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Modeling of a blow-down propulsion system

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Lockheed Martini Group

Alessandro Pallotta	alessandro1.pallotta@mail.polimi.it	10712370
Alex Cristian Turcu	alexcristian.turcu@mail.polimi.it	10711624
Chiara Poli	chiara3.poli@mail.polimi.it	10731504
Daniele Paternoster	daniele.paternoster@mail.polimi.it	10836125
Marcello Pareschi	marcello.pareschi@mail.polimi.it	10723712
Paolo Vanelli	paolo.vanelli@mail.polimi.it	10730510
Riccardo Vidari	riccardo.vidari@mail.polimi.it	10711828

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Notation

LRE	Liquid Rocket Engine
LOX	Liquid Oxygen
RP-1	RP-1 fuel
AM	Additive Manufacturing
O/F	Oxidizer to Fuel ratio

1 Introduction and literature overview

In this work a preliminary design of a 1kN semi cryogenic LRE (LOX/RP-1) equipped with a blow-down feeding system is discussed. In particular, a first literature analysis was done in order to review previous studies regarding this particular architecture. Recent developments in additive manufacture (AM) techniques were analyzed to obtain some knowledge regarding processes and precision of this new frontier. Moreover, due the reduced size of this system, some criticalities regarding boundary layer and erosion losses were researched. The second part of the paper aim at designing the engine with some imposed initial conditions and some assumptions. The whole dimensioning of the system, including the tanks and feeding lines, is carried on including the dynamics of the system. The final sizing will accomplish the maximization of the total impulse, with the initial and final constraints. An off-design analysis is then performed to quantify the performances with nozzle losses and AM uncertainties. Finally, a feasibility analysis of nozzle fuel cooling is discussed.

1.1 Blow-down heritage

The blow-down architecture is the simplest feeding technique for LRE since it does not require additional pressurizing gas tanks with failure-prone pressure regulator valves nor complex turbomachinery. The simple scheme includes only two liquid propellant tanks filled with helium or nitrogen, eventually separated by a membrane. The major downsides of this simplicity is relative to the non-stationarity of the tank pressures that induce chamber pressure drop, decrease of propellant mass flow rate and as a consequence O/F ratio variation. This chain of events degrades performances overtime and must be carefully evaluated since combustion efficiency relies upon viable domains of injection pressure and correct mass flow ratio. The interest on blow-down is although justified with respect to well-known pressure regulated feed system since this last can also manifest some criticalities in terms of long-term reliability. In particular, propulsion systems play crucial roles for mission success, such as long interplanetary trips, and they must ensure failure-free lifetime. This is a major concern when focusing on pressure regulated feeding lines in which a pressure regulator valve is present. This kind of elements can be quite complex and hence add a weakness for the whole system[1]. Considering these facts, a blow-down type architecture could be of interest since it decrease system complexity. Moreover, different feasibility analysis for blow-down units are present in the literature in which also an external re-pressurization tank is considered[2]. This is an upgrade that allows to recover performance of the feeding pressure and hence combustion properties. Although the valve complexity is removed since a pyro valve can be used to discharge the gas with a single shot application, the eventual re-pressurization can be a crucial point as the sudden change could induce unwanted instabilities. Other configurations could foresee the use of a Venturi valve to maintain constant mass flow rate by cavitating the liquid and choking the flow on the feeding line. However, neither extra tank nor Venturi valves will be considered in this work in order to meet the requirements presented in (reference a section successiva).
The whole evaluation of the dynamics of the examined propulsion system was not based upon previous works, instead a self-made model was developed.

1.2 Additive manufacturing state of art

1.3 Analysis of losses

2 Modeling of propulsion system

Initial considerations (req + hyp / assumptions + constraints + criteria)
Flowchart

2.1 Tanks sizing

2.2 System dynamics

3 Results analysis

4 Nozzle losses

5 Additive manufacturing influences

Additive manufacturing allows to create complex shapes at a lower cost, but it doesn't allow to obtain low roughness values, causing performance losses in the system. Thus, following the additive manufacturing technology choice explained in subsection 1.2, a value for the discharge coefficient C_d can be estimated from the chart in Figure 1[3], selecting a diameter value of around 1 mm as calculated in section 2 and a short-tube with conical entrance shape.
A further analysis has been developed to take into account possible variations in the injectors' diameters due to imperfections in processing. Inspecting data for laser power bed fusion manufacturing, the standard deviation from a nominal diameter of 1.903 mm is 0.0485 mm[4]. Linearly scaling the value found in literature, it can be adapted for the case analyzed as shown in Table 1.

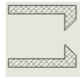
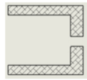
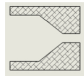
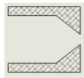
Orifice Type	Diameter (mm)	Discharge Coefficient	Diagram
Sharp-edged orifice	Above 2.5 Below 2.5	0.61 0.65 approx.	
Short-tube with rounded entrance	1.00 1.57	0.88 0.90	
Short-tube with conical entrance	0.50 1.00 1.57 2.54 3.18	0.7 0.82 0.76 0.84-0.80 0.84-0.78	
Sharp-edged cone	1.00 1.57	0.70-0.69 0.72	

Figure 1: Discharge coefficients

	Oxidizer injectors	Fuel injectors
Nominal diameter [mm]	1.0295	1.0354
Standard deviation [mm]	0.0262	0.0264
Number of injectors [-]	6	3

Table 1: Nominal values and standard deviations for injectors

Considering the injectors' diameters as random variables with normal distribution characterized by a mean value and a standard deviation corresponding respectively to the coefficients shown in Table 1, a statistical analysis has been developed to examine the effects of manufacturing imperfections. This random phenomenon causes the variation of multiple propulsion parameters with respect to their nominal value, as will be discussed.
Following the diameters' analysis, the total area of both the propellants' injectors has been calculated, to then find the actual mass flow rate entering the combustion chamber and the O/F ratio, all affected by the random variations discussed above.

$$A_{inj,tot,p} = \sum_{n=1}^{N_{inj,p}} \left(\frac{\pi (d_{inj,p,n})^2}{4} \right) \tag{1}$$

$$\dot{m}_{inj,tot,p} = A_{inj,tot,p} \cdot C_d \sqrt{2 \Delta p_{inj} \rho_p} \tag{2}$$

These modified values then enter the computation explained in section 2, making the uncertainty to propagate affecting the engine's performance. The whole process is repeated 50 times in order to have a more accurate statistical analysis, allowing to study both each simulation and the average of them as shown in the following graphs.

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The mass flow rate, dependent on the injectors' cross sectional area, is slightly affected by the variation of their diameter, very small compared to the nominal one. However, the explained fluctuations can combine generating more observable effects, as seen in ///GRAFICO O/F///, describing the progress of the O/F in time for each simulation. The high deviation from the nominal value is due to its definition as a fraction, greatly affected by the combined variations of its terms. O/F is a crucial parameter in the design of a propulsion system, from which many other variables depend. The temperature of the combustion chamber is one of them, being obtained from the NASA-CEAm software, which, among others, takes as input the O/F ratio and the combustion chamber pressure, related to the tank pressure through the injectors' areas and hence varying due to the analyzed imperfections. Strictly in relation with the mass flow rate and the oxidizer to fuel ratio and connected to many other parameters, also thrust and specific impulse are influenced.

Another characteristic worth to mention is the convergence of all parameters to their mean value during each simulation. In fact, as shown in Equation 3, Δp_{inj} depends quadratically on mass flow rate, which is high in the first moments of simulation. For this reason, the effect of imperfections is clearly visible in the beginning.

$$\Delta p_{inj} = \left(\frac{\dot{m}_{inj,tot,p}}{A_{inj,tot,p} * C_d} \right)^2 * \frac{1}{2 * \rho_p} \tag{3}$$

As the pressure in the tanks diminishes, mass flow rates and velocities in the feeding lines decrease, influencing the pressure cascade, including the pressure jump at injectors. This causes a gradual reduction of the effect of the injectors' areas imperfections and the variation of consequent parameters, which in each simulation settle down to converge to the nominal value, since the blow-down ratio was kept constant.

6 Cooling analysis

Bibliography

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