DE-RISK OF THE

NUMERICAL ASSESSMENT AND EXPERIMENTAL TESTING OF THE SEALING DESIGN

PROPOSAL NO. I-2022-02172

E-PUMP EXECUTIVE SUMMARY REPORT

Version *1.0*

2024-03-01

Document No.: HIT_E-Pump_ESR
Classification: confidential

Written by: Tommaso Pellegrini
Date: 2024/05/07 Signature: [signature]

Revised by: Kushal Ghate
Date: 2024/05/07 Signature: [signature]

Approved by:
Date: 15.5.24 Signature: [signature]

DISTRIBUTION LIST

INTERNAL		EXTERNAL		
NAME	COPIES	Co.	NAME	COPIES
Tommaso Pellegrini	1	ESA	Christopher Braine	1
Kushal Ghate	1	ESA	Simon Hyde	1
Ulrich Fischer	1			
Christian Schmierer	1			

ISSUE RECORD

ISSUE NUMBER	DATE	MODIFIED PAGES	REMARKS
1.0	2024-03-01	all	Initial issue

Related documents

[RD-01] HIT-ePump-D2
[RD-02] HIT-ePump-D3
[RD-03] HIT-ePump-D4
[RD-04] HIT-ePump-FR

TABLE OF CONTENTS

LIST OF FIGURES

1 Introduction

This document provides a concise, non-technical overview of the findings of the study developed within the context of this Programme. A detailed description of the methodology, results obtained and future works can be found in the related documents and final report.

2 Justification and background

HyImpulse Technologies GmbH is a new-space start-up focused on providing dedicated launch options to the small satellite market. It is one of the key players in the recent European bloom in commercial application of space technologies and, as such, it strives to push the boundaries of the European space industry technological advancement. HyImpulse is paving the way for greener, cheaper and safer launch options by developing launch vehicles based on its unique hybrid rocket motor series, HyPLOX , which uses candle wax and liquid oxygen as propellants and represents one of the most powerful hybrid rocket motors commercially available worldwide. Its inherently simple design provides flexibility in operations and the possibility to easily interface with various pressurization systems required to feed liquid oxygen to the hybrid motor combustion chamber at high mass flow rates and pressure values. The HyPLOX engine represents the base propulsive unit of the SR75 sounding rocket, capable of delivering 250 kg payload into a sub-orbital trajectory with an apogee of 200 km, already available for commercial operations involving micro-gravity and hypersonic flight. A cluster of HyPLOX engines will propel the SL1 vehicle, a 3-stage orbital vehicle capable of delivering 500kg of payload into Low Earth Orbit.

One of the options available for the upper stage of the SL1 vehicle pressurization system is the use of an electric pump to raise the pressure of liquid oxygen stored in the vehicle tanks. This solution is already in use in the Electron launcher, a prolific vehicle developed by USA/New Zealand company RocketLab, which has been able to carve and occupy a relevant niche in the world of private launch services providers.

The system offers a series of advantages, if compared to other solutions typically in use in such a context: high efficiency, simple architecture and lower overall system mass to name a few.

The application of this technology on orbital vehicles, however, represents a field in which European expertise lacks behind, and although multiple companies on the continent are investigating the topic and building business cases around it, no specific solution is being developed for hybrid rocket motors.

HyImpulse therefore proposed to start a development program on such an electric pump, starting with a de-risk study aimed at evaluating the pump performance required and its annex risks. The strategy proposed reflects the pragmatic approach embraced by HyImpulse as one of its core values, and consists in splitting the system in sub-units to be developed in parallel, with the company focusing on the engineering of the pump components while relying on commercially available solutions for components that would require specialist knowledge (such as electric motor, battery packs and inverter). The fact that HyImpulse has the capability to manufacture and test its motors and vehicles independently, allows the company to plan for validation tests where the pump is run in combination with its hybrid engines in static hot fires and in flight.

3 Findings of the study

This study developed around three main activities: first an assessment of the typical mission profile associated with a SL1 upper stage using an electric pump. This results in a clear definition of performance requirements of the electric pump to be designed. Second, a thorough analysis of the risks linked to the development of such a system. Lastly, analytical, numerical and experimental analyses of the solutions proposed to mitigate such risk from an engineering point of view.

3.1 Proof of concept study

The proof of concept study lays the foundation that justify the whole research program. Using the required performance parameters of SL1's upper stage and its hybrid combustion chamber as inputs,

the performance of different pressurization systems was assessed by collecting information on efficiencies and mass of the components involved per architecture type.
The outcome of the analysis shows how the system comprising of pump, electric motor, inverter and batteries would bring a 15% improvement in system mass when compared to a turbopump architecture, and as much as a 75% for a pressure fed system. The configuration would also represent the most efficient in terms of power output.
The assessment of the market shows that the strategy of relying on commercially available products that satisfy the requirements of the drive train, is indeed cost efficient, with multiple suppliers identified for motor/inverter and batteries, mostly coming from industries not related to aerospace.
The study also identifies the main risks associated with the development of the system. As HyImpulse intends to develop the pump and its drive train in separate but parallel programs, great emphasis is placed on the effectiveness and reliability of the item that physically separates the two, namely the sealing system, which is validated through a dedicated numerical and experimental study.
Other critical areas include:

- The bearing elements supporting the pump shaft, because of the extremely cold temperatures in which they operate, the high rotational speeds and the scarce lubricating effect of liquid oxygen.
- The thermal management of the electric motor, which will tend to heat up during operations. A strategy is proposed where a simpler architecture is adopted first, so to have a operational, although non ideal, configuration, to be then gradually converted into an optimal configuration where pump and electric motor are integrated in the same casing, and cooled with liquid oxygen.
- The thermal management of batteries and inverter, as they will be exposed to the vacuum of space before they start operating.

3.2 Sealing system

HyImpulse proposed a simple solution for the sealing system, that can prove far cheaper than other systems typically used for high-speed pumps.
Because of the range of rotational speeds, expected pump dimensions and operating pressures, the use of a simple lip seal can be investigated. These mechanical seals are typically used to seal rotating shafts in environments at moderate temperatures (50° to 100° C), lubricated with oil, with moderate pressure drops (up to 5 bar) and contact speeds (20 m/s). They are composed by a “lip” of thermoplastic or elastomer material, encased by a steel ring. They work by being squeezed onto the rotating shaft by the fluid pressure, hence closing any gap between the two bodies. They are lubricated by the minimal leakage they allow through, in the order of drops per minute or hour.
They are simple to install, cheap to manufacture and do not require complex purging or lubricating systems.
The application of these mechanical seals to cryogenic fluids like liquid oxygen or liquid nitrogen, with temperatures well below -150 °C, is very unusual if not a first.
HyImpulse explored its design and performance through a dedicated numerical and experimental study.
Hyimpulse identified the biggest limitation to the use of such a solution as the risk of autonomous ignition of the lip seal material, as it is heated up by the friction develop between the lip and the rotating shaft in a pure oxygen environment.
Because of the risk of combustion, the material selected was PTFE, showing the highest compatibility with oxygen amongst the materials commonly used for the task. To minimize the danger, a specific compound of PTFE was chosen, which lacks any additives that might add to the flammability of the material. Its design was approached through analytical and numerical simulations, in partnership with specialists in the field.
HyImpulse manufactured a test rig capable of testing the seal prototypes in condition similar to the operating conditions they will face in the pump, to verify their correct behavior. The rig included

monitoring of fluid pressure and temperature, rotational speed and torque, as well as thermal imagining to determine local temperatures of interest.

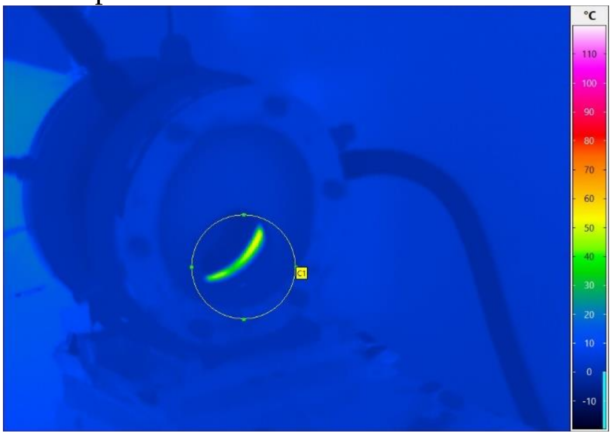

Figure 1: thermal imaging deployed during a seal validation test.

The experimental campaign highlighted a few interesting practical details about the use of lip seals in such an environment and about necessary design features for the next iterations.
First, the seals work in cryogenic conditions, provided that the design accounts for the shrinkage the seals experience when chilled to -170°C. A map of safe operating conditions was drawn for the seal tested, separating safe, conditionally safe (requiring modification to the system) and unsafe points of operation in terms of fluid pressure and shaft speed. An example is presented in Figure 2.
Second, certain designs perform better than others, with the best performing ones being installed in an unconventional manner that wouldn't work at operating conditions not involving liquid oxygen. This application provides benefits in terms of contact pressures and thermal management of the components, which ultimately leads to safe operation at a wider range of conditions.
Third, mechanical integrity of the lip material is as much of a risk factor as that of auto-ignition. The compound chosen for the first prototypes, albeit guaranteeing exceptional compatibility with pure oxygen, lacks the additives that normally contribute to wear resistance and shear damage avoidance. New compounds will be chosen for the next iteration of design as a better compromise between optimal compatibility with oxygen and mechanical integrity.
Fourth, the effect on fluid mass flow on contact area cooling is not as relevant as originally thought, allowing for the definition of an optimal flow to be provided by the system to the seal for lubrication and cooling.
As an outcome of the study, an updated list of requirements is provided to lead the next iteration of design with qualitative and quantitative measures.

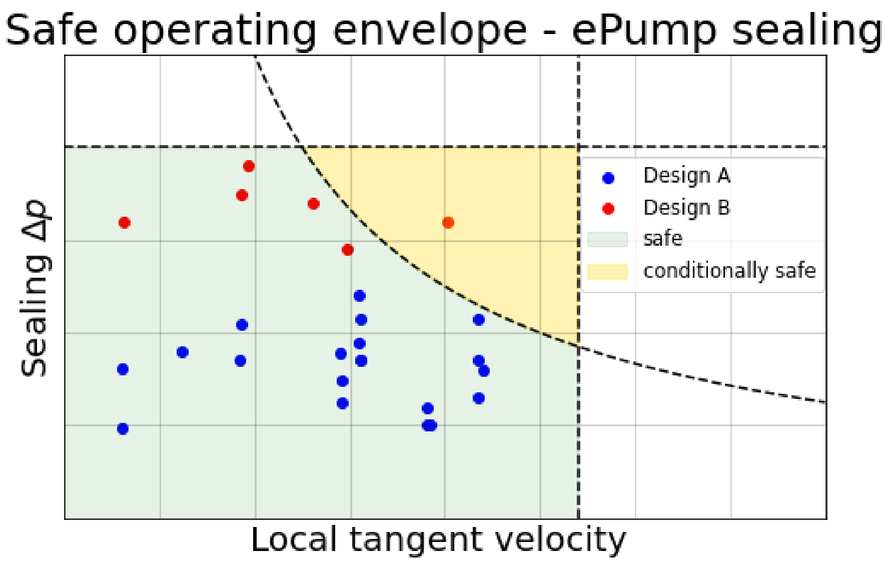

Figure 2: Example of safe operating envelope based on tests performed with different sealings.

3.3 Bearing selection

As part of the de-risk study, possible solution for the bearing system have been selected.
Starting from the required performance, and with the goal of minimizing system mass, a parametric study has been conducted to determine the optimal impeller geometry.
Parameters monitored included risk of cavitation, efficiency and dimensions.
Once the impeller geometry had been chosen, a preliminary layout of the pump assembly has been chosen. Forces and torques applied to the rotor have been determined based on well establish approaches found in literature, and the shaft has been sized accordingly. A simple finite element analysis has been perform to verify the factors of safety obtained by applying loads resulting from the forces and torque expected. The shaft sizes, along with the forces in place and the rotational speed of the shaft have been provided to industry specialists CEROBEAR GmbH, who provided an offer for different bearing options.

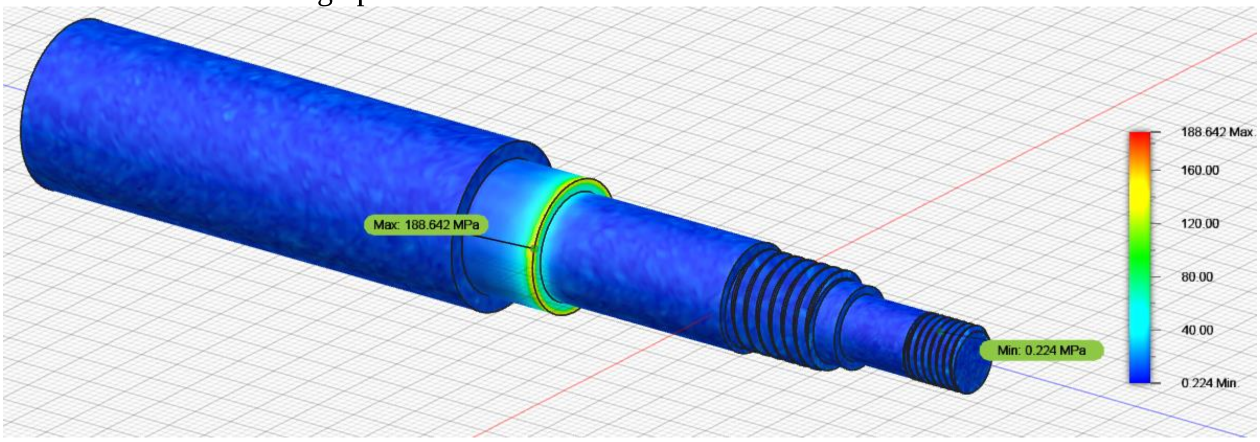

Figure 3: simplified FEA simulation on the pump's shaft preliminary design.

The bearings of choice are angular contact bearings, either of the steel or hybrid type, with ceramic rolling element and metal cages. Although the pump RPMs are well within the bearings capabilities, contact pressures resulting on the rolling elements lean towards the maximum values acceptable for such designs. In a conservative effort aimed at guaranteeing reliable performance, CEROBEAR advices a reduction in contact pressure, which will be taken in consideration for the future, detailed design of the pump components.

4 Conclusions

The study has allowed HyImpulse to explore criticalities in the development of an electric pump dedicated to hybrid rocket propulsion and to de-risk some of its most relevant components.

It has allowed a system-level analysis corresponding to a preliminary design of the electric pump; HyImpulse has proposed a development timeline based on a cost effective strategy, namely to engineer only some of the components, while purchasing items requiring specialist expertise from commercially available products. A possible supply chain was laid out and options were evaluated based on component mass and efficiency. It was demonstrated that the electric pump architecture can indeed increase substantially the performance of HyImpulse's vehicles, where applicable.

The study demonstrated the possibility of utilizing a simple lip seal to isolate the pump from the rest of the system. A series of practical considerations emerged, allowing for invaluable experience to be used in the upgrade of the sealing system design. A list of updated design requirements was drafted. A methodology to design and test the seal prototype was developed and validated.

In the context of the selection of bearing elements, a preliminary sizing of some key components was performed, including shaft, impeller and volute. Layout options for the pump were proposed.