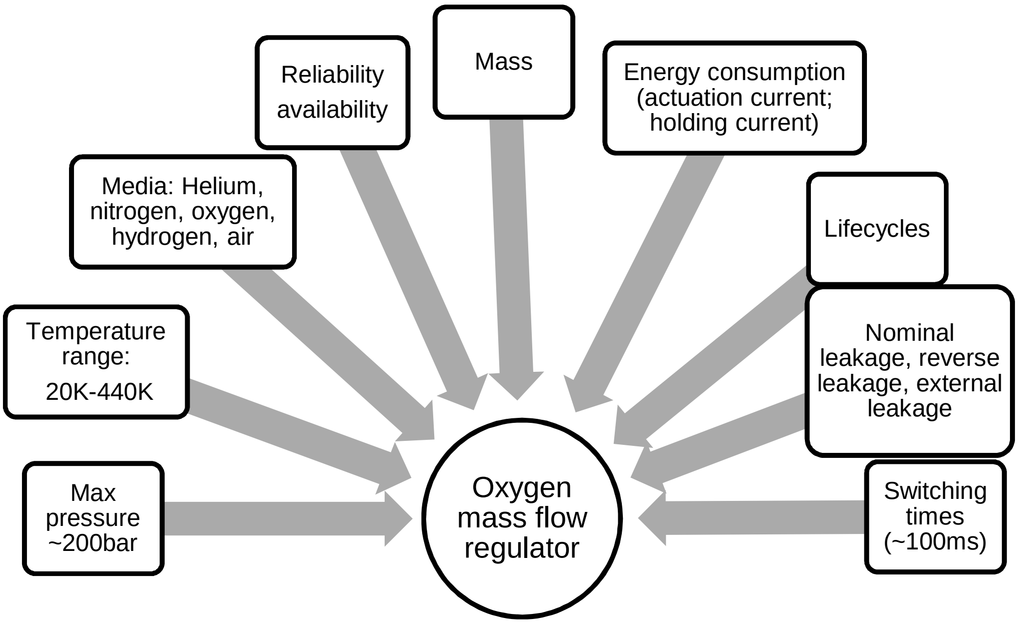

Figure 1: PPx requirement summary

All the mentioned challenges have been collected and analysed within a trade-off method resulting in the choice of a force piloted electromagnetic valve with magnetic actuation coils redundancy. The key components and the functionality principles of the valve are described in the remainder of this section. The development logic of the mass flow regulator with the primary development phases and activities will be described in the following section.

2.3 Material selection and environmental impact

The broad range of requirements has a strong impact on the design. The following section discusses aspects considered critical to ensuring reliable and robust valve functionality under the above specified requirements.

Oxygen atmosphere has a strong impact on material selection. With the exception of Polytetraflouroethylene (PTFE), classical polymeric materials are not suitable for high pressure and temperature oxygen environments due to flammability risks. For the PPO application PTFE is also not suitable due to insufficient mechanical strength for the given pressure range. Therefore, a metal-metal sealing, namely a combination of a Monel seat and a Monel poppet was selected due to high flammability resistance and functional restrictions, specifically, to maintain a small radial gap between poppet and seat over the full temperature range. The critical role the gap plays in valve functionality will be addressed in the following sections. Monel-Monel paring increases the risk of galling occurring at the sealing point and at any other points where the Monel parts come in contact. Galling can be impeded through the use of a surface coating, however, if galling occurs despite the precautions then alternative materials, sub-optimal to the high temperature oxygen conditions will need to be considered.

For the magnetic actuator, the base materials were dictated by magnetic properties. The chosen materials were 1.4546 (AMS 5512) and 1.4006 (AISI 410). Since both materials are not compatible with the GOX environment, a surface coating is necessary. To withstand both GOX and GH2 at high pressure and temperature, a 20 micron thick silver coating was chosen (Figure 4). Furthermore, to prevent damage to the coating, the design of the components required a no sliding contact to inhibit silver-silver contact. This was realised by the introduction of special guiding parts made of GOX-compatible materials like bronze or Monel.

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High temperatures cause higher levels of electric resistance which must be considered when specifying the actuator coils. Increased wire diameters combined with a high number of turns were used to realise the actuator requirements. With the need for a redundant coil, the magnetic actuator became the main mass driver of the valve.

2.4 Functional Concept

Several functional concepts of the PPx-valve were scrutinised during pre-development. The selection processes that lead to the selection of a force-piloted valve is presented in the following section. A force-piloted valve system combines the advantages of a directly actuated system, the capability for low pressure actuation in particular, and an internally piloted valve with its ability to control large cross sections with a small actuator. This is achieved by mechanically locking the pilot valve poppet (sub-poppet) and the main-poppet at some point during actuation in order to mechanically open the main-seat if the pressure forces are too small. The following Figure 2 identifies the components of interest within such a valve system.

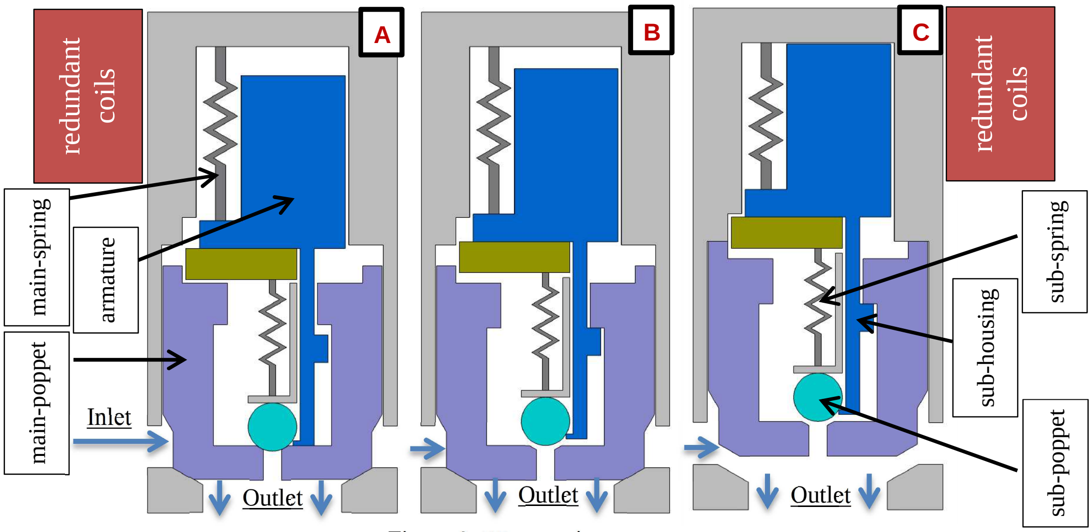

Figure 2: PPx opening sequence

In closed position, the valve is not pressure balanced, resulting in high sealing forces up to 18 kN (Figure 2A). To open the valve the actuator coils are energized and the armature is pulled towards the open position against the closing main-spring force. At 0.2 mm armature stroke, the sub-housing interlocks with the sub-poppet, opening the sub-seat in the process. This leads to a decrease of the internal pressure, generating an opening hydraulic force between inlet and intermediate volume. When the armature reaches a stroke position of 1mm, the sub-housing interlocks with the main-poppet (Figure 2B). At this point, the hydraulic force on the main-poppet has a net opening force, causing the complete cross section (main-poppet) of the valve to open (Figure 2C). If no delta-pressure is present the sub-housing will mechanically pull the main-poppet into open position, thus ensuring a complete valve opening regardless of the system pressure.

To close the valve, the coils are de-energized. This causes the main-spring to close the sub-seat while the main-poppet remains in open position due to hydraulic forces. As soon as the sub-seat is closed, the pressure in the intermediate volume will approach the inlet pressure, resulting in a closing hydraulic force on the main-poppet which in return closes the valve.

Although this functional concept provides a suitable method to handle high pressure and high temperature gaseous oxygen (GOX), it also has some characteristics that have to be taken into account. First of all, the magnetic actuator has to be more powerful than for a simple internally piloted valve, since it has to provide the opening force for the non-pressure balanced sub-poppet while simultaneously moving the armature over the entire of sub- and main-poppet stroke. In a classical internally piloted valve, the sub-poppet only has to have a small stroke distance, making the generation of magnetic forces much easier. The second disadvantage of a force-piloted valve system is the need for a very small gap between main-poppet housing and main-poppet. This gap connects flow from the inlet and the intermediate volume, thus influencing the pressure drop chain which generates hydraulic opening forces. A smaller gap reduces the required size of the sub-seat cross section and in turn the magnetic opening forces.

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3 Verification Approach

3.1 Development and verification logic

The development of the PPO consists of four phases; pre-development, design, development and qualification as shown in Figure 3. Currently the development of the PPO is in the Development Campaign phase. The following section provides an overview of the development process up until this point in addition to the current outlook. In addition, the role of activities, presented in section: Modeling and Test, in the development process will be highlighted.

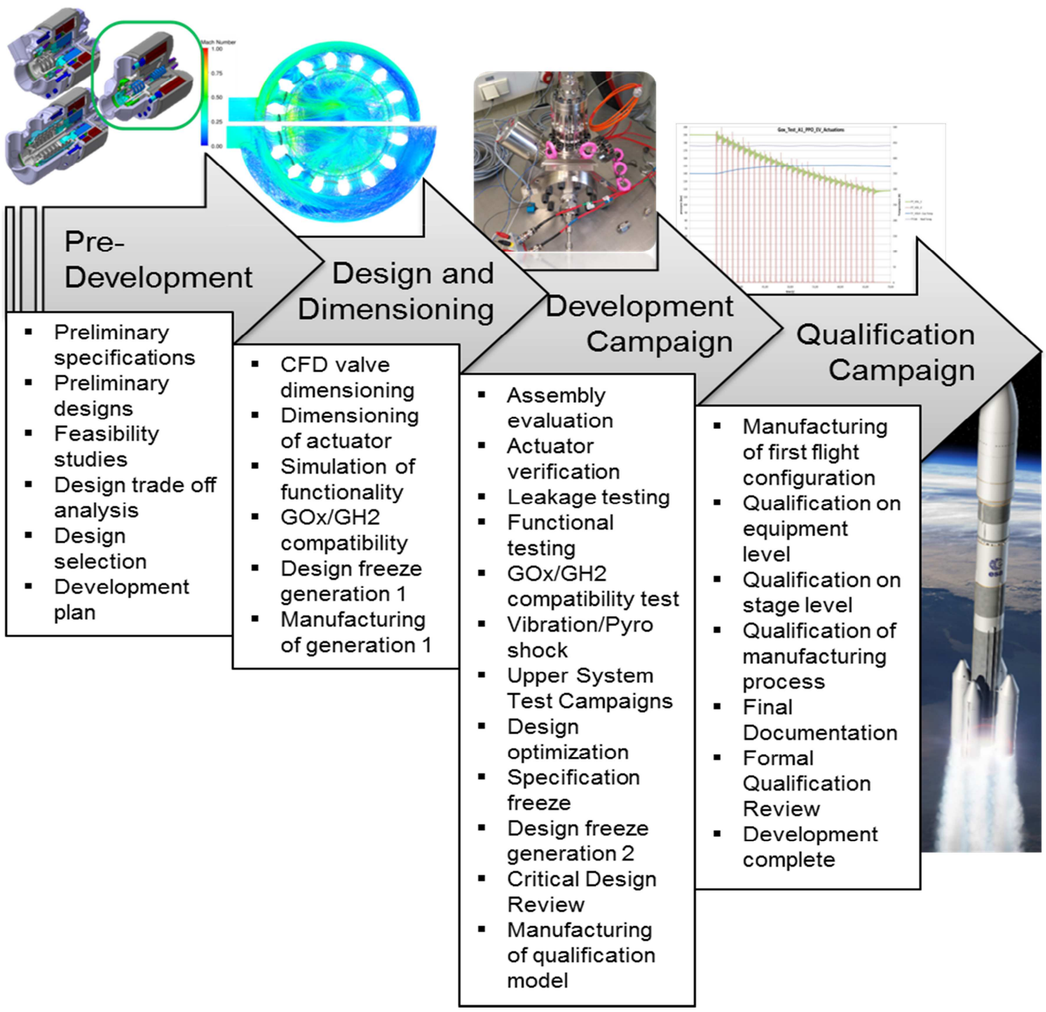

Figure 3: Pressure regulation plate development phases

3.2 Pre-development

During the pre-development phase the initial requirements for the pressurization system have been defined by the system design team. These are then made available on the equipment level to begin the design process. Based on heritage of Ariane 5 a bang-bang pressurization system design was chosen for the Ariane 6. To reduce costs, one type of electromagnetic valve, for both hydrogen and oxygen pressurization was required. Having broad experience in cryogenic hydrogen equipment but no heritage in oxygen equipment the central challenge of this phase was the selection of a preliminary concept.

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The following major drivers for the trade-off studies were considered; GOX compatibility, Internal leakage, response and manoeuvring time, number of actuations, cleanliness and contamination susceptibility, mass, operational envelope and heritage. These criteria were used to analyse the suitability of four EV concepts; double seat concept (pressure balanced), dynamic sealing concept (pressure balanced), bellows concept (pressure balanced) and force piloted concept (not pressure balanced).

During the trade-off the force-piloted concept has been clearly rated as the most suitable concept for the given application, followed by the dynamic sealing concept on the second place. To confirm concept feasibility a breadboard model relying on the same physical principles has been designed and manufactured. The test results confirmed the basic principle of the concept but many of the design details were not addressed. For example, effective sealing of large metal-metal seals was not investigated. The successful breadboard test campaign concluded the pre-development phase.

3.3 Design and Dimensioning

The design and dimensioning phase was performed in an iterative manner, refining requirements and the respective design in parallel. The culmination of the design and dimensioning phase is the production of the first generation PPO EV. The key activities leading to this point include 2D and 3D modeling of flow paths, the development of a one-dimensional functional model, selection of compatible materials and actuator dimensioning.

The 2D and 3D CFD provided key inputs for the dimensioning of seat diameters to ensure the required mass flow rates were fulfilled. In addition, CFD results were used to understand the flow dynamics within the force-pilot sub-poppet area and were used as inputs for the functional model. More detail of the CFD results will be presented in Section 4. A functional model was developed to understand the dynamic behavior of the valve, specifically, the interaction between hydraulic, magnetic and mechanical forces, and valve opening behavior. The functional model can be seen as a more detailed dynamic force budget and will also be described in more detail in Section 4.

In addition to the modeling aspects, oxygen compatibility was a significant aspect addressed during this phase. Due to limited heritage with oxygen applications at Airbus Safran Launchers (ASL) Ottobrunn (OTN), and the success-oriented schedule of the overall development project, an ‘as safe as possible’ philosophy was chosen. The following principles were followed as part of this philosophy;

- Only best oxygen-compatibility-rated materials
- Oxygen-susceptible materials (steels) are coated with a silver layer
- No direct mechanical contact between moving silver-coated parts
- No sliding contact of any silver coated surface during valve-actuation
- Fine filtering of the entering oxygen flow to prevent huge particles in the areas of high flow velocities
- No polymeric elements (besides a thin PTFE-coating on the static sealings)

Having collected all sizing parameters and having proved feasibility of manufacturing and coating processes the release for production of the 1st EV generation could be given and the next development phase started.

3.4 Development Campaign

The development campaign phase of the PPO is currently ongoing. It is the most involved phase of development due to the active feedback from initial tests and simulations into the design. It is also the first phase where compliance with requirements can first be analyzed. This section will focus on two aspects that have been addressed as part of the development campaign: functional testing and the oxygen compatibility of the PPO EV.

Functional testing of the valve is required to verify that the behavior is robust and reliable for the required operational range. As access to oxygen and hydrogen has additional safety requirements and costs, tests with inert gas are the first step in the verification process. Functional testing focuses on switching times of the PPO at different pressure levels with different hardware configurations. The current and voltage are used to investigate the performance of the actuator. Typically, pressures are used to indicate the flow behavior. Poppet position measurements through laser and inductive stroke sensors also provide important information. These results are then

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compared with the functional model to validate modeling results and to gain insight into the detailed functional behavior. A comparison of modeling and test results is presented in Section 4.5.

At ASL OTN helium and nitrogen are available for tests. Nitrogen displays physical properties very close to the ones of oxygen and is therefore the ideal inert gas to simulate oxygen applications. Helium is used to represent hydrogen. Flow rates up to 2 kg/s (GN2) and 300 g/s (GHe) at 150 bar are possible with maximum pressures reaching over 200 bar. Temperature can be varied from 77 K (LN2 temperature) to room temperature (RT) conditions. Currently, over 400 actuations have been completed in a variety of mediums. Figure 4 shows discoloration from ware on the interlock connecter after 150 actuations at high pressure. Reducing ware is part of ongoing investigations, in particular risk of galling between the monel-monel main-poppet and main-poppet seat needs to be mitigated. Initial investigations show that a thin film of lubricant is effective in reducing ware even after a large number of cycles.

Testing with oxygen and hydrogen is also required to identify changes in functionality due to differences in fluid dynamic properties. The speed of sound in a medium is pressure, temperature and medium dependent and can have a strong influence on the functionality of a pressure-piloted valve. To investigate this phenomenon nitrogen cannot be utilized as the nitrogen properties behave differently to oxygen around the critical point. Tests with cryogenic oxygen to verify functionality are an ongoing aspect of the development campaign.

Oxygen compatibility must also be verified early in the development program. To verify the robustness of the design in pure oxygen atmosphere at high pressure and elevated temperatures a specific test campaign has been initiated. The campaign is currently ongoing; however, the major PPO related test steps have been completed. The test campaign was conducted with the PPO plate equipment which includes one PPx EV actuating the flow and positioned after the foreseen filter. The test steps completed until now comprised of PPx EV actuations with temperatures up to 420 K maximal gas temperature and 190 bar maximal gas pressure. Oxygen compatibility was further tested by introducing pre-defined particles of aluminum and stainless steel into the system during test. Around 130 EV actuations have been completed at high temperature and pressure without functional anomalies or signs for ignition.

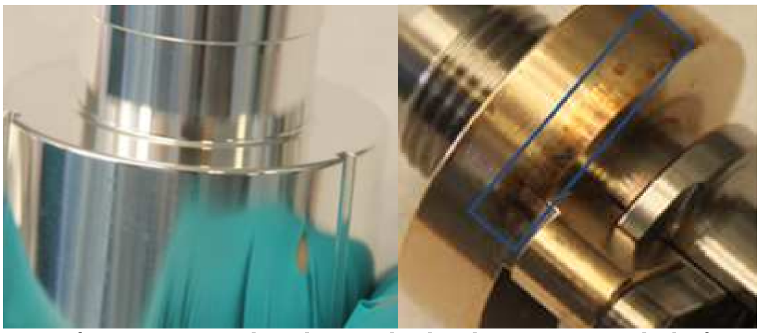

Figure 4: Left, armature coated in silver, Right, discolouration on interlock after testing

3.5 Qualification campaign

The last step of the development phase will be the qualification campaign. The test campaign will be performed on two full equipment sets featuring the latest design evolution of the EV. One equipment set will be qualified in OTN on equipment level, the other on system level in Kourou. On equipment level, the qualification plan is designed to fulfil a full product lifecycle of the product proving its functionality in all mandatory steps. Mechanical vibration and pyro testing will also be conducted at this stage. Additional margins will be added to understand the product’s limits. On system level, the equipment will be qualified within its functional domain by several subsystem and full system tests. The hardware utilized for this test will correspond to the first flight equipment for the Ariane 6 maiden flight. After finalizing the qualification campaign a detailed qualification review will finalise the development.

4 Modelling and Test

4.1 Overview

This section focuses on the simulations undertaken to support the initial concept design and development of the PPx valve. Prior to hardware manufacture simulations offer a rapid method to analyse design changes and identify

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optimisation before progressing to manufacture. The work presented here focuses on providing an overview of the work done in the initial design phase and as part of the development process up until this point.

Four aspects of the project are presented, two focusing on 2D and 3D computational fluid dynamics and two focused on simulation of valve functionality and verification through testing as conducted up until this point. Due to the scope of the paper, detailed description of simulation results is not undertaken; rather, the focus is on the feedback of simulation to the design process and the optimisation of design that is a direct consequence of this process.

4.2 Three dimensional flow optimisation

Three dimensional computational fluid dynamics (CFD) simulations were undertaken with the commercial CFD-solver package ANSYS-CFX V17. CFX is the standard flow solver package at Airbus Safran Launchers Ottobrunn. For more details of the capabilities of CFX, the development status of the software, tests and validation the reader is directed toward the ANSYS website [16]. The material properties of the fluids (O2, H2, He, N2) are derived from real gas property (RGP) tables which are extracted from the GASPAK program [17]. Menter's shear stress transport (SST) two-equation model with automatic wall functions was used. These wall functions automatically switch from wall functions to low-Reynolds number near wall formulation as the grid is refined normal to the wall ($y+ < 1$).

At the inlet of the feed line the temperature, the mass flow rate and the flow direction are prescribed. The flow direction is set to normal with regard to the inflow plane. The temperature and the mass flow rate depend on the load point to be analysed. At the outlet the averaged static pressure is set, depending on the load point to be analysed. All walls are defined as hydraulically smooth, adiabatic, no-slip walls.

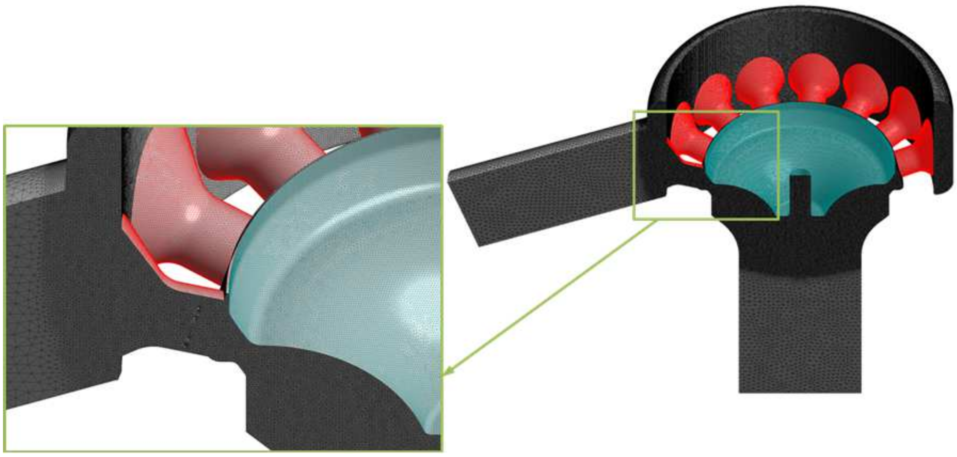

Figure 5: Main-poppet flow path 3D CFD model computational grid

A CFD analysis of the primary flow path was performed. To get meaningful results a three-dimensional CFD model was required. The model includes the feed line, the manifold with its outgoing cross-flow channels, the main-poppet and the housing downstream of the main-poppet. To reduce the computational effort, the model is split and mirrored with only one half simulated. To accelerate the grid generation process, the valve volume is filled up with tetrahedrons (see Figure 5). In the area of the cross-flow channels and the gap between housing and main-poppet seal seat a local grid refinement is applied (see detail of Figure 5). The grid cell dimensions and local resolutions chosen are derived from existing in-house experience, developed within numerous projects. Given the significant in house experience and the general nature of the flow simulation goals no dedicated grid variation study was performed.

Two valve designs were considered and are presented in Figure 6. For both designs the simulated 180° model, half model, is mirrored to a full, 360°, model for the figures. The fluid flow of the initial valve design is presented on the left of Figure 7 and the modified design on the right. When comparing the initial design with the modified design three significant changes can be observed. The angle of the inlet lines was modified due to system design requirements. The cross-section area of the manifold is increased to lower the velocities there. Lower velocities will have a positive effect on the recirculation zone at the inlet of the cross-flow channels. In addition to these points the circumferential positions of the cross-flow channels was changed: There is no cross-flow channel in line with the feed line anymore. This change was made to also improve the distribution of flow across the main-poppet seat.

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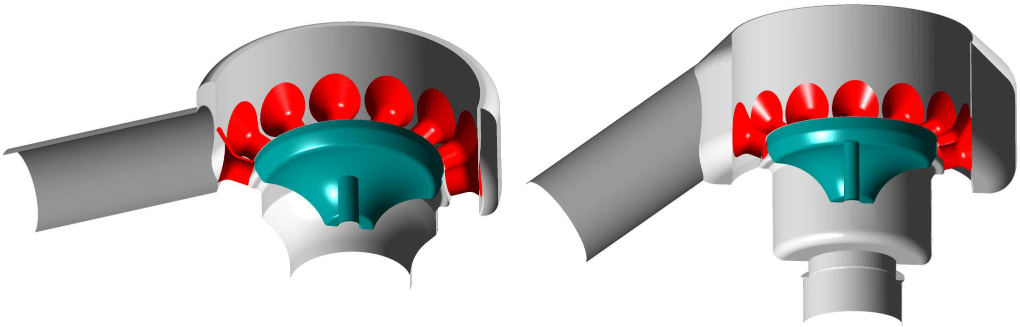

Figure 6: Main-poppet design, left, initial design, right, modified design

Figure 7 shows the streamlines through the primary flow part of the valve. As for Figure 6, the initial design is presented on the left and the modified design on the right. For a better comparison of the design versions, the streamlines are coloured with the absolute velocity normalized with the averaged absolute velocity at the inlet. In both designs the flow in the feed line is homogeneous. Entering the manifold the simulations become dissimilar. In the initial design the flow starts rotating and accelerates. Entering the cross-flow channels entails flow separation at almost every cross-flow channel inlet, except the ones opposite to the feeding, at the rear part of the manifold. This happens even though the inlets of the cross-flow channels are chamfered. Downstream of the cross-flow channels the flow is accelerated through the gap between housing and main-poppet seal seat. Here the highest velocities occur. For the modified design the flow in the manifold spirals less and the absolute velocities are lower, much closer to the inlet velocities than the initial design. The recirculation zones at the cross-flow channels inlets are smaller and the mass flow distribution at the cross flow channels is more evenly distributed. The overall variation of the velocity from the inlet to the outlet of the modified valve design is much lower.

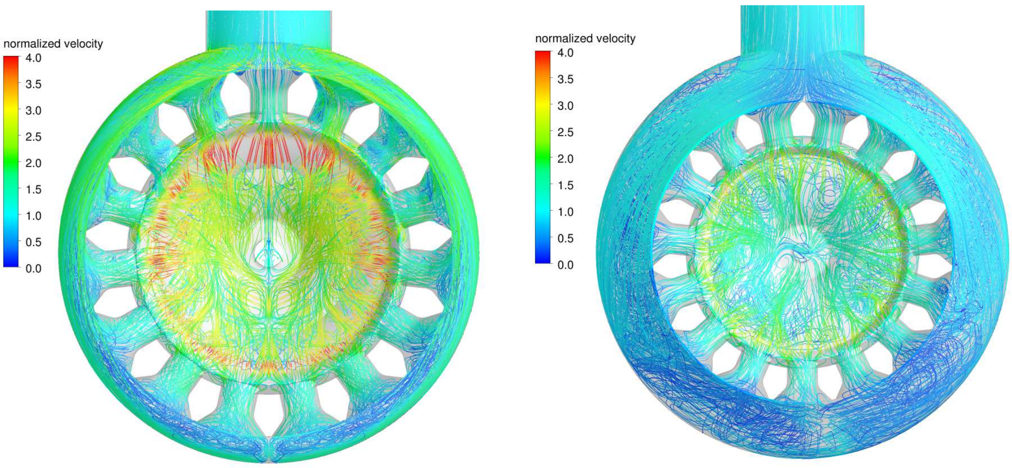

Figure 7: Main-poppet flow field, left; initial design, right, modified design

To assess the distribution of the flow through the cross-flow channels, the mass flow rate through each cross-flow channel is determined. The deviation of this local mass flow from the mean value (perfect homogeneous mass distribution at the cross flow channels) is given in Figure 8. This graph illustrates a distinct oversupply of the first cross-flow channel, positioned in line with the feed line. The third cross-flow channels left and right of the feed line shown an undersupply due to the huge recirculation zones at the cross-flow channels inlets. The variation of the mass flow through all other cross-flow channels is moderate. The modified design shows an improved, more homogeneous, distribution. Specifically the peak at the first cross-flow channel is no longer extreme and the under supply at channels left and right of the inlet are also smaller. The improvement in flow distribution leads to an increase in flow rate for the nominal operating condition.

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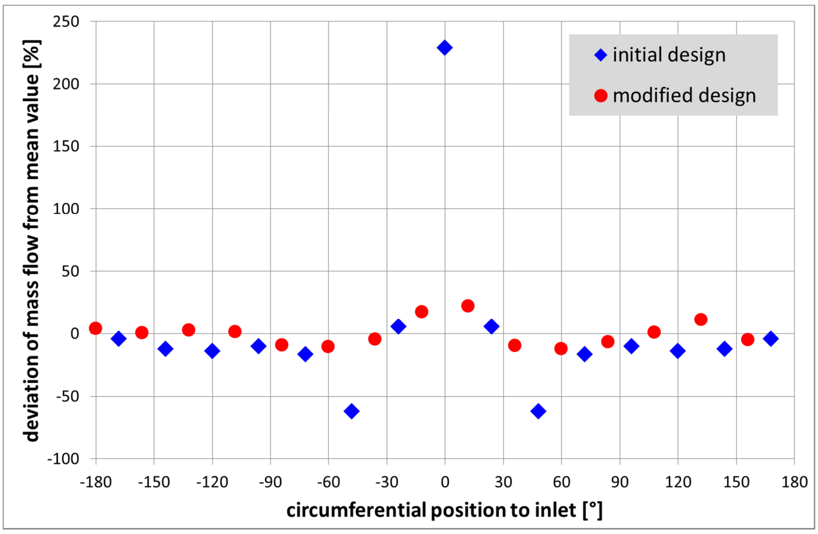

Figure 8: Main-poppet design, left, initial design, right, modified design

4.3 Two dimensional flow characteristics

Supplementary to the CFD analyses of the primary flow path of the valve, analyses of the secondary flow paths are performed. In this context, the flow through the gap between housing and main-poppet with opened sub-poppet is analyzed. Here a two-dimensional model of the geometry is appropriate. The CFD modelling is conducted in the same as described above. At the inlet upstream of the gap total temperature and pressure were prescribed. At the outlet of the CFD model, downstream of the gap between main-poppet and sub-poppet seal seat a supersonic boundary condition was set.

Figure 9 presents the overall view and some detailed views of the computational grid applied. For the analyses of this two-dimensional problem a two-dimensional hexahedral grid is generated with ICEM CFD. The detailed views show the grid in the grooves, in the narrow gap between housing and main-poppet and in the area of the seal seat of the sub-poppet. Across the narrow gap 22 cells are placed, with a refinement towards the walls. This wall refinement is going along all walls. The grooves are filled with a fine grid to enable the formation of vortices there. Also passage between the main-poppet and the sub-poppet seal seat is filled with a fine grid as sound transmission is expected to occur there.

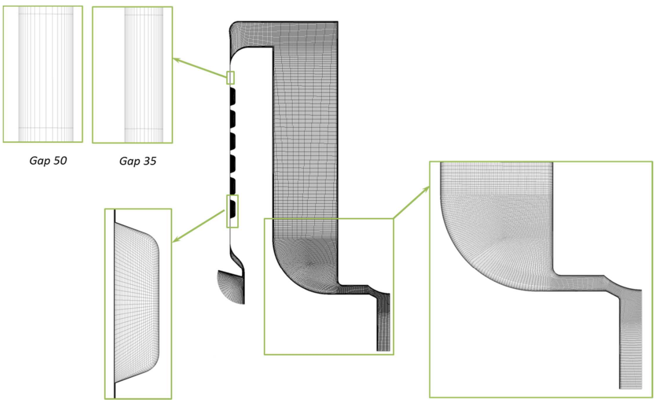

Figure 9: Gap inlet and sub-poppet outlet pressure 2D flow simulations grid size

On the left of Figure 10the streamlines and vectors in the 2D gap flow simulation model are shown. The blue arrows mark the inlet and outlet boundary condition of the CFD model. The right hand side of Figure 10 gives the Mach number iso-surfaces in the 2D gap flow simulation model. In the green boxes detailed views of the flow in the first groove (representative for all other grooves) and in the area of the sub-poppet seal seat are presented. The grooves

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are filled with subsonic spacious vortices. Downstream of the last groove sound transmission occurs (see detailed view). The supersonic jet is close to the housing wall when the flow volume is getting wider. The space is filled with huge subsonic vortices. Passing the sup-poppet seal seat the flow is accelerated again with sound transmission in the outlet channel. The corresponding shock and expansion lines in the outlet channel are depicted. Entering the outlet channel the flow accelerates around the main-poppet edge following small scale flow separation (see streamlines in Figure 10). The acceleration of the flow results in a distinct decrease in temperature. If the inlet temperature is already low, this might cause localized liquefaction. Particular modeling of this effect is not performed within this analysis framework because ANSYS-CFX cannot handle this effect with the employed fluid modelling technique.

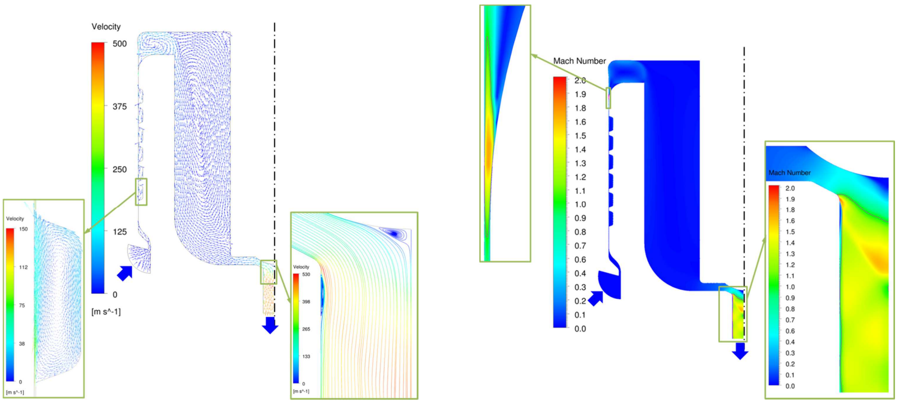

Figure 10: Gap inlet and sub-poppet outlet 2D flow simulations, left, flow field, right, mach number

The 2D CFD model was used to estimate pressure drops and flow coefficients over the sub-poppet and gap flow areas. These were identified using the functional model as being critical to the functionality of the valve. CD values of around 0.3 to 0.5 were found for the gap flow through the labyrinth seal and flow rates of around 0.8 were found for the sub-poppet. The flow coefficients were also found to be temperature, pressure and fluid dependent. These considerations have been incorporated into the functional model.

4.4 Functional Model

A one dimensional model was developed to investigate valve functionality. The functional model provides an advantage over detailed flow simulations and static force budgets by allowing analysis of valve dynamics. The opening of the valve is considered more critical than the closing due to the design and forces involved. Therefore, the results presented here focus on the opening behaviour. The valve opening sequence described in Figure 2 was simplified into a series of volumes and moving parts with the acting magnetic, spring and hydraulic forces taken into account. The concept is described in Figure 11. Each of the critical components is labelled with each of the volumes represented by P and a subscript representing the specific volume. The valve is displayed in the open configuration with the sub-poppet lifted from the main-poppet and the main-poppet lifted from the seal. The actuator is not shown in the image.

The simulation used a block analysis approach first estimating the fluid flow and volume pressures before estimating the resultant forces and the poppet motions. Inlet and outlet boundary conditions were kept constant and were defined as input parameters in the simulation. The isentropic flow equations were then used to estimate the flow rate between volumes and the pressure in these volumes during transient flow conditions. Flow coefficients from the 2D CFD analysis were employed as first order estimates to improve the accuracy of the simulation.

The simulation was designed to investigate functionality for four fluids; oxygen, hydrogen, nitrogen and helium. The fluid parameters were extracted from the NIST database using the REFPROP interface. The valve is to be used in oxygen and hydrogen atmosphere. However, much of the validation will be undertaken with nitrogen and helium so a translation of test results through the use of the model is also foreseen.

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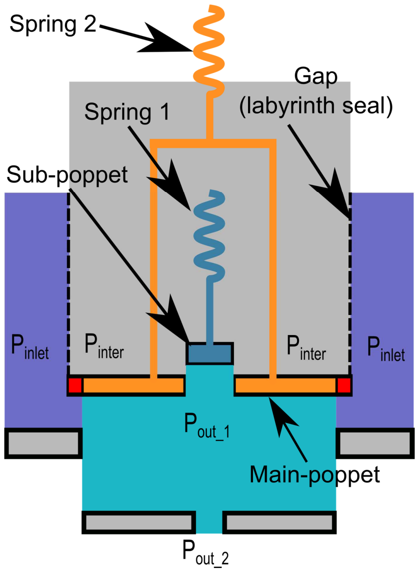

Figure 11: Simplified valve concept as basis for functional model

Figure 12 show the opening of the valve which proceeds in three stages as described in Section 2.4. The shown diagram is for the nominal inlet conditions of 135 bar and 300 K, oxygen is the medium. The sub-poppet begins to move when positive forces acting on the poppet are reached. This force balance is driven predominantly by the actuator counteracting the spring and hydraulic forces. When the sub-poppet is opening pressure from the interim volume is released. When the interim volume pressure decreases sufficiently the forces acting on the main-poppet become positive and the main-poppet begins to open. It is important to note that when the main-poppet is open, the pressure drop across the main-seat is much lower than the pressure drop across the gap (labyrinth seal). This causes a dynamic effect where the pressure force acting on the main-poppet is, for a short period following the opening, positive causing the main-poppet to open very rapidly.

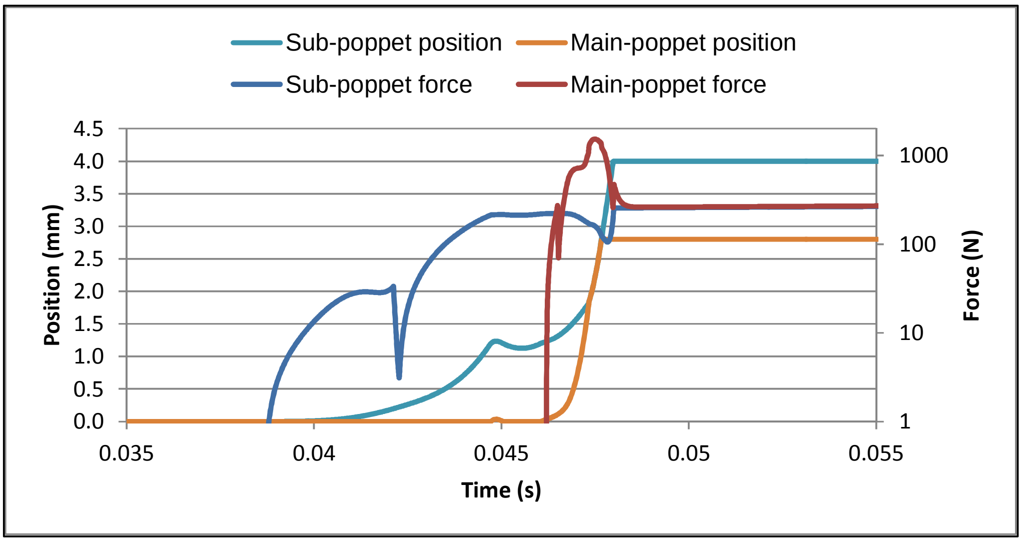

Figure 12: Simulated opening of sub- and main-poppets

Prior to validation with test data the functional model was used to identify the worst case scenarios for valve opening within the operational condition range specified. In addition, critical geometrical specifications such as flow and seal areas could be identified. Three critical aspects were identified. The first was that higher pressure conditions are more challenging and require a higher actuator force to open. This is due to a higher interim volume pressure, which,

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depending on the size of the sub-poppet out-flow area, may not decrease sufficiently to allow opening of the main-poppet. Figure 13 compares the opening conditions and the internal pressures from a 135 bar and a 200 bar case. All other parameters were kept constant.

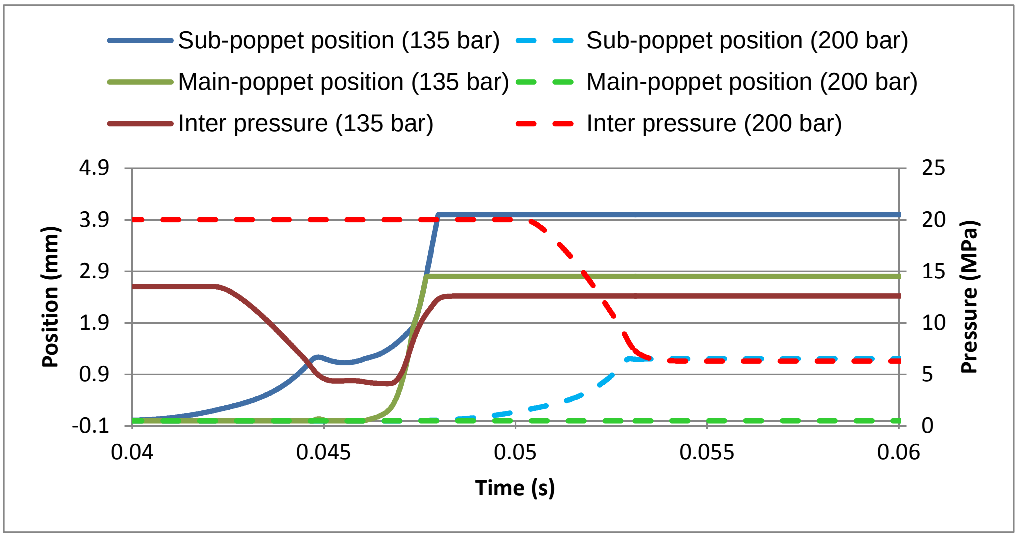

Figure 13: Simulated influence of pressure on opening behaviour

The second aspect is the influence on the speed of sound by the inlet temperature and pressure. At low temperatures (around 150 K) of gaseous oxygen GOx the speed of sound is more strongly influenced by pressure which results in lower flow ratio gap flow to sub-poppet flow. This leads to the same behaviour as with higher pressure, specifically, the pressure in the interim volume remains too high for the main-poppet to open. Figure 14 shows a comparison between nominal condition and cold conditions for the opening behaviour.

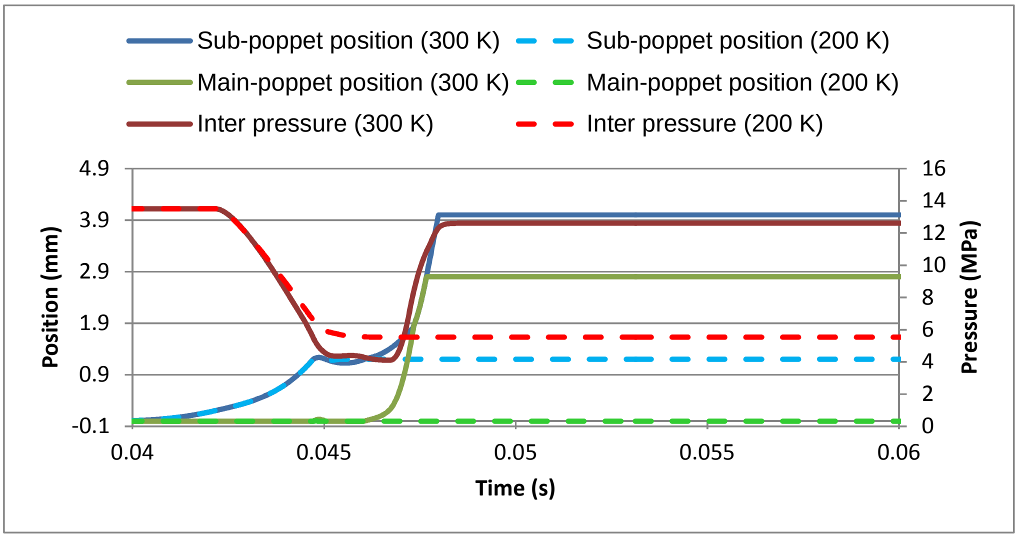

Figure 14: Simulated influence of oxygen temperature on opening behaviour

The third aspect is related to the flow area ratio from the gap inlet to the sub-poppet outlet. If this ratio is high then too much flow through the gap occurs and the pressure in the interim volume cannot fall sufficiently. When this ratio is low then the flow out of the sub-poppet is much higher than the gap and a lower pressure can be reached. In Figure 15 three different gap sizes are simulated with constant sub-poppet flow area. The two smaller gap sizes open, the middle gap size taking longer than the smaller, however, the largest gap size does not open. Smaller gap and larger sub-poppet sizes make the valve more robust against the two previous conditions and is therefore preferential. However, increasing the sub-poppet flow area increases the hydraulic forces acting on the sub-poppet and a larger

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actuator is required. Decreasing the gap size would also achieve a positive outcome. However, small gap sizes are not as robust and more sensitive to manufacturing tolerances and differences in the thermal expansion coefficient of the poppet and housing.

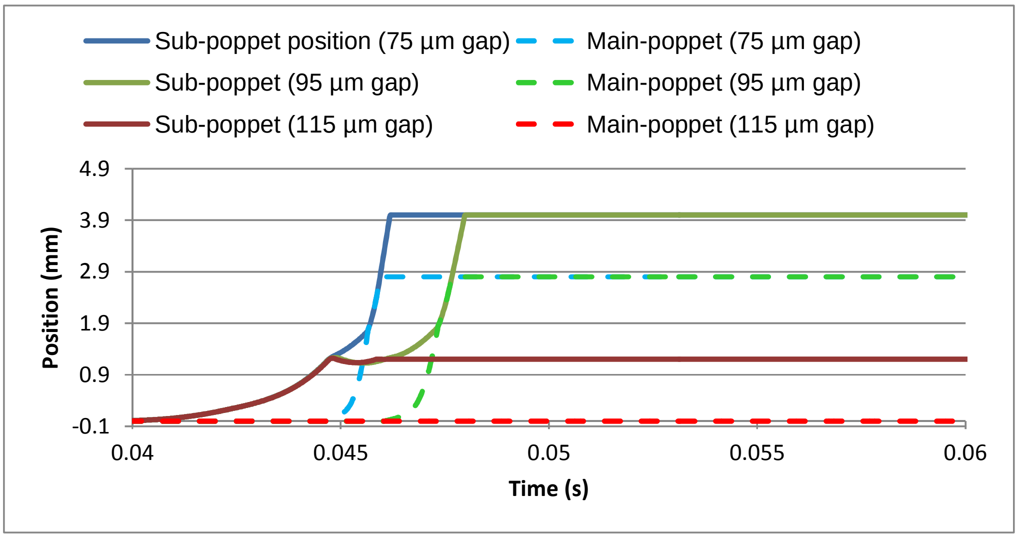

Figure 15: Simulated influence of gap size on opening behaviour

The use of a functional model provided insight into the dynamic behaviour of the model and indicates key risk scenarios restricting testing making it more efficient. The dynamic model also provides indications of potential valve improvements and addressing these aspects of design are part of on-going efforts during the development program. The functional model is closely tied to the design loop providing first case indication of improvements before test data is available and continues to be an active part of the development program.

4.5 Functional model and test comparison

This section provides a comparison of initial test data and valve simulation data. Validation of the model with test data is ongoing and is considered an important aspect of the development loop as the design is adjusted to improve the functional robustness. The test data presented below is focused on tests under high pressure hydrogen conditions and was conducted as part of hydrogen compatibility investigations. Due to the nature of the tests the diagnostics were limited to temperature and pressure measurements in addition to the actuator current and voltage behaviour. Oxygen compatibility tests are currently underway and will form the future basis for validation of the model with oxygen.

Figure 16 compares simulation and test data for valve opening at 150 bar and with ambient inlet temperature. The pressure curves presented represent the highest pressures tested with hydrogen up until this point. The pressure curves of the upstream, interim and first downstream volume are compared. However, direct measurement of the poppet strokes was not possible in this test configuration. The test configuration was with a gap size of 45µm with a sub-poppet drilling of 2.8 mm. In this configuration the valve showed optimal actuation behaviour for the full range of pressures investigated.

The test data shows that the functional concept as demonstrated by the simulation is as expected. As demonstrated by the simulation, internal pressure is critical in defining the opening of the main-poppet. The pressure must first fall significantly in the internal volume before the main-poppet can open. However, it is important to note that hydrogen is considered less critical than cold oxygen due to the lower dependency of sonic velocity on pressure.

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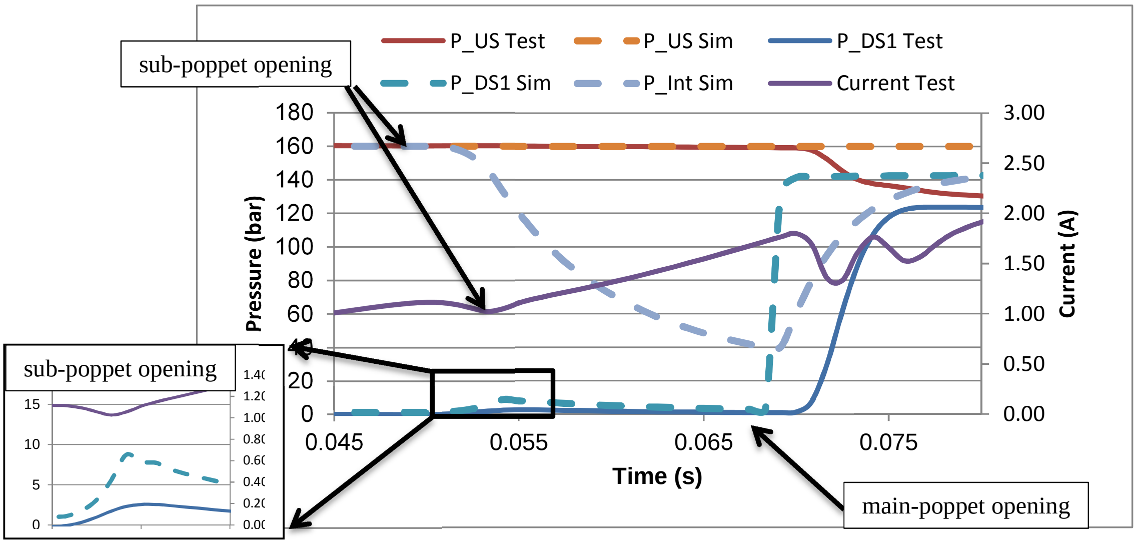

Figure 16: Comparison between functional model and test opening behaviour

4.6 Simulation and Testing Outlook

The initial valve design has been completed and has progressed to testing. The simulations conducted to support the initial development, before test data was available, have been effective in optimisation of the design based on the prescribed requirements. Specifically, the identification of critical design components and operational ranges has already positively impacted the subsequent testing and verification approach. Access to simulation and the detailed information it provides has also increased understanding of the functional behaviour and the initial test results.

Now that the first hardware is available for testing the next steps are to complete detailed verification of the functional analysis and to focus on testing of the critical operational ranges. Further testing with cold oxygen at high pressure is foreseen as well as detailed validation of the model with increased data input such as stroke measurements from test.

5 Conclusion

The development of the oxygen pressurisation plate (PPO) and the mass flow regulating electro valve (PPx) is a key component of the oxygen pressurisation system for the Ariane 6. The wide range of operational conditions and requirements present a significant technical challenge to the Airbus Safran Launcher fluid control equipment team in Ottobrunn. The pressure-piloted design, selected in a design trade-off, is currently in the development phase.

A number of numerical tools were employed in the early design phase. Results from these tools lead to significant improvements in design prior to the production of the first test equipment. Of particular note was the effective use of 2D and 3D CFD simulations to optimise the design for high flow rates and enhanced functionality through understanding of pressure drops and flow rates. The functional model also played an important role in identifying critical design aspects, such as the ratio of gap flow area to sub-poppet flow area, and critical environment conditions for functionality, such as high pressure and low temperatures.

The initial results are promising and show robust and reliable valve functionality. In particular, the successful completion of oxygen compatibility for the PPx valve is a significant step forward in the development process. However, a number of aspects still need to be addressed before conclusion of the final design phase. In particular, tests with full range of mediums and temperatures still need to be conducted. Functionality still needs to be proved for the critical case of high pressure, low temperature oxygen. This aspect will be addressed in upcoming tests.

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