A Preliminary Design Study for an Expander LOX Turbopump

Chris Maeding, Louis Souverein, Dieter Hummel, Stefan Koenigbauer, Adalbert Wagner and Jan Alting
Airbus DS GmbH, 81633 Munich, Germany
Corresponding author: chris.maeding@airbus.com

Abstract

In the recent years Airbus DS GmbH started a turbopump initiative to build-up fundamental capabilities in analyzing and designing turbomachinery within a national funded program "TARES". Turbomachinery are widely used in different rocket propulsion systems and include such parts as pumps and turbines. Turbines are used for generating power required by pumps in order to feed the propellants to the thrust chamber.
The paper is dedicated to present an overview about currently ongoing conceptual design activities of turbomachinery covering the main design phases like:

- TPA (**T**urbo**P**ump **A**ssembly) layout trade-off,
- rotational speed selection with respect to efficiency and cavitation ,
- flow path design techniques including blade profiling
- CAD design work
- preliminary structural analyses.

This paper presents the main outcome applying the established design logic to a LOX-turbomachinery. The component has been designed based on a dedicated specification for an expander cycle type engine. This includes a LOX pump unit comprising inducer and impeller as well as a subsonic single stage reaction turbine. For the turbine drive gaseous hydrogen heated within the thrust chamber cooling circuit is used.
Within this paper an overview about the main result of pump and turbine sizing, profiling, performance estimation as well as structural aspects will be addressed.

1. Introduction

Based on a proposed 120kN upper stage LOX-LH2 expander cycle pump specification and a corresponding trade-off a LOX-turbopump unit was designed. Hydrodynamic characteristics as well as the cavitation behavior were evaluated by empirical and CFD methods. The several design steps were anchored using in-house and public data. Several empirical methods within the design process were analyzed, discussed and used in order to create an initial pump design for further design optimization.
The matching subsonic turbine design is based on a preselected axial stage configuration with the ambition of simplicity at a sufficiently high overall efficiency. After defining the main flow path different approaches for airfoil definition were investigated, providing a basis design for further optimization using CFD as well. For performance prediction beside empirical methods CFD was used.
Based on the main data obtained by a first design loop, a 3D model of the overall turbomachinery was established, allowing estimating several structural aspects like Eigen frequencies, critical rotational speed and shaft bending dependent on the used bearings and seals. In a next phase the 3D model will be also used to investigate and estimate the occurring radial and axial loads during operation for further design optimization.

2. Company TPA know-how and heritage

Within Airbus DS Ottobrunn, several activities have been undertaken in the past in the field of turbopump design and testing. Noteworthy in this respect is the P111 staged combustion cycle rocket engine [1] that was developed and tested in Ottobrunn in the period from 1956 to 1968. Its single shaft turbopump comprises single stage radial liquid oxygen (LOX) and kerosene pumps and a single stage axial turbine driven by an oxygen-rich preburner, see Figure 1. Over 200 tests have been performed with this 50kN engine hardware.
During the early 1970s, a two stage high pressure LH2 pump [2] was developed and tested and at the same time, LOX "H20" pump developments were initiated, both for application in a 200kN staged combustion engine. All development work was done in the frame of the Europa III program.
In the late 90's Airbus DS (Ottobrunn) - together with Rocketdyne - developed and tested the RS-72 (Pathfinder), a storable turbopump-fed engine with a thrust range of 46-56 kN, see Figure 2 [3]. In the frame of these development tests additional run-in engine tests were performed in Lampoldshausen in Germany using a Russian turbopump [4]. Other heritage includes the LOX Vulcain 1 and Vulcain 2 turbopump tests that were performed under contract of AVIO till 2000 on the P59 test facility in Ottobrunn.

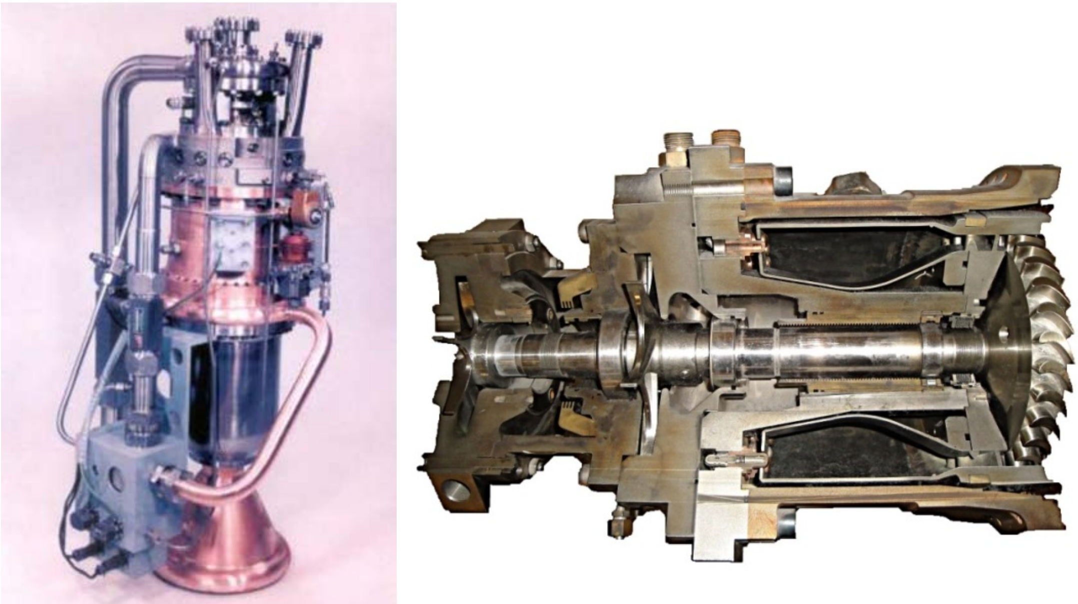


Figure 1: P111 engine and turbopump assembly with oxygen rich preburner [1]

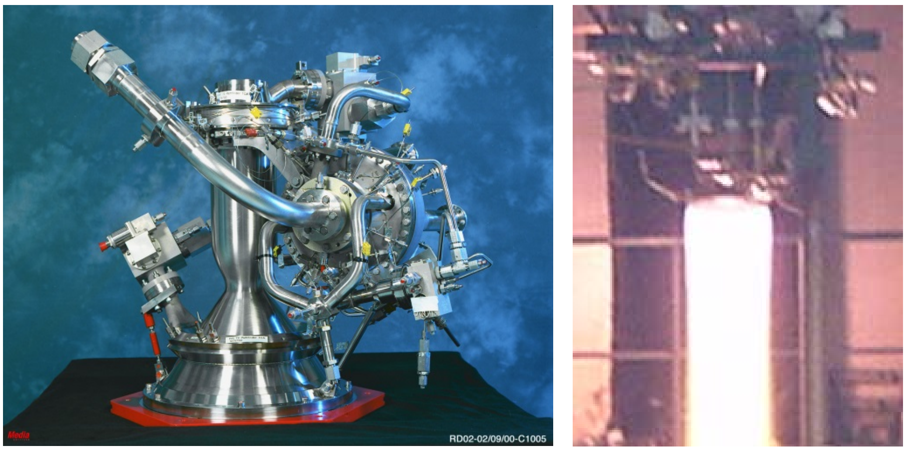


Figure 2: PW-Rocketdyne - Astrium ST Turbopump Demonstrator Engine RS-72 (Pathfinder) [4]

3. Design of a 120kN LOX TPA

Within the national funded program "TARES" a LOX turbopump unit conceptual design was established for a LOX/LH2 expander cycle having a vacuum thrust level of about 120kN (Figure 3). Due to the different physical properties of hydrogen and oxygen also with respect to the different cavitation behavior and for better overall performance optimization two standalone turbopump units were chosen for combustion chamber propellant supply. The general flow schematic of this expander cycle is presented in the figure below. Thereby, the LH2- and LOX-turbopumps are arranged in series. Each turbopump is equipped with an additional bypass pipe-line for performance adjustment and engine regulation. For this LOX-turbopump design study the following operational parameters at reference point were used:

LOX pump

- nominal flow rate (at the outlet)	22.8	kg/s
- total pressure at the pump inlet	3.0	bar
- pump inlet temperature	91.5	K
- pump outlet total pressure	81.8	bar

GH2 turbine

- mass flow rate (incl. LOX TP bypass)	2.67	kg/s
- min required bypass mass flow rate	$\geq$20	%
- total pressure at the inlet	89.0	bar
- inlet temperature	218	K
- static pressure at the outlet	75.0	bar

The dedicated turbopump design shall meet the following criteria within the operational envelope:

- maximum turbine and pump efficiency,
- sufficient cavitation margin,
- sufficient margin in terms of rotor critical speed,
- minimum TPA mass,
- compact design with minimum momentum of inertia.

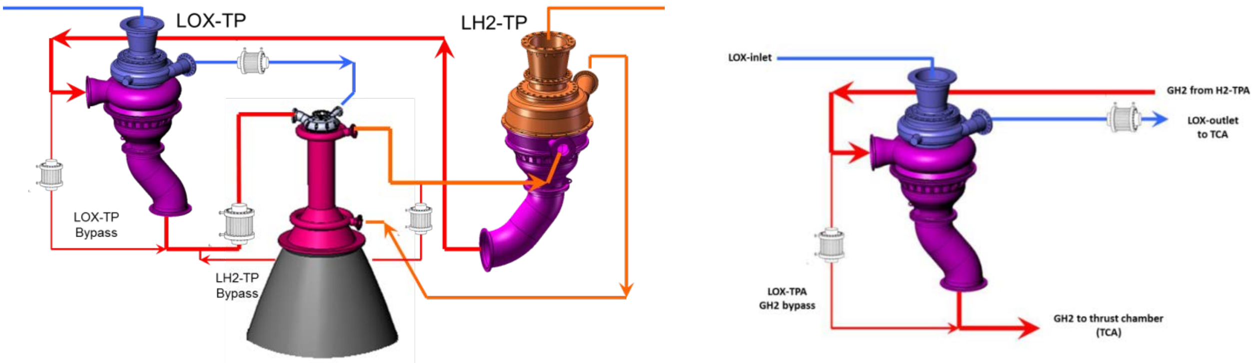


Figure 3: Expander cycle with two separate TPAs arranged in series

3.1 LOX-TPA conceptual design

In order to generate a target-oriented processing (workflow) of the several main issues, a general design logic as depicted in Figure 4 was established, taking into account two different pump configurations. These configurations as depicted in Figure 5 were selected by a separately performed trade-off. All preselected pump layouts reflect the state-of the art design used in cryogenic and non-cryogenic rocket engines.

Prior to starting this design work, a detailed literature survey covering [5], [6], [7], [8], as well as in-house experience, was performed. This survey was also addressed to carry out a first validation and to anchor the chosen design software by redesigning of already existing units as well.

Based on the survey results a quantification of the principle turbopump characteristics (main inlet geometry, number of blades, rotational speed etc.) for the further conceptual design process was done by applying adequate similarities.

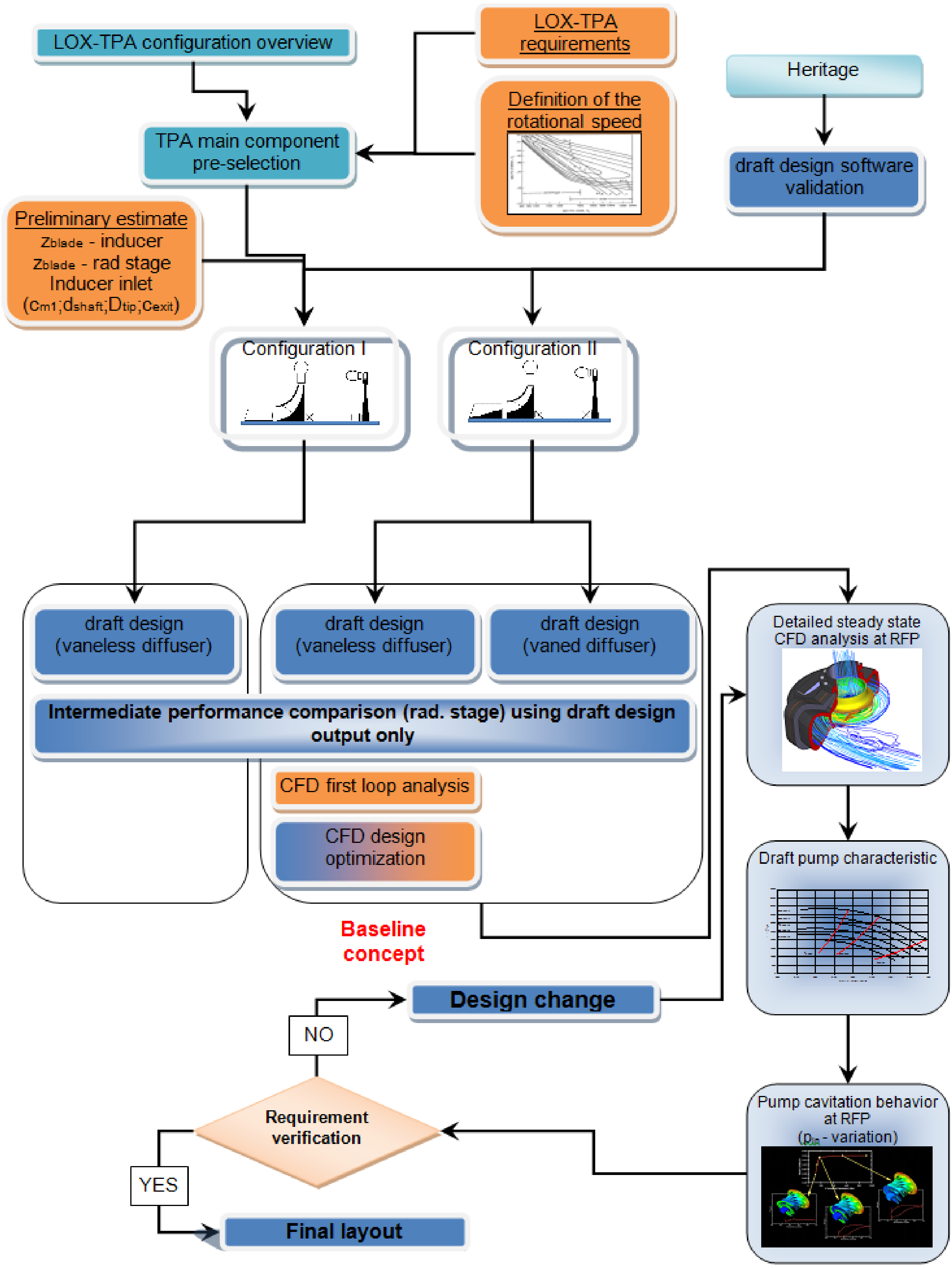
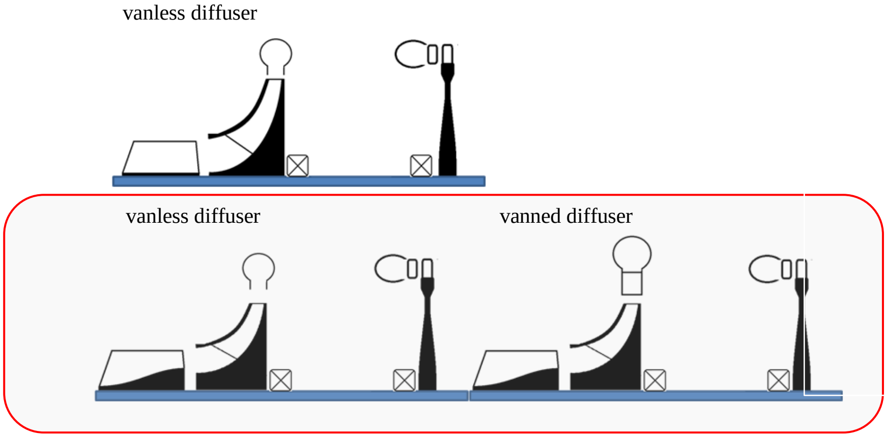


Figure 4: Pump design workflow



- radial pump stage with low head inducer
- radial pump stage with high head inducer (**baseline**)

Figure 5: Preselected configurations for dimensioning

For the selection of rotational speed at the reference conditions the following criteria were considered:

- sufficient cavitation margin (NPSH) in the whole operational domain with respect to the preselected pump design (analytical justification),
- maximum pump and turbine efficiency level,
- sufficient margin against critical rotational speeds.

In order to match these requirements different scaling approaches were applied using similar already existing pumps for scaling [5], [6], [7], [8].

One approach is based on the rotational speed similarity via the given volume flowrates and pressure heads adjusted by a corresponding scaling factor (scaling via the specific speed **Ns**). Substituting the scaling factor by the given two dependencies the unknown rotational speed was determined.

$$N_s = n \cdot \frac{\sqrt{\dot{Q}}}{H^{\frac{3}{4}}} = const \Rightarrow \quad n_{LoxTPU} = n_{Base} \cdot \sqrt{\frac{\dot{Q}_{Base}}{\dot{Q}_{LoxTPU}}} \cdot \left(\frac{H_{LoxTPU}}{H_{Base}}\right)^{\frac{3}{4}}$$

However this approach does not take into account the different inlet conditions in terms of pressure level. Therefore the suction specific speed **Nss** was also used to assess the rotational speed.

$$N_{SS} = \frac{n \cdot \sqrt{\dot{Q}}}{NPSH^{\frac{3}{4}}} \longrightarrow NPSH = \frac{p_{total} - p_{vapor}}{\rho} - H_{loss} \longrightarrow H_{loss} \rightarrow \text{assumed to be equal for both pumps}$$

$$n_{LoxTPA} = n_{Base} \cdot \sqrt{\frac{\dot{Q}_{Base}}{\dot{Q}_{LoxTPU}}} \cdot \left[\frac{NPSH_{LoxTPU}}{NPSH_{Base}}\right]^{\frac{3}{4}}$$

$$n_{Base};\ \dot{Q}_{Base};\ NPSH_{Base} \quad \rightarrow \text{values of the base configuration used for scaling}$$

Another approach presents the direct use of the Ns-Ds design-point performance diagram as presented in Figure 6. Comparing the results of the different approaches, covering a range from $\mathbf{n_{lower\ value}}$=22000rpm up to $\mathbf{n_{upper\ value}}$=27000rpm an average rotational speed value of $\mathbf{n_{nominal}}$=25000rpm was chosen for further pump design work. This value was also chosen with respect to the turbine performance. A higher rotational speed tends to provide a higher turbine efficiency level. Taking into account the restricted operational envelope, a rotational speed of 25000 rpm provides acceptable pump inlet conditions with respect to cavitation independently on the used inducer configuration.

3.2 Pump design

The pump design was made to satisfy the nominal operating conditions. Typically the specific speed **Ns** and the specific diameter **Ds** are used for the pump type selection. Figure 6 shows the design-point performance diagram for various pumps in terms of **Ns** and **Ds**. Based on this commonly used diagram existing rocket pumps were analyzed and a first efficiency and sizing assessment was done.

The design parameters were compared to available / deduced values from existing LOX-turbopump hardware. With respect to the trade-off, different layouts were selected for the first design phase mainly marked by the different inducer designs.

Pre-designs were made for the whole pump section to obtain a rough idea of the expected size and performance of the machine. A more detailed discussion on dedicated baseline pump design is given in [9].

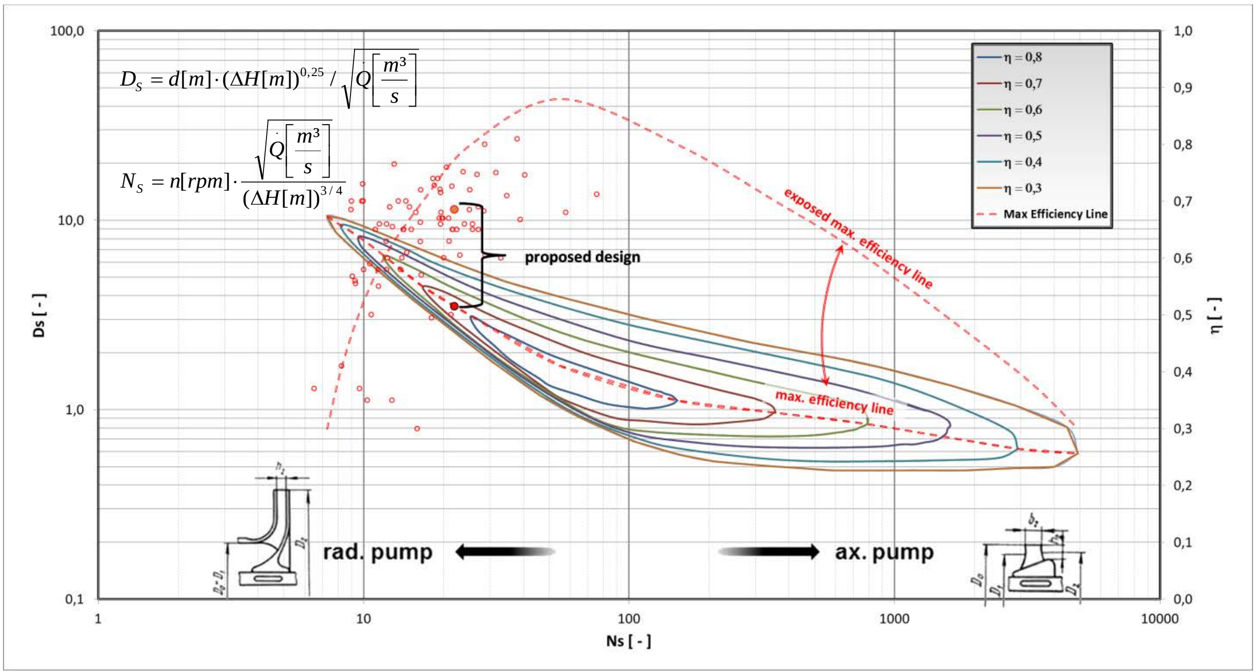


Figure 6: Ns-Ds design point performance diagram

The impeller stage suction characteristics prescribe the need for an inducer to provide sufficient inlet pressure to the radial stage. Based on this necessary inducer head a preliminary design was generated. In addition a parametric study was made with the main focus on the effect of the cant angle and leading edge sweep on the inducer performance, as well as the effect of the tip clearance (all of which were kept to zero so far in the baseline design). The effect of these parameters on the flow field and the performance was evaluated by means of CFD focusing on the selected baseline configuration.

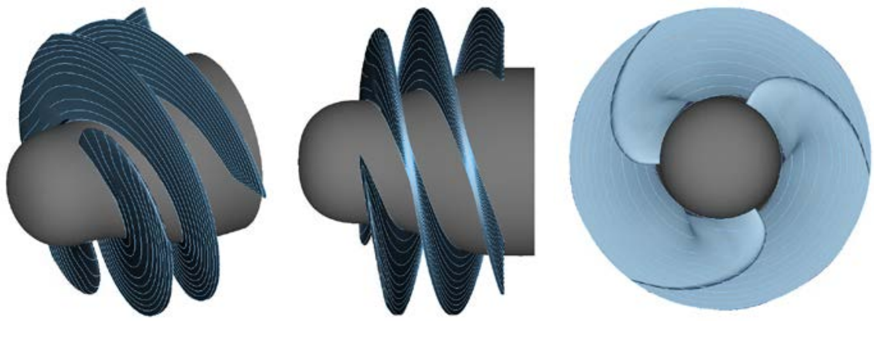
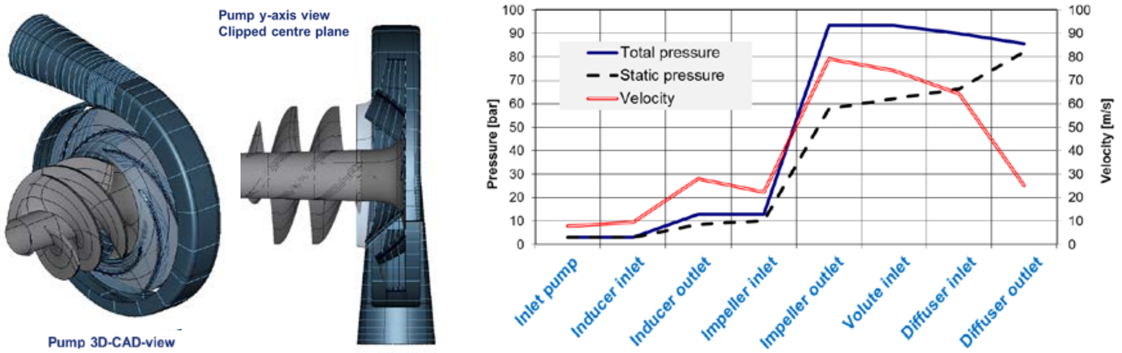
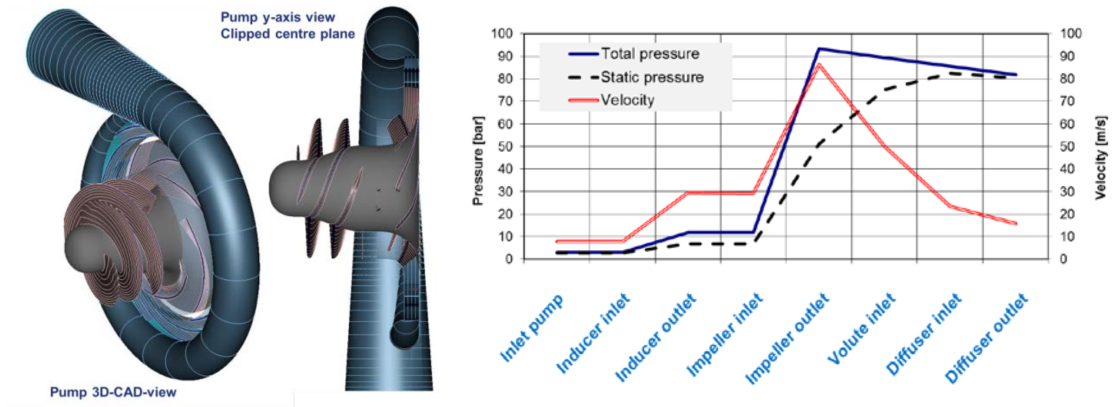


Figure 7: Final layout of the high head inducer of the baseline pump configuration

Based on the inducer total outlet pressure and the required overall nominal pressure head requirement for the turbopump, the impeller head has been determined. In addition, a casing efficiency value had to be assumed as a first estimate to account for losses in stator stages, diffusers and the volute. The impeller was designed to match the inducer configuration. The blade design was made in free-form 3D modes.
In the case of the baseline configuration, two diffuser configurations were generated based on the same meridian geometry: a vaneless variant and a vaned diffusor variant. The aim was to characterize the effect of vanes on the pump efficiency under otherwise identical conditions.
The draft layouts and the flow path parameter changes of the two different configurations are given in the figures below (Figure 8). At first instance, all further optimization efforts are only applied to the baseline configuration equipped with a high head inducer due to company heritage.



Backup configuration with low head inducer



Baseline configuration with high head inducer
Figure 8: Draft pump design and flow path parameter evolution

3.3 Turbine design

A fundamental requirement in the design of a turbine is the efficient utilization of high-energy working fluid in the smallest obtainable configuration. The final turbine type and layout selection is influenced by several trade-off factors like: complexity, efficiency, weight, life etc. Normally all these factors are evaluated in conjunction with the overall turbo pump design as well as the complete engine. In this context only the efficiency and the complexity were used as the mostly driving parameters within the trade-off. Prior to starting with the design of the GH2 turbine, available data for instance of the P111 rocket engine turbine, were used to verify and anchor the design method including CFD calculations (Figure 9) [9]. The P111 stage combustion single stage axial turbine presents a full flow reaction turbine driven by an ox-rich gas having a temperature of about 1000K. The available documentation including test and design data as well as the still existing hardware was used as input for a redesign and to generate a 3D model for CFD computation.

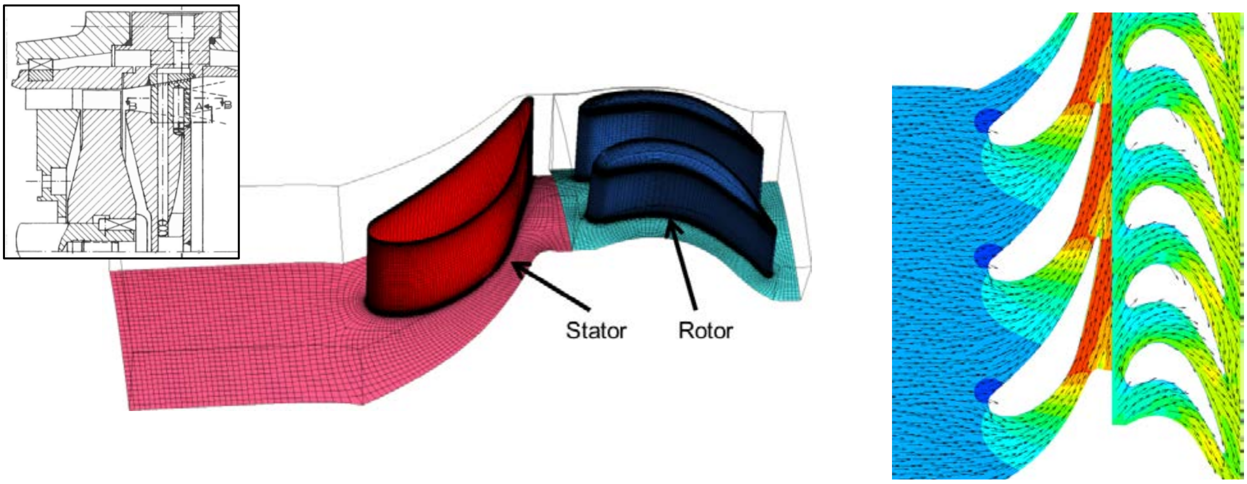


Figure 9: P111 CFD turbine analysis

For preliminary turbine investigations and trade-off among several turbine candidates the efficiency versus the isentropic velocity ratio can be used. The isentropic velocity ratio **u/c** (pitchline velocity versus theoretical spouting velocity) determines the range of efficiency in which the new turbine operates. This velocity ratio can be used to illustrate and investigate the peak efficiency behavior of single and multi- stage configurations as well as reacting staging. That means these curves serve to compare different turbine layouts based on certain initial estimates. With respect to the dedicated application the pressure ratio as well as the available energy were kept constant for staging investigation. In order to perform such an investigation, three different staging types were chosen keeping the loss coefficient constant within the stator and rotor grids. For these configurations different reaction degrees as well as different first stage stator outlet angles were considered. Taking into account the low velocity ratio **u/c** the maximum reaction degree ρ for staging analysis was fixed to 0.3. Impulse staging is usually used for turbines with a velocity ratio below 0.35. These turbines are usually characterized by a high pressure ratio linked to a sonic or supersonic flow. Reaction staging is marked by a significant lower pressure ratio operating at a velocity ratio above 0.4…0.45.
The efficiencies used for further analysis are quoted on a total to static pressure basis. The initial parameters used for turbine staging investigation are listed in the table below (Table 1). Taking into account the low inlet temperature and the moderate available pressure change through the turbine a frozen isentropic gas composition was chosen to determine the velocity ratio. In order to determine the circumferential speed an average turbine diameter of comparable size as the main dimension of the pump unit was selected. The result of the efficiency estimation within a velocity ratio range up to 0.9 is depicted in Figure 11 below.

Value	REF	Unit
Power require.	236	kW
Inlet pressure	89.0	Bar
Inlet temp.	218	K
Mass flow	2.67	kg/s
Bypass	≥20	%
Mass flow (eff.)	2.14	kg/s
Outlet pressure	75.0	bar

Table 1: Turbine main OP data

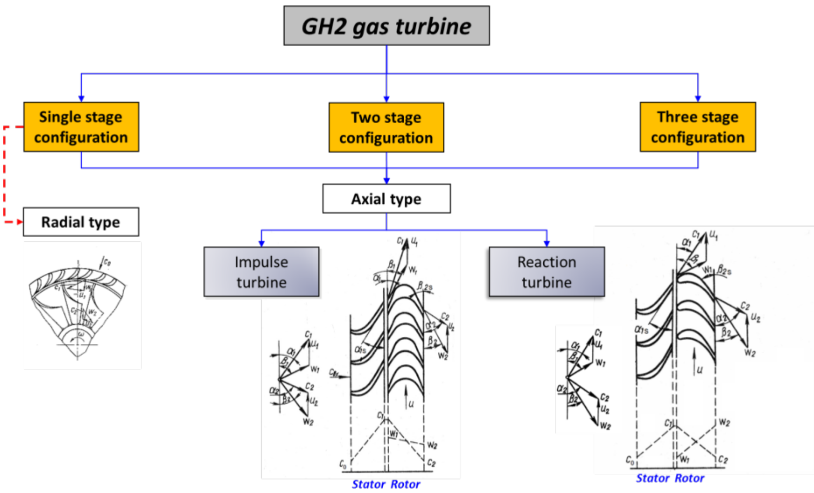


Figure 10: Turbine type trade-off

The number of stages in a new turbine depends on the available working fluid energy, efficiency and weight. Since the pressure ratio, inlet temperature and mass flow at reference point are fixed the efficiency level is affected by

varying the diameter, flow angle and the number of stages. However the stage number has a huge impact on the reachable maximum efficiency level and its location with respect to the velocity ratio.
Analyzing one, two and three stage turbine configurations and focusing mainly on the complexity of the three different designs a single stage configuration, having a reaction degree not greater than 0.15, was chosen as a baseline for further design work (Figure 10 and Figure 11), due to the simplicity of its design. A single-stage turbine system has a significantly reduced number of elements to be designed and manufactured, increasing hereby the reliability of the overall system. However this approach leads to some reservations regarding the achievable efficiency. In other words, such a design presents a compromise between efficiency and design complexity.
The impact of the stator outlet angle as well as stage reaction degree in the case of a single stage configuration at nominal operational velocity ratio **u/c** results in a efficiency scattering. The possible efficiency scattering is marked by a light blue bar in Figure 11.

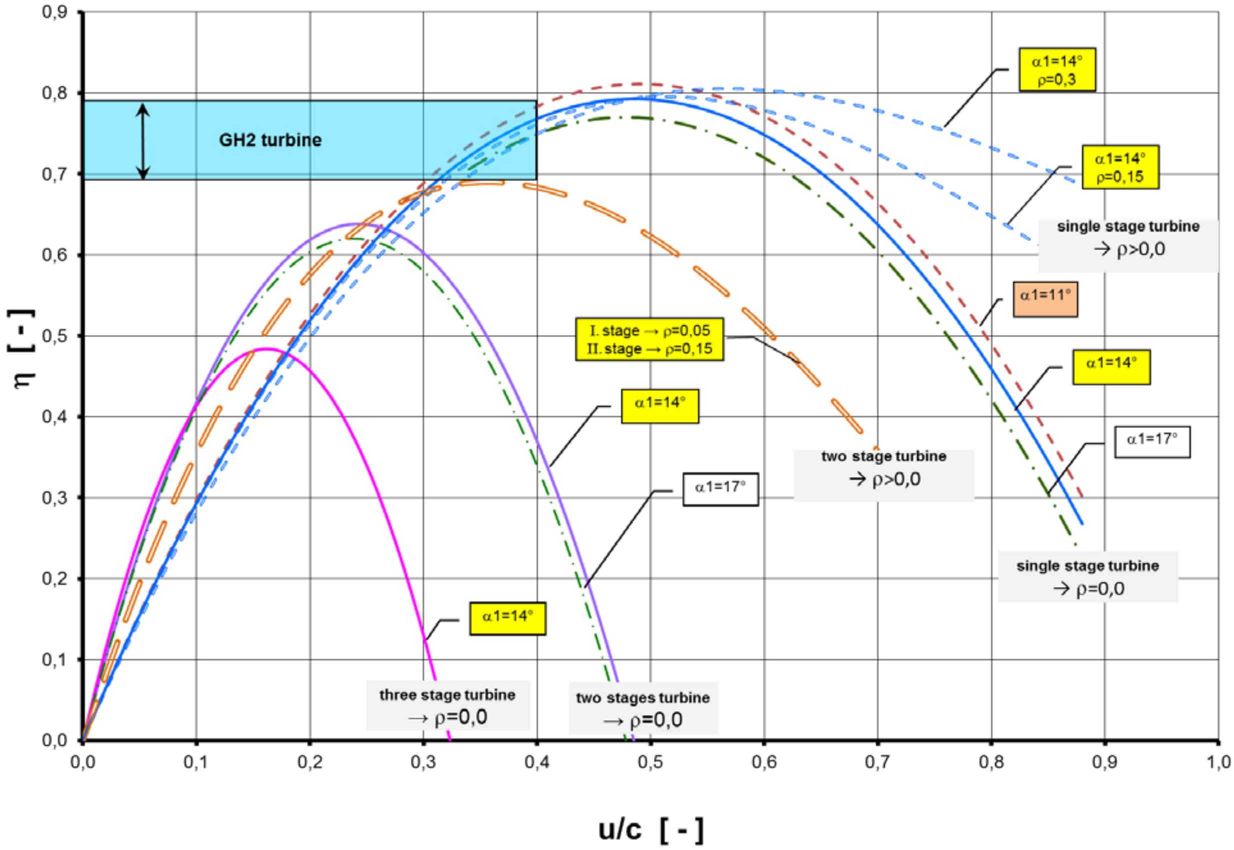


Figure 11: Turbine efficiency assessment for different staging

In order to establish a corresponding turbine design the same approach as already described for the pump unit was used. Taking into account the fixed initial values and a preselected middle turbine inlet diameter (also with respect to the maximum pump diameter) the gas path expansion was adjusted using in the first loop perspective loss coefficients. The middle turbine diameter was also selected with respect to blade height, avoiding to small values inducing additional losses especially in the rotating section. Performing iterative gas path calculations an initial draft turbine design is developed by changing the corresponding design parameters. To minimize the exit losses a minimized exit velocity with a vector close to an axial direction is required. Based on this initial design the distribution of the main parameters was checked prior to initiate the blade design for further CFD performance calculation and stage optimization. A diagram representative of the design point main parameters is given in Figure 12. The stage is marked by a low reaction degree and a non-axial exit flow affecting the efficiency level of the stage.

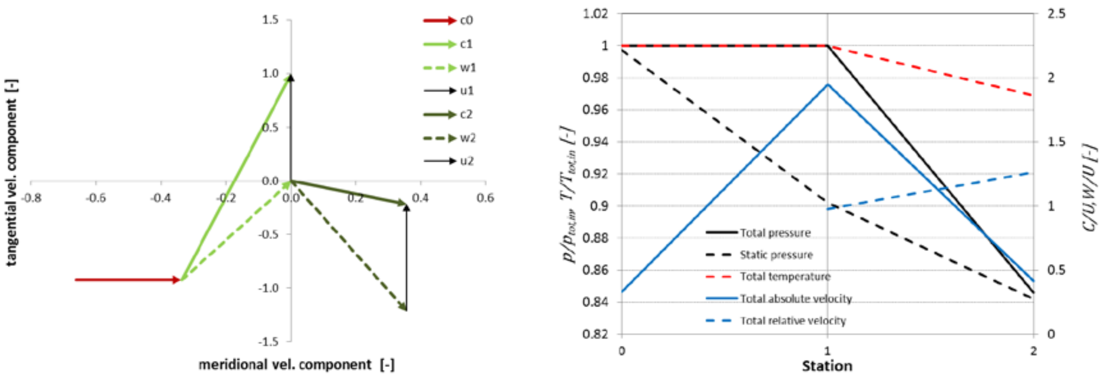


Figure 12: Turbine stage - parameter evolution

In the next step initial blade geometries for the stator and the rotor were generated (Figure 13). The geometry shall develop the required gas path vector relationships and shall pass the GH2 mass flow at reference operation conditions.

The turbine airfoil (blading) design treats the flow path evolution under the given boundary conditions at in- and outlet. For the blade profiling the following main parameters were used:

- in- and outlet angles
- turning angles
- axial width
- stagger (chord) angle
- throat opening.

Depending on the applied profiling method the missing parameters will be determined using experience and/or available statistic data. Some of these parameters are mainly driven by the flow conditions in terms of velocity. Since within the turbine stage only a moderate pressure ratio will be realized the blade design was based on a typical subsonic flow grid. The highest velocity is reached at the stator exit.

The airfoil is always designed to meet a specific set of operational conditions taking also into account manufacturing specialties. In general different approaches can be applied to generate a dedicated blade profile. All these approaches can be divided in three different groups:

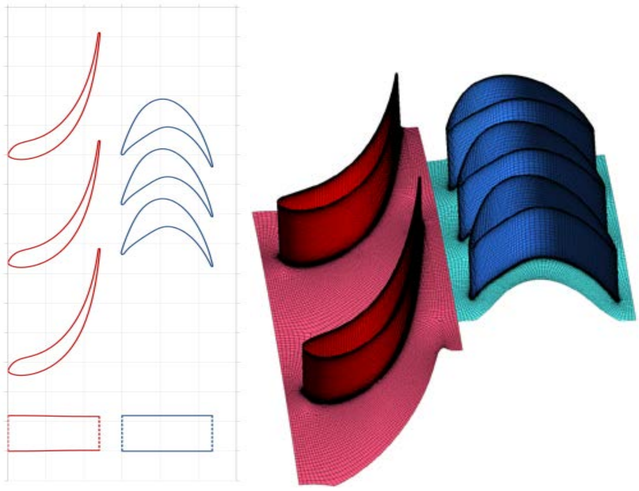


Figure 13: Turbine stage - airfoils

- graphical design
- analytical design
- design using standard airfoils

The application of standard airfoils (widely used approach) is based on the direct implementation of a dedicated airfoil in the dedicated stage design adjusting only the main proportions by scaling with respect to the requirements. Such standardized airfoils were generated for certain flow conditions taking also into account the stage reaction degree and especially the velocity level. Airfoils of this group can be also generated using standard "flat" profiles having a certain thickness distribution. In this case the airfoil will be matched to the predefined center line. For the dedicated turbine stage design two different methods were applied. In the first loop aerodynamic turbine airfoils were used, substituted in a second loop by an analytical design approach (Bezier based curves) which gives a higher freedom especially with respect to the forming process of the flow channel between two blades. This method seems to be more convenient and allows also a fast blade shape adaptation especially with respect to the CFD design optimization loop.

Using these data a complete turbine stage prototype was established used for further CFD analysis and flow path optimization. More detailed information on the dedicated turbine design and its optimization are given in [4].

3.4 Structural analysis

Structural analyses are addressed to determine the effects of all occurring loads on the structure and the corresponding components. That means these analyses are addressed to compute internal forces and stresses to verify the structural fitness. Within the first analyses static and dynamic computations using ANSYS software were done. Taking into account the experience in analyzing static loads occurring in thrust chambers and other space components special emphasis was put on rotor dynamic.
Rotor dynamic presents one of the most important points in the investigation of turbo pumps. In the frame of this work it was demonstrated that for all necessary dynamic simulations appropriate software tools are available.
In general the following inputs are always needed for structural investigations:

- geometry data (dimensions, wall thickness etc.)
- material data (properties of all used materials)
- characteristics of bearings (stiffness, damping)
- characteristics of sealing (stiffness, damping)
- eccentricity of rotor (distribution, absolute values)
- nominal rotor speed with centrifugal forces
- torsional moment (drive torque)
- pressures (distribution and absolute values)
- fluid velocities (distribution and absolute values)
- temperatures (distribution, absolute values, gradients)

For the designed rotor, as shown in Figure 14, a finite beam element model was created. Once all dimensional requirements for a structure have been defined, it becomes necessary to determine the loads the structure must support. In order to design an adequate structure, it is therefore necessary at first to specify the loads that act on it. This requires a detail treatment of all radial and axial loads occurring on pump and turbine side.
To perform an accurate analysis all information such as structural loads, geometry, support conditions, flow/leakage conditions and materials properties must be known. The results of such an analysis typically include support reactions, stresses and displacements. This information is then compared to criteria that indicate the conditions of failure. Advanced structural analysis may examine dynamic response, stability and non-linear behavior.
In a second continuing phase a detailed model of the whole turbopump will be generated in order to calculate all occurring axial and radial loads for adjusting the seals and to determine the bearing specifications. Until then a simplified rotor model consisting of the turbine, pump preselected seal package and bearing with certain stiffness for rotor dynamic analysis was used mainly to determine the margin with respect to critical speeds. The applied materials, influencing the inertia and stiffness of the rotor, were selected based on the results of the survey. Usually in order to show the response spectrum as a function of the oscillation the Campbell diagram is used. This diagram is used to evaluate the critical speed at different operating speed.

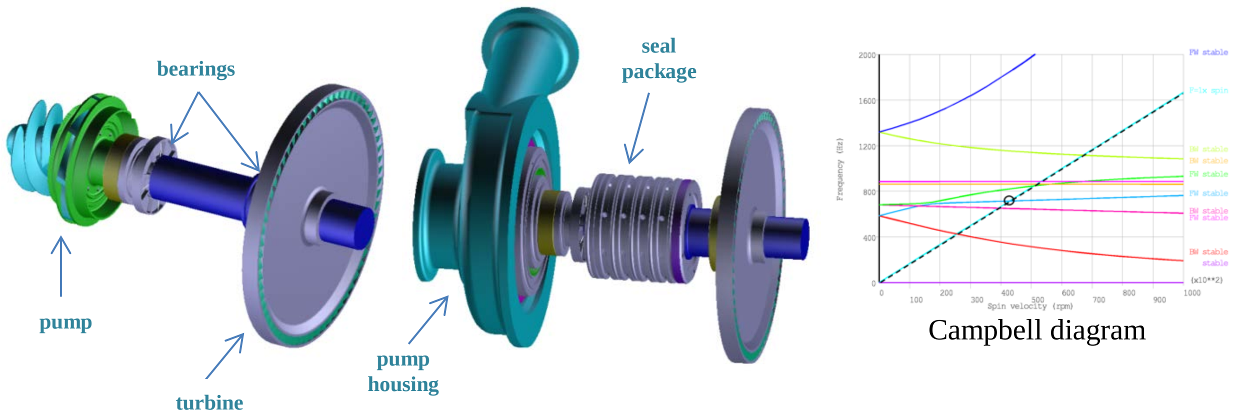


Figure 14: Rotor assembly for dynamic analysis

4. Further TPA fundamental investigation and test activities

As already mentioned above in the early 1970s a LOX turbopump "H20" [2] was developed and manufactured at Airbus DS in Ottobrunn. Especially the inducer unit was used for verifying and anchoring dedicated design tools including methods for performance and cavitation predictions. Since only restricted data are available, additional water tests will be performed at the University of Kaiserslautern, specializing in pump design, manufacturing and testing. These tests will be conducted under adequate operational conditions using water as pump fluid. The results of these tests serve to anchor especially the CFD performance analyses and to improve the Airbus DS capabilities in cavitation prediction and inducer design optimization.

5. Conclusions

The main goal of the presented program was to re-build a certain turbopump competence covering not only the analysis of existing systems, but also to acquire skills in designing such systems. With respect to the initial proposal a preliminary LOX turbopump design including the main components was established preserving proven design heritage. In the frame of this project a dedicated work flow was established and applied including the application of design and analyses software. First 3D-CFD results were obtained and analyzed for pump and turbine performance mapping and characterization. The steady state pressure data were applied for first ANSYS structural models. Further design work has to cover the investigations especially of unsteady state processes as well as further concerns related to airfoil, flow path, axial thrust.

6. Acknowledgements

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