DOI: 10.13009/EUCASS2023-739

Exploring the potential of electropump feed systems for extending high thrust and deep throttle performance for CH4/LOX rocket engines

Simona DANESCU[1], Dan IFRIM[2], Alexandru CANCESCU[3], Theodora Andreescu[4]*
** Corresponding author*
1 COMOTI Launchers and In-Space Advanced Propulsion, 061126 Bucharest, Romania,
simona.danescu@comoti.ro
2 COMOTI Launchers and In-Space Advanced Propulsion, 061126 Bucharest, Romania,
dan.ifrim@comoti.ro
3 COMOTI Launchers and In-Space Advanced Propulsion, 061126 Bucharest, Romania,
alexandru.cancescu@comoti.ro
4 COMOTI Launchers and In-Space Advanced Propulsion, 061126 Bucharest, Romania,
theodora.andreescu@comoti.ro

Abstract

The development of the current European space strategy requires basic research on the key concepts of space propulsion systems that contribute to the development and consolidation of the European space industry. Due to the increasing global demand for reusable and flexible space propulsion concepts, there is a growing trend to replace turbopump systems with electric pump systems.

In order to accomplished the European space strategy, the main goal is to develop two compact electric pumps for a 25 kN LOX/CH4 bipropellant engine, in order to apply them on a number of potential applications, from placing payload on Low Earth Orbit to resupplying International Space Station. Electric pump feed system has a high potential for the future, because of their compact size and modular design with lower complexity and higher flexibility, also capable for long operations and unlimited number of restarts without any complications added to the system.

This paper is dedicated to evaluate the pumps critical points identification and solution trade-off in order to obtained sustainable overall architecture of the electro-pumps, including all the hydraulic and mechanical components necessary for their operation. In order to achieve this goal, have been evaluated several empirical methods and the preliminary pumps designs were evaluated and optimize using computational fluid dynamics (CFD) methods. Another of the key research topics is to establishment of the testing procedure and methodologies for testing the pumps by similarity with water in order to checking and validating the pumps functionality by measuring the pumps characteristics, fluid parameters and cavitation.

This scientific work is based on the project funded by the European Space Agency (ESA) in the frame of the General Studies Technology Programme (GSPT), carried on through a co-engineering partnership with COMOTI, ICPE and ROSEAL, that will bring to the project its expertise in turbomachines design and analysis, in driving motors and sealing system along with expertise of the critical function of the electrically driven pump-feed LOX/CH4 cycle rocket engine.

1. Introduction

The space industry has made remarkable progress in recent decades, and technological advances in this field have significantly impacted on space exploration. A major influence on technological progress in the space industry has been seen with the involvement of the private sector so the commercialization of space has opened up new opportunities for innovation, competition and collaboration between academia, government agencies and the private sector.

The concepts of miniaturization and sustainable development due to technological progress, open new opportunities for fields such as telecommunications, environment, agriculture, transport, security and safety, factors that demand the development of space applications and the democratization of access to space data and services in order to provide significant benefits to society.

In accordance with the dynamics of the space industry, INCDT COMOTI is actively involved in various programs and projects to respond to the challenges of the new space exploration strategy promoted by the European Space Agency (ESA). The project funded by the European Space Agency (ESA) in the General Support Technology Programme De-Risk Framework (GSPT), implemented through a co-engineering partnership with COMOTI, ICPE, and ROSEAL, targets the development of concepts for electric pumps, based on expertise in turbopumps design and analysis, in drive

DOI: 10.13009/EUCASS2023-739

motors and in the sealing system, together with critical function expertise in the LOX/CH4 cycle rocket motor powered by electropump.

The objective of the project is to develop two high speeds centrifugal electropumps for a 25 kN LOX/CH4 bipropellant launcher engine for future suborbital flights and micro launcher applications and to achieve a quantitative understanding of the electric pump feed operation in order to extend the technology maturation of an understanding of a competitive cryogenic rocket engine, capable of throttleability and re-ignition in flight. The project will focus on creating efficient, reliable and lightweight electric pump systems to enhance the overall performance and safety of the propulsion system.

Some of the market segments for these pumps include: low-cost expandable launchers, suborbital launchers; semi-reusable launchers, highly reusable propulsion for future regular spaceflight vehicles, upper stage engines; engines for service modules, landing or descent vehicles and ascent stages.

Replacing the turbo-pump assembly of upper stages rocket with electric pump assemblies offer a number of advantages that are of interest to the potential customers:

- increased operation time compared to turbopumps due to the high thermal and mechanical stresses that the turbine is subject to;
- higher efficiency;
- capability to increase or decrease the pump’s speed, thus allowing effortless throttling of the rocket engine;
- capability to many fast re-starts;
- reusability;
- lower development and manufacturing costs.

Beyond its application to satellites and aircraft, several researches related to electrically driven pump-feed cycle rocket engine or launch services have been released. Abel and Velez proposed an electrical driven pump drive system using a brushless DC motor for booster stages. [1] Raymond configured a propellant pump using an inertia wheel and an electric motor. [2] Bahn proposed a rocket engine with an electric motor with power level below 100 kW. [3] Cassino et al. [4] and Galfetti et al. [5] studied an application of electrically driven pump to improve the performance of hybrid rockets. Solda and Lentini by involving a detailed mass breakdown comparison of pressure-feed cycle and electrically driven pump-feed cycle engines showed that the latter is advantageous in terms of mass. [6] Rachov et al. researched into the GG cycle using MMH and NTO [7] and Spitter showed that an electrically driven pump-feed cycle rocket engine outperforms GG cycle in terms of mass ratio for long burning times. [8] Moreover, Vaughan et al. reported the feasibility of an electrically driven pump-feed storable bi-propellant rocket engine for a Mars ascent vehicle. [9] For LOX/kerosene propellants, Dibrivny et al. performed an analytical estimation of electropump supply systems using the RD868T engine. Also, RocketLab announced a successful Electron rocket launching, which uses an electrically driven pump-feed cycle called Rutherford engine.[10]

2. Concept

The main technical objective is to develop two high-speed electro pumps, one for LCH4 and one for LOX for below-target missions:

- Low Earth Orbit (LEO) payload insertion;
- resupplying the International Space Station (ISS);
- missions with multiple restarts.

Turbopump thrusters have the capability to perform multiple restarts, but for these additional systems are essential to provide the necessary restart conditions. On the other hand, electric pumps are potentially capable of an unlimited number of restarts without adding complication to the system, thus becoming ideal for multiple restart missions.

The flight engine is a 25 kN LOX/LCH4 bipropellant engine throttleable and capable of in-flight re-ignition.

The requirements for both pumps are summarized in Table 1.

Table 1: Electropumps specifications

	Design Point	
	LCH4	**LOX**
Mass flow [kg/s]	2.1	6.4
Inlet pressure [bar]	3	3
Outlet pressure [bar]	135	85
Temperature [K]	115	95
Electric Motor power [kW]	90	80
Speed Rotation [rpm]	40.000	60 .000

DOI: 10.13009/EUCASS2023-739

Figure 1 presents a schematic of the proposed expander engine cycle concept. Two independent electrically driven pumps provide high-pressure propellant into combustion chamber of the cooling circuit. The engine architecture consists of centrifugal pumps for each propellant and two-motor configurations, such as mass flow rate and head rise with different rotational speeds. The battery back is composed of several unit battery cells, being determined by the required power and energy of the motor.

The two propellants will be stored in the fuel tanks and the electric pumps will raise the static pressure to the desired values and will provide the required flow rate. While LOX will be directly injected into the combustion chamber, the LCH4 will be first used to cool the thrust chamber after which it will be injected. LCH4 will also be collected the LCH4 pump in order to cool the high-speed electric motors and inverters, after which it will be reintroduced in the circuit at the pump inlet. The cooling will assure a higher efficiency from the electric motors and will assure that function at safe operating temperature. The LCH4 cooling will then be feed in the circuit to be injected in the combustion chamber.

In order to achieve a high throttleability, between 46% and 100%, the pumps and electric motors must be capable of properly operating on a large range of non-nominal conditions. The pump controller must be capable of performing a basic self-check and communicate the values of all parameters measured during operation.

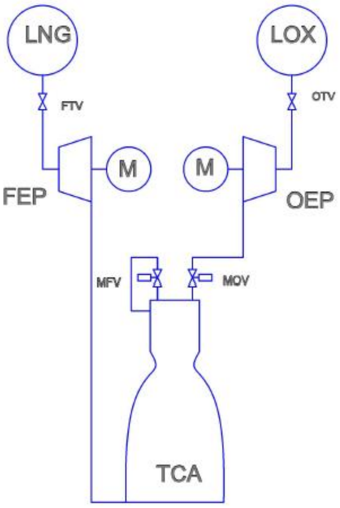

Figure 1 Schematic representation of the LOX/LCH4 Rocket Engine based on electric pump feed system and expander engine cycle

The architecture of both pumps has been carefully chosen to satisfy the necessary performance requirements: operational environment, performance requirements, envelope constraints, safety requirements, technological risk level and cost constraints.

3. System design and functional description

Electric pump feed systems use high-speed and high-performance motors to replace the traditional turbine as the driving machine of pumps [11].

Design considerations for an electropump using cryogenic liquids for space applications:

- Inducer is a critical component of the electric pump assembled upstream of the impeller to avoid cavitation, responsible for the efficient and effective distribution of fluid to the impeller inlet, ensuring smooth and efficient operation. The inducer improves pump performance by pre-accelerating the fluid and increasing its pressure before entering the impeller. Inducer design starts with establishing an optimized fluid flow path. This usually involves accurately shaping the inlet and outlet pump geometry to minimize flow losses, turbulence and cavitation.
- Impeller represent the core of a centrifugal electropump which consists of curved vanes or blades. The shape and geometry of the impeller are designed to efficiently convert mechanical energy into fluid propulsion. It must be light, strong and balanced to sustain high rotational speeds and maintain stable operation.
- Volute is the component of the electropump which is responsible for the efficient collection and redirection of fluid from the impeller outlet to the pump outlet or to the intended location within the system. It plays a

DOI: 10.13009/EUCASS2023-739

key role in maintaining fluid flow characteristics, minimizing losses and ensuring optimum pump performance. Volute design involves establishing an optimized flow path that allows for smooth and efficient fluid flow. The volute geometry is carefully shaped to gradually expand and convert fluid kinetic energy into pressure energy, thereby increasing the fluid pressure before exiting the pump.

- Sealing types and design for leak prevention: Electric pumps require effective sealing mechanisms to prevent fluid leakage from pump part to electric engine part, and maintain system efficiency. Particular attention is paid to the selection of the sealing system type, its design and selection of sealings materials to ensure reliability and feasibility.
- Electric motor design provides the mechanical power to drive the pump impeller. The motor design must meet the demanding requirements of space applications, including high efficiency, reliability and operation in extreme conditions.
- Compact and lightweight design: Space applications require compact and lightweight designs to optimize payload capacity and minimize launch costs. Electropump components, including impeller, casing and electrical systems, are designed to be lightweight but durable. Advanced manufacturing techniques, can be used to achieve complex geometries and reduce weight while maintaining structural integrity.
- High-speed operation and stability: The design of electric pumps requires special attention to rotational speeds and stability. Advanced rotor dynamic analysis and balancing techniques are used to ensure smooth operation, vibration avoiding and excessive mechanical stresses. Hydrodynamic forces acting on the rotor and other rotating components are taken into account during the design process to maintain stability and efficiency.
- System integration: Electropumps are usually integrated into larger space systems, such as rocket engines or satellite propulsion systems. Pump design should consider factors such as fluid routing, connection interfaces and compatibility with other system components to ensure seamless integration and efficient overall system performance.

The functional description of an electropump for space applications highlights its main role in fluid transfer or propelling, efficient fluid acceleration, power generation, system control and monitoring, reliability and safety. By performing these functions, the electropump is contributing to the overall success and performance of the space mission.

- Electric driving: The electric motor is typically designed to be lightweight and operate at high speeds to meet the demanding requirements of space applications.
- Impeller rotation: The mechanical energy of the electric motor is transmitted to the impeller, which is a rotating component with blades or vanes. As the electric motor spins the rotor, it transmits kinetic energy to the fluid, causing it to accelerate.
- Fluid aspiration: The electropump creates a pressure difference between the fluid inlet and outlet. This pressure difference causes fluid to be sucked into the pump through the inlet.
- Fluid acceleration: As fluid passes into the electropump, it encounters the inducer, which is a component designed to pre-accelerate the fluid and reduce the risk of cavitation. The inducer optimizes the flow of fluid and increases its speed, as well as pressure in order to avoid cavitation, preparing the fluid for subsequent acceleration.
- Impeller action: The pre-accelerated fluid then enters the impeller region, where rotating impeller blades impute additional kinetic energy to the fluid. This results in a further increase in fluid velocity and pressure.
- Fluid discharge: High-speed, high-pressure fluid exits the impellers and enters the volute, which is a specially designed component that collects the fluid and redirects it to the outlet. The volute converts the fluid's kinetic energy into high-pressure energy, increasing the fluid pressure before it exits the pump.

The electric pump design process starts with a performance requirements analysis, which will identify parameters that cannot be changed and parameters that will be optimized. The hydrodynamic design of the electric pumps has three main components, namely the rotor, diffuser and volute.

The necessary power output of the pump represents the specific work Y, which it is defines by the specific enthalpy rise (Δh). The specific enthalpy rise represents the total useful energy transmitted by the pump to the fluid per unit mass. The specific work is identical to the total useful isentropic enthalpy rise [2]:

$$Y = \Delta h_{tot} = \Delta h_{tot.2} - \Delta h_{tot.1} \tag{1}$$

The Pump Head or the Total Dynamic Head (H) described the power output of the pump. The Head Rise is the height that a column of liquid can be raised given a certain pressure. It is the difference between the total dynamic discharge head $\mathrm{H_d}$ and the total dynamic suction head $\mathrm{H_s}$ and correspondents to the increase in total pressure from the inlet flange to the exit flange divided by the specific mass of the fluid [2].

$$H = H_d - H_s = \frac{dp}{\rho * g}\ [m] \tag{2}$$

where dp represent the total pressure difference at the pump inlet and outlet.

$$p = p_{02} - p_{01} \tag{3}$$

DOI: 10.13009/EUCASS2023-739

The volume of the fluid that passes per unit time represents the volume flowrate Q and it is represent as follow:

$$Q = \frac{dV}{dt} in \, [\frac{m^3}{s}] \tag{4}$$

The specific speed $\mathrm{N_S}$ and the specific diameter $\mathrm{D_S}$ are the basic parameters for classifying pump types, as they indicate the stage characteristics and identify specific areas where pump configurations are suitable for a particular application. These parameters are also used for preliminary design predictions such as pump efficiency and diameter.

$$\mathrm{N_S} = \frac{\mathrm{NQ}^{1/2}}{\mathrm{H}^{3/4}} \tag{5}$$

The Shaft Power is defined as the driving pump power. It is the rotation speed ω multiplied by the transmitted torque M.

$$P_{Sh} = M\omega \tag{6}$$

The total efficiency is the measurement of the hydraulic work related to input shaft work.

$$\eta = \frac{P_h}{P_{Sh}} = \eta_{hyd}\eta_v\eta_m \tag{7}$$

where P_h represents the hydraulic output power, η_{hyd} is hydraulic efficiency, η_v reporesents volumetric efficieny and η_m is mechanical efficiency.

The Net Positive Suction Head is the difference between the head due to total fluid pressure and the head due to propellant vapor pressure. If the NPSH is less than a critical value, cavitation will first occur at the inlet of the impeller. If the static pressure p get reduced to the vapour pressure $\mathrm{p_v}$ of the liquid, vaporization of the liquid will be caused and so cavitation will occur [2].

Mechanical shocks cause by the imploding of the gas voids can create powerful and damaging shock waves. This phenomenon is called cavitation and if the cavitation occurs, the NPSP value decreases significantly. There are few methods to avoid the cavitation: increasing the tank pressure led to an increased NPSH, but the tank wall thickness and so the tank mass increases; decreasing the pump design speed which leads to a lower required NPSH, but also decreases the pump head; redesigning of the pump inlet by increasing the diameter and lowering the flow coefficient which leads to a higher mass of the pump and can decrease the pump efficiency.

$$NPSH = \frac{p_1 - p_v}{\rho g} \tag{8}$$

The pump head coefficient and the resulting impeller discharge diameter can have a wide range of values depending upon the flowrate, required suction performance, the required pump efficiency and head versus flow slope [1].

Required net positive suction head ($\mathrm{NPSH_R}$) is representing as follow:

$$NPSH_R = \frac{p_1 - p_{min}}{\rho g} \tag{9}$$

The Suction Specific Speed $\mathrm{N_{SS}}$ is an essential parameter that describes the impeller and/or inducer suction performance and correlates pump speed, flowrate and net positive suction head:

Using the nominal operating conditions as a guide, a pump design was developed. Impellers, diffusers, and volutes are the three major components of an electro pump's hydrodynamic design. To acquire a rough idea of the expected size and performance of the machine, predesigns have been made for the entire pump section.

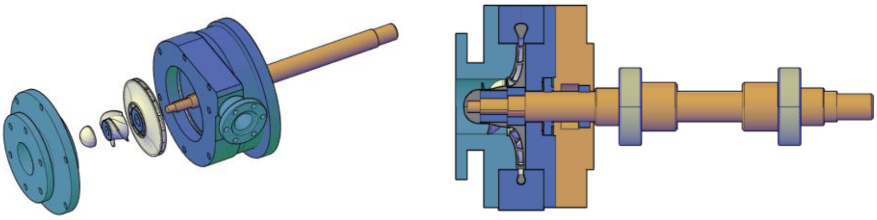

Figure 2: CH4 Pump Architecture

DOI: 10.13009/EUCASS2023-739

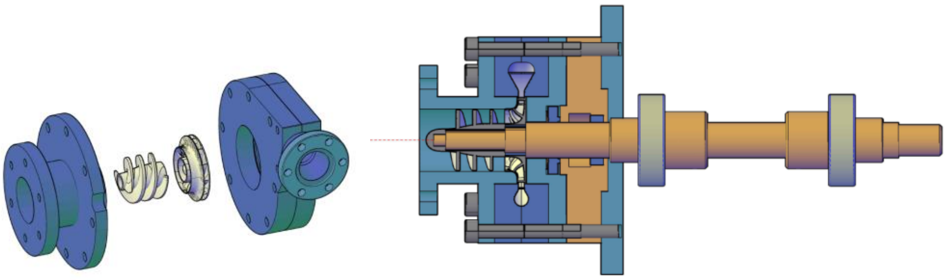

Figure 3: LOX Pump Architecture

As a partner in the project, ICPE covering a wide range of innovative concerns in the field of electric engineering and it is in charge with the electric motor concept development. Consolidation of the requirements for the electric motors is necessary in order to determine the main operating parameters. Four main types of electric motors are suitable for high-speed electric pumps for launcher engines:

- Brushed Direct Current Motors (BDC);
- Permanent Magnet Synchronous Motors (PMSM/BLDC);
- Stepper Motors;
- AC Induction Motors.

Table 2 Predominant applications for principal types of electric motors suitable for space

Brush DC Motor	**PM Synchronous Motors**	**Stepper Motor**	**AC Induction Motor**
High torque applications Limited life applications Low vacuum applications Low speed applications	High torque applications High speed applications Control moment gyroscope High positioning applications Light weight applications Smoot speed/ torque (low torque ripple and low micro-vibration) applications Low thermal emission applications High efficiency applications	High precision positioning applications Low torque applications Time switching Open loop micro positioning	High torque at increased speed application Constant power frequency applications

Electric motors used in space applications are continually being improved by new designs, materials and construction methods, resulting in improved reliability and high performance. One of the project goals is to develop a high-performance electric motor to be used in high-speed electric pumps for launcher engines. Permanent magnet synchronous motors have been proven to be the best all-around type of motor for space applications because of their long life, high torque, increased torque stability (low torque ripple), high precision, high efficiency, high-speed capability and low heat dissipation. The set of ambition requirements of the high-speed electric pumps for launcher engines leads to PM Synchronous Motors as the best choice for the electric motor design. Regarding the cooling of the electric motors, it is considered two solutions: direct cooling of the winding which uses the flow channel in the motor stator slot and the low-temperature refrigerant medium to directly cool the winding copper, which accounts for the largest loss, thereby improving the power density and reliability of the motor and liquid cooling of the exterior housing. Regarding the sealing solutions, as a partner in the project, ROSEAL proposes 3 types of sealings: labyrinth seal, floating ring seal and magnetic fluid seal with special construction of the seal housing.
The table below summarizes the three sealing solutions in terms of selection criteria.

DOI: 10.13009/EUCASS2023-739

Table 3 Sealing solutions in terms of selection criteria

	Sealing	**Efficiency**	**High rotational speed resistance**	**Low temperature resistance**	**LOX and LCH4 compatibility**	**Complexity**	**Novelty rating**	**Cost**	**Mass**
Labyrinth sealing	Average	Very Good	Good	Yes	Yes	Average	Low	Low	Low
Floating ring seal	Good	Very Good	Good	Yes	Yes	Average	Average	High	Average
Magnetic fluid seal with special design for high peripheral speeds	Very Good	Good	Good	Requires special magnetic fluid	Requires special magnetic fluid to ensure oxygen compatibility	High	Very High	Very high	High

Analysis of critical design issues and optimization solutions for the sealing system provides valuable information on different sealing options. The evaluation of the sealing solutions highlighted the specific materials required for each type of sealing, taking into account their characteristics and compatibility with the intended applications.

Labyrinth seals, floating ring seals and magnetic fluid seals were evaluated based on various selection criteria such as sealing efficiency, resistance to high rotational speeds, resistance to low temperatures, compatibility with LOX and LCH4, complexity, novelty, cost and mass. Each type of seal has demonstrated its strengths and weaknesses in meeting these criteria.

For the LOX pump, the floating ring seal combined with the screw labyrinth seal performed well for most criteria, while the two floating ring seals combined with the screw labyrinth seal performed even better. The combination of floating ring sealing, screw labyrinth sealing and magnetic fluid sealing showed the best performance, but with increased complexity and higher requirements for special materials.

Similarly, for the LCH4 pump, the same sealing solutions were evaluated and the results were consistent with those from the LOX pump analysis.

The selection of the optimal sealing solution ultimately depends on the specific requirements, priorities and constraints of the application. The analysis serves as a comprehensive guide for making informed decisions in designing and optimizing the sealing system for its intended purpose.

4. Test bench

COMOTI has successfully developed a dedicated platform for testing turbopump performance based on similarity parameters. In order to achieve the project requirement, in parallel with the development of the electric pumps, the test procedure algorithm and test methodology will be established in accordance with the technical requirements.

The main objective of the turbopumps test facility is derived the goal to provide a capability to simulate flight turbopump operating conditions in an economical test facility. The testing facility it is equipped with the following system:

- Compressor drive system;
- Recycling water system;
- Compressor input/output water parameters adjusting system;
- Control and security process parameters system;
- Multiplying oil lubrification system;
- Water tank.

Basically, the TPO test bench facility is a recirculating water flow loop consisting of a reservoir tank, gas nitrogen bottles for water tank pressurization, suction and discharge piping with associated temperature, pressure and flowrate control.

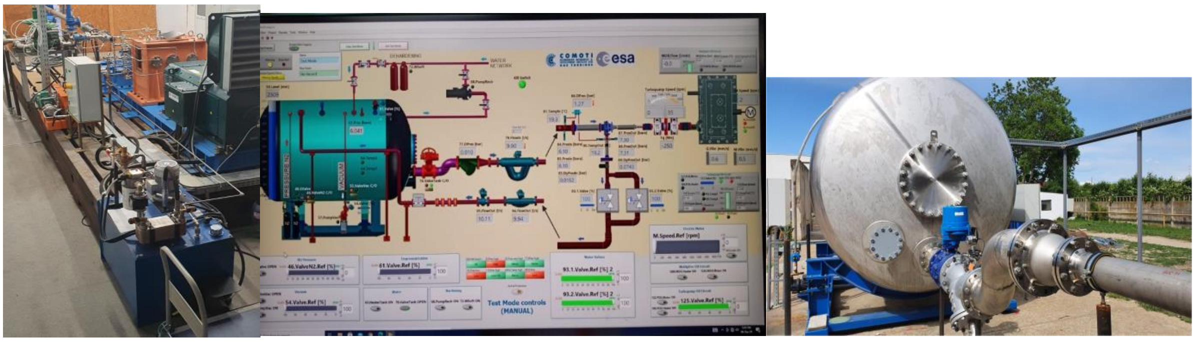

Figure 4 Testing facility of the TPO

The architecture of the TPO test platform is designed to perform turbopump testing under conditions of similarity essential to achieve an accurate assessment of actual performance using risk-free working fluids. The test platform configuration provides a wide range of tests and can be easily reconfigured for a wide range of turbopumps. The test platform highlights a wide range of fluid dynamics phenomena relevant to optimal turbopump operation: cavitation regimes, fluid flow characterization, transient processes, etc.

The pump test circuit provides for the following types of testing:

Validation of pump performance and determination of characteristic curves;

- Pump characterization, including start and stop sequences and cavitation regimes;
- Working fluid dynamics and optimization, with emphasis on nominal performance;
- Load characteristics;
- Hydraulic efficiency;
- Actuation power.

The pump test bench is equipped with the following devices:

- Working fluid storage devices and supply lines;
- Test and control chamber;
- Systems for checking, controlling, adjusting and measuring the test bench data;
- System for calculation and storage of test measurements;
- Test bench checking and control instruments;
- Tools for test bench maintenance and repair operations.

5. Future plans

In this study, a detailed overview of the system requirements for the first phase of the project is presented, and the future objectives are to validate the final design of both electric pumps in terms of the synergy of the components: pump, electric motor and sealing system. After the overall architecture configuration, manufacturing drawings will be produced and high-productivity and low-cost technologies will be developed for the electropump system components. After manufacturing the pump inducer, impellers, shaft assembly and sealing components, the test campaign will start to validate the first pump concept.

For the long-term goal, based on the roadmap to achieve a high TRL for both electric pumps, we aim to optimize the pump design and the manufacturing and testing of electrical components to validate the thermal management in the electric motor.

6. Conclusion

Keeping up with the emergence of new challenges for future launchers based on disruptive technologies, the applicability of the electric-pump cycle was reviewed through performance analysis. The present research paper ascertained that an electricpump-feed system for LOX/LCH4 of 25 kN rocket engine can be set up, resulting in a compact design. The main goal of this project is to achieve a certain electropump feed system competence by acquiring skills in designing such a system. With respect to the initial project requirements, preliminary LOX/LCH4 electropumps feeding system design including the main components has been established preserving proven design heritage. The design methodology is based on classical methods and the results of more recent studies.

DOI: 10.13009/EUCASS2023-739

Due to its flexible thrust adjustment capability, the electricpump-feed liquid propellant rocket engine can replace the turbopump-feed rocket engine to a certain extent.

A refinement of the analysis, focusing on validating and optimizing the current selected electrically driven pump preliminary design and operational parameters, will follow this study to fully determine the advantages of combining electricpump feeding system and an expander-based rocket cycle. Advancing the maturation and the synergy of these technologies should offer a game-changing perspective in the European market providing flexible, throttleable and safer space access. Cost remaining a key design driver for future launch services, the possibility of a decrease in the complexity of these systems is very attractive.

References

[1] National Aeronautics and Space Administration. 1974. Turbopump Systems for Liquid Rocket Engines. NASA Space Vehicle Design Criteria (Chemical Propulsion). NASA SP-8107.

[2] I. J. Karassik, J. P. Messina, P. Cooper, C. C. 2001. Head Pump Handbook Third Edition McGraw-Hill.

[3] National Aeronautics and Space Administration 1973. Liquid Rocket Engine Centrifugal Flow Turbopumps. NASA Space Vehicle Design Criteria (Chemical Propulsion). NASA SP-8109.

[4] T.M. Abel, T.A. Velez. 2002. Electrical Drive System for Rocket Engine Propellant Pumps. US Patent. Registration No. 0647306.

[5] G. Raymond. 2014. Device for Powering the Pump of a Rocket Engine Using an Inertia Wheel. US Patent. Registration No. 8632319 B2.

[6] PatrickR.E. Bahn. 2017. Rocket Engine Systems. US Patent. Registration No. 9677503 B2.

[7] L. Casalino, D. Pastrone. 2010. Optimization of a hybrid rocket upper stage with electric pump feed system. In: *46th AIAA/ASME/SAE/ASEE Jt. Propuls. Conference & Exhib.* AIAA-2010-6954.

[8] L. Galfetti, F. Nasuti, D. Pastrone, A.M. Russo. 2014. An Italian network to improve hybrid rocket performance: strategy and results, Acta Astronaut. *Phys:* 96:246–260.

[9] N. Soldà, D. Lentini. 2008. Opportunities for a liquid rocket feed system based on electric pumps. J. Propuls. Power. *Phys:* 24:1340–1346.

[10] P.A. Pavlov Rachov, H. Tacca, D. Lentini. 2013. Electric feed systems for liquid-propellant rockets. J. Propuls. Power. *Phys:* 29:1171–1180.

[11] Lee J, Roh T-S, Huh H and Lee H J. 2021. Performance Analysis and Mass Estimation of a Small-Sized Liquid Rocket Engine with Electric-Pump Cycle. Int. J. Aeronaut. Space Sci. *Phys:* 22: 94–107.

[12] R. E. Burcham. 1983. High-speed cryogenic self-acting shaft seals for liquid rocket turbopumps. NASA Lewis Research Center. Cleveland, Ohio. NASA CR-168194.

[13] D. Spiller, A. Stabile, D. Lentini. 2013. Design and testing of a demonstrator electric-pump feed system for liquid propellant rocket engines. AIDAA J. Aerosp. Sci. Technol. Syst. (Aerotecnica Missili & Spazio). *Phys:* 92: 123–130.

[14] D. Vaughan, B. Nakazono, A. London, A. Mehra. 2017. Technology development of an electrically driven pump feed storable liquid bi-propellant for a Mars ascent vehicle. In: *68th Intl. Astronautical Congress, IAC-17-C4.3.8.*