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Preliminary Design Method of a Turbopump Feed System for Liquid Rocket Engine Expander Cycle

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Abstract

The present research effort deals with simplified theoretical models for the preliminary design and performances assessment of centrifugal pumps for liquid rocket propulsion. These models have been developed within the Concurrent Design Facility, under development at the Italian Aerospace Research Centre (CIRA), in the framework of the HYPROB program. In particular, this work is aimed at developing a theoretical model, via the implementation of a MatLab code, capable to predict the geometry and performance of centrifugal turbopumps, thus providing useful indications for the preliminary design of the turbopump feed system.

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Keywords: Centrifugal Pump; Methane; Liquid Rocket Engine;

1. Introduction

In the development of space propulsion systems, the study of the turbopumps used in liquid rocket engines is of great interest, since its proper design allows to increase the generated thrust. Due to the complexity in analysing the flow behaviour inside the centrifugal pump, accurate Computational Fluid Dynamics (CFD) design analyses are

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required. However, in the framework of a preliminary design phase, such as those used in the Concurrent Design Facility (CDF), fast predicting methods are mandatory. Therefore, CFD analyses are not a viable option within CDF investigations, being very complex and time consuming and the turbopump design must be afforded mainly by means of engineering tools.

A MatLab tool, called PGD (Pump Global Design), which relies upon the CoolProp [1] libraries to obtain the thermodynamic data, has been developed at CIRA within the HYPROB programme. The goal of the HYPROB project is to contribute to the evolution and consolidation of the national technology and system development capabilities on rocket propulsion for future space applications. Overall the project pursues two strategic goals: i) the ability to design and build rocket engines with liquid or hybrid propellants, verified by building system and technological demonstrators; and ii) the development of ground or flight qualified enabling technologies and the related instrumental capabilities, to support the design of future space. Liquid oxygen and methane (LOX/LCH_4) rocket engine technologies represent the major effort within the project. In fact, the development of hydrocarbon, such as methane (LOX/CH_4), or hybrid is becoming a technological asset for future generation launchers and space transport systems. Today methane appears to be the most interesting avenue for liquid propellant rockets because it brings together – in addition to good operating performance – easy storage, limited danger and no toxicity, as well as relatively low extraction and conditioning costs.

In this framework, this paper describes the simplified theoretical models implemented in the PGD tool that are currently being used for the preliminary design and performance assessment of the centrifugal pumps used in a rocket propulsion system. PGD is able to determine the global geometry and performances of the turbomachines, as well as the thermodynamic properties of the fluid at discharge.

PGD has been preliminary validated using the available data of two engines, namely the RL10A-3-3A and VINCI; then it has been use for the preliminary design of the centrifugal pump of a Methane expander rocket engine.

Nomenclature

ΔH	Total head	ρ_{in}	Inlet density
p_d	Discharge pressure	N_s	Specific speed
p_s	Suction pressure	ω	Pump rotating speed
Y_s - Y_d	Friction losses in the channels before and after the pump	Q	pump flow rate
		η_H	Hydraulic efficiency
ρ_d	Discharge density		

2. Pump Global Design

Starting from engineering relationships of centrifugal turbopumps (CTP) global parameters a MatLab Tool, namely Pump Global Design (PGD) has been developed. This tool allows preliminary design of CTP at an engineering-based level.

The PGD tool requires different input parameters. They can be distinct in primary and secondary inputs, according to the scheme provided in Figure 1.

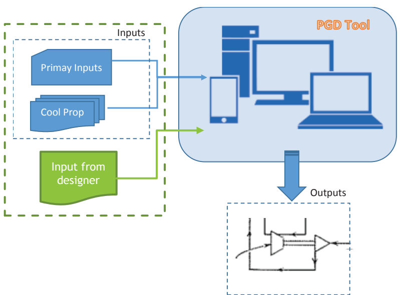

Fig. 1. PGD tool scheme

The PGD tool requires different input parameters. The primary input parameters are inlet temperature, mass flow rate, inlet pressure and discharge pressure. The PGD code makes use of CoolProp libraries through which the obtained secondary inputs, that are inlet density, vapor pressure, discharge density and temperature.

3. Theoretical models for specific speed and head-density relationship

The theoretical models for head-density relationship and specific speed, developed in the PGD tool are summarized hereinafter.

3.1. Specific speed

The specific speed was first introduced by Camerer in 1914 and further developed by Stepanoff in 1948 [2]. The pump specific speed is a characteristic value typically defined at the point of maximum efficiency, which is usually the design point [3]. It is defined as:

$$N_s = \frac{\omega\sqrt{Q}}{(g\Delta H)^{3/4}} \tag{1}$$

In the PGD tool the following empirical correlation for the impeller hydraulic efficiency, η_H is implemented [5]:

$$\eta_H = 0.41989 + 2.1524\ N_s - 3.1434\ N_s^2 + 1.5673\ N_s^3 \tag{2}$$

3.2. Relationship between head and pressure

The manometric head ΔH is the total head developed by the pump. This head is slightly less than the head generated by the impeller due to frictional losses in the pump. It represents the pressure increase generated by the pump between the discharge and suction sections and can be expressed as:

$$\Delta H = \frac{p_d - p_s}{\rho * g} + Y_s + Y_d \tag{3}$$

The expression for discharge pressure [3] is:

$$p_d = \left(\frac{p_s}{\rho_{in}} + \Delta H\right)\ \rho_d \tag{4}$$

Equation (4) shows that the pump discharge pressure p_d equals the propellant pump suction pressure p_s plus the pressure rise across the pump, Δp_{pump}.

The peripheral velocity, u, the tangential component of absolute velocity, c_u, and the relative velocity, w, are evaluated in PGD by the following relationships:

$$u = \sqrt{\frac{g\,\Delta H}{\psi}} \qquad c_u = \frac{g\,\Delta H}{u\,\eta_H} \qquad w = \frac{u\,c_u}{\mathrm{Tan}[\beta]} \tag{5}$$

4. Test case

The reliability of the present theoretical model has been evaluated by considering two test cases, namely the RL10A-3-3A and VINCI engines, as summarized hereinafter.

4.1. RL10A-3-3A Engine

The RL10A rocket engine is an important component of the United States space infrastructure [4]. Two RL10 engines form the main propulsion system for the Centaur upper stage vehicle, which boosts commercial, scientific, and military payloads from a high altitude into Earth orbit and beyond (planetary missions). The Centaur upper stage is used on both Atlas and Titan launch vehicles. The RL10A-3-3A engine design is based on an expander cycle.

Hydrogen fuel is used to cool the thrust chamber and nozzle, and the thermal energy transferred to the coolant is used to drive the turbopumps. Engine data available in literature for the RL10A-3-3A are summarized in Table 1 [5].

Table 1. Engine Data RL10A-3-3A

Engine Data			
Thrust	73.0042 [KN]	Pressure discharge	36.694 [bar]
Fuel Flow Rate (LH_2)	2.7945 [Kg/s]	Temperature discharge	26.47 [K]
ΔHead (Centrifugal Pump 1 stage)	5138.3184 [m]	Mass flow discharge	2.7714 [Kg/s]
Speed n	31494 [rpm]	Density discharge	68.639 [Kg/m3]
Torque (1 stage)	72.93 [Nm]	Pressure drop cooling system	17 [bar]
Efficiency (1stage)	0.5854	Turbine pressure inlet	56.10 [bar]
Pressure inlet	1.847 [bar]	Temperature inlet gas hydrogen	213 [K]
Temperature inlet	21.44 [K]	Turbine pressure outlet	38.76 [bar]
Density inlet	69.47 [Kg/m3]	Pressure Chamber	32.75 [bar]

The PGD tool design results and their comparison with those obtained in [5] using PUMPA code developed by NASA are provided in Table 2.

Table 2. Comparison between PGD and PUMPA results for the RL10A-3-3A engine.

Symbol	PGD tool	PUMPA
n [rpm]	31452	31494
Torque [Nm]	65.2	72.93
Power [KW]	2171	2405.2
Head ΔH [m]	5119	5138.32
Discharge density ρ_d	68.686	68.639
Outlet Diameter D_2 [m]	0.173	0.1796
Exit Blade Height [m]	0.0062	0.0058
Discharge Temperature T_d [K]	26.52	26.47

Moreover, the results provided by the PGD tool for the velocity triangles at both the inlet and outlet sections are summarized in Table 3 and Fig.2.

Table 3. Velocity triangle

Symbol	Outlet	Inlet Section
Head Coefficient ψ	0.6	
Flow Coefficient φ	0.076	
Pheriferical velocity u [m/s]	289	133.78
Tangential component of absolute velocity c_u [m/s]	236.5	89
Relative velocity w [m/s]	57	38.3
Tip blade angle β [°]	22.7	39.6
Flow angle α [°]	5.3	15.3
Diameter D [m]	0.176	

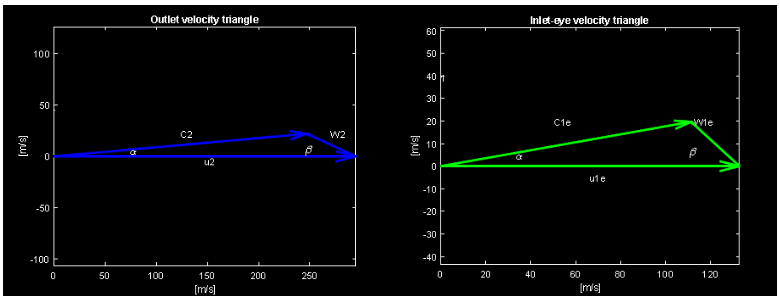

Fig. 2. (a) Outlet velocity triangle; (b) Inlet velocity triangle.

4.2. VINCI engine

Vinci is a new-generation upper-stage cryogenic rocket engine for launch vehicles [6]. It 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 engine is a cryogenic expander cycle rocket engine, is bi-propellant, fed with liquid hydrogen and liquid oxygen. Engine data available in literature for the VINCI rocket are summarized in Table 4 [7].

Table 4. Engine Data VINCI

Engine Data			
Thrust	180 [KN]	Turbine pressure inlet	180 [bar]
Fuel Flow Rate (LH2)	5.8 [Kg/s]	Temperature inlet turbine gas hydrogen	240 [K]
Speed	90000 [rpm]	Turbine pressure outlet	90 [bar]
Power	2800 [KW]	Pressure chamber	60.8 [bar]
Centrifugal Pump Pressure discharge	225 [bar]	Expansion ratio	240
Pressure drop cooling system	45 [bar]	Nozzle exit diameter	2.2 [m]

The PGD tool design results and their comparison with the experimental data are provided in Table 5; once more, fairly good agreement can be observed between the available data and the PGD results.

Table 5. Comparison between PGD results and experimental data

Symbol	PGD tool	VINCI
n [rpm]	89980	90000
Torque [Nm]	297.3	296
Power [KW]	2802	2800
Outlet Diameter D_2 [m]	0.155	1.16

The PGD tool design results for velocity triangle at the inlet and outlet sections are summarized in Table 6.

Table 6. Velocity triangle

Symbol	Outlet	Inlet Section
Head Coefficient ψ	0.6	
Flow Coefficient φ	0.077	
Pheriferical velocity u [m/s]	730.4	299.5
Tangential component of absolute velocity c_u [m/s]	589.4	222
Relative velocity w [m/s]	152	101
Tip blade angle β [°]	21.77	39.6
Flow angle α [°]	5.46	16.12
Diameter D [m]	0.155	

5. Preliminary Design of a Centrifugal Pump for Methane Expander Rocket Engine

One further application of the PGD tool is given in this paragraph: it consists in the preliminary design of a turbo-pump for the Methane Expander Cycle Rocket Engine (MECRE), similar to the LM10-MIRA, currently under development within an international collaboration between the Italian company AVIO and the Russian company KBKHA [8].

Since the available information for this methane - oxygen rocket is limited to the thrust, NASA's Rocket Propulsion Analysis (RPA) [9] software was used to guess the chamber data, which are summarized in Table 7.

The turbopump designed for the LM10 is characterized by a low volumetric flow pump with a high pressure rise, achieved with only one centrifugal stage.

Table 7. Engine Methane Data RPA

Engine Data	
Thrust	70 [kN]
Specific impulse	371.34 [s]
Total mass flow rate	19.21 [Kg/s]
Oxidizer mass flow rate	15.21 [Kg/s]
Pressure chamber	55 [bar]

The PGD tool design results for the MECRE engine are provided in both Table 8 and Table 9 and the design results for the velocity triangle at the inlet and outlet sections are also shown in Fig. 3.

Table 8. PGD tool results

Result	
ΔHead	3392 [m]
Speed n	44780 [rpm]
Torque	62.26 [Nm]
Pressure inlet	1.69 [bar]
Temperature inlet	114 [K]
Density inlet	418.93 [Kg/m3]
Pressure discharge	162 [bar]
Temperature discharge	121.6 [K]

Table 9. Velocity triangle

Symbol	Outlet	Inlet Section
Head Coefficient ψ	0.607	
Flow Coefficient φ	0.074	
Pheriferical velocity u [m/s]	236.36	106.36
Tangential component of absolute velocity c_u [m/s]	197.5	78.12
Relative velocity w [m/s]	42.66	32.2
Tip blade angle β [°]	24.39	28.72
Flow angle α [°]	5.098	11.20
Diameter D [m]	0.097	

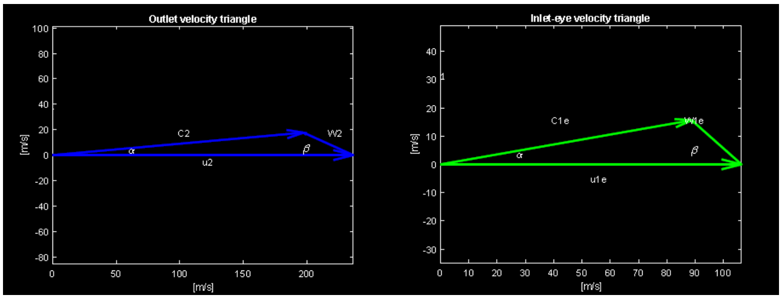

Fig. 3. (a) Outlet velocity triangle; (b) Inlet velocity triangle.

6. Sensitivity Analysis

In this section we show that the PGD tool is capable of performing parametric studies, such as those needed for its future inclusion in an optimization process. This capability is demonstrated in Fig. 4, which shows the variation of head, efficiency and power required as a function of the mass flow rate for the first stage of the centrifugal pump of the RL10A-3-3A engine. The rotational speed has been kept constant at 31452 [rpm].

In this figure, the Head is in [m], the mass flow rate in [Kg/s]; while power in [kW]. In particular, H was scaled by a factor of 10.

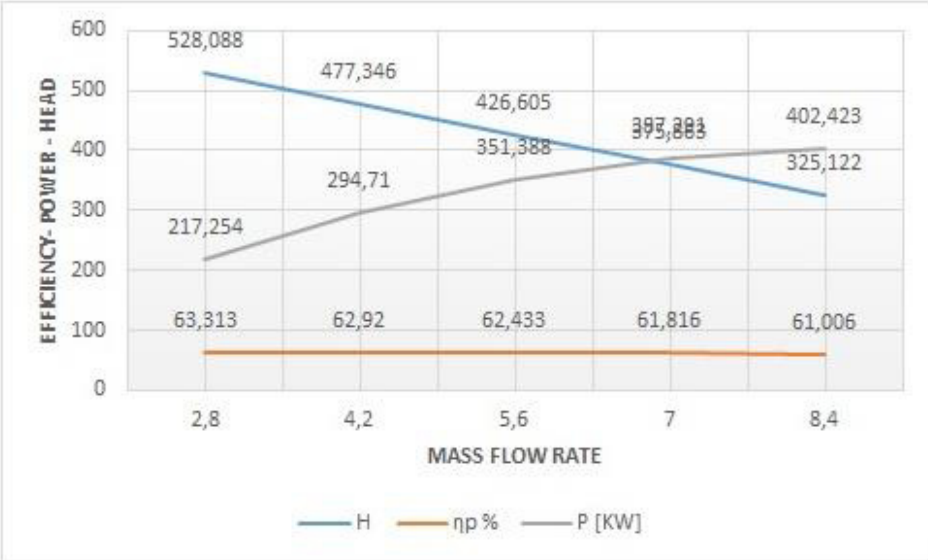

Fig. 4. Characteristic Curve RL10A-3-3A

In the similar way, the characteristic curve of the MECRE engine is shown in Fig 5.

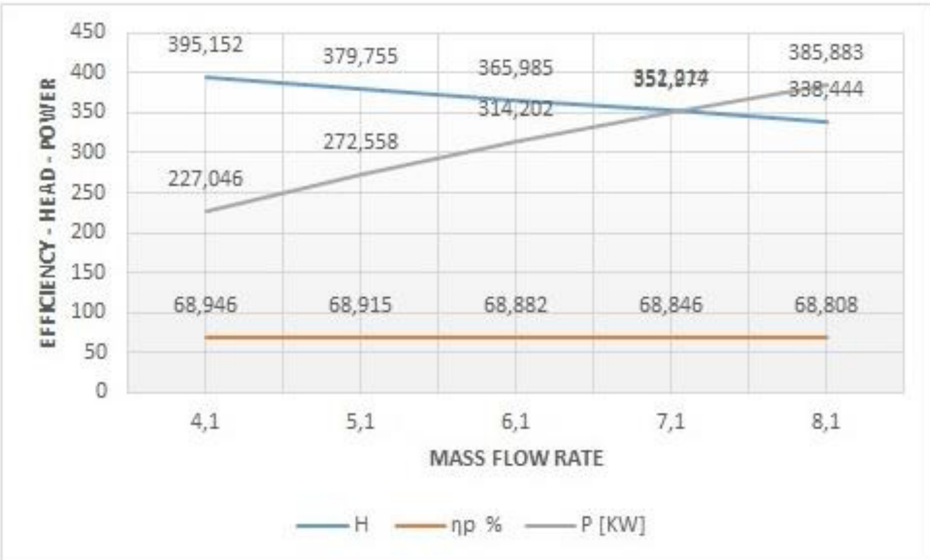

Fig. 5. Characteristic Curve MECRE

7. Conclusion

Liquid hydrogen is the fuel that provides the best performance, so it is often used in launchers. It has the disadvantage of a very low density, also has a very low boiling temperature, due to what are needed large tanks for the storage and centrifugal pumps with a high number of revolutions. The sizing of a pump for hydrogen is very complicated because the high number of revolutions creates a suction pressure drop that triggers the cavitation phenomenon. Regarding the methane represents an innovative and alternative fuel to hydrogen, and is currently in phase of study for LRE.

The PGD MatLab code developed in this work is a fast predicting methodology that is able to determine the global geometry and performances of the turbo-pumps used in Liquid Rocket Engines. Model predictions for the RL10A-3-3A and VINCI engines have been validated using the available experimental data and, for the RL10-3-3A engine, also using the simulation results provided by the PUMPA code developed at NASA. For both engines, good agreement has been found between the data available in the literature and the PGD simulations. The tool was then used to predict the main geometrical parameters and performance of a Methane turbopump feed system.

Future developments include the design of the blade profile and the performance prediction of the gas turbines used to drive the pumps.

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