75th International Astronautical Congress (IAC), Milan, Italy, 14-18 October 2024.

IAC-24-AC4.1.5.x86850

LUMEN: Liquid Upper Stage Demonstrator Engine - A Versatile Test Bed for Rocket Engine Components: Hot-Fire Test Results

Tobias Traudt[a], Wolfgang Armbruster[a], Christopher Groll[a], Robson dos Santos Hahn[a], Kai Dresia[a], Michael Börner[a], Sebastian Klein[a], Dmitry Suslov[a], Max Axel Müller[a], Eldin Kurudzija[a], Jan Haemisch[a], Jan Deeken[a], Justin Hardi[a], Stefan Schlechtriem[a]

[a] *Institute of Space Propulsion, German Aerospace Center, DLR, Hardthausen, Germany,* *tobias.traudt@dlr.de*
* Corresponding Author

Abstract

In 2017, the German Aerospace Centre (DLR) initiated the Liquid Upper Stage Demonstrator Engine (LUMEN) project, aimed at developing an experimental expander-bleed cycle rocket engine tailored for LOX/LNG propulsion within the 25 kN thrust range. In early 2024, the final stage of development was completed with hot-fire testing of the entire LUMEN engine including turbopumps. By reaching this significant milestone LUMEN is now fully operational and can be used as a test bed for developing sophisticated technology such as intelligent engine control. The open research platform concept of LUMEN, free of IPs from other entities, allows DLR to offer LUMEN as a test bed for interested domestic and international partners. The modular design facilitates the rigorous evaluation of test components in a representative environment. The whole engine can be used to develop engine related technologies which could not be tested otherwise.

The test campaign started with run-in tests with progressively escalating in complexity to ensure optimal engine start-up sequences without compromising hardware integrity. The first tests were turbopump spin tests in which the turbines are driven by pressurized nitrogen from the test bench. In the spin tests, turbopumps are started simultaneously, one discharging one propellant into the thrust chamber (TCA), while the other was using the chilldown line for dumping of the second propellant. In subsequent tests the discharge paths of the turbopumps were changed respectively. In this way the timing of pressure build-up was fine-tuned to ensure precise engine start-up.

After the spin tests the ignition of the engine was initiated successfully and a steady operation point was reached. Subsequent objectives involved traversing the comprehensive test matrix encompassing diverse TCA pressures and oxidizer-to-fuel ratios.

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 throttling range is 58% to 133% of nominal thrust.

2. Engine architecture

Fig. 1 shows a schematic representation of the LUMEN engine cycle. The choice of propellants, cycle and design features can be found in several publications [1], [2], [3], [4], [5].

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.

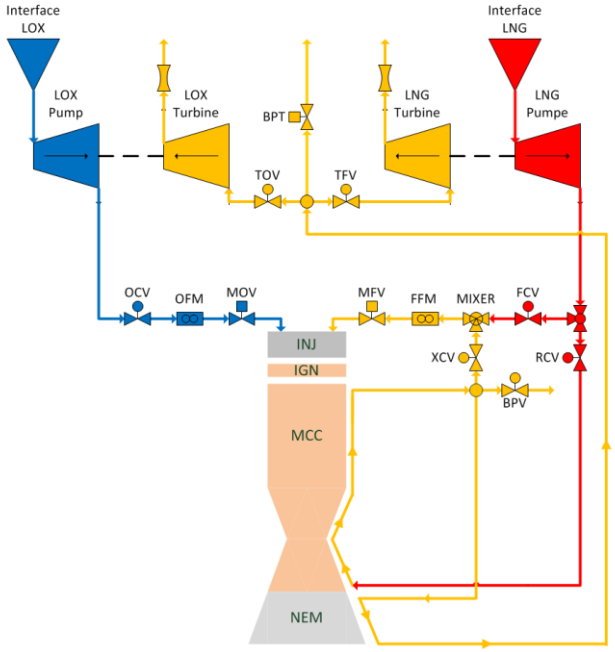

Fig. 1 Schematic representation of the LUMEN demonstrator architecture.

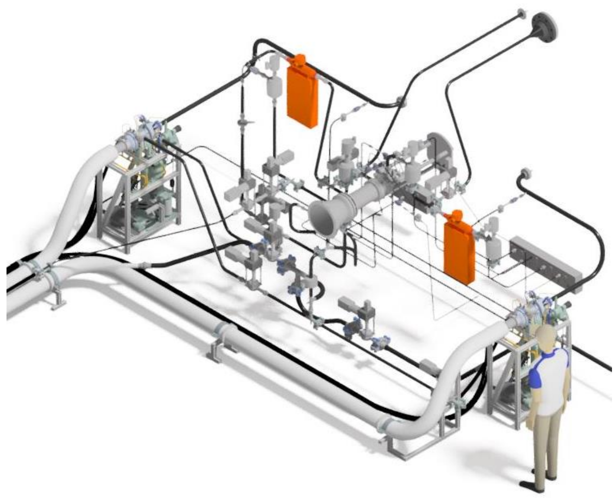

Fig. 2 LUMEN demonstrator engine layout

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.

3. Main components overview

3.1 Thrust Chamber assembly

Two thrust chambers assemblies (TCA) have been manufactured: a "conventional" one and an additively manufactured one (AM). The conventional TCA uses a machined copper liner where the cooling channel are closed galvanically. Additionally, a thrust jacket is used to transmit the loads from the nozzle to the thrust frame of the test bench. The AM TCA is printed from a copper alloy without a thrust jacket. Both TCAs were designed in a way to behave the same from a system point of view regarding pressure losses and heat pickup in the cooling channels. Due to the higher roughness in the untreated cooling channels of the AM TCA, it is a few centimetres shorter than the conventionally machined one.

Both TCAs use the same nozzle extension which is made from a nickel alloy.

More information about various aspects of the LUMEN TCA development can be found in [6], [7], [8], [9], [10], [11], [12], [13], [14], [15].

3.2 Turbopumps

The LUMEN turbopumps are unique in its design because they use oil lubrication. This was a early design choice in order to minimize resources needed for development by using off the shelf bearings with proven performance while at the same time increasing bearing life time to a calculated 1000h. This exceeds by far typical turbopump life and is in favour of the test platform approach underlying the whole LUMEN engine.

The reader may look into [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29] for more information on the LUMEN turbopump development.

4. Hot fire results

The test campaign for the LUMEN engine started in end of 2023 with the installation of the engine at the test bench. Most of the engine parts were built for the TCA and TP test campaigns and only minimal hardware changes were necessary. The setup of LUMEN is shown in Fig. 3. After the hardware installation the instrumentation was connected to the various interfaces of test bench acquisition system and additional data acquisition systems. The final step in preparation was to check the engine for tightness.

In February 2024 the engine underwent its first test as a complete system by doing cold-flow checks without ignition. During these tests the final timing for the ignition sequence was defined.

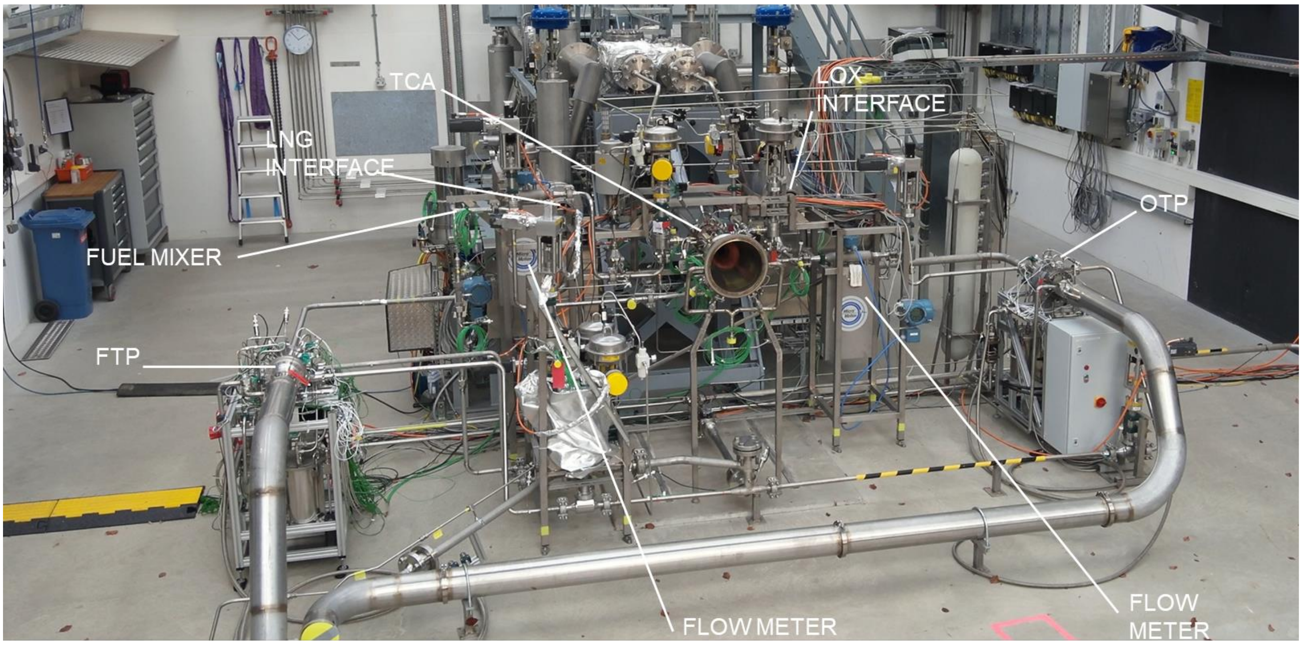

Fig. 3. LUMEN layout at test bench P8.3

The first ignition attempt was aborted by a redline at 1,5s but the second ignition was successful and the full test duration was realized. This was the first time DLR had a successful hot-fire of a rocket engine (see Fig. 4).

The following tests were used to do several things. We adjusted engine parameters and improved system modelling at the same time. The start and stop sequence were fine-tuned and some pre-tests for the next test campaign performed.

Here is a summary of the tests:

- *“cold-flow”*
  - *Spin-up of both TP with start gas from test bench (GN2)*
  - *LNG through combustor*
  - *LOX in dump*
  - *Change of configuration*
  - *LOX in combustor*
  - *LNG in dump*
- *First ignition*
  - *Redline at 1,5sec*
- *Second ignition*
  - *Successful*
  - *Nominal load point achieved*
- *Fine adjustment*
  - *Optimization of engine parameters and load points*
  - *Optimization of start- and shut-down sequence*
- *Pretests for next campaign*
  - *Self startability of cycle*
- *Max. thrust*
- *Intelligent control*
  - *Control of complete engine by machine learning algorithms*
  - *See next chapter*
  -

The pressure graph and the turbopump speeds of the second test run can be seen in Fig. 5. It shows the starting time of the engine which is in the order of 1 to 2 seconds. After the start there are some open-loop adjustments to keep the TCA pressure at roughly the same level. From 15secs

Fig. 4: Hot run LUMEN

onwards you can see the cycle reaching thermodynamic equilibrium.

5. Intelligent control of the LUMEN engine

A major test with LUMEN was the research of engine control with machine learning algorithms.

Today, technological progress happens mostly in software, as can be seen in almost every situation of our daily lives. Cars are more or less fully developed from a mechanical point of view but significant leaps in development are made by autonomous driving software for example. This

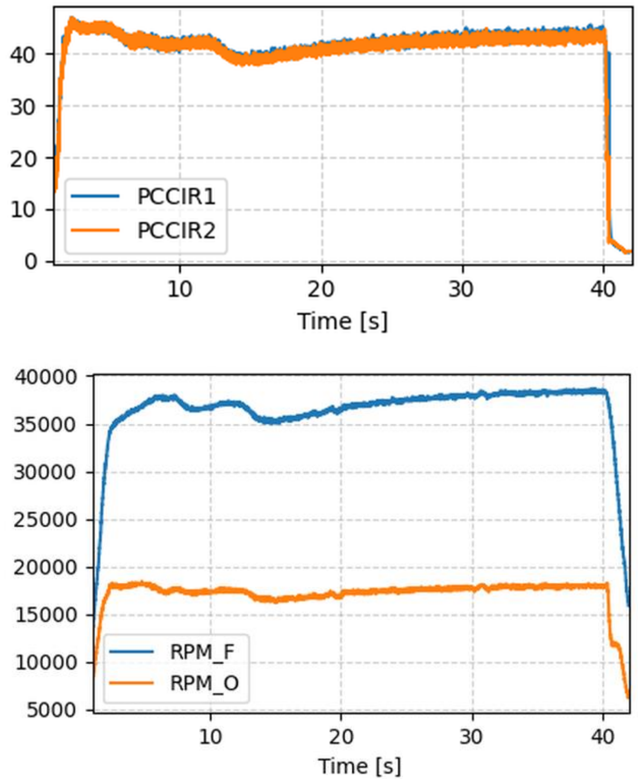

Fig. 5: combustor pressure P_cc and rotational speeds of the TP in the second test run

principle should be adopted in the aerospace field especially in the rocket engine business where the engines and technologies are basically the same since decades.

DLR is undertaking first steps to develop sophisticated intelligent control algorithms which are able to make real-time decisions based on monitoring and prediction systems that rely on machine learning amongst others to enable vastly improved engine control. The resulting full authority rocket engine controller (FAREC) would be a system which gives a significant technological advantage by improving the robustness, resilience and reusability of their rocket engines.

One major step in the research activities with the LUMEN test bed is to control the engine with machine learning algorithms. In this paper however, we will only give a short overview. More information will be published in the future.

5.1 Test of intelligent control in the LUMEN Engine

The method applied is based on training data created by simulation only, but the numerical tools are validated with experimental results. Domain randomization is used to ensure the controller is robust enough to not only work in simulation but also in reality. The computational power needed for the neural network is very low allowing for a control frequency of 20Hz which is far beyond the reaction time of the electric control valves used in LUMEN. The tests presented here are the first of its kind so future optimization can easily increase the control frequency if necessary.

The controller was trained to keep four values in the desired range

- *Combustor pressure,* p_{cc}
- *Ratio of oxidizer to fuel, ROF*
- *Injection temperature,* T_{inj}
- *Regenerative cooling mass flow rate,* $\dot{m}_{RC}$

The controller had to change the position of four control valves at the same time, namely FCV, TOV, TFV and BPV (see Fig. 2) to have enough degrees of freedom.

In the engine test p_{cc} was changed in a ramp from 40 to 60bar and back while the other three values were kept constant. The test was successful and the control error was below the predefined tolerance band.

DLRs work on intelligent control can be found in [30], [31], [32], [33], [34] out of which [34] is to highlight, because it describes the first test on intelligent control performed at DLR with the oxygen Turbopump.

5.2 Outlook on intelligent control in rocket engines

If we succeed in funding the activity, we want to develop the method even further into a so called "life enhancing control". For this purpose, several building blocks will be developed:

- *Building block intelligent control*
  - *Optimal control*
  - *Maximizes Isp in all operational conditions*
  - *First step demonstrated in LUMEN test*
- *Building block active constraints avoidance*
  - *Special controller training to incorporate the avoidance of critical system states like combustor wall temperature, critical speeds of turbopumps, etc.*
- *Building block anomaly detection*
  - *Health monitoring feedback to controller*
  - *Virtual sensing to detect sensor errors [35]*
- *Building block anomaly prediction*

  - *Give controller ability to react before something happens*
  - *Instability detection, proof of concept realized [36]*
  - *Turbine flutter prediction*

The feedback from the building blocks to the intelligent controller involve the continuous assessment and reporting of the rocket engine's condition and performance parameters. Sensors embedded throughout the engine collect data on temperature, pressure, vibration, and other critical metrics, which are then analysed in real-time. Sophisticated algorithms showed in the past that it is possible to predict the occurrence of devastating system faults in advance. For example, DLR demonstrated the prediction of combustor instabilities 500ms before they occur [36]. This was a first and important step and there are many more possibilities to apply these techniques to every part of the engine system. The feedback loop provides valuable insights into the engine's health status, identifying potential issues or anomalies early on. This proactive approach enables active avoidance of critical system states, minimizes the risk of failures, and enhances mission reliability.

6. Next steps in LUMEN testing

The next LUMEN test campaign will take place in beginning of 2025. The test campaign has the following goals

- *Improve system modelling with regard to*
  - *Childown*
  - *System*
  - *Heat transfer*
- *Life enhancing control*
  - *Intelligent control: Implementation of improvements*
  - *Virtual instrumentation*
    - *Development finalized*
    - *Implementation and test*

7. Conclusion

The first LUMEN hot runs were successful. The engine was used in 8 tests showing its reliable and reusable design. During the test campaign all major requirements of the LUMEN projects were successfully finalized and a major step in engine research was undertaken. The complete LUMEN engine was closed loop controlled by an intelligent controller, showing the versatility of the LUMEN research engine. The next steps in intelligent control and for the next LUMEN tests were presented. This makes LUMEN the ideal platform for interested international partners.

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