Liquid Upper Stage Demonstrator Engine (LUMEN): Component Test Results and Project Progress

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With the LUMEN (Liquid upper stage demonstrator engine) project, DLR is aiming to develop, build and operate a breadboard engine based on an expander bleed cycle scheme. The propellants for LUMEN will be liquid oxygen (LOX) and liquid natural gas (LNG). LUMEN will be a modular breadboard engine to be used on DLR test benches such as the P8.3 test facility. The modular approach will make it easy to take the engine of the test bench, exchange components and go testing again. This way the demonstrator will provide a test bed for future component development. The cycle will feature two turbopumps in order to simplify the turbopump design, while on the same time allowing more freedom for an exchange of components. By this approach the DLR will create a test bed for component research on engine level, open to any industrial or institutional partner. There have been several test campaigns before final assembly can take place. The combustor tests included a calorimetric combustor to obtain the heat load distribution by the combustion of LOX and LNG which determines the cooling channel design of the thrust chamber assembly (TCA). After this campaign the newly manufactured regeneratively cooled TCA tests will take place which will determine the turbines drive power. This is a crucial step, since LUMEN is an expander bleed cycle engine and hence it relies solely on the heat pickup in the TCA cooling channels.

In parallel to the combustor tests a turbopump test campaign with the OTP was performed with water on the pump side and pressurized nitrogen on the turbine side. The campaign has been completed successfully and the operational envelope of the OTP has been confirmed. After that a cryogenic test campaign took place at the DLR test bench P8.3. The OTP was installed in the same configuration as in the engine tests of LUMEN and it was run for the first time in cryogenic fluids. The test campaign was successful proving the operation of the OTP in LOX. Especially the unconventional oil lubrication system of the LUMEN OTP worked without an issue and as expected. The thermal design of the turbopump was verified and the operation procedures in cryogenic environment were tested and refined. The next and final step in turbopump development will be cryogenic tests of the FTP.

When the combustor and turbopump tests are completed, final assembly of LUMEN will start with first tests on engine level expected to take place in 2023.

Key Words: LPRE, LUMEN, expander bleed cycle, machine learing, LNG, turbopump

1. LUMEN introduction

Based on the existing competences of DLRs Institute of Space Propulsion and its test capabilities, the LUMEN breadboard engine project was established in 2017. The LUMEN breadboard engine project is intended to provide an experimental platform open to partners from the institutional as well as the industrial domain. Its focus on a modular design with an emphasis on a high level of instrumentation offers the possibility to test thrust chamber, turbopump or other engine components in a truly representative environment. The LUMEN demonstrator will be operated as a test facility on its own, to be used in conjunction with the P8.3 test facility and open to potential partners.

One of the design goals of the LUMEN engine is the demonstration of a large throttling range. For the chosen propellant combination of LOX/LNG, the LUMEN nominal load point is set to a combustion chamber pressure of p_{CC} = 60 bar and a mixture ratio of ROF = 3.4. The planned operational domain is summarized in Table 1. These pressures result in a throttling range of about 58% to 133% of nominal thrust.

Table 1. Operational domain of the LUMEN combustion chamber

	Nom.	Max.	Min.
Chamber pressure [bar]	60	80	35
Chamber fuel mixture ratio	3.4	3.0	3.8

2. Engine architecture

After selection of the expander bleed scheme as the general cycle layout, some design choices remain. Again, these design options were chosen with the requirement of risk and cost reduction in mind.

Turbopump design and arrangement

- For the chosen propellant combination of LOX/LNG, a typical design choice for a flight application would be the use of a single-shaft turbopump with LOX and LNG pump on a common shaft driven by a single turbine. This arrangement minimizes size and weight of the turbopump unit while at the same time calls for design compromise between both pumps since they need to run at a common rotational speed. For the LUMEN demonstrator two separate turbopump units are foreseen, which can be optimized individually. At the same time, this approach increases the flexibility of operation of the LUMEN demonstrator.
- The arrangement of the two turbopump units was chosen to be parallel. This arrangement allows for the development of very similar turbines with identical, but rather high pressure ratios (reduction of development costs) and it allows for a simple control of available power for each turbopump.

Chamber or nozzle expander bleed

- A nozzle expander bleed (NEB) layout was chosen to allow for a maximum heat pickup for the cycle *[1]*.

Fuel injection temperature

- To provide a fixed and controlled propellant inlet temperature at the injector, a fuel mixing system will be employed, which remixes part of the heated fuel from the cooling channel with the main cold fuel mass flow. The same principle is applied in Japanese expander bleed engines like LE-5B.

Control

- In contrast to flight-like engines, the LUMEN demonstrator as a research platform is supposed to offer a maximum amount of possibilities for regulation. To allow for changes in the cycle behaviour during testing, regulation valves are used at multiple positions instead of orifice solutions. The large number of control valves calls for new approaches for the control strategy of the system. New data-based control schemes offer interesting possibilities here *[2]*.

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.

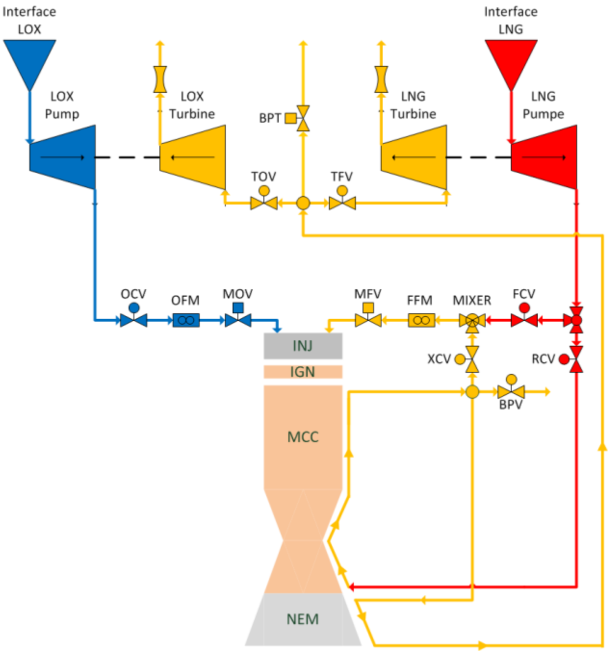

Fig. 1 Schematic representation of the LUMEN demonstrator architecture.

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.

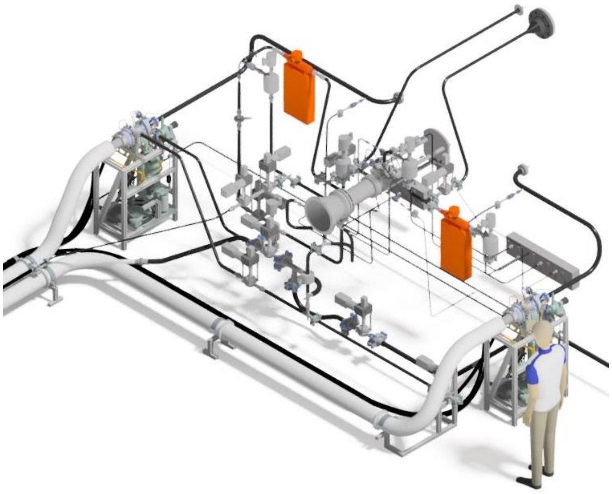

Fig. 2 LUMEN demonstrator engine layout

3. Thrust Chamber Assembly (TCA)

DLR has a long heritage in designing TCAs. The design of the LUMEN TCA is summarized in the following subsections.

3.1 Injector head and ignition system

As the propellant combination LOX/LNG has a reduced ROF range for reliable ignition when compared to LOX/H2, the ignition transient needs to be controlled more carefully to ensure the ignition, anchoring and stabilization of the combustion zone at the injector faceplate.

Furthermore, the LOX/LNG reaction speed is slower, the reduced flame speed results in less stable reaction zones, higher sensitivity to flame extinction by high shear forces and higher sensitivity to combustion instability.

In the context of the LUMEN project, test activities were carried out to test the ignition system and identify a reliable ignition sequence for the LUMEN thrust chamber at the European Research and Technology Test Facility P8 for cryogenic rocket engines at the DLR Lampoldshausen site (see Fig. 3).

The envisaged operational conditions of the LUMEN main combustion chamber require a stable combustion for the operational envelope of 35 to 80 bar combustion chamber pressure and mixture ratios of 3,0 to 3,8 which implies a stable anchoring of the combustion zone at the injector element face plate. The heritage in injector technology at DLR led to the design choice of a 42 element shear-coaxial injector as the baseline for the LUMEN system.

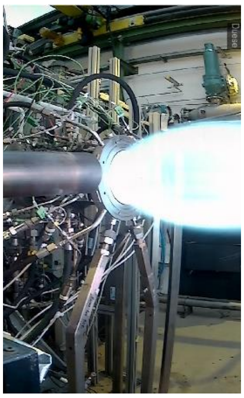

Fig. 3: Photograph of flame anchoring tests

Following the key requirements for the ignition system of the thrust chamber, a laser plasma igniter and a high-pressure torch igniter were chosen as redundant ignition technologies. These ignition systems were designed to allow for at least four ignitions during a single test run: the initial start-up and three re-ignitions of the thrust chamber. The ignition system is installed in a dedicated segment of the combustor right after the injection head. The igniter segment features optical probes also, which were used for flame anchoring investigationd [3].

3.2 Combustor

The goal of an effective design of the regenerative cooling is a trade-off between a sufficient cooling of the structure and a low pressure drop in the cooling channels. For an expander type cycle a third requirement arises: A sufficient enthalpy increase of the cooling fluid for the turbopumps to operate effectively. To prevent the combustion chamber from melting, the regenerative cooling has to be designed with a sufficient margin to respect all uncertainties. A neural network based surrogate model was used to study the robustness of the cooling channel design for other load points of the engine [4]. This model also allows for optimization of the cooling channels for either maximum life or maximum performance.

For the cooling channel design, a test campaign was carried out with a calorimetric combustion chamber to measure the heat flux distribution over the length of the combuster with a high resolution (see Fig. 4).

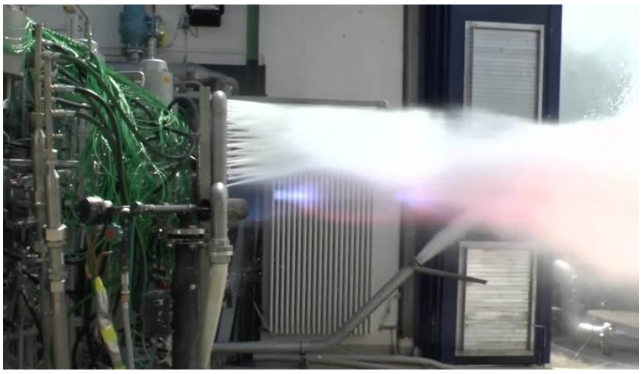

Fig. 4: Calorimetric combustor test for heat flux profile determination

All of these design and testing efforts where condensed in the TCA design as shown in Fig. 5. The TCA is being manufactured at the moment.

Fig. 5: LUMEN TCA with nozzle and nozzle extension manufactured by SLM

The TCA which is built in several segments, following the modular approach of LUMEN. The regeneratively cooled nozzle is made by SLM from a copper-nickel alloy and pre-tests with water in the cooling channels have taken place.

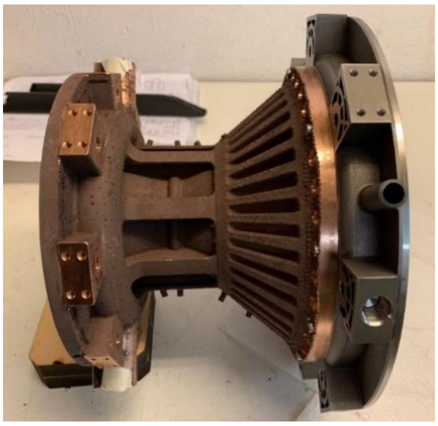

Fig. 6: TCA nozzle

3.3 Nozzle extension

The nozzle extension is also made by SLM. Fig. 7 shows the helical cooling channels for optimal cooling and maximizing the structural integrity.

Fig. 7: LM nozzle extension with helical cooling channels

The nozzle extension was also pretested in a hot run with water cooling as can be seen in Fig. 8

Fig. 8: Hot run of nozzle extension with water cooling

3.4 TCA testing

The TCA was tested in LUMEN configuration middle of this year. The LUMEN configuration is shown in Fig. 17 with the TCA in the middle and the turbopumps to the left and the right.

For TCA testing the turbopumps were not used and the valves were connected to the high-pressure supply of the P8.2 test bench.

The test campaign simulated the transients expected with turbopumps. Since these transients are unknown at this stage of the project, EcosimPro was used with DLR specific components to simulate the engine start-up. The EcosimPro model is in constant development, using test results of the ongoing campaigns for continuous improvement.

4. Turbopumps

4.1 Design overview

LUMENs turbopumps have the following overall design specifications summarized in Table 2.

The design of pump, turbine, bearing unit, seals system, thermal design and rotor dynamics has been done with inhouse tools which are in steady development [5], [6]. 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 [7] while transient structure-flow coupled simulation yielded the rotor dynamic coefficients of the floating ring seals [8].

Table 2: max. operational parameters

	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.

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 [9], [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 visible in Fig. 10 which shows the external view of the FTP.

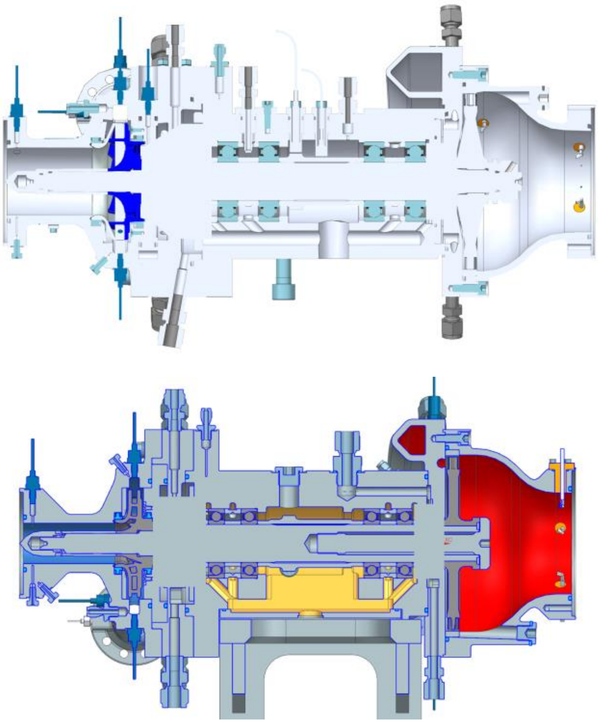

Fig. 9: LUMEN LOX Turbopump (top) and LNG Turbopump (bottom)

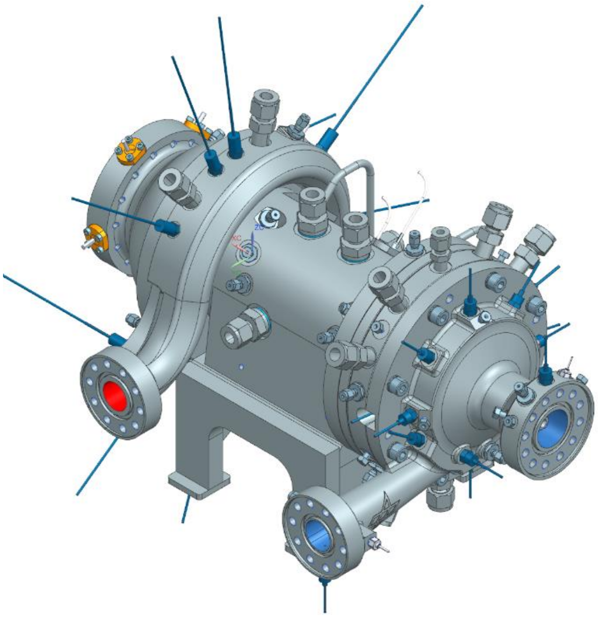

Fig. 10: LNG Turbopump with turbine on the left and pump on the right

The turbine inlet manifold of the FTP 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.

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

4.2 Testing

4.2.1 OTP water tests

The OTP has been tested on the DLR P6.2 test bench in August 2021. The test campaign was performed with water on the pump side and nitrogen on the turbine side.

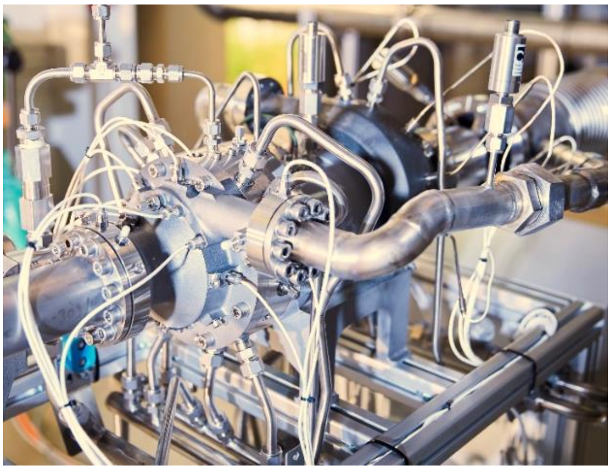

Fig. 11: OTP at test bench P6.2

Fig. 11 shows the turbopump mounted on its lubrication system with the water tank on the right and the turbine exhaust pipe on the left.

The OTPs rotational speed was controlled by the nitrogen pressure on the turbine side, while the pump exit pressure and mass-flow were controlled by an orifice after the pump discharge. Tests with three different orifice sizes were performed to screen the operational range of the OTP.

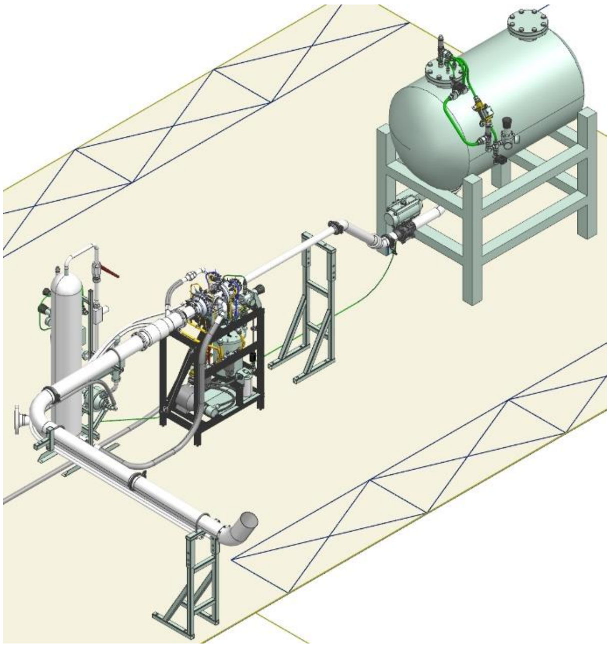

Fig. 12: OTP test setup at test bench P6.2

The tests were successful and all test objectives were met. The maximum rotational speed was reached with 25.000rpm, limited only by the available nitrogen pressure. The pump exit pressure peaked at 80bar and the mass-flow at 5.8kg/s.

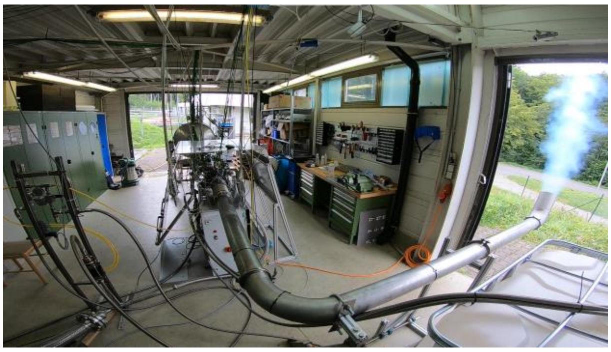

Fig. 13: Test of OTP at test bench P6.2

Over all tests the OTP accumulated a operation time of approximately 20 min. The OTP was taken apart and inspected with no sign of wear in all parts.

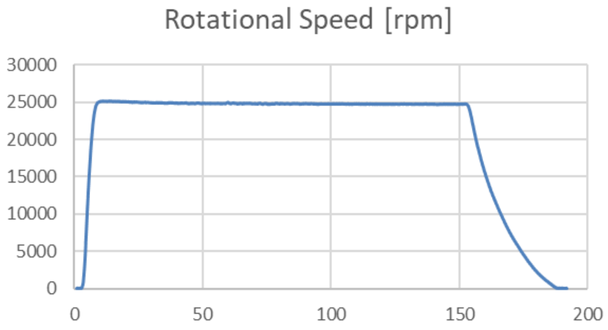

Fig. 14: Rotational Speed of the OTP during 150s test

The efficiency of the pump was as expected with a peak of approximately 68% efficiency for the higher mass flows and 25% for the lower mass flows (see Fig. 15).

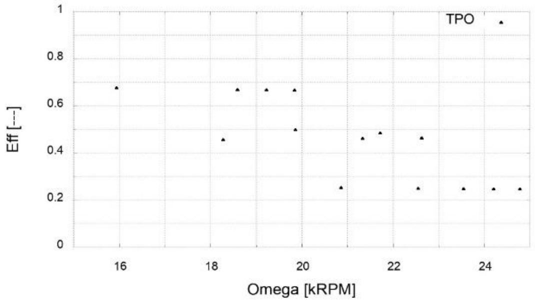

Fig. 15: Impeller efficiency

The turbine efficiency was 5% higher than expected by the preliminary design tools. However, the extensive CFD analysis by JAXA [7] indicated exactly this behaviour, which means that the preliminary tools are on the conservative side.

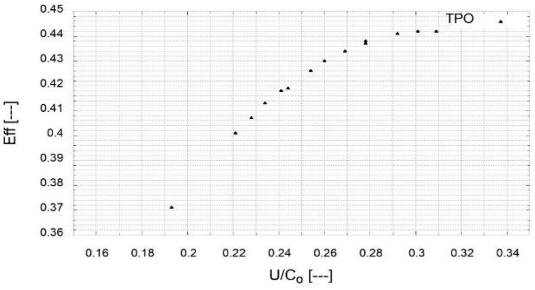

Fig. 16: Turbine efficiency

4.2.2 OTP cryogenic testing

The successful testing with water and nitrogen was followed by the cryogenic testing campaign. After the water tests the OTP was disassembled and inspected for any sign of wear. Since no wear could be detected at all the OTP was assembled again and prepared for the cryogenic test campaign. The preparation included cleaning and drying for oxygen use as well as the installation of oxygen specific parts like cryogenic seals for example.

The OTP was tested in LUMEN configuration and as such it was the first campaign to use the valves and piping which is supposed to be used for the LUMEN demonstrator later on. At the time of OTP preparation, the valve and piping setup was prepared alongside. The LUMEN setup is shown in Fig. 17 and the OTP setup at P8.3 is shown in Fig. 17. Clearly visible is the OTP turbine exhaust line while the LUMEN valves are in the background. The turbine is connected to a GN2 line which supplies the turbines with a maximum of 60bar.

The cryogenic test campaign is over. The first step were LN2 run-in tests which are successfully completed. With LN2 the operation procedures for cryogenic operation were tested and refined. The first chill-down and the consecutive tests of the OTP verified the thermal design by Saraf, et. Al. [6].

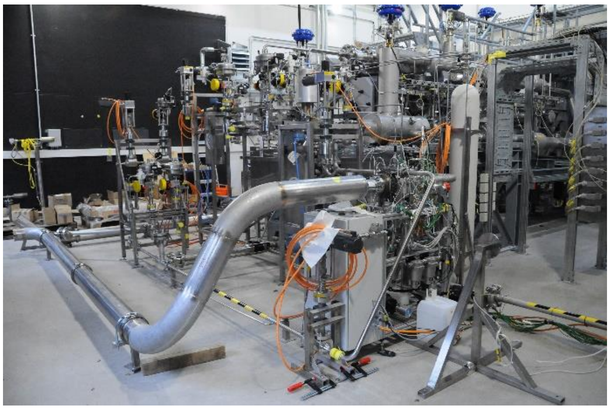

Fig. 17: OTP setup at P8.3

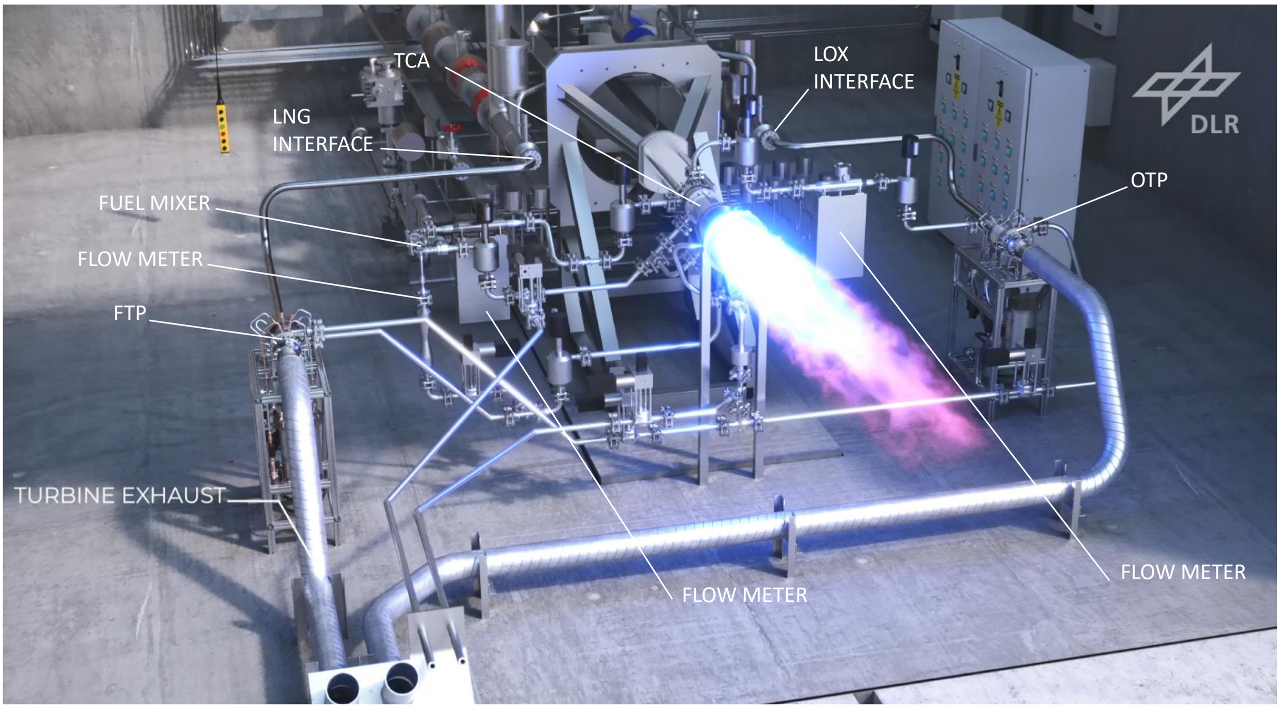

Fig. 18. LUMEN layout at test bench P8.3

It was confirmed that the chill-down time is long enough to have liquid at the pump inlet and at the same time short enough to have an oil temperature which is above the pour point by a significant margin. The OTPs performance up to the maximum LUMEN load point and the transient response of the OTP to turbine pressure were tested. The OTP reached a maximum speed of 22.000rpm in these tests, while spinning up to this speed within one second from first valve movement. The transient tests will be used in the EcosimPro simulations to improve the transient model of LUMEN.

Testing with LOX was the next step, Fig. 19 shows the OTP after one of the LOX tests. The chill-down procedure was adjusted to the new fluid and in a first test the OTP reached a speed of 10.000rpm. LOX testing could not be completed because the test campaign ended before all objectives were achieved. For this reason the OTP will be tested again in the TP campaign in October. The results of the testing will be presented in future publications.

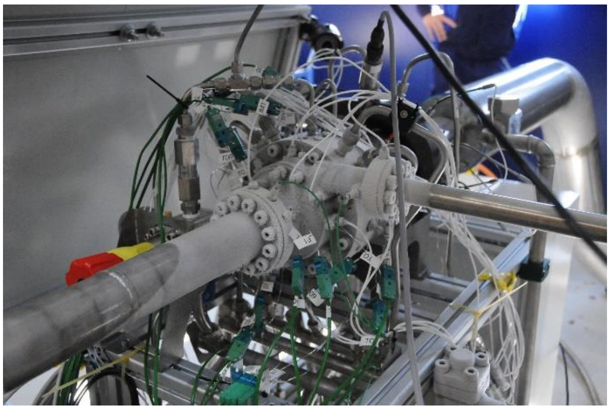

Fig. 19: OTP after LOX testing

5. Valves, Control and Instrumentation

As discussed before LUMEN uses control valves in most lines of the engines to increase the modularity and make it easier to run LUMEN with components it was not initially designed for. This way interested partners can easily test their components in the LUMEN engine. The valves used for this task are servo motor controlled electrical valves developed by DLR. The main advantage of these valves is high opening speeds of less than 0.5

seconds and a high position quality with no overshoot, no pressure dependent positioning and no hysteresis.

The valves are controlled by a rocket engine control unit (RECU) which was developed by DLR. The RECU will be used in the future for testing control algorithms based on machine learning. This way DLR will demonstrate the benefits of intelligent control for reusable engines [2].

As LUMENs main focus is research, the engine and its components are heavily instrumented. Each turbopump can be equipped with more than 90 measurement channels. For example, there are 5 total pressure probes in the turbine, up to three displacement sensors and two accelerometers besides pressure and temperature sensors.

The combustor has 77 measurement channels and the rest of the engine more than 60. There are pressure and temperature measurement before and after every major component for in depth characterization.

Additionally, the cycles three main lines (LOX, LNG before and after mixer) are equipped with mass flow sensors as can be seen in Fig. 1. There are two Coriolis mass flow meters (orange parts in Fig. 2) and one orifice plate.

6. Outlook

Upcoming activities within the LUMEN project include:

Thrust chamber hot fire tests

- The integrated LUMEN thrust chamber will be tested on the P8.2 test bench by early 2022. The tested specimen will be the same as the one that will be used for the integrated engine tests in the second half of 2022. The main goals of this test campaign are the demonstration of a) stable combustion at all load points specified, b) 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 will be tested with cryogenic media by the end of 2022. The OTP will also be tested in this campaign because not all objectives could be met.

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.

7. Conclusion

The manufacturing and testing status of all major components of LUMEN was presented. LUMEN focuses a significant amount of the DLR research programs and allows to show the benefits of this research for reusable engines.

The modular approach of LUMEN was highlighted to show the versatility of LUMEN for engine component testing in a representative environment. This makes LUMEN the ideal platform for interested international partners.

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