DOI: 10.13009/EUCASS2022-4928
9TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Design Practices on Supersonic Turbines for Liquid Propellant Rocket Engine in the Frame of CNES/DLR Cooperation

Robson H. S. Hahn[1], Sebastién Le Martelot[2], Tobias Traudt [1]*
[1]*German Aerospace Center DLR, Germany;*
[2]*National Center for Space Studies CNES, French Space Agency, France*
robson.dossantoshahn@dlr.de

Abstract
The performance of an Open cycle engine, as gas generator or expander bleed, is direct linked to the efficiency of its turbomachinery design and its optimization is, in most cases, focused in this component due to structural limitation or other options as gas generator temperature, dynamic stability or pressure drop minimization.
Designing turbines for liquid rocket engines application is always a compromise between turbomachinery requirements and energy budget, engine performance and structural limitation. For instance, in open cycle, turbine flowrate should be as low as possible for losses minimization but in a trade-off for the required power as suitable inlet total temperature and pressure for structural mass envelope within affordable safety factors.
During the past year, as part of the CNES/DLR cooperation in the frame of Turbomachinery analysis, distinct design methods and its intrinsic characteristics were compared using common boundary conditions.
In this frame, this article aims at analysing the different design methodology for a supersonic partial admission impulse turbine for LRE as well as the impact of partial admission choices on the stator performance geometry but also on the rotor, as the optimal rotor geometry is strongly linked to the number of open stator nozzles, where both airfoil and axisymmetric nozzles are analysed and compared.

1. Introduction

Designing turbines for space engine application is always a compromise between turbine performance, engine performance and size. For instance, in open cycle, turbine flowrate should be as low as possible but a minimum is still needed to obtain the target shaft power.
During the past years, as part of the CNES/DLR cooperation in the frame of Turbomachinery analysis, distinct design methods and its intrinsic characteristics were compared using common boundary conditions.
In this frame, this article aims at analysing the different design methodology for a supersonic partial admission impulse turbine for LRE as well as the impact of partial admission choices on the stator performance geometry but also on the rotor, as the optimal rotor geometry is strongly linked to the number of open stator nozzles, where both airfoil and axisymmetric nozzles were analysed and compared.
Thus, the first part is dedicated to the design of the first stator where the choice of using partial admission is made, impacting the rest of the turbine. Starting from the same technical specifications, two designs methods are used and compared, axisymmetric nozzles and airfoil blades. The former being simpler and cheaper whereas the latter is more common but can be more complex and is often more expensive in the manufacture process point of view. The obtained performance were analysed and compared at the design point as well as in the off-design conditions.
Once the stator is designed, two options were studied for the rotor design. The first one consists in using existing rotor blade geometry while the second one consists in designing a new rotor each time the stator geometry changes using Pritchard model [1]. The goal of this second part is to emphasize that rotor design is also a major part while designing a partial admission turbine and should not be considered as trivial with regards to stator design.

2. Turbine technical specifications

In order to be able to give some precise results and data, arbitrary turbine specification has been chosen. There are not related to any French or German studies or engine and are used as an example to showcase the design methodologies used in the next sections. Thus, to be able to obtain supersonic turbines with partial admission, a fictive 50kN oxygen/methane open cycle engine has been calculated and the following fuel turbine specification has been obtained, as shown in the Table *1*.

DOI: 10.13009/EUCASS2022-4928

Table 1 : Fuel turbine specifications and constraints

Parameters	Value	Unit
Target power	200 kW	kW
Inlet pressure	72 bar	bar
Inlet temperature	500 K	K
Pressure ratio	10	---

On top of these requirements, constraints have been considered using space engine common practices where every component has to be as simple and light as possible (Table 2).

Table 2 : Constrain list adopted for the design

Constraints
Impulse turbine
One stage
1 mm rotor radial gap
Minimum radius
Open rotor

3. Stator design practices

Stators profiling for supersonic impulse turbines can be divided in two main categories: axisymmetric nozzles, where simple convergent divergent nozzle is used to accelerate the injected driven fluid to supersonic speed and airfoil shaped blades, where the aerodynamic geometry is characterized by an extruded airfoil section. The main characteristics of those stators are shown at Figure 1.

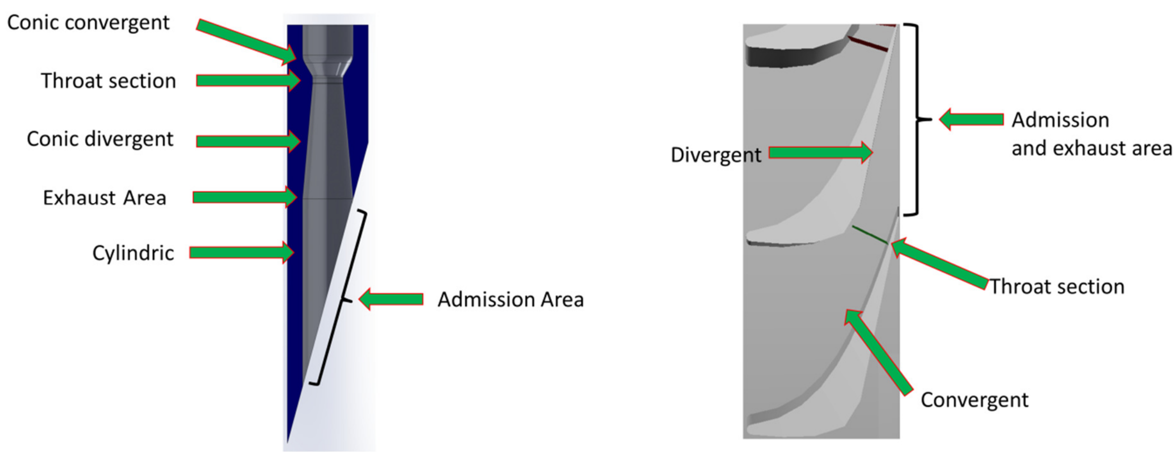


Figure 1: Comparison between axisymmetric nozzles and Airfoil stator

DOI: 10.13009/EUCASS2022-4928

The advantages of each system can be described in a comparison between simplicity on manufacturability methods and performance optimization by the other side. Axisymmetric stator nozzles are often used in Russian design, based on Ovsyannikov, Deych and Tchelikov methodology[2], [3], [6], while airfoil are common design practices for USA engines[4], [5].
Despite different resulting geometries, the comparison between losses in both geometries has shown minimum performance deviation and a possibility of interchangeability for similar operation conditions assuming adequate stator design [10].

3.1. Axisymmetric nozzles

3.1.1. Design

The use of axisymmetric nozzles for stator has the advantage of simplification in the design process and has been used as standard option for open cycle engines from Deych Tchelikov and Ovsyannikov methodologies, where performance maps were created in order to provide an initial glance of its performance.
The design procedure for axisymmetric nozzles consist in the estimation of the required exhaust Mach number in order to evaluate the friction losses as well as the losses associated to shock structure and flow divergence for conic exhaust geometry. It is defined according to the available pressure ratio defined in the system specification, as shown in the equation (1).

$$M_1 = \sqrt{\left(\frac{2}{\gamma}\right) \cdot \left(\frac{\gamma}{\gamma - 1}\right) \cdot R \cdot \left(\frac{T_{00}}{T_1}\right) \cdot \left[1 - \left(\frac{P_1}{P_{00}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right]} \tag{1}$$

Moreover, in order to achieve the predefined exhaust Mach number, the pressure is expanded according to the area ratio between critical section and exhaust area as shown in the equation (2).

$$\frac{A_{cr}}{A_e} = \left(\frac{\gamma + 1}{2}\right)^{\left(\frac{1}{\gamma-1}\right)} \cdot \left(\frac{P_1}{P_{00}}\right)^{\frac{1}{\gamma}} \cdot \sqrt{\left(\frac{\gamma + 1}{\gamma - 1}\right) \cdot \left(1 - \left(\frac{P_1}{P_{00}}\right)^{\frac{\gamma-1}{\gamma}}\right)} \tag{2}$$

The critical area is therefore defined according to the equation (3).

$$A_{cr} = \frac{\dot{m} \cdot \sqrt{R \cdot T_{00}}}{P_{00} \cdot \sqrt{\gamma \cdot \left(\frac{2}{\gamma + 1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}}} \tag{3}$$

In order to connect the divergent section of the nozzle with the exhaust plane, a scarfed cylindrical section is used with the same angle as the defined as stator exhaust flow angle α_1 as shown at Figure 2. However, in case of angles below 20°, is recommended to adjust it according to the boundary layer growth as well as possible flow disturbance due to shock structure impinging in the cylindrical channel.

DOI: 10.13009/EUCASS2022-4928

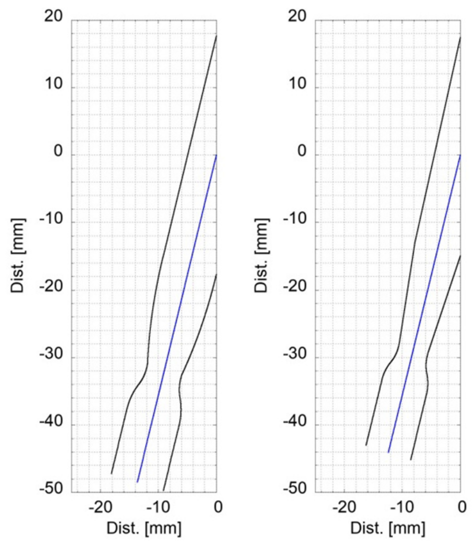


Figure 2: Two examples of axisymmetric nozzles. MOC divergent (Left) and conical divergent (Right)

For the subsonic part of the stator, the cylindrical section as well as convergent are calculated in order to have a low local velocity in order to minimize the friction losses.

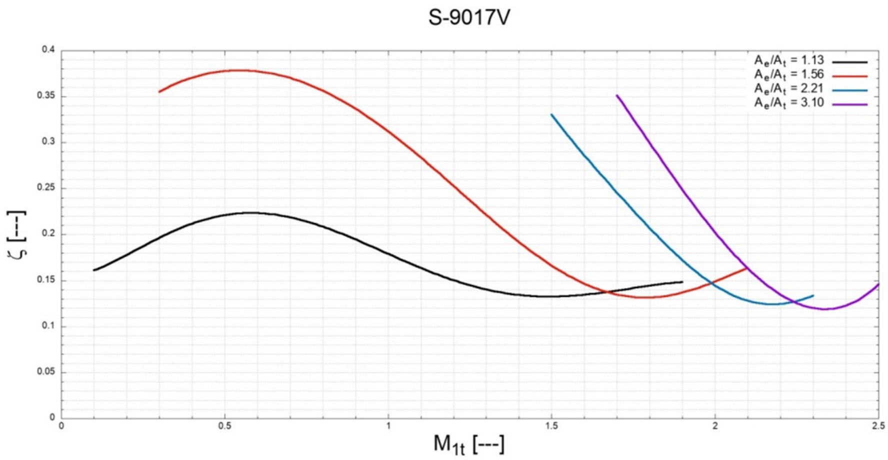


Figure 3: Loss coefficient for the axisymmetric nozzle design S9017V [2]

Furthermore, the final loss coefficient ζ can be estimated according to the required exhaust Mach number, Area ratio and exhaust flow angle α_1, as shown in the Figure 3.

Table 3: Result for the Stator design

Parameters	**Value**	**Unit**
Throat diameter	3,6	**mm**
Exhaust diameter	5,3	**mm**
Number of Nozzles	7	**---**
Stator exit angle	74,40	**deg**

DOI: 10.13009/EUCASS2022-4928

The losses between admission degree and disk friction and volumetric (leakage basis) can be used to estimate the optimum admission degree[9] as shown in the Figure 4.

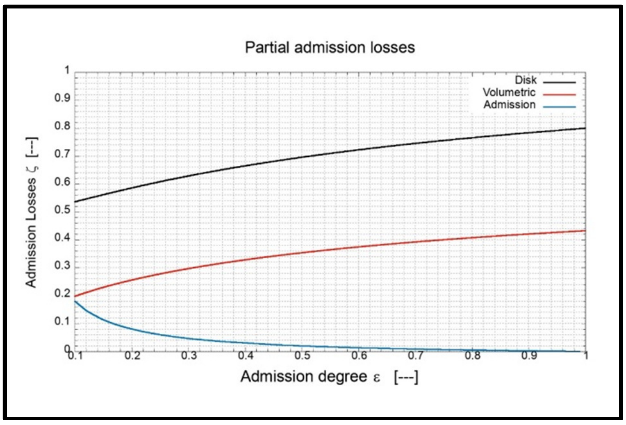


Figure 4: Partial admission losses in function

Finally, the admission degree also contributes to estimate the blade height ratio and according to the radial gap constrain of Table 2, the ratio between radial gap and blade height, as shown in the Figure 5.

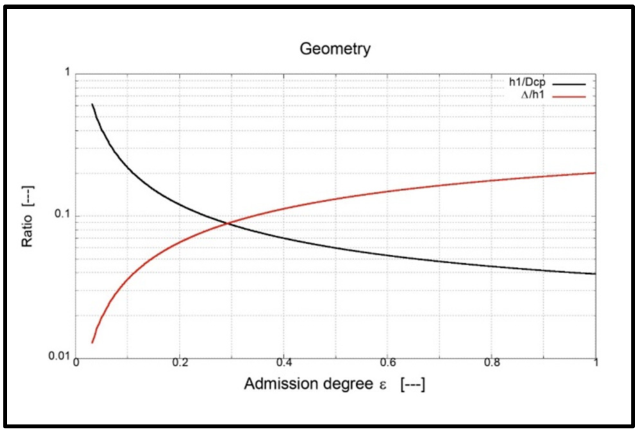


Figure 5: Ovsyannikov's design recommendations

3.2. Airfoil

3.2.1. Design

The first step when starting from an airfoil stator design is to select the flow coefficient and the rotational speed. Using the specifications and constraints from Table 1, a first analysis in flow coefficient is done starting from a standard 0,6. The best compromise is found for a coefficient around 0,2. As the flow rate is quite low considering the target power of the turbine, this was expected. Using 0,2 as a flow coefficient, a study in rotational speed is done as the next step.

DOI: 10.13009/EUCASS2022-4928

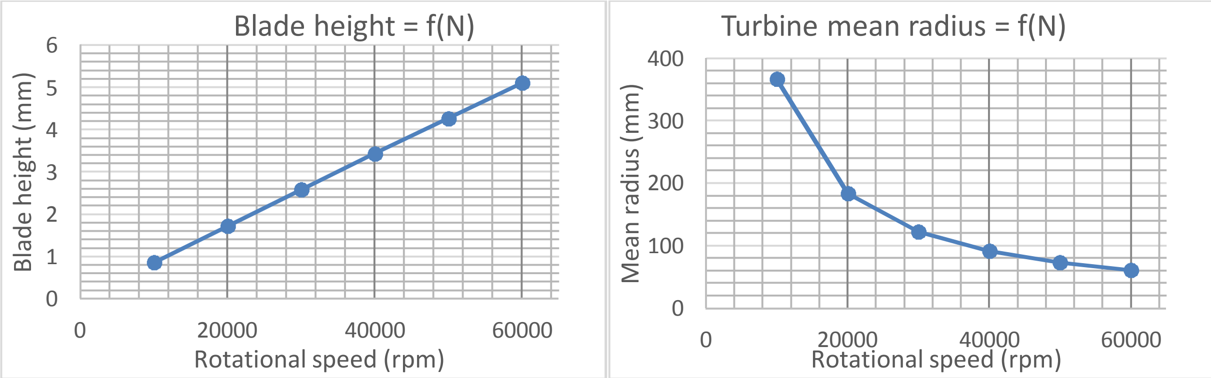


Figure 6: Blade height and mean radius as a function of the rotational speed using data from Table 1

The obtained blade height shows that partial admission could be a major addition to this turbine as blade height is quite low. In order to determine rotational speed, losses are studied in the machine Figure 7.
The losses analysis shows a change of slope around 40k rpm for the stator losses. Combining with the acceptable radius obtained around this speed, this rotational speed was chosen as a good compromise. Moreover, when reaching high speed rotational speed, the final rotational speed is a compromise with rotordynamics studies. Thus, as this study is turbine only, it is not wise to use higher rotational speed.

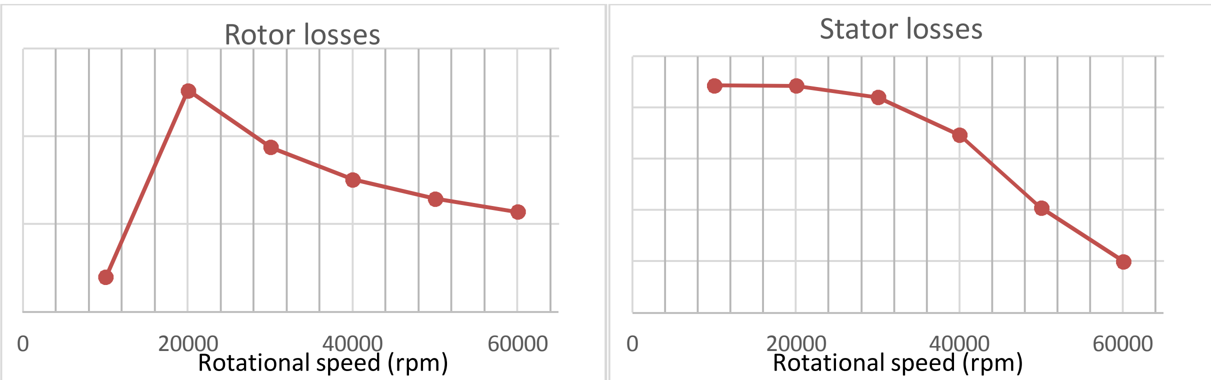
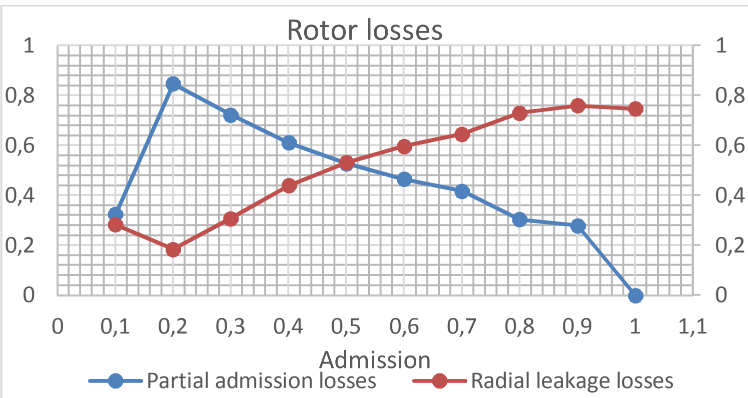


Figure 7 – Rotor and stator losses as a function of the rotational speed

The last step before the final optimization is to determine the optimal partial admission degree. To do so, a deeper losses study is done for the stator and the rotor as a function of the partial admission degree.
Considering the stator, the lower the admission degree, the lower the losses are so data from the stator cannot be used to determine partial admission degree. As for the rotor, we can determine the optimal admission degree by comparing losses due to the radial leakage to the losses created by the use of a partial admissions stator Figure 8.



DOI: 10.13009/EUCASS2022-4928

Figure 8: Rotor losses due to partial admission and radial leakage

Thus, an admission degree of 55% is chosen a starting point.

3.2.2. Stator geometry

The choices explained in section 3.2.1 lead to the following stator geometry. See Table 4 for details and Figure 9 for the corresponding blade profile.

Table 4: Result for the Stator design

Parameters	Value	Unit
Stator blade height	7,059	**mm**
Stator meridional radius	79,6	**mm**
Number of Blades	32	**---**
Stator exit angle	84,9	**deg**

As result from the calculation of the stator geometry parameters, presented at Table 4, is possible to generate the stator blade profile, as shown at Figure 9, according to the methodology as Pritchard as will be discussed in the section 4.2.

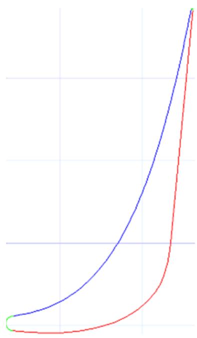


Figure 9: Stator blade profile

4. Rotor

4.1. Existing blade profile

As part of the design, the required meridional diameter as well as the spouting velocity is defined, according to the available adiabatic specific work.

$$C_{ad} = \sqrt{2 \cdot \left(\frac{\gamma}{\gamma - 1}\right) \cdot R \cdot T_{00} \cdot \left[1 - \left(\frac{P_1}{P_{00}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right]} \tag{4}$$

The increase of rotation speed will result in increase of the meridional diameter and by consequence, will require lower height for the possible defined rotor blades. According to Deych[5] and Ovsyannikov[3], some recommendations are suggested, as ratio between blade height and rotor meridional diameter, as well as the ratio between blade height and radial gap, in case of unshrouded design. Moreover, due to axisymmetric nature of the stator, the number of nozzles used is discrete in function of the total area, limiting the range of blade height.
Considering the pressure ratio $\frac{P_1}{P_{00}}$ of 10, the stator will require an area expansion ratio of 2,15 which is consistent with an exhaust Mach number of 1,92.

DOI: 10.13009/EUCASS2022-4928

Due to the rotation speed, the velocity ratio of around 0,387 is quite consistent with neat to peak efficiency for full impulse supersonic turbine with partial admission. [7] Therefore, the resulting relative inlet Mach number is approximately 1,23.
According to Deych [8], the blade profile options for supersonic inlet flow are listed in the Table 5. Between the options, the R2118V show the highest relative inlet Mach number range with minimum losses, resulting in an affordable choice for turbine blade operating at described operational conditions.

Table 5: Stator geometry from Catalogue [8]

Profile	α_{1eff}	M_{2t}
R2118V	18-20	1,30-1,90
R2522V	20-24	1,35-1,60
R2926V	23-27	1,35-1,60
R3330V	28-32	1,35-1,60
R3025V	23-27	1,35-1,70

Using the calculation method proposed by [2], [3], [5], we have the following parameters for the rotor design.

Table 6: Result for the Rotor design

Parameters	Value	Unit
Rotor blade height	8,0	mm
Rotor meridional radius	75	mm
Rotor exit angle	72	deg
η	0,564	---
U/Co	0,362	---

The resulting performance presented at Table 6, is result of the chosen blade R2118V from [8] and is shown in the Figure 10.

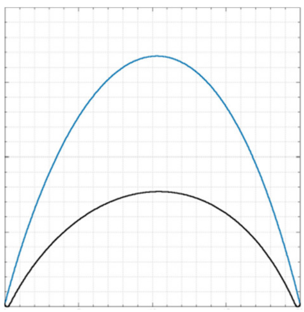


Figure 10: Rotor blade profile R2118V

4.2. Pritchard model

With use of commercial tool, capable of generate a CAD file from a 0D design, the blade options used allows to create a quick performance assessment and integrate the stator and rotor in the same design overview. Between the

DOI: 10.13009/EUCASS2022-4928

blade generation options available is possible to mention Pritchard [1], Constant passage, NACA profiling and Bezier[11].
With less degree of freedom in comparison with the stator, the rotor design considered a constant blade height and symmetric rotor. In house adjustments were adopted in order to adapt the rotor design methodology to fulfil the requirement of pure impulse symmetric design profile.
The model is based on Pritchard design methodology [1], [11] where at least 25 airfoil parameters can be used for calculation of blade geometry. However, the goal for the model was reduce the blade parameter to 11 in order to provide simplification of design without compromise the performance optimization. The result was an adjusted methodology capable to provide the design parameters for a partial admission symmetric rotor blading profile at constant height at supersonic flow conditions. The resulting design of this improved methodology is presented at Table 7.

Table 7 : Result for the Rotor calculation

Parameters	**Value**	**Unit**
Rotor blade height	9,5	**mm**
Rotor meridional radius	79,6	**mm**
Rotor exit angle	81,0	**deg**
η	0,534	**---**
U/Co	0,336	**---**

The resulting performance presented at Table 7, allows the creation of the blade profiling as shown in the Figure 11

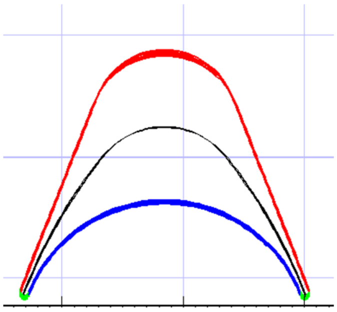


Figure 11: Rotor blade profile

5. Conclusion

The comparison between both models shown good agreement, as the input conditions resulted in similar rotor parameters and performance, with minor difference between efficiencies attributed to the design methodology and losses model calculation using distinct methods. Despite different stator conditions design and resulting geometry, the losses associated to this part shows to be minimum.
The overall efficiency difference of 3% can also be attributed to two major factors as the optimization methodology adopted by both models are intrinsic to each design methodology and the fluid properties is also responsible to contribute to the minimum deviation of performance, since the DLR uses real gas database for its calculation, while CNES tools adopted an extended perfect gas law during the time of the design methodology comparison. As result, both methodologies resulted in an agreement of approximately 0,766kg/s of mass flow in order to produce a resulting power of 200kW, achieving the requirements presented in the Table 1 while adopting the major design constrains of Table 2.
Furthermore, optimization produced a similar U/Co, which also resulted in rotor profile overall geometry with the same turning angle magnitude as well as the rotor exit angle as shown in the results of Table 6 and Table 7.

DOI: 10.13009/EUCASS2022-4928

Acknowledgement

The authors would like to acknowledge the fruitful cooperation between CNES and DLR in the frame of turbomachinery analysis, allowing further investigating the design procedures and methodologies, as well as turbomachinery design practices based on in house tools. The authors would like to also thank all involved in this cooperation and all whom make this work together possible.

References

[1] Pritchard, LJ. "An Eleven Parameter Axial Turbine Airfoil Geometry Model." Proceedings of the ASME 1985 International Gas Turbine Conference and Exhibit. Volume 1: Aircraft Engine; Marine; Turbomachinery; Microturbines and Small Turbomachinery. Houston, Texas, USA. March 18–21, 1985. V001T03A058. ASME.

[2] Tschelikov, V. D.; Baykov, A. V.; Methodology of Turbine Calculation for Turbopump unit with use of computer. Moscow State Aviation Institute, 1981

[3] Ovsyannikov, B. V.; Borovskiy, B. I.; Theory and Calculation of Feed Units of Liquid Propellant Rocket Engines. Mechanical Engineering Publishing. 1986

[4] Huzel, D. K. ; Huang, D. H. ; Modern Engineering for Design of Liquid-Propellant Rocket Engines. American Institute of Aeronautics and Astronautics.

[5] Douglass, H. W.; *et al.* Liquid rocket engine turbines, National Aeronautics and Space Admninstration SP-8110, 1974

[6] Deych, M. E. Technics in Gas Dynamics. Energya, Moscow 1974

[7] Belyaev E. N., Chvanov V.K., Chervakov V.V., Mathematical modeling workflow liquid rocket engines. Moscow, 1999.

[8] Deych, M. Ye.; Phillipp, G. A.; Lazarev, L. Ya. Atlas of the Cascade Profiles of Axial-Flows Turbine. Moscow, 1965.

[9] Hahn, R. H. S.; Traudt, T.; Deeken, J.; Oschwald, M.; Schlechtriem, S.; Negishi, H. LUMEN Turbopump – Preliminary Design of Supersonic Turbine. ISTS. 2019.

[10] Hahn, R. H. S.; Traudt, T.; Deeken, J.; Oschwald, M.; Schlechtriem, S. Design Methodology and PerformanceImprovement of Supersonic Impulse Turbine: Stator Optimization. Space Propulsion Conference, 2022

[11] Dubitsky, O.; Wiedermann, A.; Nakano, T.; Perera, J. The Reduced Order Through-Flow Modeling of Axial Turbomachinery. International Gas Turbine Congress, Tokyo, 2003