POLITECNICO
MILANO 1863

Modeling of a blow-down propulsion system

Course of Space Propulsion
Academic Year 2023-2024

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

Contents

Notation

LRE	Liquid Rocket Engine
LOX	Liquid Oxygen
RP-1	RP-1 fuel
AM	Additive Manufacturing
O/F	Oxidizer to Fuel ratio [-]
ε	Expansion ratio [-]
ε_{con}	Contraction ratio [-]
L^*	Characteristic length [m]

1 Introduction and literature overview

In this work a preliminary design of a 1 kN 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 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 in pressure 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: DRY-1

The workflow for the sizing of DRY-1 is introduced by Figure 1 and it is divided into three stages:

- **Input data**: the problem is set up.
- **Nominal sizing**: the system is sized according to initial conditions and general assumptions.
- **Dynamics**: an iterative process is set up to model the blow-down dynamics and finalize the sizing.

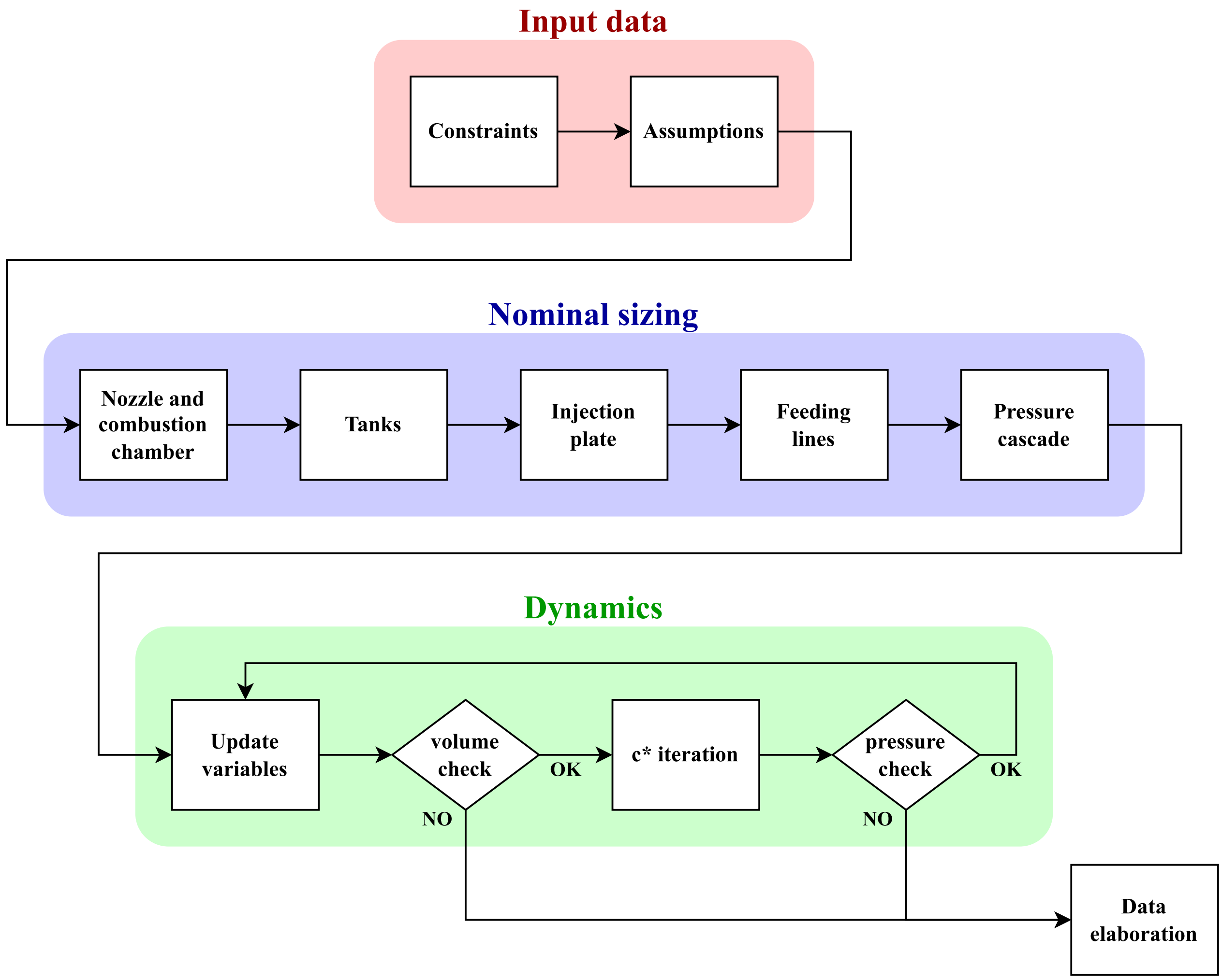

Figure 1: Flowchart of the sizing

2.1 Input data

The input data defined different kind of requirements, related to operability environment, engine performance, size constraints, chemistry, architecture and manufacturing techniques. Regardless of the development of the engine design, the system shall respect the following pinpoints:

- **Environment**: vacuum for the whole operation.
- **Thrust**: initial magnitude of 1 kN, no lower boundary.
- **Chamber Pressure**: initial value of 50 bar, always above 20 bar throughout the whole mission.
- **Allocated Space**: tanks, combustion chamber and convergent nozzle occupancy is exactly 80% of the volume occupied by a cylinder of 1 meter diameter and 2 meter length. No bounds on the extension of the divergent.
- **Propellants**: semi-cryogenic couple of LOX and RP-1.
- **Architecture**: blow-down type.
- **Manufacturing**: all the system is produced in AM, no restriction on material nor techniques.

The nominal sizing refers to the design of the overall system considering the imposed initial constraints as static conditions. This design choice was dictated by the dynamics of the blow-down system, which imposes

the maximum flow rate at the beginning of the mission, leading to the oversizing of the engine throughout the rest of the mission.
Various hypothesis were necessary to develop the system, this values are reported in Table 1.

O/F $[-]$	ε $[-]$	ε_{con} $[-]$	L^* [m]
2.42	300	10	1.143

Table 1: Hypothesis from literature and previous design

The choices of L^* and O/F were only dictated by the propellant couple[3], while ε was chosen as the characteristic of the engine refers to an in-space application[4]. Regarding the value of ε_{con} a mean value between 5 and 15 was taken. Smaller values entails longer combustion chamber and small cross sectional area, with large pressure drops. Larger values refers to bigger chamber cross sectional area, with limited length for the combustion. From the literature the suggestion for the choice of this value is to refer to previous successful engines design, considering the same application[5]. Therefore, a 400N Bi-Propellant apogee motor was taken as reference and revealed a value of $\varepsilon_{con} \approx 10$[4].

2.2 Nominal sizing

After defining the main input data, the workflow is carried out as shown in Figure 1. All the combustion simulations were performed with Nasa-CEA software, implemented in Matlab (CEAM). In particular the "rocket problem" was considered, imposing frozen equilibrium, infinite combustion chamber (M_c = 0), initial injecting temperatures of the propellant equal to the storage temperatures. The chamber pressure was set as P_c = 50 bar and the mixture ratio as O/F = 2.42. Latter refinement of this last value will be performed. The output values used from the simulation are represented (vacuum value is considered for the c_T):

c^* $[m/s]$	c_T $[-]$	T_c $[K]$
1851	1.935	3709

Table 2: First run on CEAM

2.3 System dynamics

3 Results analysis

4 Nozzle losses

5 Additive manufacturing influences

6 Cooling analysis

Bibliography

[1] Robert-Jan Koopmans et Al. “Propellant Tank Pressurisation with Helium Filled Hollow Glass Microspheres”. In: (2015).

[2] H. C. Hearn. “Design and Development of a Large Bipropellant Slowdown Propulsion System”. In: (1995).

[3] G.P.Sutton. “Rocket Propulsion Elements”. In: (2017).

[4] Ariane Group. *Chemical bipropellant thruster family*. Site: `https://www.space-propulsion.com/`. 2021.

[5] Huzel and Huang. “Modern Engineering for design of Liquid-Propellant Rocket Engines”. In: (1992).