LUMEN Turbopump - Preliminary Design of Supersonic Turbine

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(Received April 22nd, 2019)

This paper presents an improved design methodology for a supersonic partial admission impulse turbine for LRE, which is commonly used in open cycle applications, while focusing on the main losses from small dimension as well as the high rotational speed required for low thrust class engines as the LUMEN demonstrator engine. Also, the standard design models are evaluated and compared with the results using the design constrains adopted for low thrust class level turbomachinery.

Key Words: LUMEN, engine demonstrator, LOX/LNG, supersonic turbine

Nomenclature

OTP	:	Oxidirer Turbo Pump
FTP	:	Fuel Turbo Pump
$\dot{m}_y$	:	Leakage mass flow rate, kg/s
$\dot{m}_T$	:	Turbine mass flow rate, kg/s
$\mu_{заз}$	:	Flow coefficient
f_y	:	Leakage correction factor
Δ	:	Radial clearance, m
λ	:	Sealing design factor
τ_y	:	Sealing pitch ratio
ρ_T	:	Reaction degree
φ_c	:	Stator loss coefficient
α_{1T}	:	Stator flow angle, °
π	:	Total-to-static pressure ratio
$\alpha 1_{eff}$	:	Stator effective flow angle, °
$\bar{t}$	:	Pitch ratio
M_{2t}	:	Relative inlet Mach number

1. Introduction

During the development of a liquid propellant rocket engine for upper stage application, is essential to minimize the tank pressure in optimum point from a trade-off between structural integrity and mass reduction. In this frame, the turbopump driven cycle play an important role, where the main combustion chamber pressure can be increased while the tank pressure reduced at levels of cavitation mitigation.

According to the cycle architecture, is possible to achieve pressures in order of hundreds of atmosphere at pump outlet, while the inlet pressure stays below 5 bar.

In order to provide energy for the work generated by the pump, one possibility is the use of a turbine system driven by an energetic source that can be originated from a small combustor or, in case of expander cycle architecture, by the heat transfer from the cooling channels.

The feasibility of an expander cycle was demonstrated from closed scheme with RL-10, where the turbine driven fluid is used at the combustion chamber, resulting in high mass flow availability.

With the development of LE-5 upper stage engine by JAXA, was evident that the thermal inertia transient could be applied in new cycle architecture, called expander bleed, where a small portion of coolant mass flow is used to provide power for the turbomachinery.

This cycle configuration was adopted for LUMEN 2) (Liquid Upper stage deMonstrator ENgine), which is a breadboard engine, driven by two separate turbopumps (oxidizer and fuel turbopump).

As standard in an open cycle 1), the bleed mass flow rate must be minimized. Thus, in order to generate the required power to drive the turbomachinery, the energy can be obtained from the expansion of the fluid, which accelerates the fluid media. Thus, LUMEN demonstrator requires utilization of supersonic impulse turbines in order to provide enough energy to drive its pumps, while minimizing the amount of required bleed mass flow in the system.

The main models for design turbine systems applied for LRE 3) are often optimized for medium to high thrust levels (usually above 50-100kN), where the losses such as friction, leakage and non-uniform flow due to partial admission were evaluated and modelled exhaustively.

With a decrease of nominal thrust at design conditions, the turbomachinery size decreases considerably, resulting in losses outside of the well-known modelled ranges, making the design of such components imprecise.

In the same thrust class as LUMEN, is possible to identify engines as S5.98M and S5.92, which is currently in production, as well as retired engines such as S2.2100 and RD-858/859 and most recently, the new developments as BOREAS 4) and RSR 5). However, the models applied for these engines are not fully available, making the design and performance prediction a complex task for new developments.

2. LUMEN demonstrator

2.1. Turbine design

The turbine design procedures used for LUMEN turbopump are mainly based on Ovsyannikov and Borovsky methodology 4). However, some modifications were required in order to comply with the reduced size inherent of such thrust class engine. The design logic follows 5 main steps, as shown at Fig. 1.

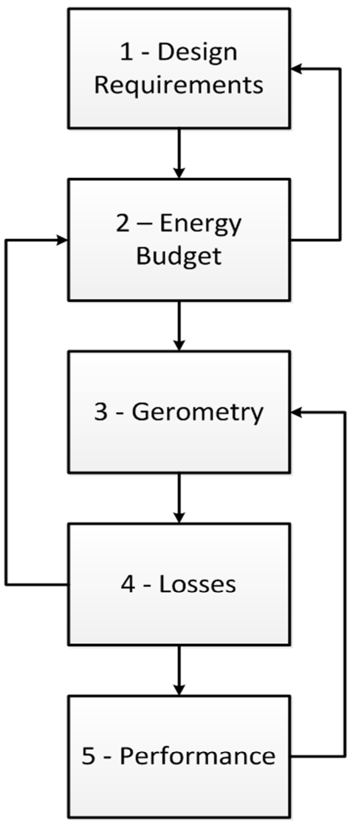

Fig. 1 Main design logic adopted for the preliminary design.

2.1.1. Input parameters

The input parameters used for the preliminary design are based on the cycle requirements. An initial evaluation of LUMEN operational envelope 2) allows to identify the upper limit for pump required power and turbine inlet pressure budged.

At such point, is possible to estimate the rotational speed for design point based on the fluid properties as total pressure and temperature at inlet and static pressure and temperature at outlet. This step provides information of the fluid density, specific heat ratio, gas constant and others properties that are used for estimate the energy budget for the system.

2.1.2. Available energy

The second step of adopted methodology consist in evaluation of available energy for the system in matter of adiabatic specific work, rotor reaction degree and the choice of circular velocity at meridional diameter.

Initial estimation of efficiency consolidates the choice of pressure ratio for the stator, while gives the initial requirements for the rotor selection, according to the stator outlet Mach number and rotor inlet relative Mach number.

At this point, the result of energy available is iterated with the design requirements in order to minimize the associated error and obtain the right parameters for geometry selection at the next step.

2.1.3. Geometry selection

With the available energy, is possible to estimate the initial geometry, as rotor and stator blade height, while adopting the main design constrains as the ratio between rotor blade height and meridional diameter, radial gap and rotor blade chord respectively.

The energy budget constrains provide the required area expansion ratio, which is possible to make a trade-off between the feasible radial gaps and tolerances and the possible geometry that can fulfil the expected performance. The geometry selection provides important information for estimative of losses on next step.

2.1.4. Losses

In a supersonic impulse design, especially at low thrust level category, the main losses need to be carefully evaluated. This step considers performance deterioration related to the partial admission, as well as the rotor and stator associated losses at design conditions.

With the selected rotor and stator geometry, is possible to evaluate the performance map of such components in order to reduce the overall losses according to the operation condition.

Also, together with the friction losses, the sealing system is analyzed to provide the first overview of the turbopump efficiency. This step is crucial to provide more precise information of the energy budget available during the design procedure.

2.1.5. Performance

The iterative process is requires in order to reduce the deviation between the input parameters, with the performance generated by the calculation. Is important to point out that the preliminary design requires deviation no more than 5% 3). Thus the final step consist in evaluate all losses together with the off-design condition in order to show the feasibility to fulfill the entire required operational envelope.

At this step, the power generated for this design becomes an input constrains and will allow possible optimization on the previous steps.

3. Design methodology adopted

According to Ovsyannikov and Borovsky methodology 3), some parameters as radial gap, ratio between blade height and meridional diameter or meridional velocity are assumed to be in a specific range in order to the losses equations to be valid. Also, some blade geometry performance map generated experimentally with dimensions considerably bigger than the required for a LUMEN size class engine. Effects as friction, leakage and boundary layer losses can have deviation which makes the performance prediction challenging.

In order to adapt this design methodology for LUMEN demonstrator, correction factors are used for scaling the performance deterioration according to the phenomena in evaluation.

Also, in such reduced size turbine, some trade-off must be take into consideration to design a system with adequate performance and with feasible tolerances which can be manufactured and at the same time, be able to withstand the operation conditions.

3.1. Losses

The most pronounced performance deviation using the standard design methodology comes from the inherent losses of such device. In a supersonic turbine, the main losses to evaluate are relative to the blade design. It’s usually associated to the relative flow Mach number and is characteristic of the blade geometry design. For high inlet Mach number, the friction and chock structures show a tendency to reduce its performance. Nevertheless, the lower performance is exceeded by increased adiabatic specific work from high expansion ratio required for the design condition.

Leakage and friction are also important secondary losses on this system design. The zero reaction design used for a pure impulse turbine has the advantage of low axial leakage, while the pressure ratio between suction and pressure side of a blade cannot be neglected. However, radial clearance between stator and rotor can minimize the inter-blade leakage, where is not possible to use shrouded design.

The Fig. 2 shows the expected axial and radial gaps of a turbine system as for LUMEN design. The image shows also circular axis-symmetric nozzle for the stator, which helps to minimize the rotor leakage due to its elliptical outlet geometry.

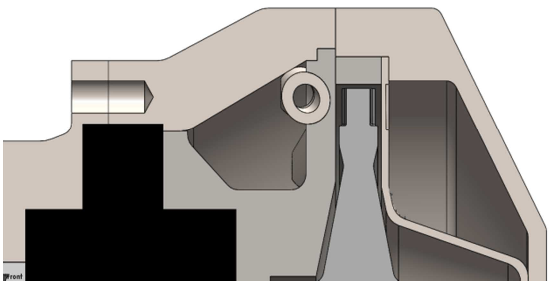

Fig. 2 Cut view of a supersonic impulse turbine with partial admission and circular axis-symmetric nozzle stator, showing the turbine radial clearance, stator cavity and exhaust chamber.

3.2. Stator

In order to comply with design requirements and yet maintain a shocked exhaust flow to eliminate the influence of ambient conditions at the at whole turbine operational envelope, the total-to-static pressure ratio adopted for FTP and OTP was respectively π=12,5 and π=13. At such conditions, at lowest inlet pressure and temperature available from engine operational conditions, the exhaust pressure is kept above the desired conditions with minimum margin for nonlinear effects on fixed expansion ratio.

The stator profile was chosen to be a circular axis-symmetric nozzle, in order to minimize the radial variation of reaction degree, while optimizing the partial admission degree due to elliptical exhaust is able to cover a bigger perimeter at the meridional diameter when compared with standard radially extruded profile geometry.

Between the options available for such design approach, the use of conical nozzles, as shown at Fig. 3, was in favor of MOC 6) exhaust profile due its simplicity in manufacture as well as its reduced size.

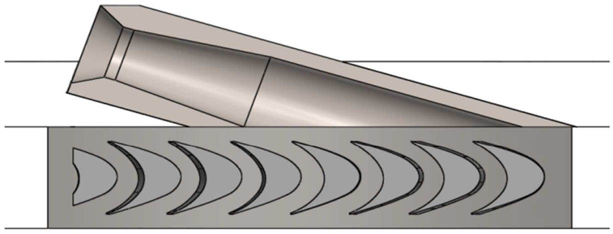

Fig. 3 View of meridional path of a supersonic impulse turbine with partial admission and circular axis-symmetric nozzle stator.

Thus, choice of stator geometry assumes a profile designed S-9017V 7) which its experimental results from losses according to expansion ratio and exhaust Mach number are shown compiled in the graph of Fig. 4.

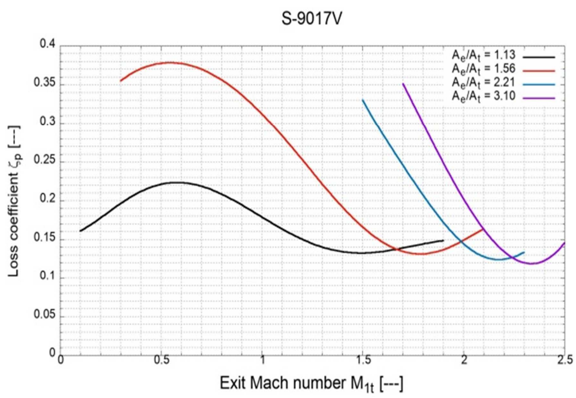

Fig. 4 Loss coefficient of S-9017V blade profile according to exit Mach number for different area expansion ratio possible.

This profile was selected for both OTP and FTP in detriment of modularity and simplicity, with adjustment of optimum area expansion ratio to comply with required exhaust Mach number for the respective design.

4. Rotor

For a design of pure impulse turbine, the rotor reaction degree adopted ρ_T=0, resulting in a pressure drop along the rotor being negligible. The chosen pressure ratio in the stator leads to a high exhaust Mach number at design conditions. For such inlet conditions, the options for blade profiling would lay in two major dependencies, being geometry from existing catalogue 8) or design from required inlet conditions.

For LUMEN application, in order to minimize the bleed mass flow rate, a trade-off between the available adiabatic specific work and the main blade losses shows the advantage to operate in a relative inlet Mach number between 1,4 to 1,7.

There's various methodology for blade design from inlet conditions as for example double-arc, polynomial, Method of Characteristics 6), etc.

However a new design would require extensive test for losses evaluation in order to create the performance map, especially at off-design conditions. On the other hand, the options available from catalogue 8) allow selecting the geometry which can fit in the design requirements. Between the available options which comply with operational requirements, is possible to mention:

Table 1. Rotor blade options according to LUMEN requirements

Blade designation	α1eff	t̅	M_2t Range
R-2118V	16°- 20°	0,60 – 0,70	1,30-1,90
R-2522V	20°- 24°	0,54 – 0,65	1,35-1,60
R-2926V	23°- 27°	0,53 – 0,63	1,35-1,60
R-3330V	28°- 32°	0,51 – 0,61	1,35-1,60
R-3025V	23°- 27°	0,48 – 0,58	1,35-1,75

By evaluating the losses at the range of operational conditions for LUMEN demonstrator 2), is possible to adopt the profile R-2118V, also designated as TR-1C, as an option which can fulfil the power requirement for OTP and FTP. The loss coefficient according to Relative inlet Mach number is presented at the graph of Fig. 5.

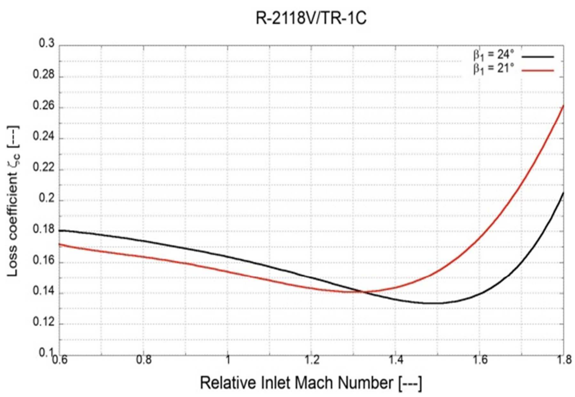

Fig. 5 Loss coefficient of R-2118V/TR-1C blade profile according to relative inlet Mach number for different inlet flow angle.

With an inlet flow angle ranging from β1=14° to β1=21° allowing a blade angle from βy=85° to βy=91° to minimize the overall drag with supersonic flow by adjusting the final angle of attack, is possible to select the optimum blade pitch/chord t̅ as shown in the graph of Fig. 6.

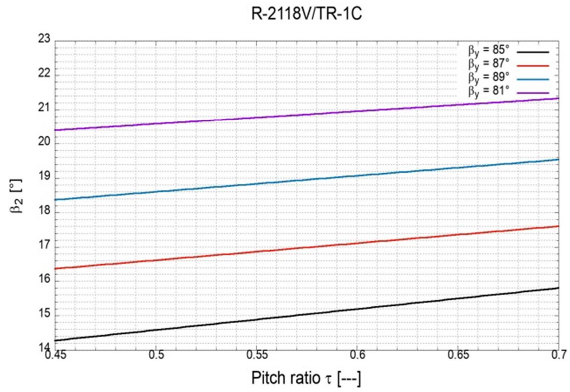

Fig. 6 Inlet flow angle in function of pitch ratio for different blade chord angle.

The step toward to evaluate the number of blades lay in a stator-rotor interaction. Is necessary performing a trade-off between the number of nozzles and the resulting losses due to degree of admission, radial clearance leakage, tip-to-root velocity difference and friction.

4.1. Radial clearance

According to the literature 3), 9), the radial gap must not exceed 3mm or approximately 10% of blade height. However, manufacturability must be taken into account, which limits the minimum gap in order of 0,2mm.

The leakage through radial clearance is modeled using the Eq. (1), (2), (3) and (4) for an unshrouded design and is modified from 3).

$$\dot{m}_y = \dot{m}_T \cdot \mu_{3a3} \cdot f_y \qquad (1.)$$

Where

$$f_y = \sqrt{\left(1 + \left[\rho_T \cdot \left\{\left(\frac{1}{\varphi_c{}^2}\right) \cdot (sin[\alpha_{1T}])^2 - 1\right\}\right]\right)} \cdot r_g \qquad (2.)$$

And

$$r_g = \left[1 + \frac{h_{1l}}{D_{cp}}\right] \cdot \left[2 \cdot \frac{\Delta}{h_{1l}}\right] \qquad (3.)$$

As well as

$$\mu_{3a3} = \sqrt{\frac{4 \cdot \Delta}{\lambda \cdot \tau_y}} \qquad (4.)$$

For LUMEN design, a lower limit of 1,0mm was chosen in order to keep margin for rotor-dynamics on complete aggregate. This value of radial gap is further evaluated on next step when the partial admission is taken into consideration.

4.2. Partial admission

For a supersonic impulse turbine, the admission degree is a critical evaluation. It comes from a trade-off between the blade geometry, turbine size and required stator exhaust velocity, as well as the loads on high cycle fatigue. 10).

With increase of admission degree, the main losses inherent of its parameters are reduced due to more uniform flow through the rotor. However, assuming a fixed meridional diameter and radial gap, the blade height decreases, resulting in more losses related to leakage at radial clearance. On graph of Fig. 7, we can see the evolution of radial clearance ratio and blade height ratio according to admission degree.

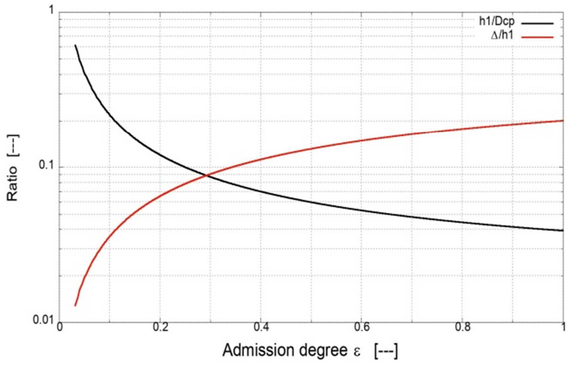

Fig. 7 Blade height ratio and radial clearance ratio in function of admission degree

For this reason, the evolution of admission related losses must be evaluated while comparing with the possible admission degree. Assuming a constant radial gap for this design due to design tolerances and manufacturability, is possible to show the evolution of losses for LUMEN design as shown on graph of Fig. 8.

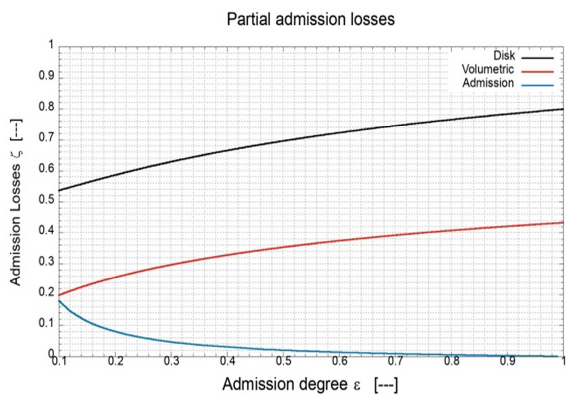

Fig. 8 Main losses associated to change of admission degree.

Thus, the disk, volumetric and admission efficiencies are presented on the graph of Fig. 9.

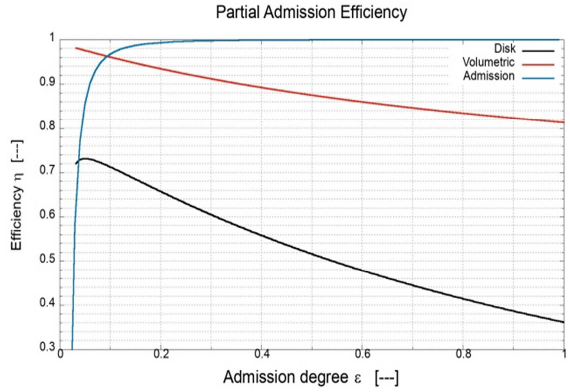

Fig. 9 Efficiency of volumetric flow, admission flow and disk friction according to degree of admission

The volumetric losses are mainly associated to the leakage while the disk losses take into consideration mainly the fluid friction with turbine disk and blade surface.

4.3. Off-design conditions

By using the statistical methodology proposed in Belyaev 11), is possible to evaluate the minimal deviation between the results and the model, as presented in the Fig. 10.

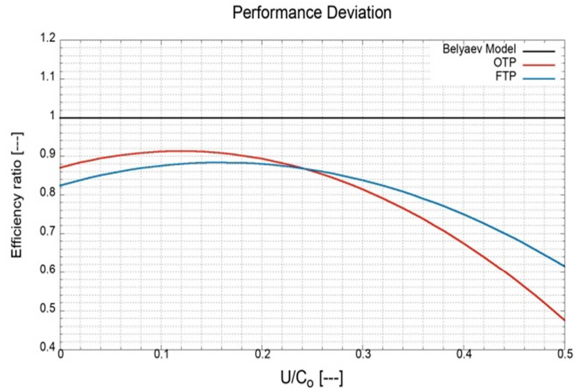

Fig. 10 Efficiency ratio between Belyaev model, based on statistical efficiency, and modified design taking into consideration the most detailed losses model out of recommended parameters range due to reduced size turbomachinery

This deviation is mainly characterized by the low size of turbine disk, resulting in high losses due to friction, viscosity and boundary layer size ratio.

The calculation of performance at operation envelope is done by evaluating the losses in function of rotational speed. The leakage ratio and disk friction model 3) results in reduction of total circular efficiency due to change in inlet pressure and velocity as well gas viscosity. The losses due to relative inlet Mach number M_2t as presented in Fig. 5 as well stator efficiency decrease due to friction and achieved exhaust Mach number M_2t as shown in Fig. 4 results in change of optimal flow angle at inlet and outlet. Thus, the efficiency ratio deviation between the Belyaev model 11) and the obtained with off-design calculation model shows the effects of reduced dimensions on losses, which is more pronounced at high rotational speeds.

5. Future work

This design approach was implemented in a C++ code with GUI in order to allow performance optimization. Initially, the blade performance was inserted as tables. Later version, the blade geometry was generated according the user requirement, where the performance is initially estimated according to the design methodology as well as a CAD file is generated to facilitate the CFD analysis.

The design methodology for the blade generation on this software is under investigation and is being validated with the current preliminary design, as well as other literature available results. The software (Blade Runner, v2.5) uses multiple design options for stator and rotor profile generation, as shown its interface at Fig. 11.

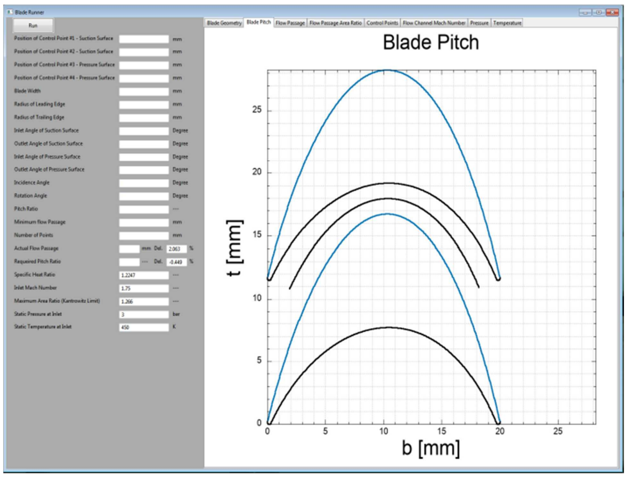

Fig. 11 Screenshot of Blade Runner v2.5 under development with a blade pitch passage as an example.

The software output, together with a CFD and experimental data from LUMEN demonstrator result will be used to validate the profile optimization and will be integrated into preliminary design option.

6. Conclusion

The preliminary design of LUMEN demonstrator turbine using modified design methodology for a supersonic partial admission impulse turbine shows a clear deviation from the statistical expected performance. The deviation was expected and is result of detailed losses evaluation, while most of the recommended parameters adopted had to be kept out of the range on the design procedure due to tolerances and trade-off evaluations for a reduced size turbine.

As the result, the FTP expected efficiency at design conditions was calculated to be approximately 46% using the modified design with improved losses model. The CFD result presented by Negishi 12) shows the total-to-static efficiency at levels exceeding 50% range, indicating that the losses model can be further improved. Experimental results will allow validate these models as well as the preliminary design methodology.

The stator and rotor blade geometry choice was driven by simplicity and feasibility and become basis for the design methodology optimization. The results also shows the possibility to achieve considerable performance for low size turbomachinery, since the results of LUMEN demonstrator design still shows margin for performance improvements.

Acknowledgments

The authors would like to express their sincere appreciation for JAXA and DLR cooperation as well as for the LUMEN project team.

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