Turbopump Design and Analysis Approach for Nuclear Thermal Rockets

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Abstract. A rocket propulsion system, whether it is a chemical rocket or a nuclear thermal rocket, is fairly complex in detail but rather simple in principle. Among all the interacting parts, three components stand out: they are pumps & turbines (turbopumps), and the combustion chamber. To obtain an understanding of the overall rocket propulsion system characteristics, one starts from analyzing the interactions among these three components. It is therefore of utmost importance to be able to satisfactorily characterize the turbopump, level by level, at all phases of a vehicle design cycle. Here at NASA Glenn Research Center, as the starting phase of a rocket engine design, specifically a Nuclear Thermal Rocket Engine design, we adopted the approach of using a high level system cycle analysis code (NESS) to obtain an initial analysis of the operational characteristics of a turbopump required in the propulsion system. A set of turbopump design codes (PUMPDES & TURBDES) were then executed to obtain sizing and performance parameters of the turbopump that were consistent with the mission requirements. A set of turbopump analyses codes (PUMPA & TURBA) were applied to obtain the full performance map for each of the turbopump components; a two dimensional layout of the turbopump based on these mean line analyses was also generated. Adequacy of the turbopump conceptual design will later be determined by further analyses and evaluation. In this paper, descriptions and discussions of the aforementioned approach are provided and future outlooks are discussed.

Keywords: Turbopump; Nuclear Thermal Rocket Engine; Conceptual Design; System Analysis.

1. INTRODUCTION

A turbopump can be viewed as a stand alone system. High energy flow drives the turbine, which in turn drives the pump which delivers propellant flow to engine. The interactions among the flows and the mechanical components of the system are complex and very demanding. Development of a high performance turbopump is a multi-disciplinary task which involves the expertise of many fields such as fluid-flow, thermodynamics-heat transfer, material science, and structural static & dynamics. In a turbopump, dynamic fluid-flow over the blades and vanes of rotating machines must be mastered for good hydrodynamic-aerodynamic performance. The stresses in blades and casings and the wear in supports, such as bearings and seals, must be considered for proper service life. Synchronous and sub-synchronous harmonic vibrations of the shaft can excite the structure or the flow to cause damage or failure of the assembly. Considerations such as these are critical in the turbopump design and development processes. Some good references in these fields of expertise are: [1.1], [1.2], [1.3], [1.4].

From the system level view, the turbopump is a major sub-system of the overall rocket engine. A turbopump bridges the propellant main tank and the reaction chamber interacting with both actively. As a sub-system, the turbopump is intricately connected to the overall propulsion system requirements, which in turn are determined through mission profiles of the overall vehicle. The starting point of a turbopump design is to obtain its design requirements through an overall propulsion system analysis for the intended vehicle mission. Within the propulsion system, this analysis is by no means one-sided. As a major sub-system, the anticipated turbopump characteristics of size, weight, performance, and complexity affect the overall propulsion system design, and the choice of the turbopump must also consider the critical issues of turbopump development discussed previously.

Here at NASA Glenn Research Center, as the starting phase of a rocket engine design, specifically a Nuclear Thermal Rocket (NTR) engine design, we adopted the approach of using a high level system cycle analysis code (NESS) to obtain an initial analysis of the operational characteristics and requirements for a turbopump used for mission propulsion. A set of turbopump design codes (PUMPDES & TURBDES) were then executed to obtain the sizing and performance characteristics of the turbopump that were consistent with the mission requirements. A set of turbopump analyses codes (PUMPA & TURBA) were then applied to obtain the full performance map for each of the turbopump components; a two dimensional layout of the turbopump components based on these mean line analyses was also generated. In the following sections, descriptions and discussions of the aforementioned approach are provided.

2. NUCLEAR ENGINE SYSTEM SIMULATOR (NESS) CODE

The NESS program was developed for rapid preliminary design and analysis of NERVA derived NTR propulsion systems. NESS is derived from the Expanded Liquid Engine Simulation (ELES) program, which was modified to include Westinghouse Electric Corporation's near-term solid-core reactor design models ENABLER and ENABLER-II [Ref. 2.1]. NESS can design and determine the weight, performance, and operating characteristics of the primary NTR system components, as well as engine sub-system parameters such as dimensions, pressures, temperatures, and mass flows.

NESS can model expander, gas generator, and bleed cycles, with all cycles using hydrogen as the propellant and the gas generator cycle using oxygen as needed. All of these engine cycles can be driven by one of several turbopump assembly (TPA) configurations, all of which are based on either an axial or centrifugal pump with an optional inducer stage. During design, NESS checks for the need to stage the pump or turbine, and allows up to four stages for centrifugal pumps, twenty stages for axial pumps, and two stages for turbines. To avoid unrealistic designs, NESS checks the maximum allowable tip speeds (1500ft/s for hydrogen), forces the inducer and the pump to have the same RPM, and designs a partial admission turbine if the blade height falls below 0.3in. The axial pump performance calculations are essentially the same as for the centrifugal pumps, with one exception being the specific speed at which NESS will stage the pump (~3200 for axial and ~800 for centrifugal) [Ref. 2.1].

The pump design process starts by calculating the main pump RPM based on net positive suction pressure (NPSP), suction specific speed, and volumetric flow rate. This information is used in conjunction with the total pump pressure rise required from the engine fluid circuit analysis to determine the total pump pressure rise required. NESS then calculates the inducer pressure rise and recalculates pump RPM (if required). Next, the number of stages, diameter, pump and inducer efficiencies (efficiency curves are based on existing pump designs), and horsepower requirements are calculated. Finally, the overall efficiency, size, and weight of the pump are calculated.

Some basic pump parameters obtained from NESS for single-TPA expander cycle NTR propulsion systems designed for 15Klbf and 25Klbf of thrust are shown in Table 2-1.

TABLE 2-1. NESS Pump Outputs..

	P-rise (psi)	**RPM**	**Suction-Specific-Speed**	**# of Stages**	**NPSP (psi)**
15K lbf	1667.6	30937	20000	3	5
25K lbf	1687.7	23967	20000	3	5

	Mass-Flow-Rate (lbm/s)	**Shaft-HP**	**Efficiency**	**Diameter (in)**	**Weight (lbm)**
15K lbf	16.61	2426.1	68.3%	7.69	88.32
25K lbf	27.68	4100.3	68.2%	9.98	152.63

The turbine design process starts by calculating the turbine exit gas pressure from the known entrance conditions, which are obtained from the engine flow path analysis. Next, U/C (blade speed over spouting velocity), turbine RPM, diameter, specific speed, and admission fraction are calculated. Efficiency is then calculated using U/C and admission fraction. At this point, the code checks to see if the turbine inlet Mach number is greater than 1.7 or if the turbine specific speed is below a minimum, at which point the code will stage the turbine. It also checks the blade root stress limit and the root stress speed limit (RPM) in order to avoid an unrealistic design. Finally, a power balance is conducted and further iterations are completed as necessary to match the pump and the turbine power requirements.

Several basic turbine parameters obtained from NESS for single-TPA expander cycle NTR propulsion systems are shown in Table 2-2. These systems are sized for 15Klbf and 25Klbf of thrust, and correspond to the pump data shown in Table 2-1.

TABLE 2-2. NESS Turbine Outputs..

	P-drop (psi)	T-drop (deg. R)	Specific-Speed	RPM	# of Stages
15K lbf	298.3	49.9	48	30937	2
25K lbf	320.0	50.0	46	23967	2

	Mass-Flow-Rate (lbm/s)	P-Ratio	Efficiency	Diameter (in)	Weight (lbm)
15K lbf	13.83	1.274	70%	6.22	38.71
25K lbf	23.29	1.294	70%	8.04	66.59

3. TURBOPUMP DESIGN CODES AND DESIGN APPROACHES

3-1. Introduction to PumpDes Code

PumpDes is a conceptual liquid pump design code, originated by Scheer [Ref. 3.1] and subsequently modified by Walker and Chen of NASA Glenn [Ref. 3.2]. The code conducts a station-by-station mean line analysis along the pump flow path, obtains thermodynamic properties of the pumped fluid at each station, and performs an evaluation of the hydraulic losses that would occur along the flow path. The properties and the variables at each station are obtained under constraints that are in compliance with the first principles of physics. Note that the flow speed in pumps is generally low and the passage length of each elemental sector is relatively long, a fully developed internal flow is assumed as the primary flow and the flow is assumed thermodynamically in local quasi-equilibrium. Losses in the flow path are estimated using empirical or semi-empirical formula derived for a fully developed flow of a channel or pipe. Dependent variables at each station are obtained by enforcing conservation laws of mass, linear momentum (or an entropy condition that $Tds = - d(Ht)$ where Ht is the total enthalpy as its substitute, based on the assumption of slow evolving, quasi-equilibrium local statistical condition is valid), angular momentum (or a substitute of a constitutive condition from geometric layout such as the discharge blade angle or the discharge flow angle being known), and lastly, energy conservation. The foundation of pump-flow analysis is built upon consideration of energy budgeting and the entropy condition because of its sufficiently slow evolving nature of flow. As a result of this process, PumpDes not only has the capacity of predicting the stage and the overall design-point performance characteristics of the pump, but also, within the confines of the laws of physics, by judiciously selecting those of the givens and those of the unknowns, the code also conducts a geometric inverse design function, providing a best-satisfying pump geometry under the given set of design point requirements.

The PumpDes code contains two major parts: an axial rotor/inducer, and a multi-stage centrifugal pump. The inducer and the centrifugal pump are functionally integrated. The code has the ability to perform design and evaluation of the centrifugal pump alone, or, it can conduct a joint design with the inducer and the centrifugal pump combined together. It is written in standard FORTRAN 77 and employs real gas properties.

3-1-1 Pump Design for NTR Engines

Designs were conducted for the 15K lbf-thrust and the 25K lbf-thrust Nuclear Thermal Rocket (NTR) Engines using the PumpDes code. Required input flow quantities to PumpDes were obtained from the results of the NESS investigations described previously. The results are briefly summarized in the following tables.

TABLE 3-1.1 Overall Characteristics of Pumps Designed for NTR Engines.

	Fluid	Overall Efficiency (isen)	Overall Shaft-HP	# of Stages
15K lbf	LH2	0.826	2278	1 + 3
25K lbf	LH2	0.821	3855	1 + 3

	Inlet Pressure (psia)	Inlet Temperature (deg R)	Inlet Tip-diameter (in)	Inlet Hub-diameter (in)
15K lbf	20.2	36.7	3.69	2.40

25K lbf	20.2	36.7	4.53	2.72

TABLE 3-1.2 Characteristics of Inducers Designed.

	Blade #	BETA2 (deg)	Chord L (in)	Wrap Ang (deg)	P-rise (psi)	NPSP_in	Cav. Index
15K lbf	3	21.5	4.71	164	30.3	8.704 (psi)	- 7.447 (psi)
25K lbf	3	23.0	5.60	161	28.5	8.684 (psi)	- 6.261 (psi)

TABLE 3-1.3 Characteristics of the Centrifugal Pumps.

	Blade #	BETA2 (1st stg)	Tip-dia (in)	Tip-span (in)	Blade-Axial L (in)	Wrap Ang (deg)
15K lbf	8/16	48 (deg)	7.197	0.205	1.076	100
25K lbf	8/16	50 (deg)	9.355	0.244	1.460	95

	P-rise/stage (psi)	NPSP_in (1st stg)	Cavitation Index (1st stg)
15K lbf	545.8	51.9 (psi)	+ 23.3 (psi)
25K lbf	553.1	48.6 (psi)	+ 22.2 (psi)

3-2. Introduction to TurbDes Code

TurbDes is a conceptual rocket engine axial flow turbine design code, authored by Scheer [Ref. 3.3]. It performs design for partial admission impulse (single stage only), full admission impulse, or full admission 50% reaction turbines, with the choice of either one or two turbine stages. The code utilizes empirical correlations to the fullest extent on geometric layout as well as on loss estimates. Modeling methodology of this code is extremely broad. A completely different source of data was adopted for each different type of turbine, with almost completely different rationale in formulating and interpreting the turbine loss evaluations, as if it were the collection of three independent works combined into one. TurbDes in its current state is adequate for low pressure ratio turbine design in rocket propulsive cycles such as the expander cycle and/or a fuel-rich pre-burner cycle. It is perhaps unsuitable for high pressure ratio applications such as the tap-off cycle or configurations powered by dedicated gas generators.

Fundamentals of the turbine gas-flow are very different from that of the pump liquid-flow. Turbine flow is fast moving and blades and vanes of an axial turbine are quite short. Flow in a turbine is therefore a developing boundary layer type flow. Although the basic laws of physics are the same, the significant differences are loss models will be entirely different from those of pumps and the entropy condition of quasi-equilibrium states in pump flow is not applicable to turbine flow. As a result, when analyzing turbines, one would need a different auxiliary thermodynamic relation, other than the entropy condition, to bridge the linear momentum and the energy conservation. Otherwise both of these two would have to be dealt with independently. This auxiliary relation comes often by rules. Besides specifying the degree of reaction of the turbine before hand, one would also need a defined rule such as: linear density variation across the stage (in both nozzle and rotor); constant density across rotor but linear variation across nozzle; etc. Other than this, the conceptual design methodology for turbines is little different from that of pumps.

3-2-1 Impulse and 50% Reaction Turbine Designs for NTR Engines

The Nuclear Thermal Rocket engine being studied is an expander cycle design and requires only a low pressure ratio turbine. The original, unmodified TurbDes code was applied for the conceptual turbine design. Two types of turbine were studied and are summarized here. Required input flow conditions to TurbDes were obtained from NESS investigations. Desired turbine power outputs were assigned to code input based on PumpDes' estimation of shaft power required for the pump stages.

TABLE 3-2.1. Characteristics of 50% Reaction Turbines Designed for NTR Engines.

	Fluid	Overall Efficiency (T-to-S)	# of Stages	HP-Output	P-in (psi)	T-in (deg R)
15K lbf	H2	0.866	2	2278	1220.7	637.2
25K lbf	H2	0.870	2	3855	1231.9	599.3

	P-exit (psi)	T-exit (deg R)	P-ratio (T-to-S)	1st Nozzle Inflow Ang.	1st Nozzle Disg Ang.
15K lbf	992	605	1.236	90 (deg)	18 (deg)
25K lbf	988	567	1.252	90 (deg)	16 (deg)

	Mean-dia (in)	Rotor-1 Blade Height (in)	Rotor-2 Blade Height (in)	Tip-Speed (ft/s)	U/C
15K lbf	7.542	0.759	0.818	1129	0.392
25K lbf	9.535	1.053	1.142	1117	0.384

TABLE 3-2.2. Characteristics of Impulse Turbines Designed for NTR Engines.

	Fluid	Overall Efficiency (T-to-S)	# of Stages	HP-Output	P-in (psi)	T-in (deg R)
15K lbf	H2	0.636	2	2278	1220.7	637.2
25K lbf	H2	0.655	2	3855	1231.9	599.3

	P-exit (psi)	T--exit (deg R)	P-ratio (T-to-S)	1st Nozzle Inflow Ang.	1st Nozzle Disg Ang.
15K lbf	921	604	1.339	90 (deg)	18 (deg)
25K lbf	918	566	1.353	90 (deg)	16 (deg)

	Mean-dia (in)	Rotor-1 Blade Height (in)	Rotor-2 Blade Height (in)	Tip-Speed (ft/s)	U/C
15K lbf	4.916	0.597	0.624	748	0.219
25K lbf	6.404	0.747	0.788	752	0.224

As seen, characteristics of these two are quite different. 50% reaction turbines are far more efficient than the impulse turbines but, in general, they have a more complicated flow path and flow physics. In this case they also have larger-sized turbine wheels.

4. TURBOPUMP ANALYSIS CODES AND THEIR APPROACHES

4-1. Introduction to PUMPA Code

A mean line pump flow modeling method (Ref. 4.1) that was developed at NASA Glenn Research Center resulted in the development of a computer flow code named PUMPA. The code is written in standard Fortran 77. This pump analysis code can model the flow in axial, inducer, mixed-flow, and centrifugal pump configurations and multistage pumps (Ref. 4.2). It can also be used to model the performance of pumps at off-design operating conditions. The off-design rotor efficiency, slip factor and diffuser pressure recovery are modeled in the PUMPA code by empirical correlations. Real gas fluid properties are obtained from GASPLUS (Ref. 4.3). This code was used to estimate the off-design performance characteristics of the 15K Lbf thrust liquid hydrogen pump. The current three stage pump configuration for the 15K Lbf thrust engine is a balance between optimizing for efficiency and axial length based on legacy pump design history (Ref 4.4). The mean line pump geometry obtained from the previous section was input into the PUMPA flow analysis code and analyzed at a range of rotational speeds and flows per speed line.

The PUMPA flow code was used to analyze the pump for the 15K Lbf thrust case for two reasons. First, the analysis done with the PUMPA code provided an independent verification of the mean line pump design and the expected performance at the design point. Second, the PUMPA code was used to size the geometric throat area of the crossover diffuser vane and the geometric throat area of the volute.

Besides verifying the expected performance at the design point, the PUMPA analysis also provides the performance prediction along 10 speed lines, starting at the 100% speed of 30,900 RPM, and 9 lower speed lines in 10% increments. A range of flows were analyzed along each speed line. Figures 4-1.1 and 4-1.2 show the expected performance maps that were generated by the PUMPA code for the liquid hydrogen pump required by the 15K Lbf thrust engine. Details of flow conditions, including absolute and relative velocity vectors and flow angles, static and total pressures and temperatures, at the leading edge and trailing edge of each impeller, are calculated for each point along the pump maps. Off-design suction performance for each stage and the initial onset of cavitation along each speed line are also modeled, but the effects of cavitation on pump pressure rise is not reflected in the predicted pump map of Figure 4-1.1.

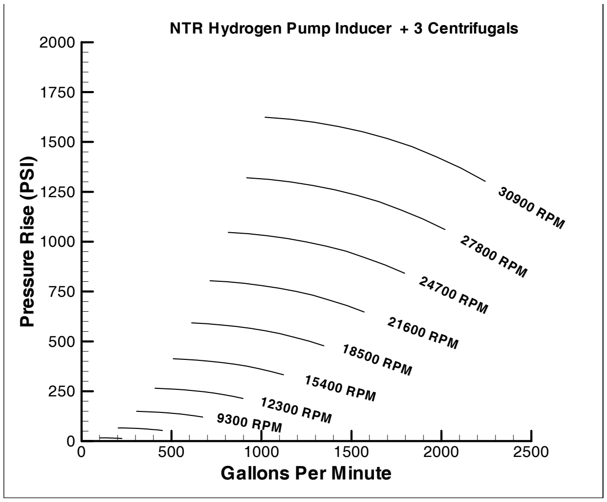

Figure 4-1.1 Pump pressure rise vs. flow and speed.

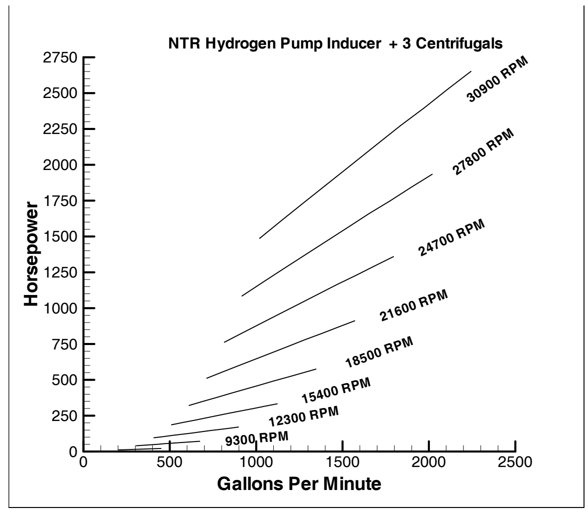

Figure 4-1.2 Horsepower requirements vs. flow and speed.

The required drive power for the complete range of speeds and flow rates that were modeled is shown in Figure 4-1.2. It is planned that these two maps will be input into the thermodynamic system model to determine the transient operation of the pump in an engine system environment.

4-2 Introduction to TURBA Code

A mean line turbine flow modeling method has been developed to provide a fast capability for modeling turbines of cryogenic rocket engines. Based on this method, a mean line turbine flow code named TURBA has been written that can model the performance of axial turbines at the design point as well as generate performance characteristic maps. The mean line method was developed for small un-cooled turbines such as those used in upper stage expander cycle pump fed chemical rocket engines, and for nuclear thermal rockets.

TURBA provides an estimate of flow incidences on the turbine rotors and stators and the losses at off-design operating conditions. The turbine configuration, flow path and number of stages that will result in an acceptable system performance can be quickly evaluated by the use of this mean line off-design flow modeling code. The code has empirically derived correlations based on tests of several rocket engine turbines and research rigs. The design point turbine efficiency is obtained from correlations of efficiency to ideal spouting velocity ratio (U/C). The off-design efficiency is obtained from historical turbine performance test data that has been normalized relative to the design point. Turbine drive gas options are gaseous hydrogen, oxygen, nitrogen, air and hydrogen-oxygen products of combustion. Real fluid properties are obtained from GASPLUS (Ref 4.3). The TURBA code output consists of flow conditions at the nozzle and rotor leading and trailing edges at each stage. In addition to the mean line flow conditions at the blade root-mean-square radius, flow conditions at the hub and tip locations are also calculated. The output summarizes the flow conditions in terms of velocities, flow angles, pressures and temperatures. Velocities and flow angles are calculated in both the relative and the absolute frames of reference. Static and total pressures and temperatures are calculated at the exit of the stators and rotors. The pressure ratio, horsepower and efficiency are summarized for each stage as well as for the multistage turbine. The calculation of all performance parameters is repeated at several mass flow rates per speed line, as specified by user input.

The two stage turbine geometry obtained from TurbDes was input into the TURBA code for independent analysis of the design point performance, and also to generate the performance map for the two stage turbine.

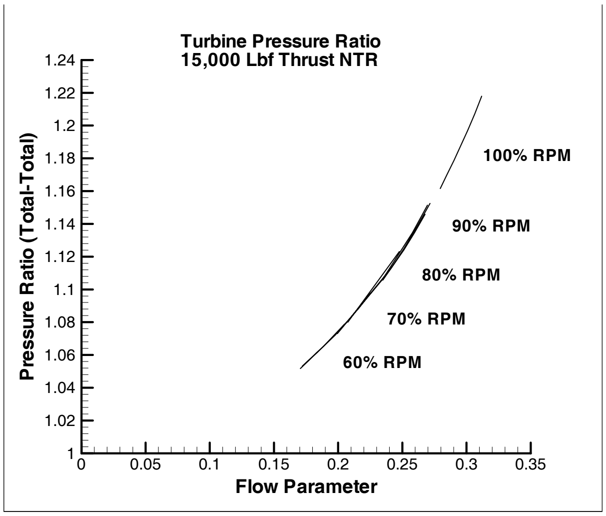

Figure 4-2.1. Pressure ratio vs flow parameter.

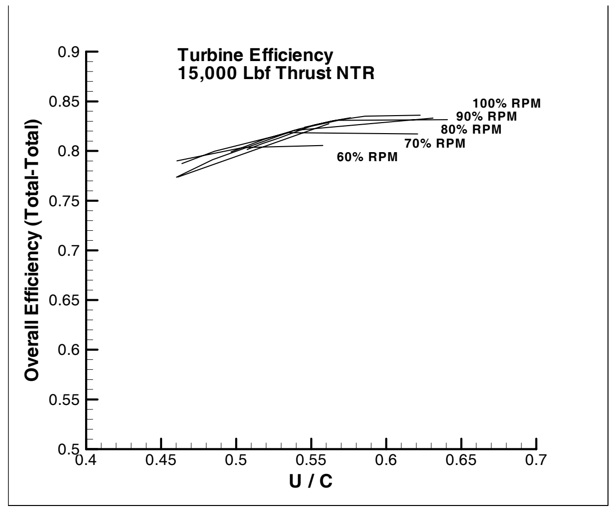

Figure 4-2.2. Efficiency vs. spouting velocity ratio.

Figure 4-2.1. shows the resulting turbine pressure ratio versus flow parameter that was generated by the TURBA code for the two axial turbine stages. Figure 4-2.2. shows the turbine efficiency vs. spouting velocity ratio (U/C).

There is general agreement at the design point with the results obtained from the TURBA code and the TurbDes code in Section 3. It is planned that these turbine maps will be input into the thermodynamic system model to determine the transient operation of the turbine in an engine system environment.

4-3 Design of the LH2 Turbopump

A conceptual mechanical design was made for the liquid hydrogen turbopump. Key parameters from the pump and turbine mean line codes were taken to generate the two-dimensional pump cross-section layout. The inducer, three centrifugal impellers and two axial turbine rotors are mounted on one shaft. The impeller configuration for this pump is shrouded and has a labyrinth seal to control internal leakages. The diffusion rate through the impeller is controlled by the taper on the shroud that can be seen in Fig. 4.7, as well as the blade back sweep angle, to limit the relative velocity ratio to a value below 1.9 at the design operating condition. Future work will be to refine the flow path and blade designs with higher fidelity design and analysis codes. The axial thrust loads produced by the three stage in-line pump configuration will be offset by the axial loads produced by the two stage turbine. The pump is located between the bearings, while the two stage turbine is overhung on the aft end bearing. The layout shows a possible turbine configuration featuring inlet and exit scrolls to guide the flow into and out of the turbine in a radial direction. Figure 4-3 shows the conceptual layout of the turbopump unit for the 15K Lbf thrust nuclear thermal rocket engine.

At this point in the conceptual design, there were no structural, thermal or rotordynamic analyses performed on the resulting turbopump layout, but these are planned for future work. Also under consideration for future work will be evaluation of an existing legacy turbopump (e.g., one designed for a chemical propulsion rocket engine) which may meet the performance requirements of the nuclear thermal rocket engine.

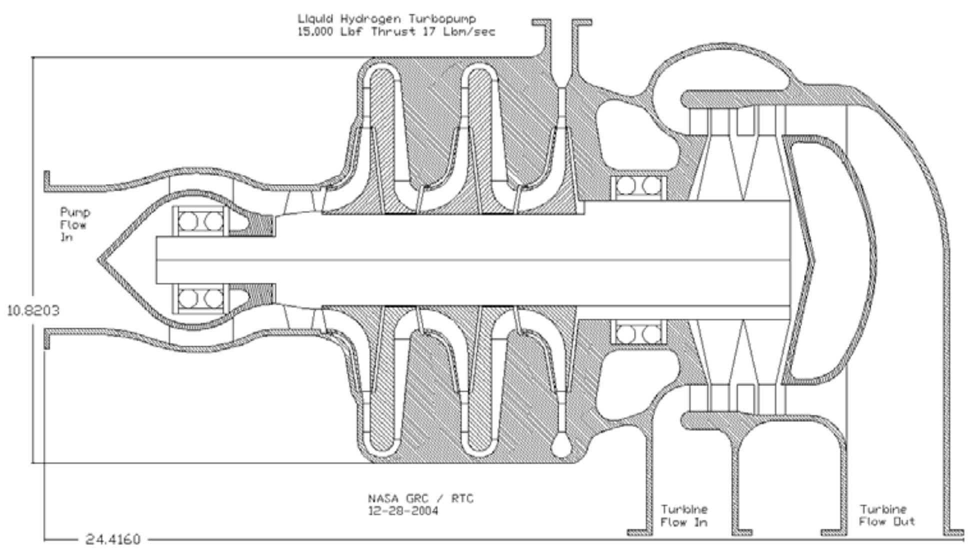

Figure 4-3 Conceptual Design of the liquid Hydrogen Turbopump for the 15K Lb Thrust NTR Engine.

The approximate overall turbopump dimensions are 24.4 inches axial length and a case diameter of 10.8 inches.

5. SUMMARY AND FUTURE OUTLOOKS

The sequence of a turbopump design and analysis approach has been presented. The procedure described represents an approach for the start-up phase of a turbopump development project within a rocket engine system development program. From the perspective of turbopump development, the next step to take is to conduct the preliminary design and analysis phase based on the conceptual performance and geometry layout. In the preliminary design phase, a three dimensional turbopump geometry will be generated, with a refined flow path including detailed pump and turbine blade designs. The preliminary design phase will also investigate suitability of the designs for meeting the performance and structural requirements using state-of-the-art high-fidelity fluid dynamic, structural and thermal analysis computer codes. Insights for refinements of the initial designs can then be provided and be implemented. More accurate and physics-based performance characteristics of the turbopump can thus be obtained.

From the system point of view, the next level of the design & analysis cycle is to apply the design characteristics and the performance maps obtained to a system simulation code such as NASA Glenn's NPSS (Numerical Propulsion System Simulation) software. Preliminary NPSS models of the NTR systems have been created. Once the component maps have been added, they will be used to perform a system analysis simulating interactions of all major components of the system in operation. Adequacy of the turbopump design for the mission requirement can then be judged, more systematically and concisely, according to the coverage of the maps with respect to the operation range and path imposed by the system and the mission requirements. Communication between the system model codes and the high-fidelity multi-disciplinary component analyses will be carried out in the future.

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