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Status of the Turbopump Development in the LUMEN Project

Tobias Traudt[a]*, Robson dos Santos Hahn[a], Hideyo Negishi[b], Felix Lindemann[a], Steffen Woidich[a], Bernd Wagner[a], Dietmar Maier[a], Christian Mader[a], Günther Waxenegger-Wilfing[a], Jan Deeken[a], Michael Oschwald[a], Stefan Schlechtriem[a]

[a] *DLR Institute of Space Propulsion, Langer Grund, 74239 Hardthausen, Germany*
[b] *JAXA Japan Aerospace Exploration Agency, Tsukuba Space Centre, 305-8505, Ibaraki, Tsukuba, 2-1-1 Sengen, Japan*
* Corresponding Author Tobias.Traudt@dlr.de

Abstract

The Liquid upper stage demonstrator engine (LUMEN) to be built at the German Aerospace Center will use the expander bleed cycle. The propellants for LUMEN will be liquid oxygen (LOX) and liquid methane or more specifically liquid natural gas (LNG). The demonstrator will provide a test bed for future component development as well as to enhance the understanding of the operation of the complete cycle. The cycle will feature two turbopumps in order to simplify the turbopump design, while on the same time allowing more freedom for a modular exchange of components. By this approach the DLR hopes to create point of contacts for interested parties to use the LUMEN demonstrator for turbopump component research on demonstrator level.

In this paper we give an overview on the current development status of the turbopumps. The critical design phase (CDR) will be finished in early 2019 and the design of the components are discussed as they are close to be manufactured. Extensive CFD work has been done since the preliminary design phase in order to proof the reliable performance of the LOx and LNG pump. On the turbine side a full 3D simulation has been performed. The design of the housing for the oil lubricated off the shelf hybrid bearings as well as the design of the shaft has been completed. To ensure smooth operation of the turbopumps throughout the operational envelope of the LUMEN demonstrator, the critical frequencies of the turbopump rotor assembly have been determined and verified by FEM calculations. Finally we give an overview on the necessary future steps to put the turbopumps into service.

Keywords: LUMEN, expander bleed cycle, methane, LNG, turbopump

Acronyms/Abbreviations

Liquid **U**pper stage de**M**onstrator **EN**gine	LUMEN
liquid oxygen	LOx
liquefied natural gas	LNG
oxygen turbopump	TPO
fuel turbopump	TPF

1. Introduction

Within the framework of the LUMEN project (**L**iquid **U**pper stage de**M**onstrator **EN**gine) a breadboard engine demonstrator intended exclusively for test bench operation is developed and operated at the European research and development test bench P8 at the DLR site of Lampoldshausen. The envisaged breadboard engine is intended to offer a deeper understanding of the operational behavior of a rocket engine system. In addition, it is supposed to enable the testing of new technologies in a fully representative system environment. To this end, a full engine cycle is to be assembled, including thrust chamber, turbomachinery, valves and other relevant sub systems. The Expander-Bleed Cycle is the most suitable cycle for the LUMEN project [1]. The demonstrator will use a fuel mixer which redirects engine coolant flow back to the injector head. There will be two turbopumps in parallel staging, which is unusual for the chosen propellant combination, where a single-shaft turbopump is favourable due to weight optimization. Since weight optimization is not a top priority for our engine and to have advantages in controllability of the engine, the parallel staging of the turbopumps was chosen. This approach is also better suited for a modular design of the turbopumps which eases research on component level.

This work will give an overview over the LUMEN demonstrator followed by an overview over design choices for the turbopumps. After this the current development status of the turbopumps will be presented.

2. LUMEN Demonstrator Overview

The LUMEN demonstrator engine is an expander-bleed cycle engine with parallel staging of the turbopumps (see Fig. 1).

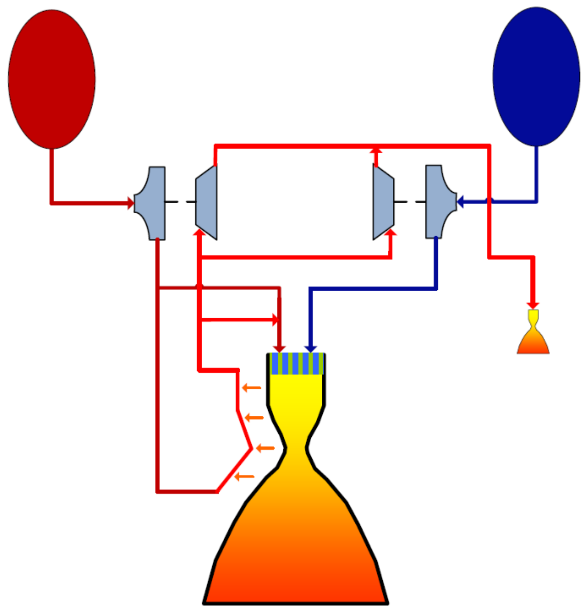

Fig. 1. Engine Cycle of the LUMEN Demonstrator

The parallel staging of the turbopumps has advantages in controllability of the engine, i.e. it lowers the demand on the control valves specifications. Another advantage is the high pressure ratio over both turbines which is in the order of 11. Fig. 1 shows a fuel mixer which is necessary because the temperature of the fuel going to the injector-head would be too low otherwise. The operating parameters of the demonstrator are listed in Table 1.

Table 1. Parameters of LUMEN cylce

Parameter	Unit	Value
Combustion chamber pressure	bar	60
Combustion chamber mixture ratio	-	3.4
Engine mixture ratio	-	2.1
Oxidizer mass flow	kg/s	5.8
Fuel mass flow chamber	kg/s	1.7
Fuel mass flow engine	kg/s	2.8
Primary cooling channel mass flow	kg/s	1.45
Thrust (sea-level)	kN	19,43
Thrust (vacuum)	kN	21.1
Engine Isp (sea-level)	s	250
Engine Isp (vacuum)	s	256
Oxidizer pump pressure rise	bar	72.2
Oxidizer pump power	kW	80

The LUMEN demonstrator will be able to be throttled from its nominal point to a minimum value of 35bar chamber pressure and at least 80bar chamber pressure at the highest load point. This requires a broad operation range capability for the turbopump system which also requires a component investigation in a large range of environment conditions.

3. Overview LOX and LNG Turbopump

For the LUMEN Turbopumps design choices have been made which are in contrast to established turbopump designs.

The turbopumps will both be single stage on the pump side as well as on the turbine side. To further reduce the amount of components there will not be an inducer since its functionality in terms of pressure increase can be performed by the test bench. In this way the potential risk of oxygen fire due to inducer blade contact is reduced as is the overall development and manufacturing time.

Maybe the most unusual design choice is the decision to use bearings which are not running in the pumped media. Instead the bearings will be lubricated either by oil or even by grease if the operating parameters allow doing so. By lubricating the bearings with oil or grease the development of the bearings can be shortened since off-the-shelf hybrid bearings for high speed applications can be used. Another advantage is the reduced risk of oxygen fire in the oxygen turbopump (TPO), since there is no thermal runaway of the bearings in pure LOx. More attention is neccesary for the LOx seals to avoid any contact of LOx and the hydrocarbon lubricant

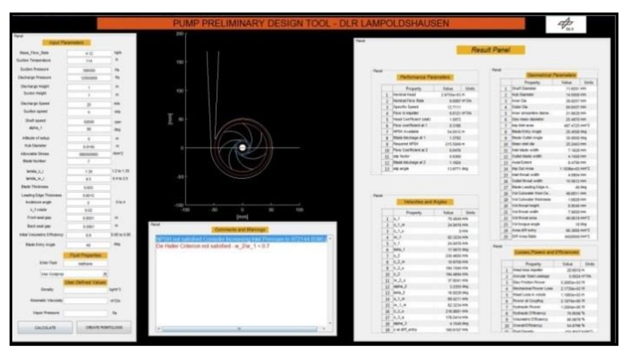

Fig. 2. Preliminary Pump Design Tool, AD-Tool

The external lubrication approach has more advantages over the traditional design of turbopumps which will be used and investigated. These are on the one hand the modularity and on the other hand the fact that the chosen approach might be a potential alternative for reusable turbopumps.

4. Pump Design

Preliminary Design

The socalled "AD-Tool" has been developed for the preliminary design of pumps for turbopump application. The tool is based on [2] and allows the design of pump impellers, the volute and the diffusor. With the AD-Tool it is easy and straight forward to come up with a new pump design for new given flow properties within a few minutes. This way new research results can be implemented easily, enhancing the tools capabilities. The tools output has been compared against several other commercially available codes.

Numerical Verification

In order to further enhance the understanding of the flow in the LNG impeller and to validate the data obtained by the AD-Tool, CFD simulations are carried out. For the simulations, Ansys CFX [3] is used to simulate the inlet to the impeller, the volute and the diffusor. The main losses in the simulation are neglected. These are the flow in the rotor housing cavities as well as the sealing flow.

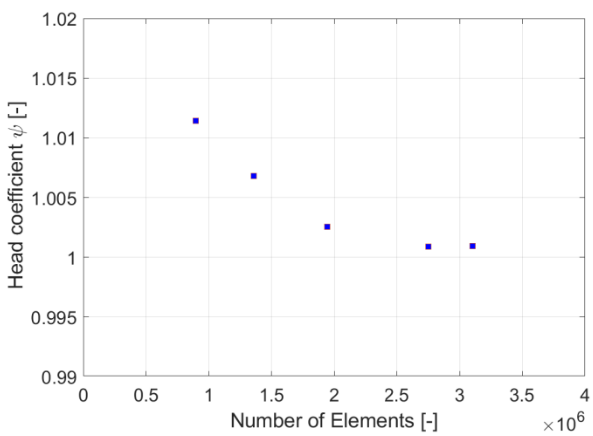

Fig. 3. Impeller Grid Convergence

A grid convergence study has been performed with regard to the head coefficient showing that grid convergence is achieved at around 2.7 million cells (Fig. 3) for the impeller.

Fig. 4 and Fig. 5 show some of the simulation results. The pressure distribution (Fig. 4) over the pump impeller is as expected. The head at the outlet of the diffusor is slightly higher than calculated with the analytical tool (see Fig. 6). The reason for this behaviour is the disregard of the main losses as mentioned before. However, the lowest load points deviate most from the analytical tool indicating that the losses at this point might be over predicted by the analytical tool.

5. Turbine Design

Since the LUMEN engine will be an open cycle the turbines for the LOX turbopump and the LNG turbopump will be supersonic turbines. The pressure ratio of the turbines is in the order of 11. The relatively low thrust class of LUMEN makes it necessary to use partial admission for both turbines.

Preliminary Design

The preliminary design follows the main guidelines of Deich [4], Tschelikov [5] and Ovsyannikov [6]. For the stator a circular nozzle design was chosen, because it has advantages for manufacturing and when

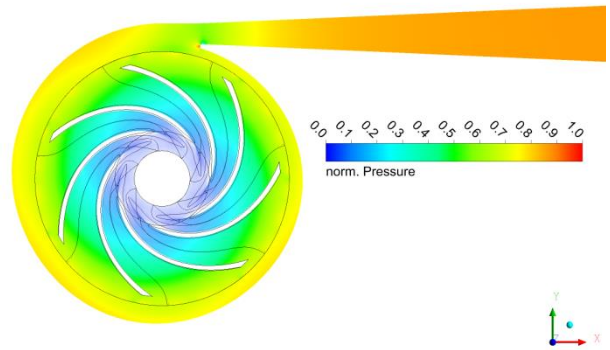

Fig. 4. Normalized Pressure in the LNG Pump impeller, Volute and Diffusor

being used in partial admission. Both turbines have roughly the same dimensions with slight deviations in blade height in order to minimize losses due to inlet flow. The number of nozzles and with it the degree of partial admission is different due to the different power demand of the LOX and the LNG turbopump. There are three nozzles for the LOX turbine and five nozzles for the LNG turbine.

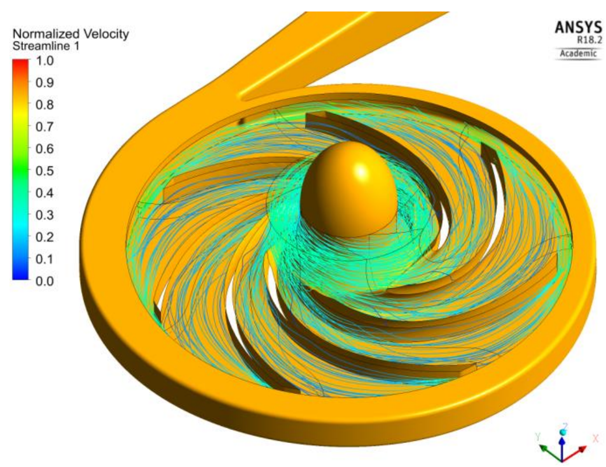

Fig. 5. Streamlines in the LNG Pump Impeller

The stator nozzles and rotor profile chosen was selected in order to maximize the performance according to the required operational conditions. Its performance was derived from extensive work in MEI (Moscow Power Engineering Institute) [7], and was possible to evaluate the off-design conditions according to Belyaev [8] method together with a modified approach presented in Ovsyannikov [6].

In the nominal operating point the preliminary design showed an efficiency of the turbine for the LNG turbopump above 44% inlet to outlet (Total-to-

Static),allowing to achieve the required power balance for the TP system.

Numerical Verification

Numerical verification of the turbine design has been performed by JAXA in the frame of a research agreement with DLR. A preconditioning density-based CFD solver known as CRUNCH CFD [9] is used for this work, which was developed by CRAFT Tech and extensively validated relative to rocket applications by JAXA for more than 10 years.

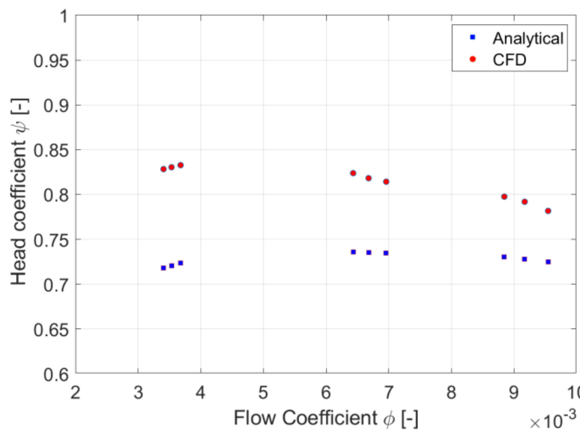

Fig. 6. LUMEN Load Points: CFD vs. Analytical Tool

A three-dimensional steady RANS simulation is carried out with a computational domain of the stator and rotor of the turbine assembly as shown in Fig. 7. The guide vanes and outlet of the turbine are not considered, because they are in a preliminary state. The domain is discretized in 24 million nodes with compressible Favre-averaged Navier-Stokes equations. For the frozen rotor simulation a k-ω SST turbulence model is used.

For the stator the results show that the massflow in every nozzle is almost the same and differs only within 0.3% from nozzle to nozzle. The massflow per nozzle is only about 2% lower than the calculated one.

For the rotor there is flow separation visible even in the design point (see Fig. 8). This is expected, since the chosen profile is optimized for a broad range of relative inlet Mach number. Despite of the flow separation, the efficiency calculated from the CFD results is above 50%, which is better than expected.

In future work, the authors will investigate the turbine more in detail. A full 3D simulation of the whole turbine assembly with guide vanes and outlet will be performed. The simulation will be steady and unsteady.

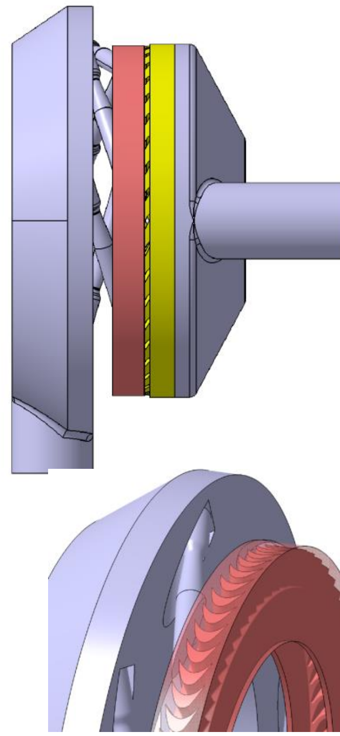

Fig. 7. Preliminary Inlet, Stator, Rotor, Guidevanes (yellow) and Preliminary Outlet of the Turbine for the LNG Turbopump (top). Computational Domain for Numerical Verification (bottom)

6. Rotordynamics

The so called tool "Rotan" (**Rot**or **An**alysis) has been developed for the LUMEN project. It is uses the open source tool RotFE [10]and is a graphical interface which allows parameter studies of various input values..

The main feature is the automated calculation of the following variable parameters

- rotormaterial
- rotor length (for every element)
- rotor diameter (for every element)
- impeller position
- different impellers
- turbine position
- different turbines
- bearing positions
- different bearings
- sealing positions
- different sealings
- position of various additional parts

Another feature is the prior automated calculation of the rotordynamic coefficients of seals.

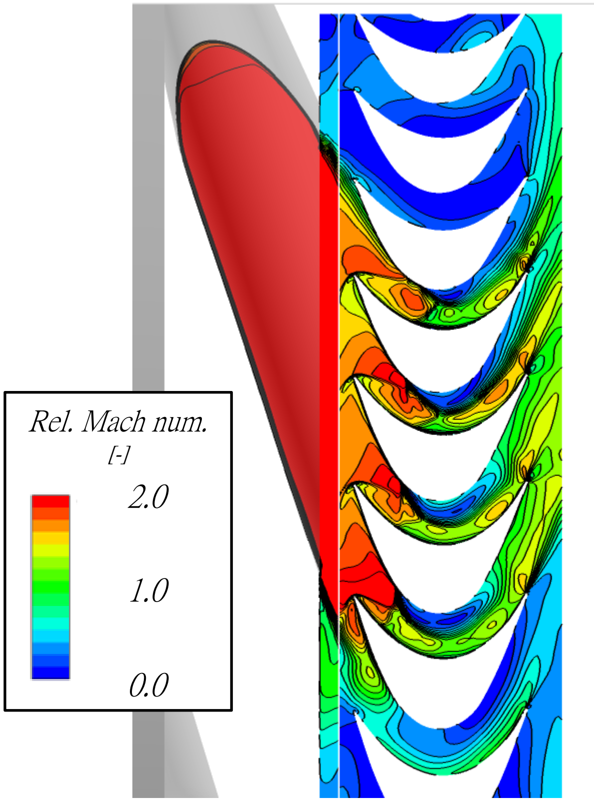

Fig. 8. LNG Turbine 3D steady RANS Simulation: Absolute Mach Numbe

With these features the best configuration can be found out of thousands of configurations in a very short time.

To visualize the results the RotFE-build-in tools can be used to display the Campbell diagram or to plot the shape of every mode of every configuration of interest.

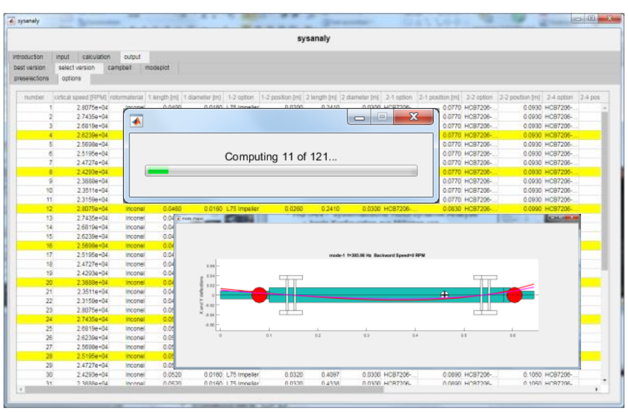

Fig. 9: Systematic Rotordynamic Analysis Tool, Rotan

To compare different configurations an alternative visualization has been implemented which plots over the variable parameter chosen by the user.

Rotan has been used to ensure the subcritical operation of the LUMEN LOX Turbopump.

7. Manufacturing Study

To establish a supply chain for the LUMEN demonstrator turbopumps the following parts are manufactured for study reasons (see Fig. 10).

The impeller has been machined in two pieces and then EB-welded, while the turbine and the shaft are machined. No additive manufacturing techniques have been used in order to establish a baseline design against which future components can be benchmarked.

Fig. 10. Manufacturing Studies of the Turbine

8. Conclusion and upcoming steps

The status of turbopump development in the LUMEN project has been presented.

The AD-Tool has been developed for the easy and fast preliminary design of pumps. The LNG pumps performance as well as the LNG turbines performance have been verified by CFD simulations.

A rotordynamic tool (Rotan) was developed to easily perform a parameter study and find the best configuration for the turbopumps. With Rotan subcritical operation of the LOX Turbopump has been confirmed.

In future work we will present simulations of the LNG pump with losses included and full 3D unsteady simulations of the supersonic turbine. For the LNG turbopump the rotordynamic characteristics will be presented.

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