RADIAL TURBINE GLOBAL DESIGN FOR LIQUID ROCKET ENGINE APPLICATION

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ABSTRACT

This work deals with the design of radial turbines, in place of the more commonly used axial ones, to drive the turbo-pumps that supply both the fuel and the oxidizer to the thrust chamber of an expander-cycle rocket-engine.

The present work aims to show a methodology for estimating the compact radial turbine performance prediction for expander cycle rocket engine application, avoiding a detailed fluid dynamics analysis. The Radial Turbine Global Design (RTGD) code according to the type of fuel, hydrogen, methane or kerosene, determines the optimal velocity triangles, on the mean line, to minimize the overall dimensions, the losses, the flow rate and the pressure ratio, in order to maximize turbine performance for liquid rocket engine application.

The model developed has the objective to estimate the efficiency and optimization of the parameters related to it, and losses prediction.

KEYWORDS

RADIAL TURBINE, ROCKET ENGINE, FEED SYSTEM

NOMENCLATURE

A	Area
c	Absolute velocity
c_0	Spouting Velocity
M	Mach Number
p	Pressure
r	Radius
T	Temperature
u	Impeller Tangential Velocity
w	Relative Velocity
z	Number Blades
Δh_0	Total Enthalpy Drop
Δh_{loss}	Total Enthalpy Loss
Δp_0	Relative Pressure Loss
α	Flow Angle
β_{1_opt}	Inlet Optimum Blade Angle
ω	Angular Velocity

Subscripts

1	Rotor inlet	2	Rotor outlet

INTRODUCTION

Radial turbines find nowadays-widespread use in turbochargers for automotive applications, but their use in aerospace applications has not so frequently been reported. Nonetheless, radial turbines have been extensively investigated, both experimentally and numerically, at NASA Lewis Research Centre [1], starting in the mid-1960s, but not for space propulsion application.

Radial turbines have higher efficiency and a high angle of incidence with respect to axial flow turbines, thus providing the following advantages: low expansion ratios, compactness and high reliability at low cost, good performance even with unsteady flows.

The main purpose of this paper is to demonstrate the applicability of the radial turbine whit respect to the axial ones for the expander cycle rocket engines, therefore the RTGD code was developed through the implementation of engineering models, in order to obtain the main parameters necessary for the preliminary design of the radial turbine.

The RTGD code features loss models and allows to account for trailing edge blockage and to compute flow conditions for low pressure ratios at or beyond stator and/or rotor chocking.

In this framework, has been used as test case the data reported by the literature for the axial turbine of the VINCI [2] engine.

A diagram of the radial turbine elements is report in the Figure 1.

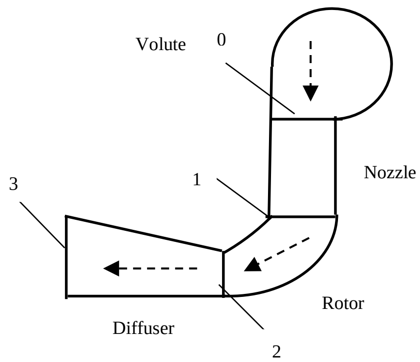

Figure 1: Radial Turbine Stage Cross Section

VINCI Engine

Vinci [2] is a new-generation upper-stage, cryogenic rocket engine for launch vehicles, see Figure 2.

Figure 2: VINCI Engine System

VINCI is being developed by Snecma and other European partners as part of a European Space Agency (ESA) program. Firing tests started in April 2005 on a test stand run by the German Aerospace Center (DLR). The Vinci is the upper stage of the Ariane 5. It has a design thrust of 180 [kN], a design I_{sp} of 465 [s] and uses an expander cycle.

In this rocket, hot hydrogen gas, generated in the regenerative cooling passage of the thrust chamber, drives two turbines. The first turbine drives the liquid hydrogen pump, while the second turbine drives the liquid oxygen pump. The two-separate turbo-pumps, each equipped with an inducer, pressurize the propellants.

The schematic of VINCI engine is shown in Figure 3.

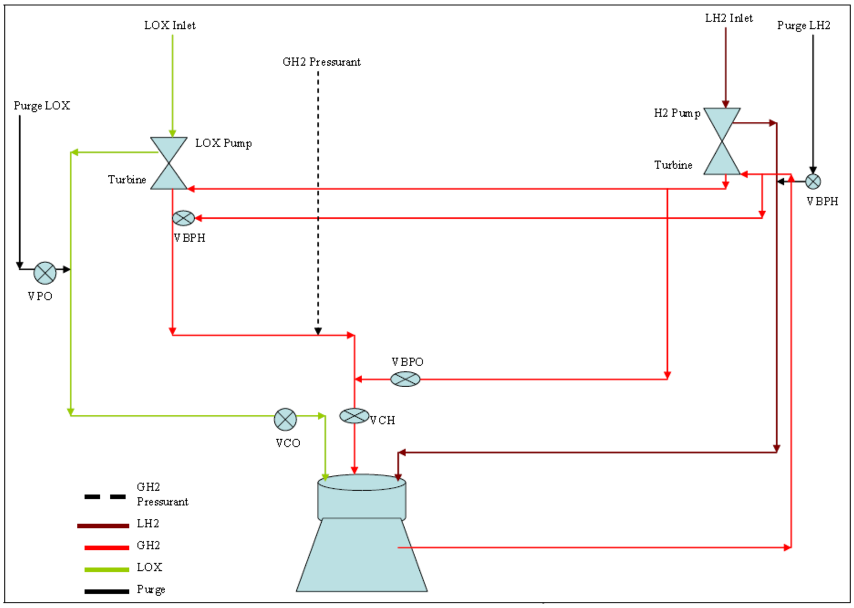

Figure 3: Schematic of VINCI System [1]

The Table 1 lists the primary turbine data of the VINCI engine [2].

Rotational speed [rpm]	90000
Power [kW]	2500
Turbine flow rate [kg/s]	4.8
Turbine inlet pressure [bar]	180
Turbine discharge pressure [bar]	90
Turbine inlet temperature [K]	240
Turbine pressure ratio	2

Table 1**:** Axial Turbine VINCI Engine

RADIAL TURBINE GLOBAL DESIGN: GENERAL INFORMATION

An engineering-based design tool, namely Radial Turbine Global Design (RTGD), has been developed in Matlab environment to allow a preliminary design of radial turbines for expander cycle engine.

The only limit of Matlab software is that there are no thermodynamic tools already implemented, therefore it was necessary to use the Coolprop libraries [3] to calculate the thermodynamic properties of a wide variety of fluids.

This point is extremely important, because it allows RTGD to always use the real-fluid thermodynamic properties: density, the specific heats, c_p and c_v, their ratio γ and the viscosity, μ.

RTGD relies on a one-dimensional model that allows determining several turbine's features, including the turbine's geometry and its efficiency.

The following diagram shows the RTGD inputs and outputs.

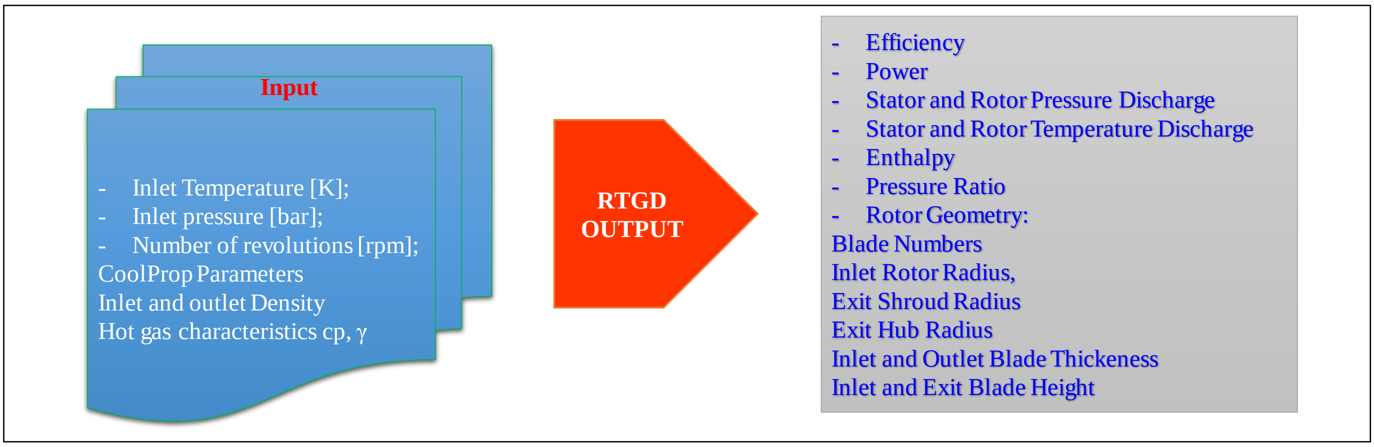

Figure 4: RTGD Diagram

The inlet temperature and pressure are defined by the outlet cooling system for expander rocket engine, while number of revolutions and diameter depending by the centrifugal pump [1, 4].

The main objective is loss prediction and performance of a radial turbine.

Table 2 show the rotor geometry results.

Number Blades	17
Inlet Rotor Radius [m]	0.077
Exit Shroud Radius [m]	0.058
Exit Hub Radius [m]	0.014
Inlet Rotor Blade Thickness [m]	0.003
Outlet Rotor Blade Thickness [m]	0.0016
Inlet Blade Height [m]	0.0034
Exit Blade Height [m]	0.044
Mean Blade Pitch at The Rotor Exit [m]	0.021

Table 2: Radial Rotor Geometry

Several authors proposed of the optimum ratio between geometrical parameters in order to obtain maximum efficiency. A comparison with the literature has been realized in order to verify the rotor geometry good design obtained with RTGD, show in Table 3.

Ratio	Rohlik [4]	Balje [5]	RTGD
$\frac{D_{2s}}{D_1}$	≤ 0.7	0.78	0.75
$\frac{D_{2h}}{D_2}$	0.4		0.40
$\frac{D_2}{D_1}$	$0.2 \div 0.6$		0.47
$\frac{c_2}{u_1}$		$0.2 \div 0.4$	0.28

Table 3: Ratio Maximum Efficiency

CODE STRUCTURE

The RTGD [6] code structure can be split in two different parts, in which the second is a consequence of the first and cannot be seen as a standalone code. In addition, the first requires an iterative procedure to compute some of the parameters required in the second part:

- Preliminary geometric design; in this first part the turbine geometry and velocity triangles are computed.
- Losses prediction; the second part will analyze, using several loss models and correlations, the efficiency that the geometry already produced in the first can achieve.

Running the code using different input parameters allows appreciating their impact on the achievable performance changes. This feature can be clearly considered one of the most important goals of this work, because it can provide an important information for a further design strategy, not only for the expander but also for the cycle parameters.

Loss Prediction

In this part, the different types of losses will be analyzed.

The losses in the rotor are associated with many complex phenomena that make the extraction of power from the rotor degraded with respect to what is prescribed by the Euler equation. The losses analysed in this work are estimated in order to determine the radial turbine performance and the effective work done by the rotor blades, and therefore the developed power. We shall consider different types of losses for VINCI engine: incidence, passage, tip-clearance, trailing edge, windage losses and kinetic-energy loss at the rotor exit.

The rotor is the main element to be investigated, which is strongly integrated within the turbine, therefore, the radial turbine rotor design represents the most complex element to be realized. The cause of this complexity depends on the three-dimensional fluid-dynamic interactions between the stator and the rotor and between the rotor and casing, which are not entirely known.

The inlet rotor conditions depend on the outlet stator conditions, which in turn depend on the outlet conditions of the cooling system in the expander cycle rocket engine. The outlet rotor conditions depend on the inlet pressure required by the injectors. While, the rotational velocity depends on the mechanical stresses of the centrifugal pump.

The stator outlet flow enters in the rotor with an absolute velocity c_1 inclined of the α_1 angle respect to the tangential direction of the reference system.

The rotor rotational velocity generates a dragging speed of the inlet blades which has the same direction as the tangential component of the inlet flow absolute velocity.

The inlet rotor flow relative velocity is a function of the rotor rotation velocity as well as the absolute flow velocity:

$$c_1 = \frac{u_1}{\sin \alpha_1} \tag{1}$$

In the ideal case the rotor inlet flow has zero incidence, therefore the relative velocity is exclusively radial. The zero incidence generates low fluid losses but does not allow the losses minimum value. In the radial blades hypothesis, the inlet relative velocity will have an unguided flow component, therefore, this velocity will have a component of radial relative velocity with zero incidence, direct radially as the blades, and by a relative tangential component in the opposite direction to the slip velocity:

$$w_{u1} = -c_{u1\_slip} \tag{2}$$

Aungier [7] states that are obtained minimal losses when the average flow enters the rotor with an incidence generated by only component c_{u1_slip}.

$$c_{u1\_slip} = \omega\, r_1 \frac{\pi}{z} \tag{3}$$

The number of revolutions is a parameter set by the centrifugal pump [4], since the pump is directly connected to the turbine in the expander cycle rocket engine.

Generally, in real applications, many vanes are not used for several reasons, e.g. excessive flow blockage at rotor exit, a disproportionally large wetted surface causing high friction losses, and because the weight and inertia of the rotor may become too high.

The optimum number of blades [9] in the RTGD is determined by a relationship that is a function of the rotor inlet flow angle α_1.

The incidence losses refer to the losses that occur at the inlet of the radial inflow turbine rotor blade passages when the turbine is operating at a non-zero incidence and, therefore, the flow does not enter the passage in the optimum direction. Losses in the rotor blade passage are mainly due to the occurrence of secondary flows, and these are considerably affected by the flow deviation from optimum incidence.

The minimum loss for incidence can be determined as a function of the relative tangential velocity:

$$\Delta h_i = \frac{1}{2}\, w_{u1}^2 \tag{4}$$

The incidence angle is obtained from the difference between the inlet flow angle and inlet optimum flow angle β_{1_opt} [10]. The experimentally optimum incidence should lie within the range of about -20° to -40° [11].

According Reference [8] the incidence angle value calculated is constant -31.7° in the case examined in this work.

The term passage losses include a wide spectrum of different phenomena occurring to the fluid crossing the rotor. In fact, after a rapid acceleration in the flow direction, the fluid is turned in the meridional plane along the camber line: this creates a complex pattern of secondary and cross-stream flows, which still today are not completely understood. Moreover, this causes the growth of boundary layers with loss of kinetic energy and blockage. A fully detailed model that considers separately all these loss sources, as the ones existing for the axial turbines, has not yet been developed. In fact, in axial turbine cascades, this can be done by a careful set up and measures, but this is not actually possible for radial turbines, due to the three-dimensionality of the flow pattern, which does not permit to differentiate the losses.

A passage loss model, namely the CETI model [8], was implemented to estimate more realistically the losses due to the secondary flow and friction in the rotor passages, between the inlet and the exit throat section of the rotor.

In this model, secondary flow and friction loss formulations are combined into one correlation as:

$$\Delta h_p = 0.11\, \frac{w_1^2 + w_t^2}{2} \left(\frac{L_h}{D_h} + 0.68 \left(1 - \left(\frac{r_t}{r_1} \right)^2 \right) \frac{\cos[\beta_t]}{\frac{h_t}{c}} \right) \tag{5}$$

where L_h and D_h represents hydraulic length and hydraulic diameter respectively, the subscript t denotes the throat.

The impeller blades mate up against the turbine housing with a small clearance to avoid mutual contact. In addition, the fluid pushes on the leading surface of each blade essentially creating a pressure difference between the leading and trailing blade surfaces i.e. across the blade. This pressure difference gives rise to a flow through the blade-housing clearance gap. This flow results in pressure dissipation and a consequent loss.

In the RTGD code this loss is calculated using Baines [11] equation, model that consider the axial and radial clearances influences:

$$\Delta h_c = \frac{u_1^3\, z}{8\,\pi} \left(K_a\, \varepsilon_a\, \frac{1 - \frac{r_2}{r_1}}{c_{r1} b_1} + K_r\, \varepsilon_r \frac{r_2}{r_1} \frac{z_a - b_1}{c_2\, r_2\, b_2} \right) \tag{6}$$

where z_a is the axial length, ε_a and ε_r represent axial and radial clearance, K_a and K_r are discharge coefficients for the axial and radial tip clearances respectively.

Trailing edge losses [12] arises due to mixing occurring, as the adjacent rows, of the two-blade surfaces exit the blade row. Moreover, in the case at supersonic velocities shock losses also contribute. In the fourth step the RTGD code determine the trailing edge loss as a function of the exit Mach number, the exit pressure p_2 and temperature T_2, the relative velocity rotor exit w_2 and relative pressure loss Δp_0, as follows:

$$\Delta h_t = \frac{2}{\gamma\, M_2^2} \frac{\Delta p_0}{p_2\left(1+\frac{w_2^2}{2\,T_2 C_p}\right)^{\frac{\gamma}{\gamma-1}}} \tag{7}$$

Windage losses [12] are frictional losses occurring on the back face of the turbine disk:

$$\Delta h_w = K_f \frac{\rho_{avg}\, u_2^3 \left(\frac{D_2}{2}\right)^2}{g\, \dot{m}\, w_2^2} \tag{8}$$

where the friction coefficient K_f is a function of Reynolds number.

The only external loss that is usually considered in radial turbine modelling is that of disk friction. This occurs because of the fluid leakage between the rotor disc and the stationary back plate, where the windage flow causes quite strong friction. Depending on the turbine, this leakage could also be recirculated into the turbine annulus or taken away.

The back face of the impeller hub is an annular disk that spins with the impeller. Either this disc may mate with a fixed surface separated from it by a small clearance or it may spin freely far from other fixed surfaces. In either case, the fluid adjacent to the disc exerts a shear on the disc with result that the fluid does unproductive work.

Finally, the rotor exit kinetic loss is expressed as:

$$\Delta L_k = \frac{1}{2}\, c_2^2 \tag{9}$$

Table 4 shows the loss contribution for VINCI [2] engine.

Incidence [%]	5.36
Passage Loss [%]	57.33
Clearance Loss [%]	14.44
Trailing-edge loss [%]	0.0012
Kinetic loss [%]	22.87

Table 4: VINCI: Loss Models

TURBINE DESIGN

In RTGD tool two different methodologies are implemented for estimating performance, the first [7] function of the inlet and outlet rotor geometry, and by the ratio between the rotor exit velocity and spouting velocity:

$$\eta_{ts\_1} = 0.629 + 1.526 \left(\frac{A_2}{A_1}\right)^{0.5} \left(\frac{c_2}{c_0}\right)^{0.5} - 1.09 \left(\frac{A_2}{A_1}\right) \left(\frac{c_2}{c_0}\right) - 4.697 \left(\frac{A_2}{A_1}\right)^{1.5} \left(\frac{c_2}{c_0}\right)^{1.5} \tag{10}$$

In the second approach the total-to-static efficiency is calculated as a function of the total enthalpy drops and losses:

$$\eta_{ts\_2} = \frac{\Delta h_0}{\Delta h_0 + \sum \Delta h_{loss}} \tag{11}$$

Therefore, the efficiency is obtained by the ratio between the total enthalpy drop and total enthalpy losses in the radial inflow turbine stage. In the RTGD are used the turbine geometry thermodynamic parameters of the working fluid, as well as the velocity triangles. This data is necessary for the design procedure, with a loss correlation system, the turbine efficiency can be optimized by varying the parameters of velocity ratio or incidence to minimize the predicted losses.

The turbine exit pressure can be expressed as a function of the specific work and the total-to-static efficiency:

$$p_2 = p_{00} \left(1 - \frac{W_s}{\eta_{ts}\, c_p\, T_{00}}\right)^{\frac{\gamma-1}{\gamma}} \tag{12}$$

The RTGD design results and comparison with the experimental data for VINCI engine are provided in Table 5.

	RTGD	**Vinci Axial Turbine**
η_{ts_1}	0.869	0.79
η_{ts_2}	0.863	
Pressure Ratio	1.83	2
Specific Work [kJ/kg]	531.9	
ΔH [kJ]	612	676
Mass Flow [kg/s]	4.72	4.8
Power [kW]	2540	2500
Exit Pressure [bar]	98.4	90.0

Table 5: Results VINCI Engine

The results show that the radial turbine is an advantage compared to the axial one. In particular, the radial turbine turns out to be advantageous because it has a higher efficiency and a lower expansion ratio than the axial turbine. Both priority requirements for a turbomachinery expander cycle rocket engine.

CONCLUSIONS

The choice of a simple and, therefore, computationally inexpensive simulation tools was motivated by the fact that the RTGD MatLab tool that has been developed are going to be some of the building blocks of a Concurrent Design Facility aimed at design all different components of the entire rocket-engine.

Tools developed in this paper were used to predict the main geometrical parameters and performance characteristics of a radial turbine for a future expander-cycler rocket-engine fed with methane as the liquid fuel.

Several loss models have been incorporated into the code, which showed that the passage and tip clearance losses account for most of the overall losses compared to the other loss mechanisms such as: incidence, trailing edge, windage and exit kinetic energy.

It has been demonstrated that it is indeed possible to use single-stage radial turbines to drive the turbo-pumps that supply methane and oxygen to the thrust chamber of a rocket-engine with characteristics similar to the LM10-MIRA demonstrator that is currently being developed.

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