LUMEN: Test Platform for Rocket Engine Technologies. Project Overview and Upcoming Steps in the Development

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LUMEN is a breadboard rocket engine designed for LOX/LNG propulsion, with a primary focus on serving as a versatile test bed for components and technologies for industrial and institutional partners. The engine's main emphasis is on addressing challenges related to rocket engine reusability, such as multiple starts and landings.

LUMEN is being developed as a modular engine to be utilized at the DLR P8.3 test facility. Its design allows for easy removal from the test bench, component exchange, and subsequent testing. This approach also simplifies the turbopump design by incorporating two turbopumps instead of a single shaft one which would be a possible choice for the propellant combination. This provides greater flexibility for component exchange and technology development.

In addition to component technology maturation, the modular system approach enables the testing of technologies that would otherwise be challenging to assess in full-scale or simulation environments, such as health management and its feedback to engine control. LUMEN will demonstrate the benefits of machine learning for health monitoring and anomaly detection, which will be integrated into the engine's control system. The closed-loop neural network-based control approach employed in LUMEN allows for improved approximation of the highly nonlinear behavior of the rocket engine, as demonstrated by previous tests if the oxygen turbopump (OTP) conducted by DLR in late 2022 [1]. In these tests the pump discharge pressure and mass flow were controlled at the same time to within 2% accuracy. It is foreseen to use intelligent control for the whole engine and the next steps are outlined in [2].

The aforementioned turbopump test campaign included qualification of the OTP and initial tests with the fuel turbopumps (FTP). The turbine design was validated and showed very high efficiencies of the partial admission supersonic turbine of 45%. The off-design performance prediction of DLRs turbine models is investigated in detail in [3].

The unique design of the OTP with oil lubrication made it possible to use the turbopump for a total time of 70 minutes with no signs of wear and no hardware changes. The next use of the OTP will be in the LUMEN demonstrator test in the beginning of 2024.

In August 2022, the thrust chamber assembly (TCA) underwent testing, and an analysis was conducted on the chill-down behavior of the LUMEN TCA system, as described in reference [4]. Additionally, in May, another test campaign was carried out to verify the temperature increase in the cooling channels of the TCA, which is a crucial parameter for expander bleed cycle engines that utilize enthalpy increase to drive the turbopumps. Preliminary findings from this campaign will be presented.

Finally, the upcoming LUMEN development steps will be presented.

Key Words: rocket engine, LNG, expander bleed cycle, machine learning, turbopump

1. Engine overview

The design, manufacturing and initial testing of the LUMEN hardware was presented in detail in [5], [6], [7] [8], [9], [10], [11], [12], [13], [14], [15]. The thrust chamber assembly was designed using the year long experience of the DLR in combustor research, while the turbopumps were designed from scratch. A focus on research were the driving requirements so the decision was made to set up an environment of in-house tools for turbopump development in order to be in full control of all design parameters and incorporate research results into the design tools.

New techniques like machine learning were employed in the system analysis. For example, a model for quick combustor cooling channel design has been developed and implemented in EcosimPro for an optimized and quicker system design.

The results of the system analysis, risk mitigation and a design to requirement approach lead to the following choices [16]

Turbopump Design and Arrangement:

- *When considering the propellant combination of LOX/LNG for a flight application, a common design choice is to use a single-shaft turbopump. This configuration consists of LOX and LNG pumps placed on a shared shaft, driven by a single turbine. By adopting this arrangement, the turbopump unit can be made smaller and lighter. However, it also necessitates a compromise in the design of both pumps, as they need to operate at the same rotational speed. For the LUMEN demonstrator, two separate turbopump units are planned, allowing for individual optimization. This approach enhances the operational flexibility of the LUMEN demonstrator. The decision was made to arrange the two turbopump units in parallel. This arrangement enables the development of highly similar turbines with identical, yet relatively high, pressure ratios. This not only reduces development costs but also simplifies the control of available power for each turbopump.*

Chamber or Nozzle Expander Bleed:

- *A nozzle expander bleed (NEB) layout was selected to maximize heat pickup for the cycle [1].*

Fuel Injection Temperature:

- *To ensure a consistent and controlled propellant inlet temperature at the injector, a fuel mixing system will be utilized. This system remixes a portion of the heated fuel from the cooling channel with the main cold fuel mass flow. A similar principle is employed in Japanese expander bleed engines like LE-5B.*

Control:

- *Unlike engines designed for flight, the LUMEN demonstrator, being a research platform, aims to provide a wide range of regulation possibilities. Instead of relying on orifice solutions, regulation valves are employed at multiple positions to accommodate changes in the cycle behaviour during testing. The increased number of control valves necessitates novel approaches to the control strategy of the system. New data-based control schemes present interesting possibilities in this regard. First experimental results of intelligent control using machine learning algorithms were presented here [11].*

Fig. 1 shows a schematic representation of the LUMEN engine cycle, which incorporates the general design features mentioned above. The LUMEN breadboard demonstrator is following an expander bleed engine cycle scheme. The combustion chamber is cooled with LNG in a counter-flow arrangement. The heated cooling fluid is partially remixed into the main fuel mass flow to actively control the fuel injection temperature. The remaining cooling mass flow is further heated within the nozzle extension (co-flow arrangement) and then divided between the LOX and LNG turbines. The demonstrator architecture also includes a number of purge valves for pre-conditioning of the system using LN_2, which are not shown in Fig. 1 for simplicity. An external GN_2 supply will also be used as a turbine starter system to accelerate the engine start-up transient.

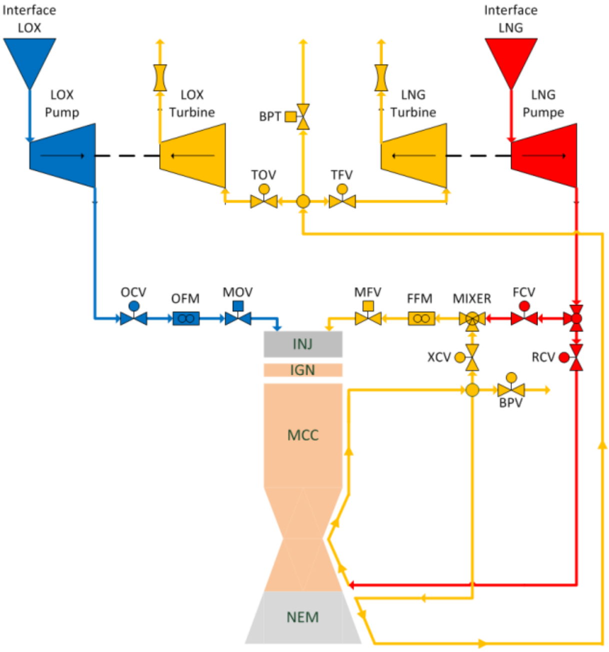

Fig. 1 Schematic representation of the LUMEN demonstrator architecture.

The cycle features two bypass valves. The turbine bypass is designed as a fast-acting security valve, which allows for a rapid reduction of turbine power in case of an emergency shut down. The second bypass is designed as a control valve, which allows controlling the amount of LNG mass flow to be further heated within the nozzle extension. This measure is needed if the fuel mass flow for combustion chamber cooling is larger than the combined mass flow needed for remixing and operation of the turbines. In this case, the bleed mass flow can be adjusted to the need of the turbine and the heat addition in the nozzle extension is resulting in the maximum temperature increase of the bleed mass flow. From a performance point of view, this bypass should be zero. However, this design choice was made to be able to adjust the cooling mass flow to the combustor if necessary. This way combustors from external partners can be tested in the cycle even if they have a cooling demand which is different from the LUMEN combustor.

The large number of fluid control elements allows for several options for the operation of the cycle. One option for example is the independent control of combustion chamber and cooling channel pressure. This option allows for super-critical conditions within the cooling channels while operating the combustion chamber at sub-critical conditions.

To allow for a maximum degree of accessibility for instrumentation, the LUMEN demonstrator is designed with a lot of space between components. Fig. 2 shows the current layout of the LUMEN demonstrator engine as it will be tested at the P8.3 test facility.

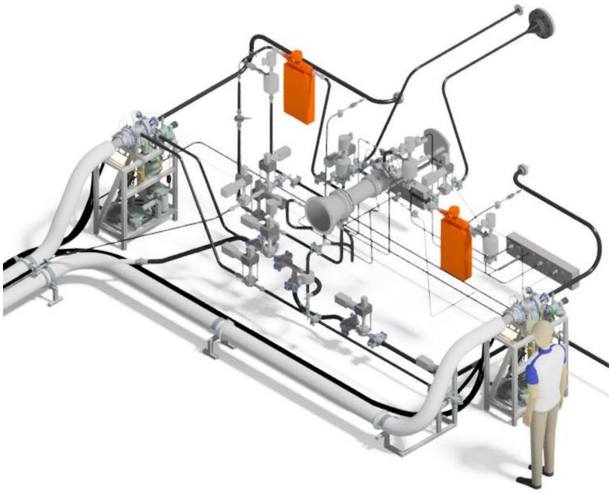

Fig. 2: LUMEN demonstrator engine layout

2. Recent advancements in turbopump testing

There was a single test campaign in which both turbopumps were installed at the P8.3 at the same time to maximize the outcome of the test campaign. The turbopumps were tested in LUMEN configuration which is a precursor to the whole LUMEN setup seen in Fig. 2. The valves installed in LUMEN for flow control make it easy to control pump mass flow and discharge pressure during turbopump only tests.

2.1 Turbopumps design overview

LUMENs turbopumps have the design specifications summarized in Table 1. The design of pump, turbine, bearing unit, seals system, thermal design and rotor dynamics has been done with in-house tools which are in steady development [6], [17]. 3D simulations have been carried out for refinement and verification of the design. A cooperation with JAXA led to full 360° transient simulation of the turbine [14] while transient structure-flow coupled simulation yielded the rotor dynamic coefficients of the floating ring seals [15].

Table 1: maximum operational parameters of the Turbopumps

	OTP	FTP
Pump outlet pressure max. [bar]	105	112
Pump power max. [kW]	150	190
Rotational speed max. [rpm]	28000	50000
Pressure ratio turbine	13.6	13.1

The turbopumps use oil lubricated bearings, which significantly enhances bearing life time. The minimum life time of the bearing system is 1000h and exceeds by far typical turbopump designs. Oil lubrication demands special care to be taken during the thermal design of the turbopumps, because the oil might freeze on the pump side, which is at cryogenic temperatures, while it might disintegrate on the hot turbine side [17].

Both turbopumps have a single stage pump and a single stage supersonic impulse turbine. The design of the pump and the turbine was published in several articles [13], [10].

The overall design of the LOX and LNG turbopump is similar in most details, but there are some significant changes attributed mainly to the higher rotational speed of the FTP. The bearings are smaller than the ones for the OTP which results in lower load capability and higher allowable rotational speeds. The shaft is shorter to increase the first critical speed and the turbine is fastened by an elongation bolt to optimize clamping forces at high speeds.

Another difference is the turbine inlet manifold of the FTP which is bigger because the stator of the FTP turbine has 5 instead of 3 stator nozzles as in the OTP. This is one of the reasons why the seal drain holes on the turbine side are now a part of the bearing housing, while they were integral to the stator part on the OTP.

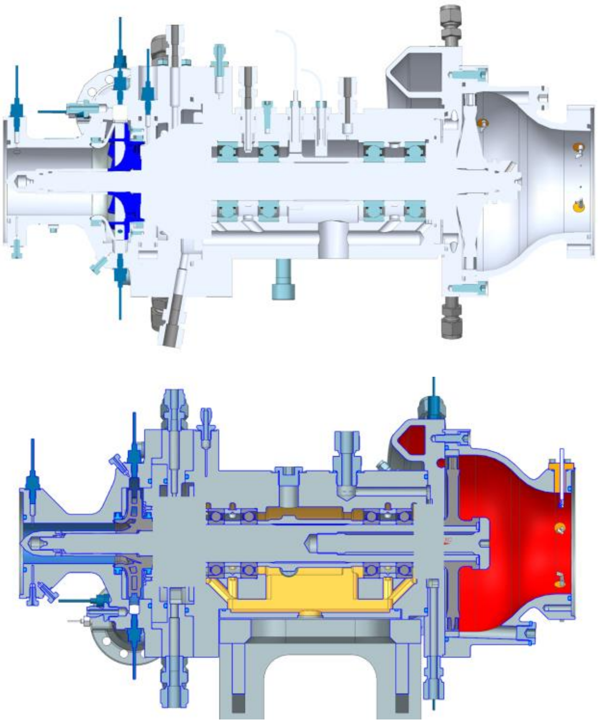

Fig. 3: LUMEN LOX Turbopump (top) and LNG Turbopump (bottom)

Both turbopumps are modular and allow for easy exchange of pump and turbine to test new configurations or configurations from interested partners.

2.2 Oxygen turbopump (OTP) acceptance testing

In a past test campaign the OTP run in tests were done with water, followed by a test campaign with LN2 and first tests with LOX [5]. These tests could not be finished because they had to be interrupted to not interfere with the tests of the thrust chamber assembly (TCA).

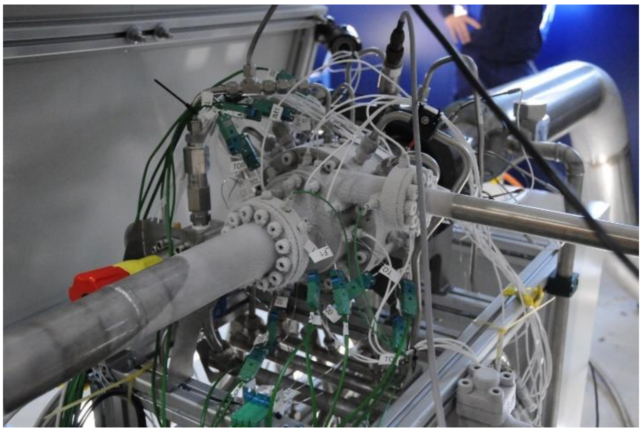

Fig. 4: OTP after the test with LOX

The second OTP campaign was successful in fully qualifying the turbopump. The accumulated turbopump life time is now 70min proving the enhanced reusability of the aforementioned design choices. Especially the oil lubrication works perfectly without any issue.

20 tests with water were done, 11 tests with LN2 and 12 tests with LOX. No hardware changes were necessary, meaning that the OTP is still running with the same bearings, impeller, turbine etc.. Inspections after the tests showed no visible signs of wear on any of the parts.

As presented before [5] the OTPs efficiencies are as expected with the turbine slightly exceeding the anticipated efficiencies. This validates our design procedure from preliminary to detailed design [8], [7], [13].

2.3 Neural network closed loop control of mass flow and pressure

The OTP was operated in LOX for 41 minutes and in some of the tests closed loop control based on machine learning was used [1]. We developed and trained a neural network controller for the LUMEN turbopump using simulations only. This controller was then applied in real-time closed-loop control during testing at the test bench. The purpose of the controller was to track a predefined reference trajectory for the pump discharge pressure and mass flow rate by adjusting two flow control valves. Over a test duration of 85 seconds, the mean absolute percentage error remained well below 1%. This successful demonstration of closed-loop control for the LUMEN oxidizer turbopump represents an important initial step towards implementing an intelligent engine controller for the entire LUMEN engine. Notably, this marks the first time at the DLR Institute of Space Propulsion that a neural network-based controller has been tested in a physical application with multiple flow control valves, going beyond simulation.

The ability to directly utilize the trained neural network at the test bench was made possible by the robustness of the neural network against modelling errors. This robustness was achieved through the application of domain randomization during training. In other words, the model parameters of the simulation model were randomly modified at the beginning of each episode. By incorporating simulated delays, noise, a prediction horizon, and the stacking of observations, the neural network learned to perform satisfactorily even in the presence of model deviations. Our ongoing research also focuses on fault-tolerant and safe reinforcement learning techniques, aiming to qualify future rocket engine control systems.

The main advantage of the neural network control for turbopump operation is the possibility to train the model in a way to avoid constraints of turbopump like critical speeds, cavitation and others. The model will be improved in this regard and tested in the future [2].

2.4 Fuel turbopump (FTP) acceptance testing

Once all the parts of the FTP had been manufactured, it was assembled and it was decided to test it directly with LNG. The tests were successful: we were able to show that the design would work in cryogenic conditions and that the thermal design would also work for LNG. Bearing temperatures were excellent and the oil lubrication system worked as intended. The FTP reached 23,000 rpm during the tests and discharge pressures were in the region of 35 bar. Total test time was 280s in 5 tests.

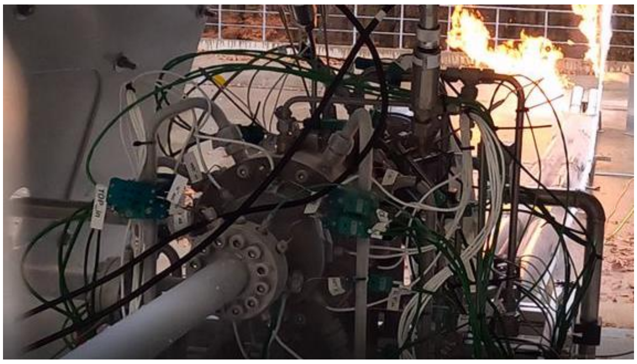

Fig. 5: FTP during testing with flames from seal gas exhaust in the background

The next campaign is scheduled for October and full acceptance with nominal speeds and discharge pressures is expected.

3. Thrust chamber assembly (TCA)

3.1 TCA design overview

The ignition system of the thrust chamber incorporates redundant technologies, including a laser plasma igniter and a high-pressure torch igniter, allowing for multiple ignitions during a single test run. Optical probes were employed to investigate flame anchoring [9].

The design of the combustor focuses on achieving effective regenerative cooling while minimizing pressure drop in the cooling channels. A neural network-based surrogate model was used to study the robustness of the cooling channel design and optimize it for either maximum life or maximum performance. A test campaign with a calorimetric combustion chamber was conducted to measure the heat flux distribution along the length of the combustor [5].

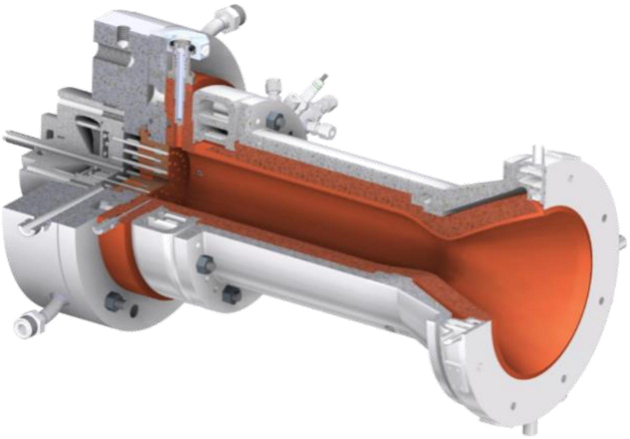

Fig. 6: conventionally manufactured combustor

These design and testing efforts have culminated in the TCA design (see Fig. 6). Two combustors were manufactured, one conventionally and one using selective laser melting (SLM). The conventional one has a machined copper liner with galvanically closed cooling channels. The combustor has an outer shell for transferring loads from the nozzle to the thrust frame. There are manifolds on either end to distribute and collect the cooling fluid.

The second combustor is one integral part completely manufactured in a copper alloy.

The TCA follows a modular approach, consisting of several segments. On the left hand side in Fig. 6 is the injector head and on the right hand side is the regeneratively cooled nozzle extension. The latter is made from a copper-nickel alloy using SLM, has helical cooling channels for optimal cooling and structural integrity. Pre-tests with water cooling have been performed for the nozzle extension to ensure its effectiveness.

The propellant combination of LOX/LNG presents challenges in achieving reliable ignition and stable combustion. The slower reaction speed and reduced flame speed of LOX/LNG result in less stable reaction zones and increased sensitivity to flame extinction and combustion instability. Test activities were conducted at the European Research and Technology Test Facility P8 to test the ignition system and determine a reliable ignition sequence for the LUMEN thrust chamber [5]. The desired operational conditions of the main combustion chamber require stable combustion within specific pressure and mixture ratio ranges. To achieve this, a 42-element shear-coaxial injector was chosen as the baseline for the LUMEN system, leveraging the injector technology heritage at DLR.

3.2 TCA acceptance tests

In the ongoing test campaign, the conventionally manufactured combustor was qualified for the LUMEN demonstrator tests which will take place in 2024. The SLM combustors qualification will be performed in June 2023.

The main test goals of the test campaign were

1. *Develop reliable "demonstrator-like" start sequence*
2. *Reliable ignition with regenerative circuit*
3. *Verify combustion efficiency*
4. *Verify heat transfer prediction*
5. *Find minimum of cooling mass flow*
6. *Qualify TCA design*
7. *Injection temperature screening*
8. *Provide validation data for system engineering*

All points were successfully realized in the tests. The maximum test time was 65s.

Point number 3 was met with very good accuracy and will be presented in future work. It is of course interdependent with point 4, the cooling mass flow, which also was very close to the prediction of [12]. The wall temperatures were all within limits.

The TCA was tested at the conditions summarized in

Table 2. The lower ROFs were used in the first tests to limit the heat load on the combustor and enhance its lifetime.

Table 2: TCA test matrix

	min	**max**
Combustor pressure [MPa]	4	6
ROF [-]	3	3,5
Fuel injection temperature [K]	210	265

The injection temperature screening was important from a TCA stability as well as a system point of view. LUMEN uses a mixer on the fuel side to establish a desired injection temperature, as Fig. 2 shows. The mixing itself influences mass flows going either through the fuel control valve (FCV) or through the cooling channels (see Fig. 1) while the minimum cooling mass flow is a fixed value for the given operating point. The screening showed no instability in any range, the injector performed well in all points, giving the system analysis full freedom for finally defining LUMEN operation points. The same applies to the ROF values tested.

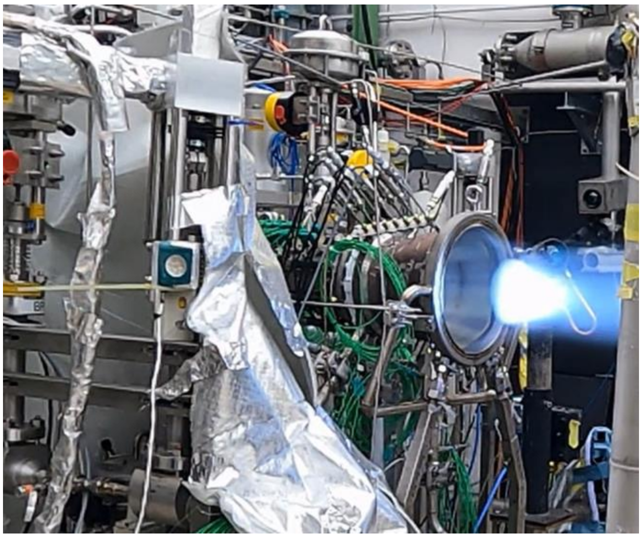

Fig. 7: TCA at 6 MPa combustor pressure

Another important step towards the demonstrator tests were the use and characterization of all valves in open and closed loop control.

4. Outlook

Upcoming activities within the LUMEN project include:

SLM Combustor hot fire tests

- The integrally manufactured SLM combustor will be tested on the P8.2 test bench by June 2022. The main goals of this test campaign are the same as for the conventionally manufactured combustor a) stable combustion at all load points specified, b) demonstration of the expected combustion efficiency and c) the predicted heat flux to the cooling fluid. The test data will be used to further anchor the system analysis tools in preparation for the integrated demonstrator tests.

Turbopump testing

- The FTP acceptance tests will take place by the end of 2022.

LUMEN demonstrator test campaign preparation

- The data gathered by testing of both thrust chamber and turbopumps as well as other fluid control elements like valves will serve as a basis for the prediction of the operational behaviour of the integrated engine cycle. Considering the transient behaviour of those core components, the critical transients (chill-down, start-up and shutdown) will be developed numerically using the EcosimPro/ESPSS environment.

- A Neural network engine control model will be developed and it is likely that it will be tested in the demonstrator campaign

5. Conclusion

An overview of the current status and testing activities of all major components in the LUMEN project was presented. LUMEN represents a significant focus within the DLR research programs and serves as a platform to demonstrate the advantages of this research for reusable engines.

The modular approach of LUMEN was emphasized to showcase its versatility in facilitating engine component testing within a representative environment. This feature positions LUMEN as an ideal platform for international partners who are interested in conducting their own tests and experiments.

In especially technologies which cannot be developed without the availability of an entire rocket engine system benefit significantly from LUMEN.

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