Pressure regulation strategy for a launcher's pressurisation system

0D/1D Model Development and Analysis

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TUDelft

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Preface

Abstract

This thesis addresses the development of a pressure regulation strategy for the pressurization systems of the fuel and oxidizer tanks in the first stage of Maiaspace's mini-launcher. The work focuses particularly on the creation of pressurization system models capable of replicating system behaviour with sufficient accuracy for design studies, while prioritizing fast development and computational efficiency. Reliable tank pressurization is a critical requirement for mission success, as deviations in propellant or tank pressure can compromise feed system operation or even lead to structural failure of the tanks. This study contributed to refine the design, assess its functionality, develop a regulation strategies, and establish a plan for system-level validation of two proposed options of the pressurisation system.

The modelling approach employs 0D/1D simulations, selected for their balance between fidelity to thermodynamic, fluid-dynamic, and heat-transfer phenomena and manageable computational cost. Key assumptions relate to the simplifications inherent in such models, particularly regarding heat transfer and fluid stratification. The models were partially validated against available test data, and a provisional test plan has been defined to extend validation to the remaining aspects.

The results show that the models successfully reproduce the global behaviour of the pressurization system, capturing pressure losses, transient dynamics, and subsystem interactions within the expected performance envelope. Regulation strategies for both the oxygen and methane tank pressurization systems were developed. Time-series comparisons between simulations and test data confirm the representativeness of the models, though discrepancies, primarily linked to heat transfer effects and ullage dynamics, highlight the accuracy limitations of the 0D/1D approach.

Overall, this work contributes to Maiaspace's system design process by providing a validated framework for evaluating pressurization strategies during early development stages.

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Nomenclature

Abbreviations

Abbreviation	Definition
CFD	Computational Fluid Dynamics
CFRP	Carbon fiber-reinforced plastic
ESPSS	European Space Propulsion System Simulation
ISO	International Organization for Standardization
LCH_4	Liquid Methane
LH_2	Liquid Hydrogen
LOX	Liquid Oxygen
NIST	National Institute of Standards and Technology
PID	Proportional–Integral–Derivative
R1, R2, ... R4	Representation Level
TRL	Technology Readiness Level
0D	Zero-Dimensional
1D	One-Dimensional

Symbols

Symbol	Definition	Unit
A	Cross Section	
c_d	Discharge Coefficient	null
C_m	Flow Characterisation Parameter	
c_p	Specific Heat at Constant Pressure	[J/(kg K)]
c_v	Specific Heat at Constant Volume	[J/(kg K)]
D	Diameter	[m]
F	Thrust	[N]
h	Height	[m]
h_c	Convective Heat Transfer Coefficient	[W/(m^2 K)]
k	Thermal Conductivity	[W/(m K)]
K	Incompressible Pressure Loss Coefficient	[1/m^4]
L_c	Characteristic Length	[m]
$\dot{m}$	Mass Flow Rate	[kg/s]
Nu	Nusselt Number	null
p_{down}	Downstream Pressure	[Pa]
Pr	Prantdl Number	null
p_{up}	Upstream Pressure	[Pa]
$\dot{Q}_{conv}$	Convective Heat Flow Rate	[W]
Q	Volumetric Flow Rate	[m^3/s]
r	Radius	[m]
R		
Ra	Rayleigh Number	null
S_h	Hydraulic Section	[m]
T_{down}	Downstream Temperature	[K]
T_{up}	Upstream Temperature	[K]
v_e	Exhaust Velocity	[m/s]

Symbol	Definition	Unit
γ	Heat Capacity Ratio	null
Π_{crit}	Critical Pressure Ratio	null
ρ	Density	[kg/m^3]
ζ	Adimensional Pressure Loss Coefficient	null

γ	Heat Capacity Ratio	null
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Introduction

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The focus of this research was to develop a pressure regulation strategy, through the implementation of 0D/1D models, for the pressurisation system of the first stage of Maiaspace's launcher. Pressurization systems are responsible for injecting or generating a gas to pressurize propellant tanks; tank pressurization is necessary to ensure a correct functioning of the propellant feed system and to support the structural integrity of the propellant tanks. Failing to meet the requirements for propellant or tank pressure could directly jeopardize mission success. Verifying the proper functioning of the pressurisation system from the earliest development stages, and repeating this verification after each design iteration, is essential for advancing the launcher design. Therefore, verification is required at every stage of development, which poses a critical bottleneck in fast-paced launcher programs: accurate studies are computationally expensive, whereas faster methods often sacrifice precision. 0D/1D models provide a practical compromise between simulation speed and accuracy. This thesis investigates their suitability for the cryogenic fuel and oxidizer pressurisation systems of Maiaspace's mini-launcher, with their performance partially validated against test results and complemented by a provisional test plan.

In this introduction chapter, the context and the relevance of this research are introduced in section 1.1, followed by the formulation of the main research questions and the definition of the research objective, respectively in section 1.2 and 1.3. To conclude, the methodology used to carry out the research during the thesis is introduced in section 2.1. A comprehensive literature review was performed before the start of the thesis research phase, which is reported in chapter 3. This review lead to a the formulation of the main research questions, as well as the research objective. Subsequently, chapter 4 describes the implementation and assumptions of the 0D/1D pressurization system models. The outcomes and results of the simulations performed on these models are presented and discussed in chapter 5 in terms of pressurization system functioning, with a particular focus on the definition of the pressure regulation strategy. chapter 6 of this thesis deals with the validation plan of the models. Finally, chapter 7 concludes this report by stating the overall conclusions of the work carried out during the thesis and recommendations for future studies. Some appendices are included at the end of the report, to describe specific modelling choices or discuss results that deviate from the main thesis scope.

1.1. Research Context and Relevance

In recent years, the space sector has undergone a global transformation, largely driven by the emergence of the NewSpace Economy, which fosters competition and promotes the rise of new companies. Furthermore, the high return on investments in space technologies makes the sector particularly attractive for new businesses to thrive in [46]. This phenomenon has accelerated the creation of new companies and contributed to the ongoing shift toward the privatization of space, resulting in the proliferation of commercial space enterprises and start-ups. Given the remarkable evolution of space technologies and the surge in satellite applications, the demand for satellite launches has increased substantially. This growing need has, in turn, driven launcher technologies to advance at an astonishing pace over the past decade [6]. Some representative examples are presented below.

With the advent of NewSpace, small launchers' development has seen a significant increase. And fitting into the frame of the privatization of space and the start-up age, the most significant change is the growing presence of launch service providers, or companies specializing in launching satellites and spacecraft with private-designed rockets [24]. In a single decade, 2015-2025, new rocket types, and new actors, have entered operation all over the world: SpaceX Falcon Heavy/Starship, ULA Vulcan, China new modular Long March fleet (LM 6/7/5/11/9), Indian GSLV MkIII, Japan H3 or Russia Angara and Soyuz 5. On top of this, more than 100 private small launchers projects are in-development [50] in several start-ups: Maiaspace, RFA, PLD Space Isar Aerospace are among those in Europe. Despite the significant growth of such projects, the analysis suggest that there is eventually only room for a handful of small launchers by mid of next decade [50].

Maiaspace is one of the emerging players in this evolving small launcher landscape. As a European startup focused on developing reusable launch vehicles, Maiaspace aims to provide dedicated, cost-effective, and flexible access to space for small satellite operators. Positioned at the intersection of advanced aerospace engineering and the growing commercial space sector, the company is working on a next-generation launcher designed with reusability, efficiency and sustainability in mind. Within this competitive and rapidly expanding market, Maiaspace stands out by emphasizing sustainable launch solutions and two launch vehicle configurations to adapt to the mission needs: reusable and expandable. Its presence reflects the broader trend of private companies playing an increasingly central role in space access, particularly in serving the growing demand for launching small satellites into customized orbits. By integrating itself into the NewSpace ecosystem, Maiaspace contributes to redefining space transportation dynamics in Europe and beyond.

The emergence of numerous start-ups developing small launch vehicles is primarily driven by the advantages they offer, most notably the potential for faster development. Depending on their size and intended purpose, these launchers generally provide greater flexibility in orbit selection, scheduling of launch dates, and allocation of resources exclusively to small satellites, capabilities that larger launch vehicles cannot offer as readily, while also typically requiring longer development times. However, small launchers also have their drawbacks. They are currently the least cost-effective option on the market since most are still under development [37]. In addition, in terms of reliability, the majority of the small launchers in development have yet to make their first orbital flights thus their reliability still remains to be proved. In this context, there is a need to improve the design, reliability and development time of these systems since the attractiveness of a launcher depends on improving their performance and begin operation faster than the competitors. On average, 2 to 4 years of delay in the development of these launchers are common for the new rising companies. Therefore, it is crucial to establish a more effective design process for each subsystem, and this can be done by compromising between accurate system modelling and simplified approaches that trade some precision for faster computation, thereby enabling quicker iterations in the design process.

This thesis focuses on the pressurisation subsystem of Maiaspace's launcher first stage. The pressurisation system ensures that propellants (fuel and oxidizer) are delivered to the engine under the correct pressure, a function that is both safety-critical and performance-defining. Given its importance and complexity, especially under the varying conditions experienced during flight, this subsystem requires careful modelling and validation. The main goal of this work is to design and evaluate a pressure regulation strategy that supports system reliability and performance improvement during the launch phase. By simulating different operating conditions, the project aims to provide insights that will directly inform engineering decisions and testing protocols within the company's development roadmap. Through this work, the project aims to contribute to the body of knowledge by offering a methodology for launchers sub-system development, supported by initial validation activities. This approach, combining design efforts with targeted empirical validation, could serve as a template for other early-stage aerospace ventures navigating similar challenges. While the validation presented is not yet complete, the remaining activities are foreseen and documented in a dedicated test and validation plan.

From an academic perspective, the development of a reliable pressure regulation strategy for tank pressurization intersects multiple research domains, including systems engineering, thermo and fluid dynamics, control systems, and aerospace propulsion. A correct ullage pressurization is needed for several reasons, namely to support the structural integrity of the tanks under launch and flight loads, to provide sufficient net positive suction head for pump-fed propulsion systems to prevent cavitation at

the pump impeller, and reduce propellant losses caused by boil-off during flight [38]. On the applied side, the aerospace industry increasingly depends on high-fidelity system modelling and simulation to shorten development cycles, minimize risk, and validate design decisions early in the process. Simulation tools like the used software offer a platform to model, analyse, and optimize dynamic system behaviour in a multi-physics 0D/1D simulation under various operational conditions.

While several studies treat the accurate modelling of tank pressure evolution dependent on the pressurant gas injection temperature and pressure [33, 29], variable external conditions and filling or draining scenarios [34, 23], complete pressurisation system models are less frequent in literature. However, these models allow to study the functioning of these systems in detail, focusing on the effects that the regulation and the coupling between sub-systems have on the overall pressurization systems functioning. Moreover, existing literature tends to focus more on component level analysis rather than integrated system performance across variable flight scenarios. Some research emphasizes using empirical testing, while others advocate for purely simulation based approaches, revealing a divide in methodological preferences. What remains under-explored is a structured, simulation driven strategy that is rigorously validated through planned physical tests, a hybrid approach with strong potential for improving subsystem design in early stage development.

1.2. Research questions

To define the scope of this research and establish a structured path for the thesis, it was necessary to first develop a strong theoretical and technical understanding of pressurisation systems within liquid rocket propulsion. A detailed review of historical, current, and emerging launcher technologies was conducted, with a particular focus on the role of pressurisation systems in maintaining tank pressure, ensuring correct propellant delivery to the feed-system, and preserving the propellant tanks structural integrity under various flight conditions. In parallel, modelling approaches, from empirical to high-fidelity numerical simulations and from commercial softwares, were analysed to understand their capabilities and limitations in capturing the dynamics of pressurisation systems.

This groundwork helped highlight key challenges in designing pressurisation systems for modern reusable rockets, particularly in the context of mini-launchers like those being developed by Maiaspace. The complexity of integrating such systems into constrained vehicle architectures, while ensuring performance, reliability, and reusability, emerged as a critical area requiring further investigation. Additionally, the need for accurate, system-level simulations to guide design iterations and control strategies became evident.

From this context, the following research questions were formulated to address specific technical gaps and support the design and simulation of Maiaspace's main stage pressurisation system. Each question targets a fundamental aspect of the system, from initial design requirements to numerical modelling, control implementation, and simulation validation, ensuring a comprehensive approach to the study.

RQ.1 What is the design of a pressurisation system for the various configurations of Maiaspace's launcher reusable main stage?

RQ.1.SQ.1 What is the most effective strategy for pressure control within the pressurisation system of Maiaspace's main stage?

RQ.2 What are the numerical simulations that can be implemented on the chosen software to study the pressurisation system in terms of: pressure losses experienced, performance, heat transfer effects on individual components or parts of the system and design modifications due to layout constraints?

RQ.2.SQ.1 To what extent do the implemented simulations yield physically accurate and reliable outputs suitable for informing subsystem design decisions?

1.3. Research objective

Based on the research questions outlined in the previous section, the following research objective has been established for the upcoming MSc thesis:

RO.1 To develop and partially validate a robust pressure regulation strategy for the fuel and oxidizer pressurisation systems of Maiaspace's main stage through modelling and comparison with available tests, with remaining validation planned in a structured test plan.

2

Background

2.1. Methodology

This research employs a simulation-based systems engineering approach to address ge inthe challenges associated with designing and validating a pressure regulation strategy for the fuel and oxidizer pressurisation systems of Maiaspace's reusable main stage. The methodology integrates theoretical analysis, numerical modelling, and simulation validation to investigate the performance and robustness of the pressurisation system under various flight conditions.

The research is conducted within the framework of the AGILE methodology, which Maiaspace adopts to ensure rapid iteration, continuous integration of feedback, and adaptive planning throughout development cycles.

This iterative approach aligns well with the simulation-based development process, allowing progressive model refinement and early identification of design trade-offs and integration challenges.

The theoretical foundation of this work is rooted in the principles of thermofluid dynamics and control systems engineering. Thermofluid dynamics provides the necessary framework to model the behaviour of pressurized fluids in dynamically changing environments, considering factors such as compressibility, pressure drops, and heat transfer. Control systems theory, particularly feedback control and regulation techniques, is essential for defining and analysing the performance of pressure control strategies within the pressurisation loop.

The modelling and simulation tasks are conducted using a commerciam software, a multi-physics 0D/1D system simulation platform widely used in the aerospace industry. This software was chosen due to its capability to accurately represent the physical interactions within fluid, thermal, and control domains, which are all crucial in modelling a pressurisation system, similarly to what is done in [52, 53]. This includes both fuel and oxidizer circuits, complete with tanks, regulators, valves, feed lines, and associated sensors and controllers.

The methodology begins with the definition of system requirements, including target pressures, expected operating ranges, tank capacities, and launch vehicle boundary conditions. Component models are developed using aerospace and thermofluid libraries, representing individual elements such as pressurant gas tanks, regulators, and flow control valves, as well as pre-developed custom component from Maiaspace. Then, these components are integrated into a complete system model, which incorporates control logic to regulate pressure dynamically during simulated flight events. The simulation model is configured to reflect real-world constraints, such as layout limitations, thermal coupling with surrounding structures, and time-varying boundary conditions related to flight profiles.

A central aspect of the methodology is the execution of a comprehensive simulation campaign, which includes nominal operation scenarios, in which the system performs under ideal design conditions, to test the resilience and stability of the overall pressure control strategy. The scenarios considered also explore how layout constraints and thermal interactions affect system behaviour. Key outputs

such as pressure regulation stability, response time, heat transfer effects, and pressurant mass usage are analysed to assess system performance. Particular attention is given to the physical realism of the simulations and their ability to produce results that are both internally consistent and aligned with expected physical behaviour, an aspect that is treated by laying out a comprehensive validation plan.

The simulation results will be compared with empirical data obtained from ongoing and planned system and subsystem tests conducted by Maiaspace. This comparison will serve as a partial verification and validation step for the results of the simulations obtained [31]. Despite the strength of the simulation approach, several limitations must be acknowledged. The absence of complete system-level test, for the system studied, means that full empirical validation of the simulation results is not yet possible. Moreover, some simplifications and assumptions in the simulations, may reduce the accuracy of certain predictions. Nonetheless, by combining a rigorous modelling framework with an AGILE development process and structured verification and validation methodology, this research aims to generate meaningful insights into the design and control of pressurisation systems for reusable mini-launchers, supporting more robust, efficient, and adaptive system development at Maiaspace.

2.1.1. Maiaspace: Company Introduction
Maiaspace was founded in 2022 as a wholly-owned subsidiary of ArianeGroup, building upon the heritage of ArianeWorks, an internal effort aimed at fostering AGILE, experimental development of next-generation space technologies. Its mission is to design, manufacture, commercialize, and operate the first mini-launcher in Europe that is both partially reusable and more environmentally responsible, while maintaining high responsiveness to customer needs and market dynamics.

The company's key offering is the Maia rocket: a two-stage launcher powered by Prometheus engines and designed to deliver payloads to Low Earth Orbit (LEO) or Sun-Synchronous Orbit (SSO). The first stage is designed for reuse, with vertical landing capabilities, while an optional kick stage, Colibri, further enhances its payload flexibility. Depending on configuration, Maiaspace aims to transport payloads ranging from a few hundred kilograms up to 1.5 tonnes (or more with optional stages) to LEO.

Beyond technical innovation, Maiaspace emphasizes sustainability from the outset: using bio-methane/LOX propellants, designing for reuse, eco-responsible practices, and minimizing environmental footprint in launch infrastructure. Furthermore, the company is working from existing facilities, from the former Soyuz launch pad (ELS) at the Guiana Space Centre—for its first flights, aligning with its cost and environmental objectives. Maiaspace targets first launch attempts in a few years, followed by commercial operations. Alongside its technical roadmap, the company has already begun forging partnerships, securing launch site access, and obtaining its first commercial contracts. These efforts underscore the confluence of technological, economic, and regulatory challenges Maiaspace must navigate.

2.2. Maiaspace's First Stage Pressurization System
This section introduces Maiaspace's launcher first stage, with particular emphasis on the design of the pressurization system, which constitutes the focus of the present study. The designs studied represent options for pressurisation system design that were proposed for this thesis work, in addition the work presented here supported their further refinement and the verification of their functionality.

The lower stage of Maiaspace's launcher is powered by three Prometheus engines, fuelled by liquid bio-methane LCH_4 and liquid oxygen LOX. For the two propellant tanks, several different types of pressurization systems were investigated in this thesis. The first option studied consists in the propellant tanks being pressurized with an inert gas which is stored at high pressure stored inside pressure vessels. During nominal pressurisation, the gas undergoes an expansion over a pressure regulator, after the storage vessels. This regulation is needed to meet the constraints on pressure of the downstream components, as well as keeping the tank pressure within a predefined pressure corridor, to achieve correct pressurization of the propellant tank. The pressure is regulated around a target pressure, with minimum and maximum allowable boundaries defined to meet external constraints. In addition, an autogenous pressurization approach was studied for pressurizing the propellant tanks.

3

Literature Review

This chapter presents the review of available literature on pressurization systems that was performed before at the beginning of the thesis to define the orientation of this research, and formulate the research questions and objective presented in the previous chapter. An introduction on the role and importance of pressurisation systems in launchers is given in section 3.1 by justifying the need of these systems whit basic and straightforward relations, and introducing the main constraints. In section 3.2 an overview of pressurisation system types is given, followed by the descriptions of the different types of control used for these systems in section 3.3. At the end of both sections, a trade-off analysis is carried out: first between different system types, and then between the pressure control strategies most suitable for the application considered in this thesis. To conclude the literature review, the various modelling techniques applicable to pressurisation systems are examined according to their level of accuracy and scope of use, whether for targeted investigations or system-level analyses. This is followed by a trade-off aimed at selecting the most appropriate modelling approach to conduct the present study within the context of the company's development framework (section 3.4).

3.1. The need for a pressurisation system

The pressurisation system in a liquid rocket typically consists of high-pressure gas stored in separate tanks or generated by the system, and used to maintain pressure in the fuel and oxidizer tanks. The equations and concepts for this introduction to rocket pressurization are taken from standard rocket propulsion books, Sutton [47] and Zandbergen [55], as well as the standard work on rocket pressurization, in the author's opinion, which is "Rocket propellants and pressurization systems" by Ring [44]. The key parameters governing the pressurisation system are: pressurant gas pressure p_g and temperature T_g, and mass flow rate of the pressurant gas $\dot{m}_g$. The ideal gas law provides a relationship for the pressurant gas:

$$p_g V_g = nRT_g \tag{3.1}$$

where V_g is the volume of the pressurant gas, n is the number of moles of the gas, R is the universal gas constant and T_g is the absolute temperature of the pressurant gas. For a blow-down pressurisation system, the pressure decreases over time as the gas expands, following:

$$P_t(t) = p_{t0} \left(\frac{V_t}{V_t + m_p/\rho_p} \right)^{\gamma} \tag{3.2}$$

where γ is the adiabatic index of the pressurant gas, and p_{t0} is the initial tank pressure. For a regulated pressurisation system, a control valve maintains a constant p_t, ensuring stable mass flow rates.

The mass flow rate of the pressurant gas $\dot{m}_g$ must be sufficient to compensate for the decrease in propellant volume and to maintain the required tank pressure. This mass flow rate is given by the

equation:

$$\dot{m}_g = \frac{d}{dt}\left(\frac{p_t V_t}{R T_g}\right) \tag{3.3}$$

where V_t is the ullage volume in the propellant tank.

Liquid thermal rocket propulsion systems rely on controlled combustion of a fuel and oxidizer to generate thrust. The efficiency and performance of these systems depend heavily on the ability to deliver the propellants at the correct pressure and flow rate to the combustion chamber. The combustion process is influenced by the injection pressure of the fuel and oxidizer, which in turn, is connected to the tank pressurisation, depending on the feed system used. Feed systems are the ones responsible for delivering propellants in the combustion chamber at the desired pressure. Two different kinds of feed system can be used: gas pressure-fed or pump-fed systems, as illustrated in Figure 3.1.
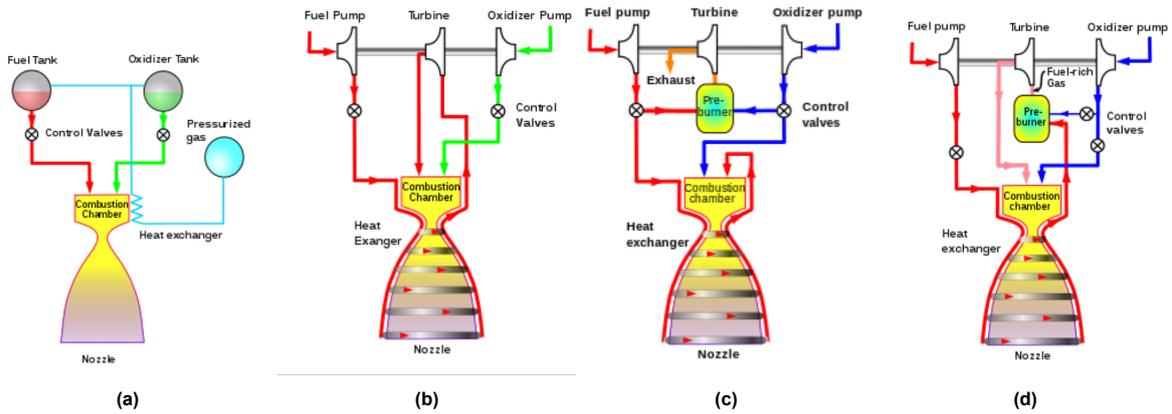
Figure 3.1: Liquid-propellant rocket engine cycles. (a) Pressure-fed cycle. (b) Expander cycle. (c) Gas-generator cycle. (d) Staged combustion cycle. [9].

In pressure-fed systems, propellant pressurisation is vital to ensure the delivery of propellant at target conditions. In this case, the propellant mass flow rate into the combustion chamber $\dot{m}_p$ depends on the pressure in the propellant tanks, which is maintained by the pressurisation system. The flow through the injector can be approximated using the following equation based on Bernoulli's principle:

$$\dot{m}_p = C_d A_i \sqrt{2\rho_p(p_t - p_c)} \tag{3.4}$$

where C_d is the discharge coefficient, A_i is the injector area, ρ_p is the propellant density, p_t is the tank pressure and p_c is the combustion chamber pressure. Since p_t is regulated by the pressurisation system, maintaining adequate pressure ensures a stable and predictable propellant mass flow rate.

In pump-fed systems, efficient propellant pressurization prevents cavitation inside the pumps. A pressurant mass flow rate that is too low will lead to a decrease of pressure in the feeding line, reducing $\dot{m}_p$ and negatively affecting engine performance. Potentially, this phenomenon can lead to cavitation if a pump-fed feed system solution is adopted. Cavitation occurs when the local pressure of the propellant drops below its vapour pressure, causing the formation of vapour bubbles. When these bubbles collapse, they generate intense shock waves that can damage nearby surfaces, such as pump impellers or propellant lines in rocket engines. This phenomenon is especially problematic in high-speed fluid systems, where rapid pressure changes can trigger cavitation, leading to reduced performance and structural damage. Conversely, excessive pressurant flow can add unnecessary mass and complexity to the system.

In addition to cavitation avoidance, the propellant storage tanks must withstand the various loads they will encounter throughout their lifecycle, which represents an even greater challenge for reusable launchers. These loads primarily consist of compressive stress along the launcher's body axis, resulting from atmospheric drag and payload weight on one side and thrust on the other. Excessive compressive
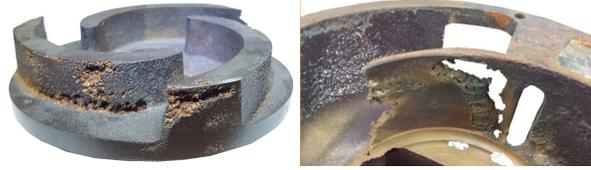
Figure 3.2: Pump Cavitation Damage [7].

Figure 3.3: Buckling Damage on Tank [5].

stress can cause the tanks to suddenly bend and undergo severe deformation, a phenomenon known as buckling.

Stiffeners are usually included to the tank structure to prevent this phenomenon. However, these components add dry mass to the launcher, and might not provide the necessary support to the tank structure in sections where the stiffener is not present. To mitigate this risk the tanks must remain slightly pressurized, typically by several bars, throughout the flight to prevent buckling. An alternative solution would be to add stiffeners to the tank structure, but this would imply adding more mass to the system. Additionally, in configurations with a common bulkhead separating the oxidizer and fuel tanks, precise pressure control is required to ensure the structural integrity of the bulkhead and prevent deformation. Moreover, the shift toward reusable launch systems has significantly impacted the design philosophy of pressurisation systems. Unlike expendable vehicles, which are only required to perform under nominal conditions for a single flight, reusable systems must withstand repeated thermal, mechanical, and pressure cycling across multiple missions. Materials and system layouts must be chosen to resist fatigue, corrosion, and seal wear over repeated flights. This demand for reusability adds another layer of complexity to pressurisation system design but is essential for achieving the cost and operational benefits associated with reusable launch vehicles.

For a bang-bang regulated system the pressure is kept within a lower and upper boundary; the first constrained by the minimum pressure to prevent pump cavitation in pressure-fed systems and buckling of the tank structure, the latter constrained by the maximum pressure sustainable by the tank structure. To define the upper and lower boundary for the regulation ($p_{upper-reg}$ and $p_{lower-reg}$), however, a margin needs to be applied to take into account the valve opening and closing delay, which includes algorithm delay in sending the signal dt_{alg}, valve initial response time dt_r and manoeuvring time dt_m. In addition, another margin should be considered to take into account the accuracy of the pressure sensor reading dp_{uncert}. Based on this, the upper and lower margins for bang-bang pressure regulation can be expressed as:

$$p_{upper-reg} = p_{upper-bound} - \frac{dp}{dt_{open}}(dt_{alg} + dt_r + dt_m) - dp_{uncert} \qquad (3.5)$$

$$p_{lower-reg} = p_{lower-bound} + \frac{dp}{dt_{closed}}(dt_{alg} + dt_r + dt_m) + dp_{uncert} \qquad (3.6)$$

This type or regulation consists in opening a valve when the tank pressure reaches the lower boundary, thus increasing the mass flow rate and pressure, and closing it when the pressure reaches the upper boundary. Therefore, the mass flow rate in Equation 3.3 should be expressed as the difference between the available mass flow rate $\dot{m}_{available}$ and the mass flow rate needed $\dot{m}_{needed}$ to keep the tank pressure stable. The pressure variation over time dp/dt depends on this difference, as showed in the following equation:

$$\frac{dp}{dt} = \frac{\gamma \frac{R}{M_u} T_u}{V_u}(\dot{m}_{available} - \dot{m}_{needed}) \tag{3.7}$$

where T_u and V_u are the ullage temperature and volume.

In conclusion, in this section the need for a pressurization system was justified, and the main constraints for tank pressure regulation introduced. In the next chapter the design, purpose and functioning of several pressurisation solutions are presented and explained, as well as the state of the art of the systems used on current launchers.

3.2. Pressurisation Systems

In the previous chapter, the need for a pressurisation system for the propellants was justified by describing the fundamental equations that link the propellant injection pressure to the thrust equation and describing the possible damages caused by low pressure in the lines and tank.

Pressurisation system design begins with a preliminary study of the various design approaches, this can become a relatively complex task due to the great number of tank-pressurisation techniques that have been developed. The five principal selection criteria for selecting a pressurization system design are: mission and vehicle requirements, fluid and material compatibility, system reliability, cost, and system weight and size, according to [19]. In this chapter, several design solutions and pressurisation systems configurations for reaching a controlled nominal pressure value of the tank ullage are presented in subsection 3.3.1. Consequently, the equation for pressurant mass estimation is derived in subsection 3.2.2. In conclusion, the state of the art of the current pressurisation solutions for launchers are presented and discussed in subsection 3.2.4.

3.2.1. System Type and Pressurant Selection

The selection of the pressurant gas is a critical aspect of pressurisation system design, particularly with respect to its compatibility with the propellants it will come into contact with. Additionally, the overall complexity of the system must be carefully evaluated to determine whether it introduces potential challenges or contributes positively to system performance and reliability.

This chapter presents three primary types of pressurisation systems, categorized according to the source and nature of the pressurant gas.

Inert-Gas Systems
Modern inert-gas pressurisation systems primarily utilize helium or nitrogen as the pressurant, with helium often being the preferred choice over nitrogen and other gases. This preference is due to the lower molecular weight of helium, which provides a system-weight advantage. Additionally, helium has a lower condensation temperature, a crucial factor influencing the amount of residual gas remaining after expulsion from the storage tanks or during ullage slowdown. Furthermore, helium's thermodynamic properties result in a smaller pressure rise compared to nitrogen during lock-up periods in the mission cycle.

When an inert-gas pressurant is in direct contact with the propellant, the ullage space contains both the pressurant and some evaporated propellant. This stable condition occurs when the propellant's vapour pressure aligns with the liquid level temperature. Consequently, the partial pressures of both the pressurant and the propellant vapour can fluctuate during flight, depending on factors such as the propellant surface temperature, gas solubility, and ullage-gas venting loss. These aspects are especially critical when calculating the required pressurant mass for propellants with high vapour pressures.

Inert-gas pressurisation systems vary in complexity, from simple blow-down systems without temperature control to advanced storage vessels equipped with multiple heat exchangers. More sophisticated
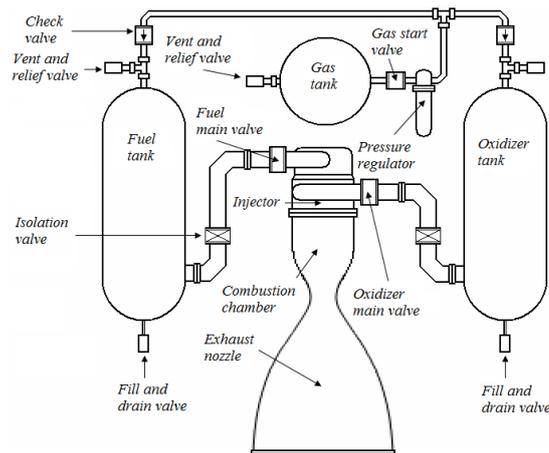
Figure 3.4: Schematic of a General Inert Gas System for the Fuel and Oxidizer [48].

designs aim to minimize the amount of required pressurant and reduce the size and weight of storage containers. For instance, in cryogenic-propellant propulsion systems, helium is stored at the lowest possible temperature to maximize its density. It is then heated for use as a pressurant.

In the Saturn S-IC system, helium was stored within the LOX tank and subsequently heated using a turbine-exhaust heat exchanger to provide pressurisation for the RP-1 fuel tank [21]. The Saturn S-IVB system took this a step further by storing helium within the LH_2 tank, achieving even lower storage temperatures. The helium was then heated via an engine-mounted turbine exhaust heat exchanger before being used as a pressurant for the LOX tank. Additionally, an O_2/H_2 burner was employed to heat the helium for repressurizing both LOX and LH_2 tanks.

Evaporated Gas Systems

Evaporated-propellant pressurisation systems are primarily used in large vehicles with pump-fed propulsion systems Figure 3.5. These systems are mostly applied to oxidizers since most fuels tend to boil violently when heated, hydrogen being an exception. Due to the high molecular weight of oxidizer vapour, oxidizer tanks require more pressurant mass in evaporated-propellant systems compared to inert-gas (helium) systems. However, this additional mass is effectively minimized by storing the pressurant as a liquid within the main propellant tanks, eliminating the need for separate storage vessels.

The simplest form of this system is self-pressurisation, where the propellant boils within the tank during propellant outflow. This method requires a propellant with high vapour pressure, and the resulting pressure depends significantly on the mission profile. While reliable, the system requires a relatively high pressurant mass due to the need for low pressurant temperatures and high densities. In some cases, an auxiliary pressurisation system may be necessary to meet engine start requirements, as seen in vehicles like Centaur [18].

A more efficient pressurisation condition can be achieved when the pressurant is heated (subsection 3.2.3) to a temperature that is structurally and operationally suitable, and the ullage-gas temperature is stratified. For example, in the Saturn S-II stage [43], which utilizes evaporated-propellant pressurisation for both oxidizer and fuel tanks, propellant vapour is superheated to minimize the required gas mass.

For the main stage pressurisation of the oxidizer tank, relatively warm gaseous oxygen is used, with temperatures reaching 275K. This oxygen gas is generated by extracting a portion of LOX (at approximately 94K) from the pump discharge area and passing it through a shell-and-tube heat exchanger (see Figure 3.7 in subsection 3.2.3). The turbine outlet gas, at high temperature, provides the heat necessary for vaporization. The vaporized LOX is then routed to a collector before being directed to the oxygen tank ullage through a flow restrictor and gas distributor.

For the fuel tank, hydrogen gas is extracted from the engine thrust-chamber cooling jacket, where

it serves as a coolant. This pressurant is collected from the four outboard engines and delivered to the ullage through a hydrogen-tank flow-control orifice and gas distributor. One critical consideration in evaporated-propellant pressurisation is ullage-pressure decay before and during engine start transients. This decay can result from condensation of ullage gases, causing heat transfer to the propellant or the surrounding structure before engine ignition.
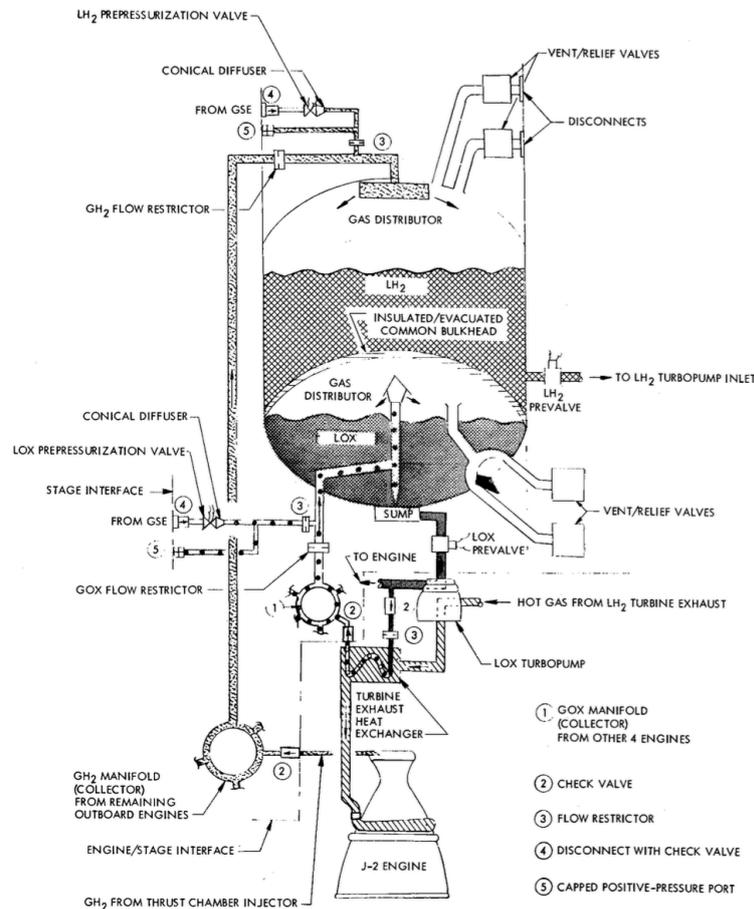
Figure 3.5: Schematic of the Evaporated Propellant pressurisation System for the Fuel and Oxidizer of the Saturn SII Stage [43].

Autogenous Systems

The use of engine-generated vaporized propellants for tank pressurisation has been demonstrated to enhance system simplicity and overall reliability compared to other proposed pressurisation methods for space vehicles. This approach, known as autogenous pressurisation (see Figure 3.6), is feasible in systems with pump-fed engines and is particularly effective with propellants that vaporize easily, such as hydrogen, light hydrocarbons, oxygen, fluorine, and fluorine-oxygen compounds or mixtures. This technique has been successfully implemented in launch vehicles like the pump-fed Titan booster [43].
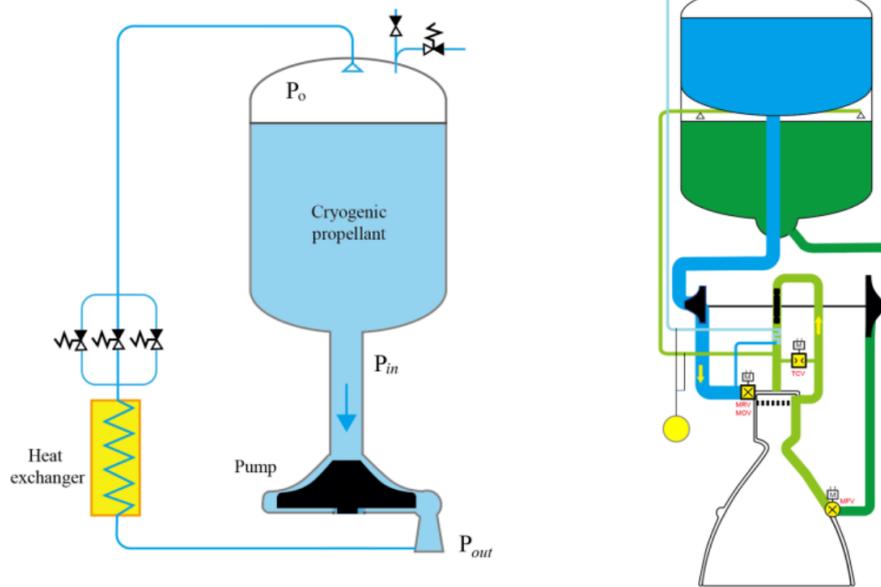
Figure 3.6: Schematics of an Autogenous pressurisation System [22].

A key advantage of autogenous pressurisation is that the pressurant source comes directly from the engine rather than requiring a separate subsystem. This is achieved by utilizing the same engine-driven pumps that deliver high-pressure propellants to the thrust chamber [10]. Since turbopumps are used, there is no need for high-pressure gas storage or an independent gas generation system.

Beyond eliminating the need for separate high-pressure gas storage, autogenous pressurisation offers several additional benefits. One notable advantage is that removing inert pressurant gases eliminates the problems introduced by dilution of the inert gas with the propellants [10]. In addition, these systems are simplified with respect to the other options since they eliminate one high pressure leak source (pressure vessels) and require fewer components, making them more reliable [10]. However, this pressurization method has intrinsic limitations, such as higher propellant consumption caused by pressurant dissolution, which demand precise pressurant control. Such condensation of the ullage is caused by the increase in pressure, and in turn it has the effect of increasing the pressurant mass needed [11]. Therefore, achieving this control requires a detailed understanding of the engine propellant's thermal behaviour and mass transfer properties [42].

3.2.2. Pressurant Mass Estimation

As previously discussed, mass is one of the main constraints when designing a pressurisation system. For this reason, and for design reasons as well, it is very important to have a correct pressurant mass estimation accounting for the major function of the pressurizing gas to pressurize the propellants inside their tanks. However, it is also important to keep margins for losses along the line and for secondary use of the pressurant, while still trying to minimize the total mass. To add further insight, in addition to tank pressurization, pressurant gas in a launcher can be used to actuate valves, drive pneumatic mechanisms, thereby enabling reliable operation of various subsystems. As suggested by [19], it is crucial to assume or calculate the values of the following parameters before starting calculations of pressurant requirements:

- Operating temperature ranges of the feed-system components and fluids;
- Propellant properties, weights, and corresponding volumes at the extremes of the operating temperature range and loading accuracy;
- Nominal tank volume, tolerances, and variations due to temperature and pressure;

- Initial ullage volume, portion of the propellant tank not occupied by liquid;
- Trapped-propellant volumes at the end of expulsion;
- Operating propellant-tank pressure: nominal value and variations;
- Mission duration and engine firing times.

Derivation from Sutton and Ring

The pressurant mass estimation in ideal conditions is derived from Sutton [47] in this section. This derivation is valid under the assumption of an adiabatic process with no heat transfer to or from the walls, an ideal gas, and a negligibly small initial mass of gas in the piping and the propellant tank. The pressurant tank has a constant volume but a variating pressure, while the ullage volume is assumed to be at a constant pressure but changing in volume, with the expulsion of the propellant. Initially, the ullage volume is assumed to be zero and at the end it occupies the full propellant tank volume V_{prop}. The subscript 0 refers to the initial conditions before the start of the discharge. The subscript p refers to the propellant tank, and the subscript g to the gas in the ullage volume, both at the end of expulsion. The derivation starts with the conservation of energy principle, balancing the energy at the start and at the end of the process:

$$E_{start} = E_{end} \tag{3.8}$$
$$U_0 = U_p + U_g + W \tag{3.9}$$
$$m_0 c_v T_0 = m_p c_v T_p + m_g c_v T_g + p_p V_{prop} \tag{3.10}$$

The work done by the gas in displacing the propellants is given by $p_p V_{prop}$. Using the ideal gas law $pV = nRT$ and the ideal gas relations $c_p = c_v + R$ and $\gamma = c_p/c_v$, Equation 3.10 can be written as:

$$c_v p_g V_0/R + c_v p_p V_{prop}/R + p_p V_{prop} = m_0 c_v T_0 \tag{3.11}$$
$$m_0 = (p_g V_0 + p_p V_{prop} \gamma) / (RT_0) \tag{3.12}$$

This, in turn, may be expressed as:

$$m_0 = \frac{p_p V_{prop}}{RT_0} \left(\frac{\gamma}{1 - p_g/p_0} \right) \tag{3.13}$$

This equation gives the required pressurant mass as a function of the starting pressure and temperature of the pressurant tank, and the volume and pressure of the propellant tank. It is evincible from this equation, that heating of the pressurizing gas represents a good solution for reducing the storage gas and tank mass requirements. Gas heating can be accomplished by adding one or multiple heat exchangers into the gas line, a heat exchanger is a device that heats or cools fluid by transferring the heat between the fluid and, in this case, a heat source. The type and design of the heat exchanger and the duration play a key role in the reduction of storage gas mass. The energy source for the heat can be chosen between several possible energy sources: the exhaust gases from the rocket thrust chamber or from other devices. Some options adopted on current designs are presented in subsection 3.2.3.

Ring [44] adds to this mass estimation a compressibility factor Z which is empirically derived and accounts for the thermodynamic conditions within the pressurized region. The resulting expression for mass estimation proposed by Ring is as follows:

$$m_0 = \frac{p_p V_{prop}}{RT_0} \left(\frac{\gamma}{1 - Zp_g/p_0} \right) \tag{3.14}$$

Collapse Factor

To better estimate the amount of pressurant gas required, non-ideal effects and their impact on pressurisation should be taken into account. In particular the effects of properties distributions within the ullage gas, liquid or cold supercritical propellant, and tank walls, focusing on the temperature distribution which has a more significant effect on pressurisation efficiency [13]. This is done in literature by defining a collapse factor. This factor has a direct effect on the sizing and design of the pressurisation system [49]. The global Collapse Factor (CF) is a proportion of the real mass of pressurant needed

$(m_0)_{real}$ over the ideal estimated mass needed $(m_0)_{ideal}$, its value can be obtained in a number of ways, including testing and by detailed analyses.

$$CF = \frac{(m_0)_{real}}{(m_0)_{ideal}} \tag{3.15}$$

If this factor is higher than one, it means that the system is working less efficiently than predicted, thus needing more mass of pressurant than what initially estimated.

In this thesis, the NASA's semi-empirical Epstein [16] equation for predicting the collapse factor is reported:

$$CF = \left[\left(\frac{T_0}{T_s} \right)(1 - e^{-p_1 \, C^{p_2}})(1 - e^{-p_3 \, S^{p_4}}) + 1 \right] \ * \ e^{\left[-p_5 \left(\frac{1}{1+C} \right)^{p_6} \left(\frac{S}{1+S} \right)^{p_7} Q^{p_8} \right]} \tag{3.16}$$

where T_0 is the incoming gas temperature (injected in the ullage) and T_s is the saturation temperature of the gas at initial tank pressure. The factors p_1 up to p_8 are fitting parameters that can be obtained from experiments or via a detailed simulation, and vary depending on the mixture of propellant and pressurant used. The parameter C^{p_2} is the wall-to-gas effective thermal capacity, expressed as:

$$C = \frac{(\rho C_p^0 t)_w}{(\rho C_p)_g^0 \, D_{eq}} \frac{T_s}{T_0} \tag{3.17}$$

with t the wall thickness, the underscore w for wall properties and g for pressurant gas properties, D_{eq} the equivalent tank diameter, and the density ρ and specific heat capacity C_p. S^{p_4} is the modified Stanton number:

$$S = \frac{h_c \theta_t}{(\rho C_p)_g^0 \, D_{eq}} \frac{T_s}{T_0} \tag{3.18}$$

with θ_t the total liquid outflow time and h_c the gas-to-tank wall free convection heat transfer coefficient Finally, Q^{p_8} is the ratio of total ambient heat

$$Q = \frac{q \, \theta_t}{(\rho C_p)_g^0 \, D_{eq} T_0} \tag{3.19}$$

with q being the heat flux from ambient to tank wall.

3.2.3. Heat Exchangers
The addition of a heat exchanger results in a weight penalty and adds additional complexity to the overall system, for this reason in some launchers the heat exchanger is added when the heat source is already available, resulting in a smaller weight penalty. However, the heat exchangers in the pressurisation line, by warming up and expanding the pressurant gas, allows for a reduction in gas mass for the same desired gas pressure, as discussed in subsection 3.2.2. In this section, some of the designs and applications of heat exchangers in pressurisation systems are discussed as presented in [43]. For the design of the component itself, the shell-and-tube heat exchanger, Figure 3.7, is the most used solution for aerospace pressurisation systems. In terms of heat sources, there are various solutions with the hot exhaust gases from the turbine being a common solution. In the Saturn V stages, turbine-exhaust heat exchangers were used to vaporize the liquid oxygen and to expand gaseous helium for pressurisation. On the Titan vehicle, these heat exchangers were used to vaporize N_2O_2.

Another solution is the one used on the Apollo SPS Figure 3.8 that consists of using the propellant itself, which is stored at a higher temperature than the pressurant, as a heat source.

An example of removing the heat exchanger itself was on the Saturn S-II and S-IVB stages where the gaseous hydrogen extracted from the engine regenerative cooling was used as a heat source for the main stage pressurisation tank. In this case, is necessary for the engine gas generator to be started before the evaporative process starts.
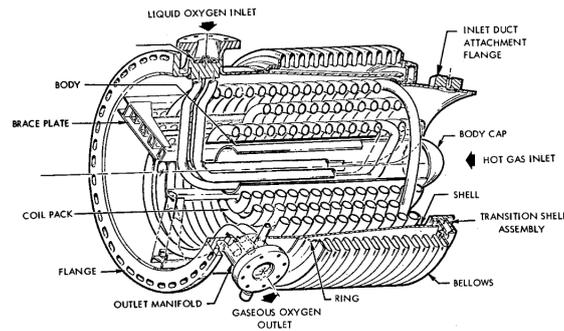
Figure 3.7: Shell-and-tube heat exchanger [43].

① SOLENOID VALVES
② REGULATORS
③ CHECK VALVES
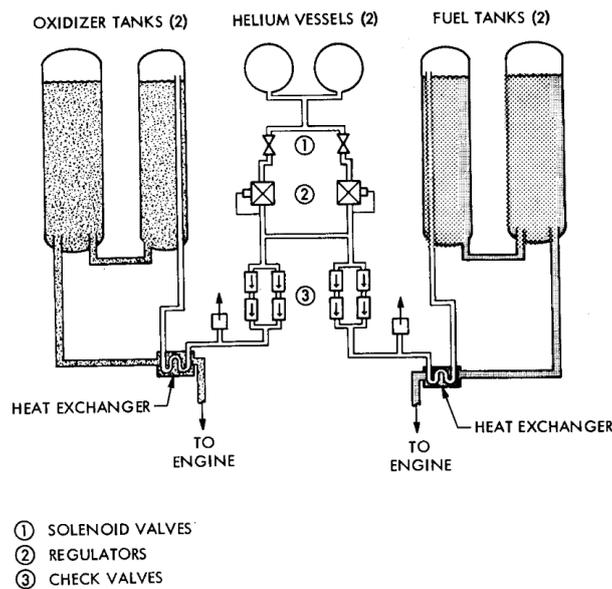
Figure 3.8: Schematic pressurisation System for Apollo Service Propulsion System [43].

The heat exchanger can work with a range of stable pressurant flow rates that are defined as its capacity range. The critical flow capacity is the point where the pressurant volumetric flow rate Q reaches a maximum value for the system, and an increase in mass flow rate produces $\dot{m}$ a decrease in pressurant flow rate. This critical point is defined as:

$$\frac{\delta Q}{\delta \dot{m}} = 0 \tag{3.20}$$

A heat-exchanger system is stable when its outlet pressure and temperature do not vary more than 2 percent from the nominal value.

In conclusion, while the integration of heat exchangers introduces additional weight and complexity to a propulsion system, their benefits in optimizing pressurant efficiency often outweigh these drawbacks, particularly when existing heat sources can be exploited. Through various examples used in past launchers, it is evident that heat exchangers play a crucial role in enhancing pressurisation system performance by reducing the required mass of pressurant gas. Their design, capacity, and integration with available heat sources are central to ensuring stable and efficient operation within defined system limits.

3.2.4. State of the Art and Current Designs

A research was conducted on both existing and under development launch vehicles to gain background knowledge on how liquid rocket tanks are pressurized, focusing primarily on European and American systems.

Table 3.1 presents and summarizes several pressurisation system configurations used in the first stages of selected launch vehicles. The information on these launchers was gathered from sources [4, 32, 21, 55, 25], as well as publicly available data where applicable.

This investigation centered on key characteristics relevant for this research, such as tank configurations (such as arrangement, bulkhead design, and materials), the type of top tank feed line, the pressurisation method (autogenous or exogenous) and the system type. For exogenous systems in particular, the placement and integration of pressurant tanks within the stage layout were also considered.

The Space Shuttle first stage, used heated gaseous hydrogen and oxygen generated by the RS-25 engines to pressurize the external tank. Liquid hydrogen LH_2 was routed through the engine's combustion chamber, vaporized, and fed back into the tank, while liquid oxygen LOX was heated via a heat exchanger in the oxygen pre-burner.

The Falcon 9 launcher uses helium as a pressurant, which is stored in composite over-wrapped pressure vessels (COPVs) immersed in the liquid oxygen LOX tank. The helium is chilled, circulated through engine heat exchangers, and warmed before pressurizing both LOX and RP-1 (kerosene) tanks.

For the European launchers, Ariane 5 and Ariane 6, not a lot of information is publicly available or detailed regarding their pressurisation systems.

Table 2: Bibliography of Pressurization Systems for First Stages.

First Stages	Propellant		Tanks					Feed Line Top Tanks	Tank Pressurization Systems		
	Oxidizer	*Fuel*	*Arrangement*	*Bulkheads*	*Shape*	*Material*	*Insulation*		*Oxidizer*	*Fuel*	*Pressurant Tanks*
Ariane 5	LOX	LH2	LOX above	common	LH2 cylindrical LOX cylindrical	Al alloy	polyurethane	external	GHe	1) GHe 2) Autogenous GH2	?
Ariane 6	LOX	LH2	LOX above	separated	LH2 cylindrical LOX cylindrical	?	?	?	?	?	?
Space Shuttle	LOX	LH2	LOX above	separated	LH2 cylindrical LOX ogive	Al – Li alloy	SOFI1 ablator phenolic	external	Autogenous GOX	Autogenous GH2	NA
Starship	LOX	LCH4	LCH4 above	common	LH2 cylindrical LOX cylindrical	carbon fiber or stainless steel	?	immersed	Autogenous GOX	Autogenous GCH4	NA
Falcon 9	LOX	RP-1	LOX above	common (insulated)	LH2 cylindrical LOX cylindrical	Al – Li alloy	?	immersed (insulated)	GHe (3-4bar)	GHe (3-4bar)	immersed
Saturn V	LOX	RP-1	LOX above	separated	Cylindrical with hemispherical end caps	Al 2219 T87	?	immersed	GHe	GHe	immersed

3.2.5. System Selection for Early Development

This trade-off analysis has been conducted to support the early-phase decision-making process for the pressurisation system of Maiaspace's micro-launcher, considering its current state of development. At this stage, key performance, structural, and operational requirements are sufficiently defined to explore and compare viable technical solutions that were already proposed by the company. Based on the findings of the preceding literature review, this analysis compares inert gas, evaporated propellant, and autogenous pressurisation systems in the context of the launcher's known technical requirements and dual-configuration architecture (expendable and reusable). The objective is to identify the most suitable pressurisation strategy by evaluating key performance, operational, and integration criteria. This comparison serves as a foundation for subsequent design work, focusing on solutions that offer a balanced trade-off between complexity, reusability, reliability, and system performance.

The main parameters considered for this choice are:

- **Mass and Volume Contribution**: In launch vehicles, mass and volume are premium resources, every kilogram added to a subsystem is a kilogram subtracted from payload capacity or performance margin. pressurisation systems contribute significantly to the dry mass through components like storage tanks, regulators, tubing, and insulation.

- **System Complexity and Maturity**: System complexity impacts: development time, integration risk, cost of testing and validation, operational reliability. A more complex system requires more components, more failure modes, and greater control logic. System maturity (measured by Technology Readiness Level, TRL) indicates whether the technology is flight-proven or experimental.

- **Pressurant Used**: The pressurant gas properties, such as density, molecular weight, heat capacity, and chemical reactivity, impact: system performance, thermal interactions with propellants and tanks, storage requirements, contamination risk to engines or propellant lines.

- **Cryogenic Compatibility**: If the propellants are cryogenic, cryogenic compatibility becomes a decisive factor in system design, impacting component selection, material choice, and overall reliability.

- **Reusability Fit**: Reusability is a major design driver for new-generation launch systems. A pressurisation system that can withstand multiple flights, requires minimal turnaround or re-servicing, doesn't rely on ground-refilled consumables.

Table 3.2: Trade-off comparison between different pressurisation systems

Parameter	Inhert Gas	Evaporated Propellant	Autogenous
Mass and Volume Contribution	High mass and volume added	Mass added (less than inert system)	Uses mainly existing components
System Complexity	Low	Low	High
Pressurant Used	Helium	Heated vapor/gas	Self-derived vapor
Cryogenic Compatibility	High	Medium	High
Reusability Fit	Medium	Low	High

Inert gas pressurisation offers a high level of technological maturity, with well-established safety and reliability. Its simplicity makes it attractive for rapid development and integration, particularly in expendable configurations. However, it imposes significant mass and volume penalties due to the need for heavy high-pressure storage vessels and does not scale well for reusable systems, as it relies on consumables that must be replenished after each flight.

Evaporated propellant systems provide a moderate balance between simplicity and performance. They eliminate the need for separate pressurant tanks and can integrate effectively with propulsion systems. However, they introduce thermal management complexities, particularly in managing cryogenic boil-off, and have more limited operational heritage. This makes them suitable primarily as an intermediate solution where some performance gains are desired but full reusability is not yet critical.

Autogenous pressurisation stands out as the most mass and volume-efficient option, offering the best

long-term compatibility with reusable architectures. It removes the dependence on separate consumables by using the vehicle's own propellants, thus simplifying logistics and improving turnaround time. While this approach introduces greater system complexity and development cost, it aligns most closely with the performance, reliability, and operational goals of a modern reusable micro-launcher.

The trade-off analysis concludes that both inert gas and autogenous pressurisation systems warrant further investigation as part of this thesis work. Autogenous pressurisation presents clear advantages in terms of mass efficiency, integration with reusable architectures, and long-term operational sustainability. However, it involves greater system complexity, requiring dedicated development effort, validation, and testing to ensure reliability and control.

In parallel, inert gas systems offer a mature, low-risk solution that can support early-phase development, testing, and potential expendable configurations. Their simplicity and flight heritage make them attractive for accelerating initial launches while more advanced systems are being developed.

Given the distinct benefits and challenges of each option, a dual-track approach is recommended. Inert gas pressurisation should be explored for near-term implementation and system validation, while autogenous systems should be developed in parallel as the preferred solution for future reusable operations. This approach balances immediate development needs with long-term performance and reusability goals.

3.3. Control

In the previous sections (Figure 3.3.1), various types of regulated systems were introduced. This new section expands on that foundation by providing a detailed examination of how the control of pressure is achieved in a launcher's pressurisation system. Effective pressure control ensures that the propellants are delivered to the engines under the required conditions for reliable and safe operation. Typically, this is done by monitoring the ullage pressure, the gas volume above the liquid propellant, and adjusting the pressurisation system accordingly. The section will explore different design configurations, control strategies, ullage characteristics, and pressure boundaries that define how pressurisation systems are implemented in practice.

3.3.1. Design and Configurations

One of the simplest and most common means of pressurizing the propellants is to force them out of their respective tanks by displacing them with high-pressure gas [17]. The two main configurations for control of the pressurisation during the operational phase are blow-down and regulated systems (Figure 3.9). The selection of the system is made based on the required pressure at the pump or engine inlet.
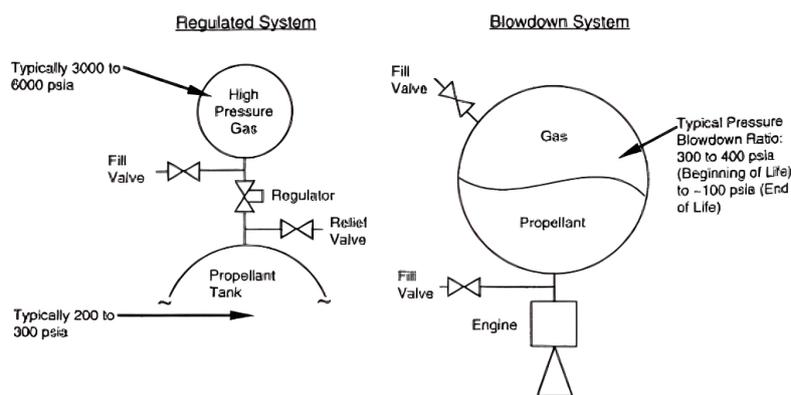
Figure 3.9: Blow Down and Regulated System Simplified Layout [55].

These systems will be further explained in the two following sections. Several options for the design and layout of pressurisation systems are presented in [18].

Sizing of the lines and the selection of the valves depend on the pressurant flow rate. The volumetric

flow rate of pressurant into the tank must equal the volumetric flow rate of propellant to the engines. Once the propellant-tank ullage pressures and temperatures have been computed, the volumetric gas flow rate can be converted into a mass flow rate. This mass flow rate will be constant throughout the system, from source to delivery point, for steady-state operation. Pressurant volumetric flow rate at the tank equals the propellant volumetric flow rate [17]:

$$\dot{m}_g = Q_p \rho_g \tag{3.21}$$

Blow-Down Systems

In blow-down systems, the gas required to expel the propellant is already stored inside the tank at high pressure levels. The gas can be directly in contact with the propellant, and in this case it is defined as a surface tension device, or separated by a flexible diaphragm or bladder, called positive expulsion devices. Surface tension systems are mainly used to control passively propellants in microgravity by utilizing vanes, screens, or sponges to guide the liquid toward the tank outlets. This ensures that the pressurizing gas remains separated from the outlet, preventing unwanted gas ingestion. The two main types of positive expulsion devices are diaphragm and bladder. A diaphragm is a membrane sealed against the tank that separates the propellant from the pressurant (Figure 3.10). Bladders are balloons with a small opening attached to the tank outlet, that contain the propellant.
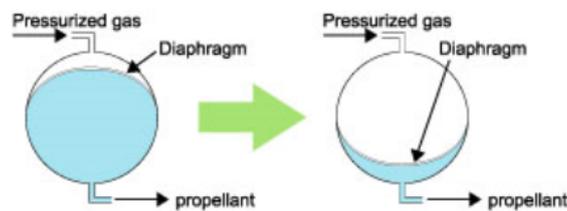
Figure 3.10: Diaphragm Blow-Down System.

Once the engine feeding starts, the pressurant gas forces the propellant outflow to the engine and the ullage pressure experiences a decay. As the pressure inside the slowly decreases with the expulsion of the propellant, the thrust decreases likewise. For this reason, blow-down pressure fed systems are not suitable for a mission that requires manoeuvrers at constant thrust. The sizing of the propellant tank of a blow-down system is based on three design parameters: propellant volume to be expelled, initial and final ullage pressure [43]. In pressure-fed systems, the final tank pressure is dictated by the minimum chamber pressure and thrust requirements, while in pump-fed propulsion systems by the pump inlet pressure requirement. The main advantages of these systems are reliability and simplicity.

A blow-down pressurisation system was used on the Titan II second stage oxidizer tank. In some booster vehicles, the pressurisation uses a combination of pressure-regulated and blow-down modes of operation. An example of this is the Atlas vehicle, where the blow-down mode was useful since it eliminated the need for a separate pressurisation system for the engines after the regulated system was dumped with the booster engine package [43]. This system allowed to sustain an adequate engine pump NPSH despite the decreasing tank ullage pressure due to the increasing propellant hydrostatic pressure given by acceleration.

Regulated Systems

Three types of regulated systems exist: pressure-regulated systems, pressure-switch systems and passive flow control systems [43].

Pressure regulated systems use a modulated pneumatic regulator to control and keep the ullage pressure at the desired value during flight. These systems are used when a constant ullage pressure is required during flight.

Pressure-switch systems use ON-OFF transducers that convert fluid pressure changes above and/or below a given boundary into electrical signals, as illustrated in Figure 3.11. These systems generally use a number of parallel set of switches, flow restrictors and electrically operated valves to implement pressure control. These components present an advantage in term of design and manufacture with

respect to the pneumatic regulators. The example showed in the figure has only one main and one control ("booster") flow restrictor that increases the supply pressure in case of a decrease in ullage pressure with respect to the nominal value, but many configurations are possible with more main and control restrictors.
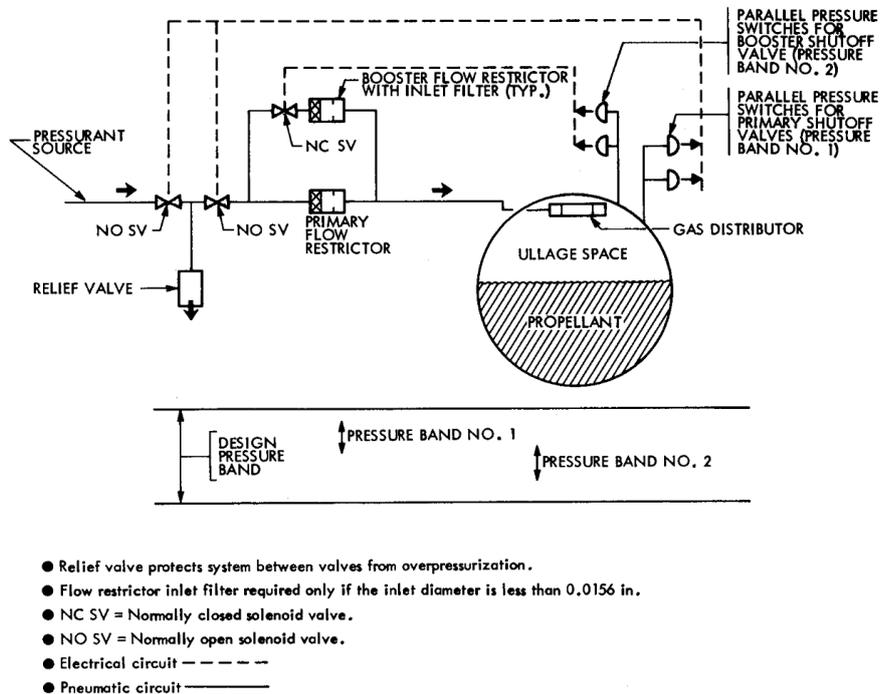
Figure 3.11: Pressure-Switch System [43].

Passive flow control systems use flow restrictors that are calibrated previously to operation, rather than having an active response or setting a target pressure. The main advantage of passive systems is that they are relatively inexpensive. However, there is a clear reliability flaw in these systems, since they are not able to compensate for unforeseen changes in the ullage or pressurant conditions. For instance, the pressurisation system of the Centaur vehicle united pressure-switch and flow control.

3.3.2. Ullage Pressure Requirements

The volume of gas above the propellant inside its storage tank is called ullage. This is plays a necessary and important role, maintaining structural integrity of the tank providing space for the expansion and compression of the pressurant gas and providing the NPSH required for the propellant pumps during transient and startup phases. Several characteristics and properties of the ullage are important for and should be considered in the design of pressure-control systems [44], in this section these properties will be briefly discussed.

First of all, the volume of the ullage significantly affects the response of the pressure control devices. Pressure rise rate in a closed volume is proportional to flow rate into the volume and inversely proportional to the volume Figure 3.12.

Due to the effects of friction and inertia within mechanical systems, pressure-control devices may struggle to keep up with rapid increases in pressure. These high pressure rise rates are typically caused by small ullage volumes combined with high regulator flow rates, which can lead to overpressure conditions within the regulation system Figure 3.13.

Therefore, increasing the ullage volume allows the system to minimize deviations from the desired pressure range, preventing both overpressure and underpressure events. However, these issues cannot be solved solely in this manner but rather by an improved component design, since increasing the ullage volume leads to added weight of unusable propellant tank.
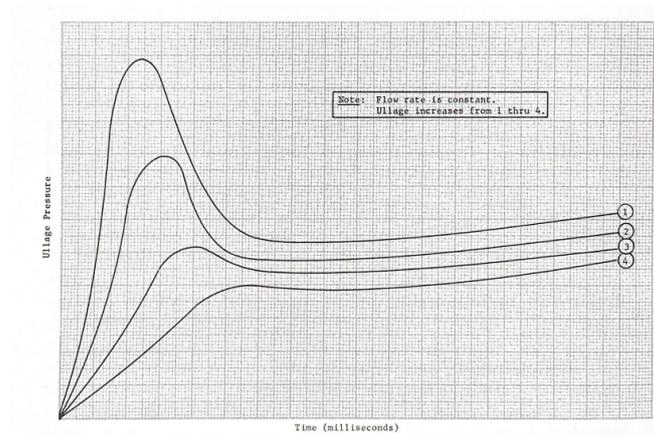
Figure 3.12: Ullage Pressure versus Time, for Varying Ullage [44].
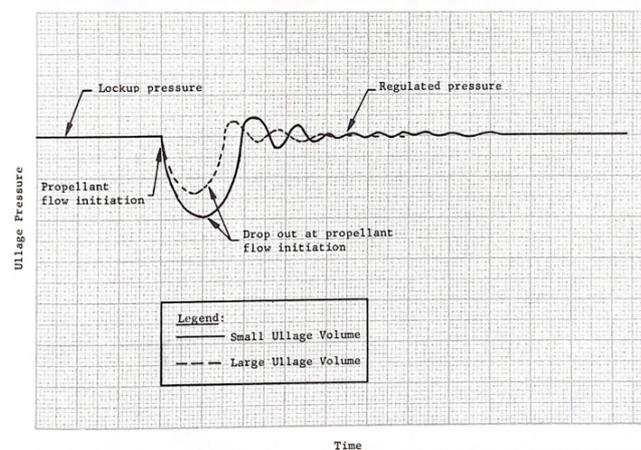
Figure 3.13: Ullage Pressure versus Time, for Varying Ullage Volume [44].

Ullage temperature affects directly the overpressure of a pressurisation system. Pressure rise rates of an ullage pressurized with high flow rates for a system with warmer ullage are much higher compared to a colder ullage. This difference is a direct result of the heat transfer between the cold propellant and the cold portion of the ullage close to it with the warmer pressurizing gas injected. In [27], an experimental study was conducted investigate the behaviour of cryogenic tanks during rocket launch, focusing on systems using liquid oxygen as the propellant and high-temperature helium as the pressurant. Ground experiments were conducted with two diffuser configurations (radial and anti-cone) to evaluate pressurant requirements, temperature distribution, and energy transfer within the tank. The results showed that the pressurisation system effectively maintained stable tank pressure and liquid discharge. However, the energy distribution varied significantly between the two diffuser types. The radial diffuser led to more heat being absorbed by the tank walls, while the anti-cone diffuser directed more energy into the liquid propellant. In both cases, only a small portion of energy remained in the ullage gas, indicating room for improvement in diffuser design. Overall, the findings highlight the effectiveness of high-temperature helium for pressurisation and underscore the importance of diffuser geometry in optimizing system performance.

The composition of the ullage, and the pressurant gas injected, is an important parameter as well. The properties of the mixture of gases change based on the composition, for instance density, specific heat, gas constant. Thus, as a consequence the flow characteristic will change as well, affecting the operation of regulating components as demonstrated by Ring [44].

In conclusion, ullage plays a critical role in the design and performance of pressurisation systems in

liquid propellant tanks. Its volume, temperature, and composition directly influence pressure dynamics, system stability, and overall efficiency. While increasing ullage volume can mitigate overpressure conditions, it comes with trade-offs such as added structural mass and reduced propellant capacity. Therefore, a balanced approach, combining thoughtful ullage design with optimized component performance, is essential to ensure reliable and efficient pressurisation system operation, thus efficient pressure control.

Tank Pressure Boundaries

During operation, the ullage pressure must be controlled by keeping it within its minimum and maximum limits. The minimum allowable pressure is determined both by the tank structural requirements to avoid buckling or other phenomenons (see section 3.1), and by the propellant feed requirements. The maximum pressure is determined by the maximum structural loads of the tank. An example of the boundaries determining the limits for ullage pressure inside the propellant tank is showed in Figure 3.14. This example shows the ullage pressure boundaries for a ground launched stage with relatively high propellant head. To meet the initial tank pressure requirement, prior to the vehicle launch a pre-pressurisation
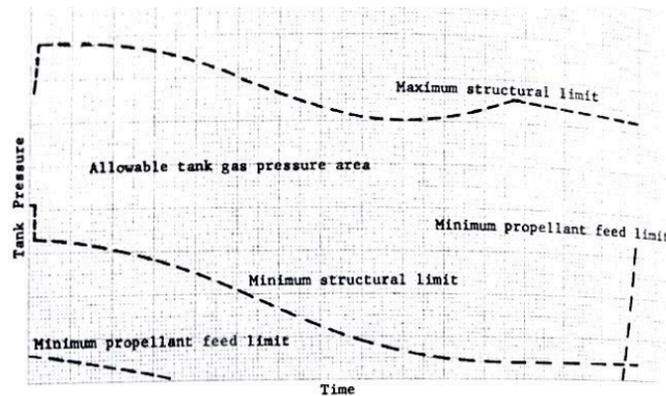
Figure 3.14: Flight Tank Ullage Pressure Limits for Ground Launched Stage [44].

of the ullage is required. Many of the ground pre-pressurisation systems are designed with pressure makeup capabilities after the initial pressurisation [43].

3.3.3. Pressure Control Selection

In the previous chapters, various control solutions for pressurisation systems have been introduced. The selection of the most suitable pressurisation control system is a critical design decision that directly impacts the performance, reliability, and cost of a launch vehicle. For the Maiaspace micro-launcher, which is being developed in both reusable and expendable configurations, this choice must be guided by a clear set of trade-off criteria, including:

- **System Complexity and Reliability**: evaluating how intricate the system is and how likely it is to function without failure.
- **Mass and Volume Efficiency**: considering how much mass and space the pressurisation system occupies relative to its effectiveness.
- **Reusability Fit**: assesses how well the system supports multiple launch cycles without significant maintenance or degradation.
- **Performance Consistency**: how reliably the system can maintain the required pressure profiles throughout the mission. Consistent performance is essential to ensure proper engine operation and structural integrity, especially under varying mission conditions.

Based on these criteria and the current state of development of Maiaspace's launcher system, three types of pressurisation systems warrant focused exploration in this research project:

Pressure-regulated systems employ modulated pneumatic regulators to actively maintain a near-constant ullage pressure during engine operation. This results in a more stable thrust profile, better engine performance, and greater control authority, which is essential for reusable stages, that require consistent

Table 3.3: Trade-off comparison between different modelling approaches.

	Blowdown	Pressure Regulated
System Complexity and Reliability	Simple system High reliability	More complex Can be designed for high reliability
Mass and Volume Efficiency	High	Adds mass and volume but can be optimized
Reusability Fit	Not fitting	High
Performance Consistency	Degradation of performances	Thrust control and varying

performance and safer reentry and landing phases. Therefore, pressure-regulated systems are ideal for the reusable configuration since they maintain stable pressure across the mission envelope, generally support missions with longer durations or more complex manoeuvrers. In addition, they are better suited for engines with tight NPSH and performance margins and allow safe reuse by reducing thermal and mechanical stress on tanks and plumbing. The increased system complexity, cost, and validation effort associated with regulators and feedback control loops, along with the typically greater mass and volume of pressure-regulated systems, are necessary trade-offs to enable reusability and support thrust-varying flight profiles.

Blow-down systems are inherently simple and reliable. They store high-pressure gas in the tank and allow it to expand and expel the propellant during flight. While ullage pressure drops over time, this drawback is acceptable for missions that do not require constant thrust or pressure, particularly in short-duration or expendable flight profiles. However, as previously mentioned, they would be unable to satisfy the requirements of a reusable launcher in terms of active regulation.

3.4. Modelling
Understanding and accurately predicting the behaviour of pressurisation systems in rocket propulsion is essential for ensuring both performance and reliability. This includes modelling the complex interactions within tanks and feed lines, such as fluid dynamics, thermal exchanges, and pressure evolution under varying conditions.

To analyse and optimize these systems, different modelling approaches are employed depending on the level of detail, computational resources, and design stage requirements. These models help simulate key phenomena such as: gas expansion, heat transfer between pressurant and propellants, pressure drops in lines, and the dynamics of multi-phase flows.

This chapter presents the two primary types of models commonly used for pressurisation system analysis: 0D/1D models, which offer a simplified, system-level perspective ideal for early-stage design and parametric studies, and Computational Fluid Dynamics (CFD) models, which provide high-fidelity insights into localized flow and heat transfer phenomena within specific components. Each modelling approach brings unique advantages and limitations, which are discussed in the following sections.

3.4.1. 0D/1D Models
In the design and analysis of pressurisation systems for space propulsion, accurate modelling plays a crucial role in predicting system behaviour, optimizing performance, and ensuring mission reliability. Among the various modelling approaches, one-dimensional 0D/1D simulation offers a powerful balance between computational efficiency and physical fidelity, making it particularly well-suited for system-level analysis in the early and intermediate phases of development. Two commercial softwares used for 0D/1D modelling are introduced in this chapter.

EcosimPro
One of the most advanced tools for 0D/1D modelling in aerospace applications is EcosimPro, particularly when used in conjunction with the European Space Propulsion System Simulation (ESPSS)

libraries. Developed as part of a European initiative, ESPSS aims to establish a standardized platform for propulsion system simulation, enabling consistent and accurate modelling across agencies and industrial partners.

EcosimPro, with its integrated ESPSS libraries, provides a robust environment for modelling complex pressurisation circuits in both hydraulic and pneumatic domains. The software includes a wide range of components that allow the user to simulate entire systems, from tanks and valves to controllers and heat transfer elements.

One of the core strengths of EcosimPro lies in its ability to capture transient behaviour and multi-domain interactions. For example, in the modelling of a pressurisation system using electro-valves [36], the tank component can be represented with a high level of detail, incorporating key physical phenomena such as: vaporization, vertical fluid temperature stratification, heat transfer interactions, phase changes and fluid dynamics. These features are essential for accurately simulating real mission conditions, particularly in cryogenic environments or during dynamic operations such as startup, venting, or re-pressurisation.
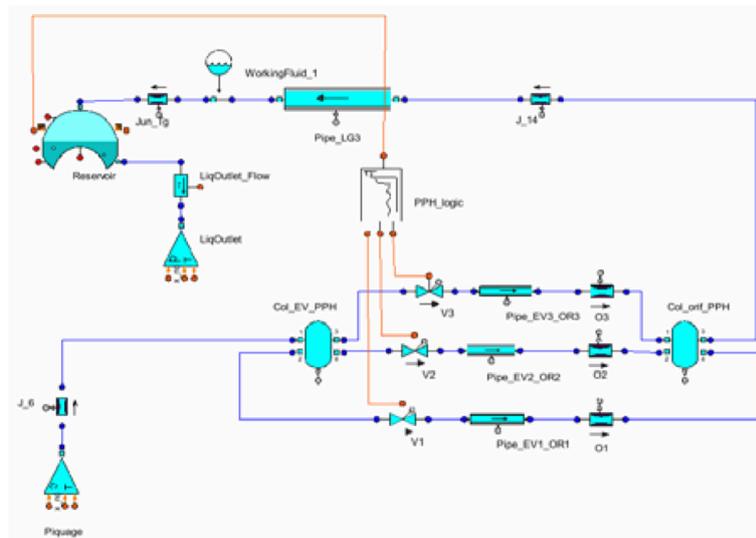
Figure 3.15: Tank pressurisation Model on EcosimPro [36].

A central component of this modelling capability is the Fluidflow1D library, which enables the 0D/1D transient simulation of two-fluid, two-phase systems [51]. This library is particularly well-suited for modelling the pressurisation systems of launch vehicles, where interactions between pressurant gases and cryogenic propellants must be precisely captured.

An example of EcosimPro's capabilities for modelling pressurisation in a tank can be seen in its application to the liquid hydrogen LH_2 tank of the CALLISTO vehicle [15]. In this case, a detailed 0D/1D thermal and hydraulic model was developed to simulate the tank's behaviour across the entire mission timeline. This model takes into account the thermal environment specific to the mission, allowing for an accurate evaluation of tank performance under realistic operating conditions. The simulation covers all critical phases of the mission, beginning with the initial chill-down of the tank and progressing through propellant loading, boil-off venting, and pressurisation, all the way to post-flight residual propellant venting. By capturing each of these stages, the model provides a comprehensive understanding of how the pressurisation system behaves over time. Through this simulation, the total required propellant mass, the boil-off rates and the heat fluxes entering the tank structure can be estimated. These outputs are essential for analysing the pressurisation system's impact on the mission, helping to optimize design choices, improve thermal management strategies, and ensure overall system reliability. These insights are essential for understanding the impact of pressurisation system behaviour on the overall mission performance, mass budget, and thermal control strategy. Furthermore, in [42] an EcosimPro model of the pressurisation system is used to perform a modelling analysis of three pressurant control strategies for autogenous pressurization in a liquid oxygen/liquid methane (LOX/LCH$_4$) propulsion system.

A comparison of the values of tank pressurization during flight were compared to the simulation results of an equivalent EcosimPro model in [1], which demonstrated coherent results.

One of the key strengths of using EcosimPro for pressurisation system analysis lies in its ability to provide accurate results without the computational cost of high-fidelity models. 0D/1D modelling strikes an effective balance between detail and efficiency, making it especially valuable during early design phases or for system-level evaluations. EcosimPro allows for fast simulations of complex, transient processes, enabling engineers to model entire mission scenarios with high temporal resolution. This speed does not come at the expense of depth: its models are capable of capturing essential physical phenomena, such as phase changes, pressure dynamics, and heat transfer, with reliable accuracy. Moreover, EcosimPro supports the integration of multiple subsystems, allowing users to couple thermal, fluid, and control models within a single simulation environment. This integration is critical when assessing the performance and behaviour of the entire pressurisation circuit, including its interaction with tanks, valves, lines, and external conditions. Another important benefit is flexibility. The platform can be adapted to a wide range of mission profiles and system architectures, from simple pressure-fed arrangements to more advanced autogenous systems. It is also well-suited for iterative design processes, where rapid reconfiguration and performance evaluation are essential. Finally, EcosimPro's compatibility with experimental validation makes it a powerful tool not only for simulation but also for supporting and interpreting test data. This enhances confidence in design decisions and facilitates the transition from digital modelling to physical implementation.

EcosimPro, supported by the ESPSS libraries, provides a highly capable platform for the 0D/1D modelling of pressurisation systems in space propulsion. Its ability to represent detailed physical processes while maintaining system-level perspective makes it an indispensable tool in the design and validation of pressurisation strategies for launch vehicles and spacecraft. As the complexity of propulsion systems grows and the demand for reusable, efficient architectures increases, tools like EcosimPro will continue to play a pivotal role in the development of next-generation space systems.

AMESim

Another software that can be used for the same applications is the AMESim (Advanced Modelling Environment for Simulation of engineering system) software. AMESim is a software for modelling, simulation and dynamics analysis of hydraulic and mechanical systems based. The software package provides a 0D/1D simulation environment to model and analyse multi-domain (hydraulic, hydraulic resistance, mechanical, pneumatic, thermal, control, et al) systems, and to predict their multi-disciplinary performance [53]. There are a series of different libraries each related to the previously listed physical domains. Each of this libraries can have some limitations imposed by the assumptions made as fundamental hypotheses. AMESim is based on an intuitive graphical interface in which the system is displayed throughout the simulation process. It uses standard symbols in the engineering field such as ISO symbols for hydraulic components or block diagram symbols for control systems to represent individual components within the system. Most importantly, the user can program his own specific submodels in C with AMESet, or assemble different standard sub-models to create super-components to be customized with AMECustom. In [31] an example of analysis and simulation verification of hydraulic system based on AMESim is given, and in [39] the modelling and simulation of an aircraft engine fuel system is presented.

For instance, a study was conducted on system dynamic characteristics of spacecraft propulsion systems [53], based on the simulation of the AMESim model developed here [52] and shown in Figure 3.16. The simulation result demonstrates the adequacy of the modular modelling methodology adopted by AMESim for simulating spacecraft propulsion systems. In order to investigate the system dynamics of spacecraft propulsion system with complex pressurisation pipelines and propellant supply pipelines, a modular and extensible simulator was developed. The model accurately predicts the transient behaviour of the spacecraft propulsion system during start-up and shutdown process, as well as the effect of pipe initial pressure on the priming water hammer amplitude. The computational transient model of the spacecraft propulsion system is primarily necessary for engineers to predict the propulsion system performance and modify the design. It also can be used as a tool for mission operations personnel to predict pressurant and propellant tank blow-down pressure, pressure regulator performance, latching isolation valve timing, pressure transducer telemetry, and inlet conditions at the main engine during
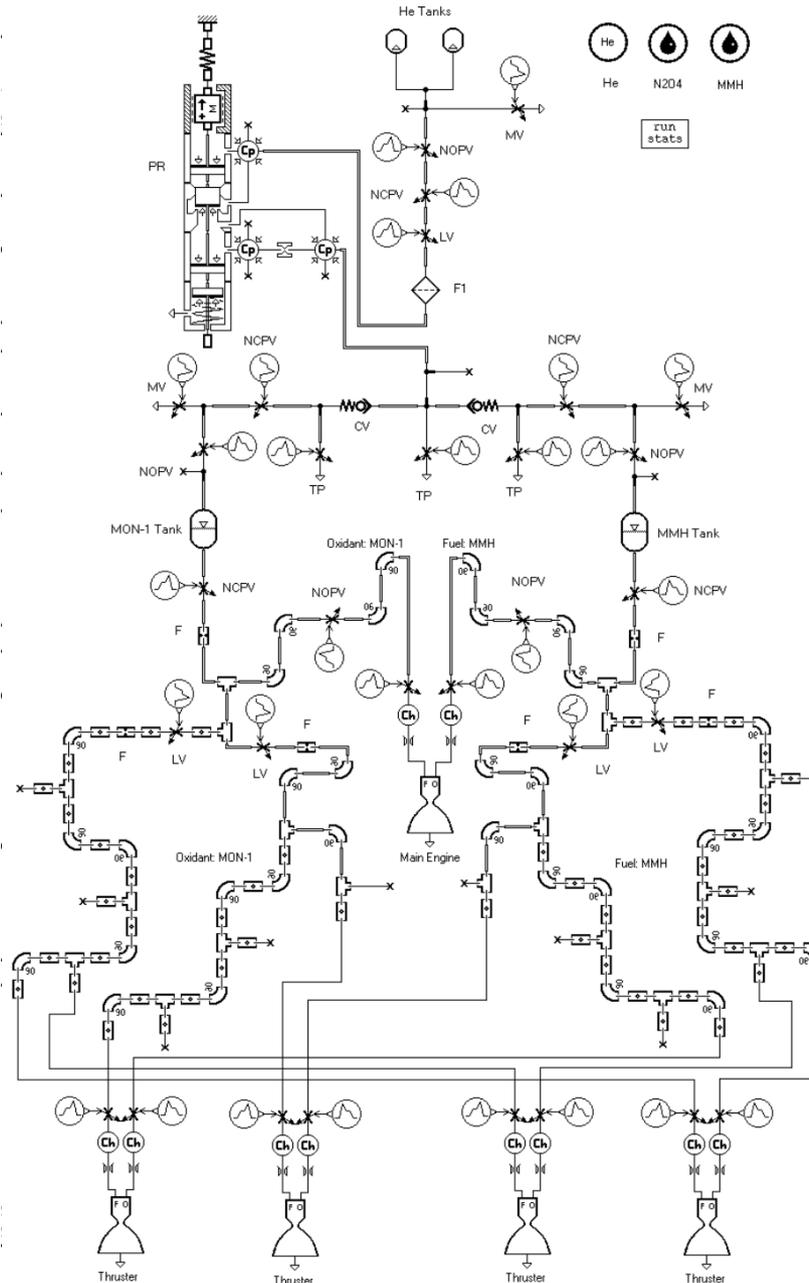
Figure 3.16: Propulsion System Model on AMESim [31].

manoeuvrers.

The model accurately predicts the global behaviour of the spacecraft propulsion system during start-up and shutdown process, and it also describes correctly the transient behaviour of complex subsystems. The simulation result demonstrates the adequacy of the modular modelling methodology for spacecraft propulsion system dynamic simulation.

Analytical Models

One-dimensional analytic models are a valid alternative to commercial softwares and still play a crucial role in the simulation and analysis of pressurisation systems in cryogenic liquid rocket propulsion. These models strike an effective balance between computational efficiency and physical accuracy, allowing for rapid evaluation of various design scenarios while maintaining a high level of detail in system

behaviour.

An example of this approach is the analytic model presented in a recent study [12] focused on simulating tank pressurisation and cryogenic propellant conditions throughout all mission phases of a liquid rocket vehicle. In this model, the propellant tank is divided into five discrete nodes: the tank wall exposed to the ullage gas, the ullage gas itself, a saturated vapour region at the liquid-vapour interface, the liquid phase, and the tank wall in contact with the liquid. By applying conservation of mass and energy across these nodes and incorporating real-time fluid property updates (using NIST Refprop), the model is able to predict ullage and liquid conditions with high fidelity.

The model includes complex physical phenomena, such as liquid stratification, evaporation, bulk boiling, and condensation, enhancing the realism of the simulations. Moreover, the model has been validated against both legacy Saturn-era data and more recent LH_2 tank pressurisation tests, confirming its robustness and reliability. Importantly, this 0D/1D model has proven to be a valuable design tool, successfully supporting the development of systems like the Altair Lunar Lander and Ares V stages. It has been used to evaluate pressurant requirements, losses due to evaporation and venting, and the dynamics of tank draining under various configurations and mission phases.

This represents a valid example of an analytic model for the pressurisation of a tank. In a similar fashion, models for the entire pressurisation system, similarly to what is proposed by Ring [44], or other specific components can be built and their functioning can be assessed.

Another study [26], focuses on determining the helium pressurant requirements for the Centaur liquid oxygen tank, a critical factor in evaluating the feasibility and sizing of a gas pressurisation system. The challenge lies in accurately predicting the pressurant demand during the initial pressurisation ramp and subsequent propellant expulsion, which is complicated by the tank's heat input and injector geometry. Existing analytical models [14] [45], while effective for liquid hydrogen tanks, had not been validated for liquid oxygen applications, making them unreliable for this case. Previous models for liquid oxygen were also largely empirical and lacked general applicability. To address these limitations, a full-scale test was conducted using a thick-walled Centaur LOX tank for this study. The results demonstrated that the analytical tools, once validated, could reliably estimate the total helium requirements for the pressurisation system, enhancing the design process for the Centaur launch vehicle.

3.4.2. CFD Models

In the design and analysis of pressurisation systems for liquid-fuelled rockets, precision and reliability are paramount. While 0D/1D models and system-level simulations offer a valuable first-order understanding, they are limited in capturing the detailed physical phenomena that occur in complex geometries and dynamic environments. Computational Fluid Dynamics (CFD) fills this gap by providing a powerful tool to simulate the intricate behaviour of fluids within the pressurisation system, offering insights that are otherwise difficult or impossible to obtain through analytic models or simplified simulations.

CFD helps simulate the stratification of temperature and vapour concentration within the ullage volume, especially in large cryogenic tanks. It enables the visualization of mixing behaviour after pressurant injection, and how that affects boil-off rates, wall heat fluxes, and eventual pressurisation efficiency.

While CFD is a powerful tool, it comes with computational costs and requires careful setup. Accurate geometry, boundary conditions, mesh quality, and physical models (for instance turbulence, phase change) are essential for reliable results. CFD is best used in combination with lower-fidelity models and experimental validation to ensure accuracy and practicality. To cite some relevant studies, in [35], a comprehensive set of analysis tools has been developed to simulate pressurisation in propellant tanks, incorporating a multi-node lumped parameter method, multiphase unstructured CFD with accurate real-fluid property models, and a hybrid modelling approach. These tools are designed to address the various pressurisation regimes encountered throughout the different phases of spaceflight. The CFD approach is applicable to short duration injection based pressurisation problems where mixing is the dominant physical mechanism. In [2], a CFD and thermodynamic model is used to predict the boil-off and the self-pressurisation rates for different g-levels and for a variety of heat distributions and engineering design parameters. A comparison between experimental data and model predictions was done and shows that while the thermodynamic model effectively predicts the rate of self-pressurisation, it is not as accurate in estimating the actual pressure increase. On the other hand, the computational

model successfully captures both the self-pressurisation rate and the vapour pressure magnitude, particularly at lower propellant fill levels.

In conclusion, CFD simulations are an indispensable asset in the design and optimization of rocket pressurisation systems. Their ability to resolve complex flow behaviour, heat transfer, and multiphase dynamics at a high level of detail provides critical insight into both component and system-level performance. When integrated with analytic models and experimental data [30], CFD enhances the fidelity of simulations, reduces development risks, and contributes significantly to the reliability and efficiency of modern rocket propulsion systems.

3.4.3. Modelling Approach Selection

In the previous sections, the main different types of modelling approaches employed for the design and analysis of propulsion systems were presented, namely 0D/1D and CFD models. To operate a decision on which modelling approach is best suited for the applications of this thesis project, it is necessary to perform a trade-off.

First, the main decision parameters of the trade-off have to be established. Since the thesis project is done at a company with an already ongoing development of the system, this decision is based on the main drivers and needs at an intermediate state of the technology development. At this stage, some choices in terms of pressurisation system design were already made, but based on the integration of the components, on the layout of the lines and subsystems, and on the functionality of the system itself, several layouts and parameters within the system are tested. In this context, it is important to be able to test the system performance quickly and iteratively while still capturing the most critical physical behaviours affecting pressurisation.

To choose the appropriate modelling approach for the design of the pressurisation system at this stage of the development of Maiaspace's launcher, we consider the following decision parameters:

- **Computational Efficiency**: The ability to perform multiple simulations rapidly is essential, especially when exploring a large design space or running parametric studies. This favours 0D/1D models, which are orders of magnitude faster than CFD.

- **Fidelity to Physical Phenomena**: The model should capture key dynamics such as heat transfer, pressure evolution, and phase changes. While CFD excels in fidelity, advanced 0D/1D models, especially those using tools like AMESim or validated analytical methods, can provide sufficient accuracy for system-level analysis.

- **Development Stage**: Given that this project is in an intermediate design phase, many system-level parameters and layout decisions are still under evaluation. This supports the use of 0D/1D tools, which are more adaptable for evaluating different configurations quickly.

- **Integration with Existing Tools and Data**: EcosimPro and AMESim allow integration of thermal, fluid, and control subsystems. If prior modelling infrastructure or component models exist in these tools, which is the case for AMESim, leveraging them promotes consistency and speeds up development.

- **Flexibility and Customization**: Since the system architecture is still evolving, flexibility to model new scenarios is vital. 0D/1D environments with custom sub-model capabilities (e.g., AMESim with AMECustom, or analytical models built in-house) provide the adaptability required.

- **Validation and Reliability**: Validated models, either through past use cases or via integration with experimental data, are essential to ensure confidence in predictions.

- **User Expertise and Tool Maturity**: The availability of internal expertise and the proven maturity of a modelling environment are decisive in ensuring reliable results and efficient use of resources. Since AMESim is already well established within the company and supported by existing technical expertise, it represents a practical and robust choice.."

Given the context of the project, the primary modelling approach suggested by the trade-off outcomes is the simulation on EcosimPrp/AMESim. This approach shows a strong balance between modelling depth and computational efficiency. It supports transient multi-domain simulations, critical for evaluating integrated pressurisation system behaviour, especially in cryogenic and dynamic environments.

Table 3.4: Trade-off comparison between different modelling approaches.

Parameter	EcosimPro/ AMESim	Analytical Models	CFD
Computational Efficiency	Full system simulation with pre-coded components.	Medium	High computational costs for targeted simulations.
Fidelity to Physical Phenomena	High	Medium-Low	Very High
Development Stage	Preliminary Design/ Advanced Design/ Prototype	Preliminary Design	Advanced Design/ Prototype
Integration with Existing Tools and Data	High	Medium	High
Flexibility and Customization	Medium	Low	High
Validation and Reliability	Medium	Low	High
User Expertise and Tool Maturity	High	Medium	High

For rapid sensitivity analysis, estimation of the pressure losses, estimation of pressurant requirements, or quick feasibility checks, building an analytical model tailored to the specific propellant-tank configuration can provide valuable insights. It is especially useful when high-volume simulations are needed or when validating specific assumptions.

CFD should be used selectively in later stages or for validating localized phenomena—e.g., ullage mixing post-injection or detailed heat transfer effects in complex geometry. CFD is indispensable for final verification, but not optimal for layout iteration or parametric studies due to cost and time, therefore this approach will not be adopted during the thesis project.

In conclusion, the modelling strategy for the thesis should be hierarchical and adaptive: employing 0D/1D models as the backbone for system-level simulations and integration testing and incorporating analytical models for quick trade studies and validation cross-checks. Using CFD analyses selectively for high-fidelity evaluation of critical subsystems is recommended for future projects once the design stabilizes, therefore it falls out of the scope of this research project. This hybrid approach ensures the project meets its development goals with optimal use of resources, ensuring fidelity where needed and speed where possible.

<div style="text-align: right; font-size: 4em;">4</div>

<div style="text-align: right; font-size: 2em;">Models</div>

This chapter presents all the models built and subsequently used for the purpose of this thesis. The models are build in a commercial software, which was the selected 0D/1D modelling approach following the literature study and trade-off in subsection 3.4.3. The outcomes of the simulations are discussed in the following section.

The first part of the thesis was dedicated to the implementation of component and sub-system models, that were then integrated into a full pressurisation system preliminary model with the purpose of confirming the functionality of the merged sub-system models. section 4.1 presents these in detail, with all the assumptions and an explanation of the pre-developed model components. In section 4.2 the models implemented respectively for the propellant and oxidizer are described, and the iterative methodology adopted at Maiaspace is reflected in the successive improved versions of certain models.

4.1. Component/sub-system Models

This section describes the individual components and subsystems that comprise the pressurisation architecture of Maiaspace's reusable main stage. The pressurisation system ensures that both fuel and oxidizer are delivered to the engines under the correct conditions throughout all flight phases. Each subsystem has been modelled using a combination of standard libraries and custom-developed components, allowing for the representation of thermodynamic, fluid dynamic, and control behaviours.

The modelling process adopts a modular approach, wherein each key element, such as storage vessels, valves, and propellant tanks, is independently modelled, verified and in some cases validated, then integrated into the larger system architecture. The models are validated using data from past tests, performed either internally or externally to the company, for instance from the suppliers of specific components; where such data are unavailable, this thesis outlines a comprehensive provisional test plan to address the remaining validation needs (chapter 6). This methodology facilitates early detection of component-level performance issues and simplifies iterative development and validation.

4.1.1. Storage Vessels

The inert pressurant storage vessels represent the starting point of the pressurisation chain. Any fluctuation or drop happening here propagates downstream, and it is therefore important to study. Therefore, monitoring the pressure decay over time during discharge of the vessels is relevant and was evaluated in this study. High-pressure gas can undergo significant temperature drop due to expansion, which may affect other system components, for instance in terms of freezing risk. Storage tank sizing and pre-fill conditions are critical design drivers for pressurisation system mass and volume. For this reason, the initial storage pressure and temperature need to be studied, as well as their effects on the pressurisation capability of the system. In addition, the mass flow rate into downstream components needs to be monitored as well. For this sub-system model, the mass flow rate out of the tank was imposed as a boundary condition, with a constant pressure and temperature. Once this sub-system model is integrated within the complete pressurisation system model, mass transfer is modelled via a

gas outflow into the downstream pressurisation circuit based on valve commands and pressure differentials. Pressurant gas depletion and its effect on system performance determine the mission duration feasibility and number of pressurisation cycles.

The schematics for the modelling of this component is displayed in Figure 4.1. The storage vessels are modelled as a high-pressure tanks containing the pressurant gas. The vessels are responsible for maintaining sufficient pressure levels to drive the propellants from their tanks to the engine feed lines. Initially, the pressure vessels were modelled as one single pressure vessel with an equivalent volume, assumed to be rigid and adiabatic, with predefined initial pressure and temperature conditions. Consequently, to increase the complexity of the model, each vessel was modelled singularly as a rigid, adiabatic volume with known initial pressure and temperature conditions. The pressureant is treated as a real gas, and its properties are taken from the NIST database [28].
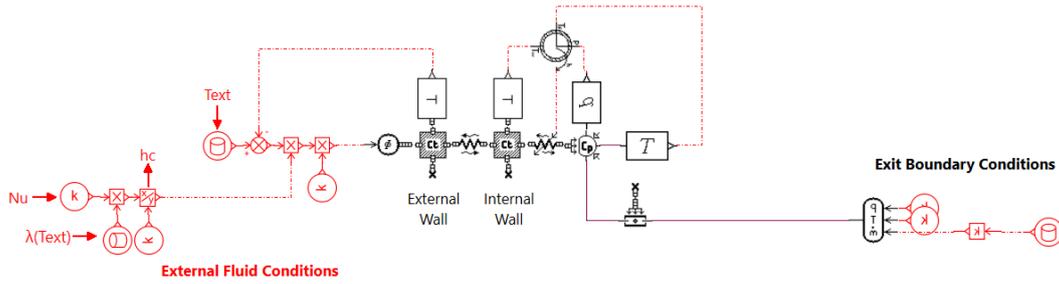
Figure 4.1: Pressurant Storage Vessel Schematics.

Optional thermal interaction with the external environment through the walls can be toggled to reflect the interaction with the external environment when the conditions need to be monitored and are considered non-negligible. The heat exchange of the inert gas with the exterior is modelled by adding the liner and insulation layers with conduction enabled between them, then adding convection from the wall to the internal gas. The pressure vessels have an internal liner, and are insulated from the external environment by an insulation layer, made by a material frequently used for insulation, due to its low specific heat capacity and low thermal conductivity. In addition, a custom component simulates the convection of the gas inside the vessels. The outer wall is connected to signal components that simulate the temperature T_f and convection coefficient h of the external fluid Equation 4.1.

$$\dot{Q}_{conv} = h_c A (T_f - T_{wall}) \tag{4.1}$$

where A is the surface of the external wall, and T_{wall} its temperature. For this preliminary case, the external environment is assumed at constant temperature and pressure, and the convection coefficient is constant. The thermal conductivity of the fluid, under the specific conditions of pressure and temperature assumed, is obtained from CoolProp [3]. In this simulation, natural convection is assumed because the velocity field of the external fluid environment around the spheres is not yet characterized. If required, this aspect will be investigated in future work through dedicated CFD simulations to quantify the associated heat transfer in three dimensions. Since the geometry is assumed to be spherical, the correlation for the Nusselt number (Nu) for natural convection over a sphere from [8] was used:

$$Nu = 2 + \frac{0.589 Ra_D^{1/4}}{[1 + (0.469/Pr)^{9/16}]^{4/9}} \tag{4.2}$$

The Nusselt number can also be expressed as a function of the convection heat transfer coefficient h:

$$Nu = h_c \frac{L_c}{k} \tag{4.3}$$

With k being the thermal conductivity of the fluid at a specific pressure and temperature, calculated with CoolProp [3]. Here, the characteristic length L_c for the Nusselt number is the equivalent diameter of the sphere D. In this study, steady-state heat transfer parameters were employed to model the interaction between the gas pressure vessels and their surroundings. This choice was motivated by

the limited availability of detailed transient data on local fluid temperature and velocity fields, which prevented a reliable time-dependent analysis. The Nusselt number correlation used to model heat transfer between the pressure vessels and their surroundings represents a major assumption in the analysis as well. The vessel geometry was simplified to a sphere rather than a cylinder with spherical end caps, and convective heat transfer was modelled as natural convection due to the lack of detailed information on the local temperature and velocity fields around the vessels. While these assumptions introduce uncertainty, they provide a practical first-order estimate of the heat transfer behaviour. As noted earlier, these uncertainties could be reduced in future work by validating the model against representative experimental data or by performing dedicated CFD simulations to better predict the external fluid behaviour and identify the dominant heat transfer mechanisms.

The model assumes a spherical geometry, uniform wall temperature distribution and an input profile for the mass flow rate of He. However, it neglects internal stratification of the pressurant gas, which may occur in large tanks or under low-flow conditions. Nonetheless, it accounts for the convection of the inert gas inside of the vessel and the heat transfer coupling. Thus, it is sufficient to capture the dominant thermal trends relevant for design and sizing. The simulation results, reported in Figure 4.2, of the pressure vessel discharge model provide important insights into the thermo-fluid dynamic behaviour of high-pressure gas under realistic operating conditions. The model accounts for both the internal heat transfer between inert gas and the vessel wall and the external heat exchange with the ambient environment, which together influence the pressure and temperature evolution during discharge.
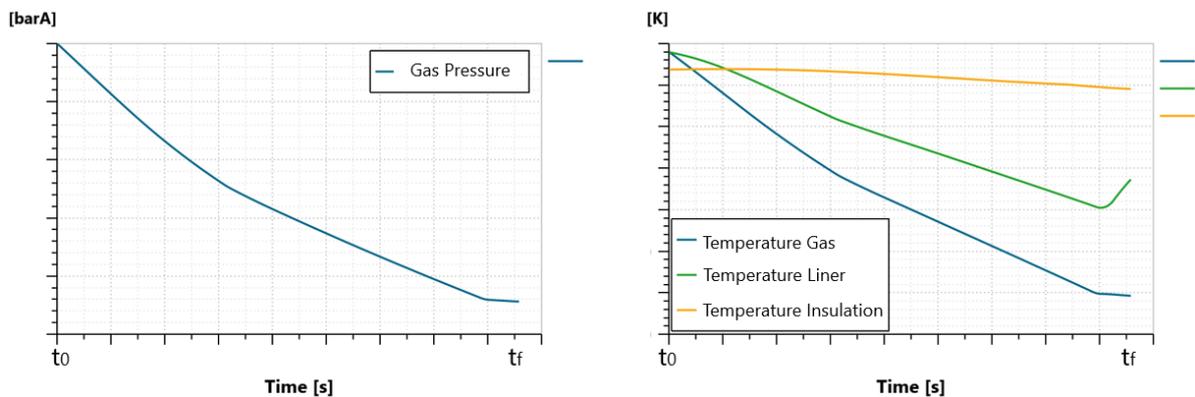
Figure 4.2: Pressure (left graph) and Temperatures (right graph) Evolution during Discharge.

As expected, the expansion of pressurant during discharge leads to a significant temperature drop in the gas. This cooling effect is primarily driven by the likely isentropic decompression of the stored gas, which is only partially mitigated by heat exchange with the vessel wall. The pressure vessel wall plays an important role as a thermal buffer. The heat transfer from the wall to the pressurant slightly reduces the rate of temperature decay, especially in the early stages of discharge. However, due to the relatively high thermal resistance of the wall and the rapid nature of the gas expansion, this heat transfer is limited in magnitude and duration. During fast transients, the external environment contributes minimally to the internal thermal balance due to the thermal inertia of the insulation. For longer discharges or in scenarios involving intermittent pressurisation, this external heat transfer may become more relevant.

From a design perspective, the results highlight the need to account for thermal losses in sizing discharge durations and evaluate the structural and thermal properties of the pressure vessel wall.

4.1.2. Pressure Regulator
Pressure regulator plays a critical role in ensuring that the high-pressure gas from the storage vessel is reduced to appropriate levels before it enters the propellant tanks. It regulates downstream pressure dynamically and maintains system stability under varying flow demands.

The control strategy adopted for the pressure regulation was implemented in the models by using a combination of components from the pneumatic and control libraries.

The regulators were not modelled in detail, meaning taking into account the design of the components themselves, but they are considered as orifices with a variable section that changes based on the control command.

A relevant phenomena to study within the pressure regulators is the pressure drop across the regulator, to compare its value with the estimations taken into account for the pressure losses in subsection 4.1.4. The dynamic response of the regulator in terms of response time and the related overshoots, oscillations and settling time. This is relevant, since poor regulator performance can cause pressure spikes or insufficient pressurisation in the propellant tank. Flow choking behaviour at high upstream pressures was analysed as well as the sensitivity to temperature and upstream pressure variations.

4.1.3. Tank

The propellant tanks (for both fuel and oxidizer) are central to the pressurisation model, as they interface directly with both the engine and the pressurisation subsystem. Their ability to maintain structural integrity and stable pressure during all mission phases is critical to launch success.

The tanks are modelled with a fixed volume but variable fill levels, accounting for ullage volume and gas-liquid interface. The schematics of the tank component is displayed in Figure 4.3. The shape of the tank is at first approximated as a sphere, with an equal volume to the real tank. Then, in the complete models described in subsection 4.2.2 and 4.2.3, to increase the accuracy of the tank model, the geometry is recreated by giving in input the radius as function of the height of the tank. In this way, the geometry of the tank can be replicated with higher accuracy, therefore the area of the gas-liquid interface inside the tank is more representative of the actual system, and evolves based on the fill level. The gas in the ullage zone is treated using a real-gas model; pressure rise and decay are calculated based on incoming flow from the pressurisation system and temperature interactions.
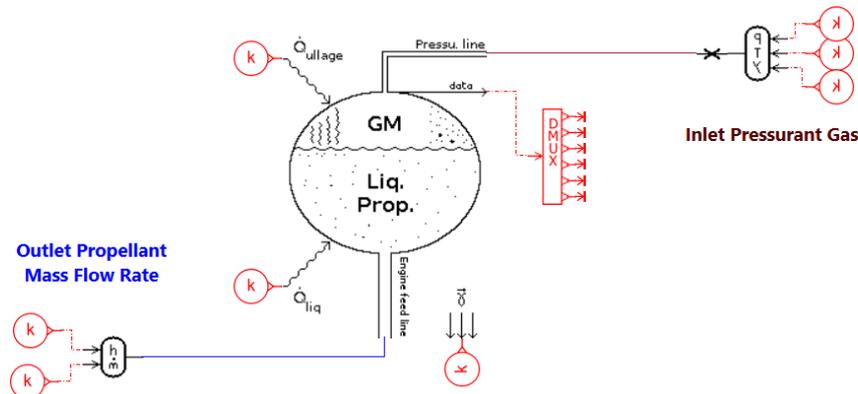
Figure 4.3: Oxidizer Tank Schematics.

At first, the tanks are modelled as adiabatic volumes, then the heat flow rate to and from the surrounding environment is given in input based on external calculations. The tanks walls are not modelled, since there is no significant effect that we can investigate thoroughly in this model by adding complexity to them. Furthermore, the evolution of acceleration is taken into account in the tank model, to allow for a more accurate representation of transient fluid behaviour under varying dynamic conditions.

4.1.4. Pressure Losses

In the development of an accurate model of the pressurisation system, it is essential to account for distributed and localized pressure losses throughout the gas path. To this end, pressure drops at key locations were quantified using empirical correlations from Idelchik's handbook [20]. The Handbook of Hydraulic Resistance" by I.E. Idelchik is a comprehensive reference that provides empirical data and formulas for calculating pressure losses (hydraulic resistance) in incompressible and compressible fluid flows through various piping components and geometries. These empirical correlations were implemented in a dedicated Python script, enabling modular and parametric analysis across varying flow regimes. The main assumptions for these pressure loss evaluations are a maximum mass flow rate at minimum pressure and maximum temperature. These assumptions enable proper sizing of the

lines and the calibration of pressure loss values for the various sections of the system, based on the expected operating conditions throughout.

Once the Idelchik dimensionless pressure loss coefficient ζ is calculated, Equation 4.4 is used to calculate the incompressible pressure loss coefficient K in $[1/m^4]$. The coefficient K is then used to estimate the pressure loss Δp, as in Equation 4.5.

$$K = \frac{\zeta}{2\,A^2} \tag{4.4}$$

$$\Delta p = \frac{K\,\dot{m}^2}{\rho} \tag{4.5}$$

The values of K calculated for lines include the pressure loss of the line plus the losses of $40°$ and $90°$ elbows, where present.

Some assumptions and limitations of this model include a steady-state flow and single-phase gas. In addition, the Idelchik coefficients were selected conservatively in the absence of precise geometry. Using Idelchik's handbook to calculate pressure losses in a pressurisation system is valuable because it provides reliable baseline estimates for steady-state flow conditions, which are often the dominant regime during normal operation. Even though the handbook does not capture fast transients or start-up behaviour, these steady-state calculations allow to size lines, select components, and estimate overall system performance with confidence before performing more detailed transient simulations or experimental validation. Essentially, it offers a practical first-order assessment that is grounded in established empirical data, reducing uncertainty in the early design stages and giving a good estimate to input into the 0D/1D models of this thesis. In Appendix A, all the Idelchik models employed to define K, as well as empirical values of K given from suppliers of specific components, are presented.

The evaluated pressure losses were either directly entered into the models as fixed resistance components, or used to tune pressure drop models within standard libraries. This approach ensured consistency between analytical loss estimation and the numerical simulation model, providing a robust baseline for evaluating dynamic pressurisation behaviour.

4.2. Full pressurisation System Models

This section presents the systematic construction and refinement of simulation models for the complete pressurisation system of the launch vehicle lower stage. The objective is to develop transient, physically representative models capable of predicting the behaviour of the pressurisation subsystem under various mission scenarios, and to support system sizing, control strategy development, and performance verification.

The section is structured into two main parts. The first in subsection 4.2.1 focuses on the development of a preliminary generic model, which serves as a foundational framework. This simplified model is used to validate modelling assumptions, assess baseline system behaviour, and establish a modular simulation architecture within the modelling framework. It provides a benchmark for qualitative understanding of pressure dynamics and is used to identify critical parameters and sensitivities in the system. This model exhibits substantial design and layout differences compared to the models developed within the scope of this thesis, as it is based on the layout of an alternative design configuration studied in parallel at the company but not considered in this work.

The second part in subsection 4.2.2 and 4.2.3 expands on this foundation with the creation of advanced, configuration-specific models tailored to distinct launcher architectures. These include fully integrated pressurisation systems for both the oxidizer and fuel, with geometry, component behaviour, and operational conditions aligned with realistic launcher configurations. Each model incorporates detailed representations of storage tanks, control valves, flow resistances, and thermal interactions, as required by the particular mission scenario and propellant combination.

Throughout this chapter, careful attention is given to the modelling assumptions, boundary conditions, and design choices made at each stage of development. This includes decisions regarding flow regime treatment , component-level approximations , and simplifications required to ensure simulation stability and computational efficiency. Whenever applicable, empirical correlations, such as those from

Idelchik's handbook mentioned in the previous chapter, are used to model pressure losses and localized flow effects.

The goal of this section is to provide a clear and justified methodology for the progressive construction of reliable pressurisation models, which will later be used for transient analyses and performance evaluation in the section of this thesis dedicated to the outcomes chapter 5.

4.2.1. Preliminary Model
The preliminary model of the pressurisation system was constructed as a first integrated representation of the overall architecture, serving as a baseline for validating individual subsystem behaviour and their interactions. This model was built by assembling and interconnecting the previously developed component-level models, which had been validated or dimensioned independently. These components include the high-pressure storage vessels, pressure regulator and tank.

To transition from isolated components to a full system simulation, the following key additions and integration steps were made. Each major component was linked through modelled fluid lines, representing the actual layout of lines in the system. These lines were implemented using custom pipe models, depending on the required fidelity. Line segments were parametrized by length, internal diameter and the pressure loss coefficient calculated in subsection 4.1.4 that takes into account also the losses relative to $90deg$ and $45deg$ elbows in the line. However, the material properties and heat exchange of the pipes were neglected for the preliminary model.

The inputs and initial parameters considered for the preliminary model are not representative of a real rocket configuration that can be studied and analysed to obtain realistic results. This model served more as a baseline for the configurations that were studied later, in order to ensure compatibility between the components models previously developed and check for a correct initialization, functioning and convergence of the model. Furthermore, the results from this model will not be presented in the "Outcomes" section.

4.2.2. Inert Gas Pressurisation System Model
The fundamental operation of the inert gas pressurisation system is first introduced, followed by the presentation of the different model versions at varying levels of maturity. The pressurant gas used for this system is an inert gas, stored at high pressure inside the pressure vessels. The exact number of these pressure vessels, and therefore the pressurant gas mass requirement, is initially defined from the mass budgets and iterated and refined through these simulations, which provide a more accurate estimate of the total pressurant demand by accounting for additional physical phenomena. A regulation of the gas pressure is performed.

Due to the AGILE iterative process followed at Maiaspace, several configurations of the two pressurisation systems were studied. Each of the configurations was iterated upon and improved, according to the new input trajectories, constraints, etc. The main use of these models, is to simulate the functioning of the pressurisation systems with a higher complexity that what is calculated in the company preliminarily with the calculation referred from here on as "budgets". These were calculation performed previously in the company to determine the quantity of pressurant needed, accounting for some pressure losses which were assumed and less detailed than what modelled in this thesis. In addition, the budgets gave an initial indication of the tank needs in terms of incoming mass flow rate needed to pressurize the two tanks. The models implemented in this thesis add complexity to these calculations, by simulating the regulation, thus the mass flow variation we can study how this impacts the other parameters, performances and eventually the functioning of the system. In addition, the interactions between the various systems, the subsystems transients, were not taken into account in the budgets. For this reason, the inputs for the models were taken from the budgets, to align and compare thoroughly the results.

First Version
The first configuration of the inert gas pressurisation system was built along the line of the preliminary model: integrating the subsystems previously built for the storage vessels and regulator. A predefined number of storage vessels was considered for this configuration. The number of storage vessels was taken as an input from the budget studies done by the company, where the quantity of gas needed for the mission was defined, in order to realistically evaluate this pressurisation system option. The lines,

filters and junctions added in this model to connect the subsystems' models are representative of the real layout and have the relative pressure loss coefficients K calculated in section 4.1. A comparison between the pressure losses calculated previously and the effective pressure losses as simulated by the model was done. The sketch of the first configuration model is presented in Figure 4.4.

The simulation is conducted from lift-off $t_0 = 0\ s$ to the end of the flight t_f. Throughout the flight, the system is subject to varying acceleration based on the trajectory, the effects of this acceleration are non-negligible mainly in the tank and are therefore taken into account from this first version of the model and in the following configurations as well.

Second Version
The model for the second configuration of the inert gas pressurisation system, shown in **??**, was built starting from the model of the first layout, described in the previous pages. The main scope of this model was to simulate the case were a gas tap-off, destined to other subsystems than the pressurisation, was added. By adding this tap-off, the pressurant need is also increased with respect to the previous model that did not take these gas outflows into account.

Third Version
A third version of the inert gas pressurisation system option was implemented after iterating on the design. As previously done, the third version was built starting from the model of the second version, described in the previous pages. The sketch for the model is similar as the one displayed in **??**.

In this version, the main changes implemented consisted in modifying the pressurant gas needs, and modifying and refining the regulation. In this version, the tank is no longer approximated as a simple sphere, unlike in earlier iterations. Instead, its actual geometry is represented by defining the tank radius as a function of height and providing this relation as input to the model.

This model represents the final version of the inert gas pressurisation system as studied and designed within this thesis. It was therefore employed to define the regulation strategy (section 5.2), which constitutes the primary research objective of this work. For this purpose, more detailed information on the valves was required, particularly those involved in the regulation stage, as they represent a critical point due to the rapid actuation and the pressure losses induced by their design and by the opening and closing process as a function of the mass flow. Due to the way the pressure regulator was modelled, described in section 4.1, the pressure losses caused by the regulators were incorporated into the component through the use of the incompressible pressure loss coefficient K in $[1/m^4]$, which is an empirical parameter taken with a reasonable approximation. These assumptions and approximations are expected to provide an accurate representation of the pressure losses and the expansion through the regulators. Nevertheless, this approach will be validated against the supplier's valve test data, for which a dedicated validation model has been prepared.

4.2.3. Autogenous Pressurisation System Model
The autogenous pressurisation system presents significant differences with respect to the preliminary model. The thermodynamic properties of liquid and gas were obtained from the NIST Chemistry Web-Book [28]. This pressurisation system was studied in two versions: one fully autogenous and one hybrid, which employs two pressurant gases coming from different systems. The main pressurant is gas coming from the autogenous system, that is mixed with an inert pressurant.

Although this model was iterated upon, the first version is not showed in this report because its outcomes are not considered relevant for this work. Despite the differences with the previously developed models, some of the subsystems presented in section 4.1 were used, for instance: the pressure regulator, inert gas pressure vessels and propellant tank. The real geometry of the tank expressed as radius as a function of the height $r = f(h)$ was provided to the model.
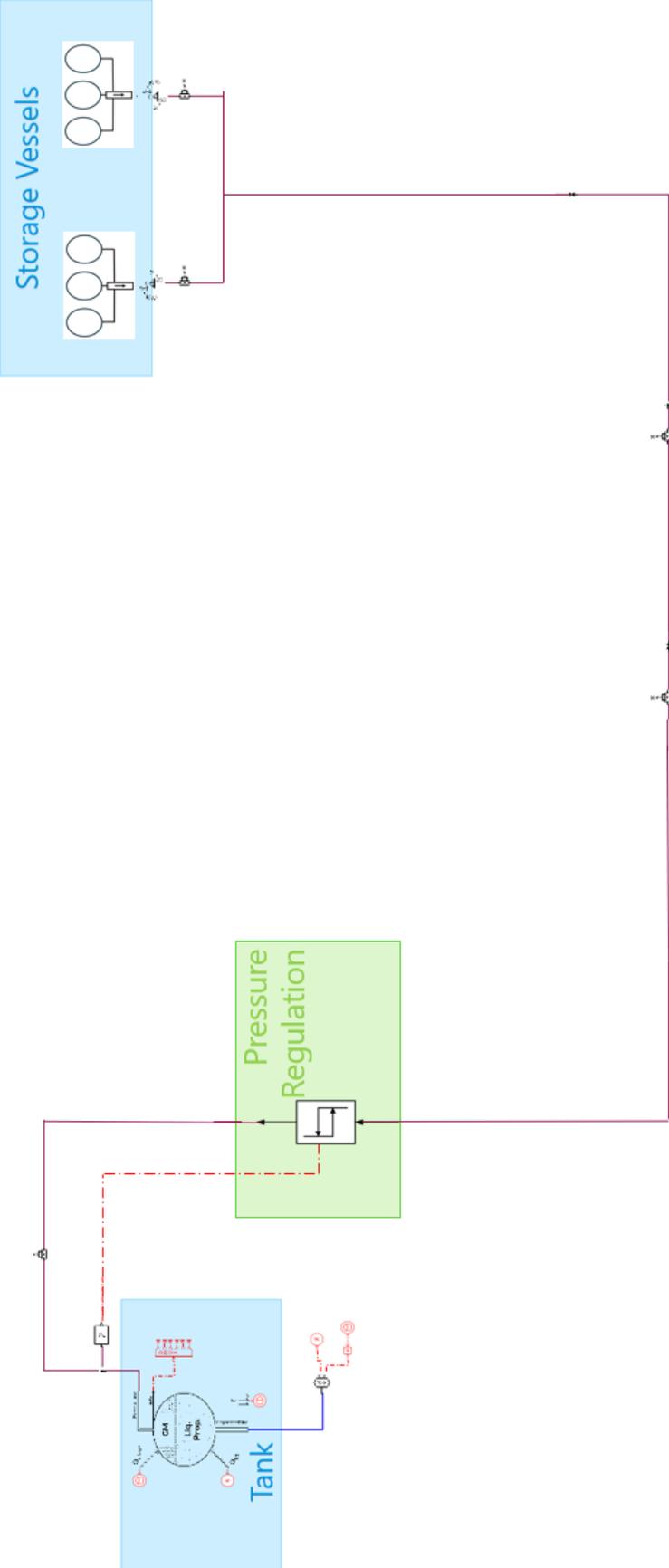
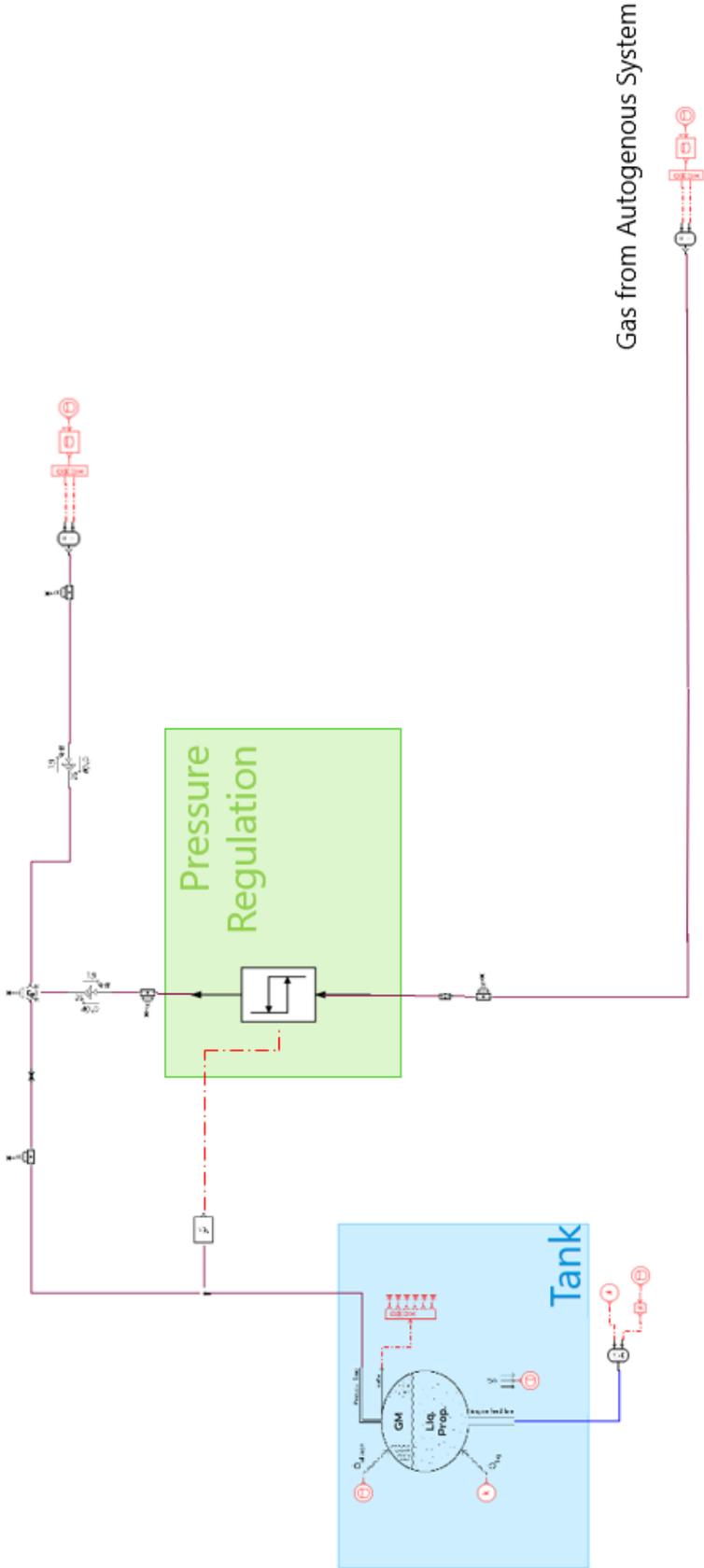**Figure 4.4:** First Version (v1) Inert Gas pressurisation System Model.

Figure 4.5: First Version (v1) Autogenous Pressurisation System Model.

5

Outcomes

In this chapter, the outcomes of all the studies performed using the models presented in chapter 4 are presented and their relevance and impact on the overall pressurisation system design is discussed. First, in section 5.1 there is a presentation of the overall results regarding the functionality of the pressurisation system and monitoring of the key parameters, this is done together with a discussion of the main phenomena observed and, were needed, iterated upon. In the second section, section 5.2, the pressure regulation strategy is explained more in detail and the results of the studies on the improvement of the regulation are also reported.

5.1. Simulation Results

The primary objective of these simulations is to verify that the system under analysis achieves the required pressure within the acceptable boundaries inside the fuel and oxidizer tanks. This outcome depends not only on the correct functioning of the system as designed, and on the representativeness of the models with respect to the real system, but also on the selection of an appropriate regulation strategy, which is determined by these models for the first time. In connection with this main objective, several additional parameters must be monitored to ensure proper system operation, such as compliance with the temperature, pressure, and mass flow constraints defined for each specific subsystem.

In this section, the simulations' results of the models presented in the previous chapter are showed and discussed. The iterative AGILE methodology is reflected in the progressive increase in model realism, with respect to all the components being present and modelled, and convergence toward full functionality as successive model versions are developed.

5.1.1. Inert Gas Models

The results and key findings of the models are presented and discussed for each version in chronological order, to provide a clearer understanding of the iterative process applied to the models and to the baseline of the pressurisation system layout, highlighting the reasons why the changes were introduced.

First Version

Despite bing a first iteration, therefore not complete, the first version of the inert gas system model gives important insights in the functioning of the system already, especially when observing the evolution of tank ullage pressure.

The purpose of a pressurisation system is to maintain the ullage pressure at a target value. In this case, this is achieved using a control strategy, aligning to what already explained in subsection 4.1.2. This type of control maintains the controlled variable within a predefined range, here defined as a pressure corridor bounded by minimum and maximum acceptable values. The defined acceptable pressure for the control reflects the constraints and requirements of propellant pressure for the engines and the NPSP, as well as the minimum and maximum limits required to ensure the structural stability of the

tank. A more detailed discussion of the potential issues arising from incorrect tank pressurisation is provided in section 3.1.

The pressure evolution is acceptable since it remains within the boundaries for the entire flight. However, it does not reflect the typical functioning of the employed control. During the beginning of the flight, the ullage pressure rises rapidly due to the high incoming mass flow rate, and then decreases quickly as a result of the ullage temperature drop. This decrease in ullage temperature continues afterwards, causing the subsequent pressure increase to occur more slowly.

T

Overall, the mass of pressurant remaining in the pressure vessels is higher than what was predicted by the budgets in this simulation. This can be calculated with the pressure and temperature inside the pressure vessel at the end of the simulation.

Second Version
The second version is more refined and has an increased level of detail than the previous one, the details of the differences in modelling and assumptions of this specific version are in subsection 4.2.2.

Since the mass flow rates of the tap-off is imposed by adding an orifice, the value is not constant, unlike in the budgets. This simulation allows to have an insight on the overall variation experienced by the mass flow passing through the orifice with the change in upstream conditions, as well as having more realistic mass flows that are influenced by the functioning of the other subsystems. The addition of this outgoing mass flow rate results in the tank ullage pressure being even less regulated than in the previous simulation. This provides important insight into the system requirements: first, the gas mass stored in the pressure vessels should be augmented to ensure stable operation of the system throughout the entire flight; second, the incoming gas should enter the tank at a higher temperature.

Third Version
The third version of this pressurisation system is the final configuration that was investigated in this work. An extensive description of the study of the pressure regulation strategy for the high pressure regulation, derived from this model, is done in section 3.2.

The ullage pressure regulation is achieved within acceptable boundaries.

The ullage pressure curve in this version reflects a more stable behaviour than the two solutions previously studied.

Since the simulation of this final version proved that the system is functioning accordingly to what was envisioned, then conclusions were drawn from what is observed within this pressurisation system, for phenomena that are especially evident from this simulation. Most of the variables are affected by the regulation. The variation and oscillation of mass flow rate is the first direct consequence of this, and it impacts all the other variables.

The evolution of temperature before the pressure regulator was monitored to check its alignment with the supplier constraints. The insulation layer studied acts as a good insulator according to this simulation, which exhibits a temperature evolution that is smooth and not directly influenced by the gas temperature fluctuations. For reusable stages, ending the flight with a predictable, safe residual pressure and temperature is critical for turnaround and inspections. Even for expendable vehicles, uncontrolled venting or post-burn risks should be to be avoided. The final temperature of the gas inside the pressure vessels is therefore a parameter to monitor, to check that it does not drop below the minimum temperature specified for the downstream components. Therefore, the evolution of temperature in the pipes leading to the pressure regulator was monitored as well, to check its alignment with the supplier constraints.

The final values of temperature and pressure inside the pressure vessels were compared with what calculated in the budgets, for verification.

5.1.2. Autogenous Model
The simulation of the second option studied for the pressurisation system gave relevant insights on the functioning of the autogenous pressurisation system as it was investigated for this thesis. It is clearly
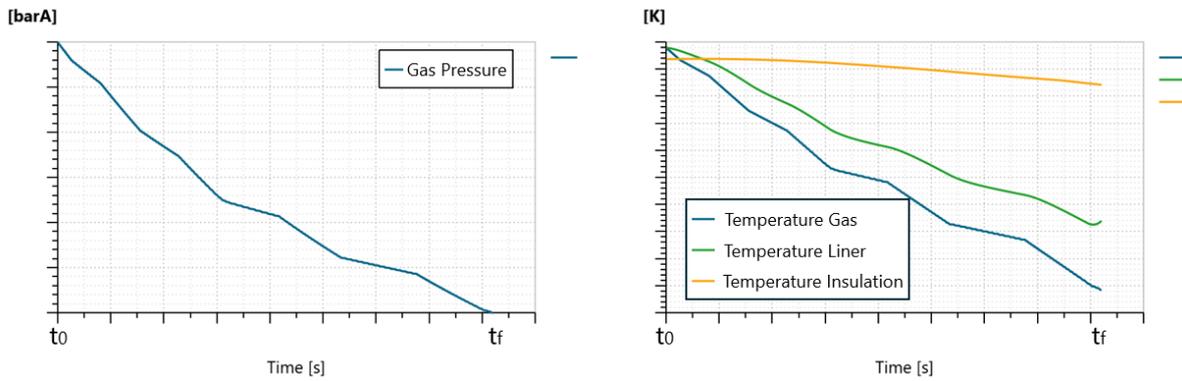
Figure 5.1: Pressure Vessel Pressure (right) and Temperature (left) Evolution.

visible by the evolution of ullage pressure, where the pressure curve is kept within the acceptable value set for the regulation. At first, the tank pressure curve in the simulation dropped below the lower acceptable lower boundary.

For this reason, the regulation was performed with a different target value of pressure than the actual acceptable value calculated, to keep the ullage pressure within acceptable values. This change in the regulation is explained further in subsection 5.2.2, and it allowed to reach a stable tank pressure curve for the autogenous option. It is important to note that this option was proved to be less stable than the inert gas option, but offers several other advantages.

5.2. Pressure Regulation Strategy

The main research objective of this thesis is to define a pressure regulation strategy for the investigated pressurisation systems. This was done first by choosing the design of the system and iterating it until a regular pressurisation was achieved based on the design alone. On a second moment, the regulation strategy for all the regulators was refined and improved until reaching a reliable functioning of the systems.

The improvement of the pressure regulation strategy was done by studying two main regulations, first the pressure regulation investigated in subsection 5.2.1, then the pressure regulation presented in **??**. These strategies were studied for the regulators of the two pressurisation systems options introduced in chapter 4.

5.2.1. First Pressure Regulation Solution

The pressure regulation of the inert system was analysed in detail only in the third model version, which had the highest refinement with respect to the system functionality out of all the model versions.

The final pressure regulation strategy for the pressure regulation of the inert gas pressurisation system, defined for the third model configuration and the specified flight input, consists of three main phases of regulation.

The transition between the first two phases occurs after a time interval t_1. Then, at time $t_2 > t_1$ the regulation switches to the third phase.

5.2.2. Second Pressure Regulation Solution

For the regulation of the autogenous pressurisation system, there are not multiple phases unlike in the previous regulation strategy. The solution analysed consisted of a simple regulation with a constant regulation, that remains unchanged throughout the entire time of simulation.

6

Validation and Test Plan

This chapter presents the validation strategy for the pressurisation system models developed in the previous sections, combining a thorough review of existing experimental data with the definition of a forward-looking test plan. The main aim is to ensure that the numerical models accurately capture the physical behaviour of the system across relevant operating conditions and can be used for design, sizing and mission analysis.

In the first part of section 6.1 the item to validate were identified, discussed and summarised in a table. The second part of the section reviews available test data from past campaigns, including those conducted in the company and those provided by component suppliers. These tests cover various elements of the pressurisation chain such as storage tanks, regulators' valves and pressurisation lines.

At the beginning of **??** model outputs are compared against available test to validate key aspects such as expansion process and thermal behaviour of the pressure vessels. The section then outlines an upcoming tests scheduled by the pressure regulator supplier, identifying which elements of the system will be instrumented and which performance parameters will be measured. This includes the test preparation, definition of parameters to be validated with this test and the choice of test duration and representativeness of the test. The dedicated model built for the test preparation is also presented.

Finally, based on the identified validation needs and model sensitivities, a dedicated test plan is proposed for the upcoming hot-fire test campaign, in section 6.2. The plan is designed specifically to acquire the critical data needed to validate the full pressurisation system model under realistic dynamic conditions, representative of actual launcher operation. Parameters to measure and expected validation targets are defined to ensure alignment between experimental efforts and simulation goals. This integrated approach strengthens the credibility of the modelling work, and provides a clear roadmap for the continued refinement and qualification of the pressurisation system through testing.

6.1. Model Validation

The objective of verification and validation is to establish the credibility of a computational model by assessing the degree of accuracy of the computational results, as stated by Oberkampf and Roy [40]. In particular, verification is defined as the process of determining that a computational model accurately represents the underlying mathematical model and its solutions [54]. This verification, was done at every step of the model development during the course of this thesis. The results of each system and sub-system model were compared with expected results or analysed to check their agreement with the physically expected outcome. Therefore in this chapter, the focus is on the validation of the models, defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended use of the model [41].

First, the phenomena to be validated within the pressurization system models were identified and listed in subsection 6.1.1. Then, in subsection 6.1.2 a review of scheduled and completed tests was done and the phenomena identified in the previous section were linked to the respective tests by defining a

level of representation of the test with respect to each validation item.

6.1.1. Identification of Validation Items

First, the relevant phenomena to be validated were identified and later summarized in Table 6.1, starting with the phenomena concerning every component and completing with the ones that can be observed exclusively on the integrated system model. This process is important, because selecting and isolating the single validation items allows for a thorough analysis and validation of the model results. The selection of these validation items and the relevance of the underlying physical phenomena are discussed in detail.

Table 6.1: Classification of the Identified Phenomena to Validate.

Validation Item	Name
Pressure vessel	**V.1**
Pressure Regulator	**V.2**
Tank	**V.3**
Control	**V.4**

Starting from the inert gas system, the first subsystem to validate are the pressure vessels. To do so, the discharge of the high pressure gas needs to be characterized, as well as the heat exchange through the walls. This is an important phenomenon to validate, especially due to the 0D/1D approximations of the pressure vessel model, that do not take into account stratification, and due to the important assumptions in the heat transfer modelling, mentioned in subsection 4.1.1. Furthermore, the regulators' stability and correct operation must be verified under real test conditions, as theoretical analysis alone may overlook practical instabilities such as oscillations, drift, overshoot, or sensitivity to external disturbances, which can compromise overall system performance. A potential cause of control instability, not accounted for in the models, that needs to be monitored is the accuracy of the pressure sensor, that need to be quantified during the test in order to define precise margins for the regulation to input in the models to increase accuracy. The models use empirical pressure loss coefficients K reasonably assumed for this application for the regulators and their filters, which can be tuned for this specific system based on the tests results, in order to increase the accuracy of the models. Therefore, the pressure loss of the filters and over the regulators themselves will need to be evaluated against the test data, and modified accordingly where needed. The model does not include the presence of a diffuser for the LOX and LCH_4 pressurant injection in the tank. This component highly affect the mixing of the incoming pressurant with the ullage volume. Therefore, it is important to validate how the absence of this component in the model affects the final ullage pressure and temperature. The tank geometry was approximated, especially for the LOX tank, the effects of this approximations should be quantified in terms of their effect on the actual tank pressurization. Another important assumption of the models involves the thermal exchanges within the tank. An equivalent heat flow rate accounting for 1D thermal stratification, heat exchange between the ullage and the liquid, and between the ullage and the wall, was inputted to tank ullage. This represents a big assumption that needs to be validated against the test data to check the realism of the model. Finally, the effects on the autogenous pressurization system performances given by the initial gas conditions (different temperatures and pressures) should be validated against the test data.

6.1.2. Review of Scheduled and Completed Tests

To support the validation of the pressurisation system models, a structured review of both completed and scheduled tests was carried out. The objective of this review was to identify and classify experimental data relevant to the modelling of pressurisation subsystems, assess its applicability for model validation, and highlight any remaining gaps that need to be addressed in future test campaigns. A comprehensive search was conducted across internal company documentation repositories, test reports, supplier datasheets, and archived test logs. Tests involving single components or the entire pressurisation system, divided between fuel and oxidizer, were categorized in Table 6.2.

Based on the conditions and relevant tests selected, the items identified in Table 6.1 were assigned to one or more test for their validation. To ensure an understanding of the validation plan, a representativeness scale was assigned to each test and the relative validation item. This scale was defined with

four degrees of representation:

R1 : most representative. Test performed specifically for this system/subsystem, with all the real conditions (flight test).

R2 : most representative that can be done on ground. Test performed specifically for this system/subsystem, with all the conditions that can be recreated on ground: same physics, same operating conditions, same hardware.

R3 : ground test with same physics, same operating conditions, but different hardware. Test designed for another system (e.g. ground system, upper stage) to validate the same items, with a different hardware (e.g. different volume) but same physics and operating conditions.

R4 : same physics but different operating conditions and different hardware. Test designed for another system to validate the same items, with a different hardware and operating conditions (e.g. mass flows, temperature), but with the same physics.

Table 6.2: Review of Scheduled and Completed Test with Associated Validation Items.

Validation Test Reference			Validated Items	Representativeness
Already Existing (Company)	**Scheduled/Upcoming**	**Already Existing (Supplier)**		
Inert gas pressure vessel test			**V.1**	R4
	LS combined tests (hot fire)		**all**	R2
	First Flight		**all**	R1
		Pressure Regulator Qualification Tests	**V.2**	R2
			V.4	R3

6.2. Hot-Fire Test Plan

To thoroughly validate the pressurisation system models, a dedicated hot-fire test campaign will be required. At this stage, the test plan remains provisional and not yet fully defined, but it establishes the foundation for future validation efforts. The section outlines in subsection 6.2.1 the measurement goals and test objectives, with the key parameters to be monitored, and the expected outcomes in subsection 6.2.2, providing a structured framework to ensure that the simulations are comprehensively assessed against experimental data once the tests are carried out.

6.2.1. Measurement Goals

The main test objective of the hot-fire test, for the scope of this thesis, is to validate thoroughly the pressurisation system models, reproducing the functioning of the systems with a level of representativeness R2, capturing phenomena not modelled in the 0D/1D assumptions, the interactions between the subsystems and the coupling between the two systems.

This test will allow the validation of multiple items identified in the validation plan, while also ensuring that the corresponding parameters can be directly monitored and compared with model predictions. However, since the test will be carried out on ground, the exact conditions experienced during flight cannot be reproduced, for instance the accelerations to which the system is subject during flight, the external pressure and temperature at higher altitudes. For these specific conditions, the system can only be tested on the first flight. The test set-up will comprehend all the entirety of the pressurization system and propellant tanks as described in the models. More constraints of the test set-up and conditions might arise further on in the planning if safe operations cannot be ensured for some components or conditions. These are not discussed in this preliminary plan, but should be taken into account nonetheless.

The phenomena that need to be validated during this test, divided in thermal and fluid are the ones identified in subsection 6.1.2 and in Table 6.1 their level of representation with respect to real flight

conditions is discussed. In the next section, the main goals for the hot-fire test are defined, presented and later discussed.

Test Objectives
Based on the validation items discussed previously, the test goals for the hot-fire test are respectively:

1. Perform the full sequence of tank filling, discharge and pressurisation representative of the flight:

    a) Ground tank filling in the same conditions as during pre-flight preparations to reach realistic initial conditions

    b) Start-up sequence and engine ignition

    c) Flight-representative engine functioning and tank discharge and pressurisation

2. Collect data relevant for 0D/1D model validation:

    a) Collect ullage pressure evolution inside both tanks

    b) Collect ullage and liquid temperature evolution inside both tanks at different levels

    c) Collect pressure evolution before and after main sub-systems within the pressurisation system

    d) Collect temperature evolution before and after main sub-systems within the pressurisation system

These test objectives are defined to ensure that the setup will be equipped with instrumentation that provides sufficient data to draw meaningful conclusions about the system's operating point and efficiency. In addition, the system must be also representative of the hardware and design parameters implemented in the models.

6.2.2. Discussion of Expected Outcomes
The scheduled hot-fire tests are designed to provide a comprehensive validation of the pressurisation system models for both the fuel and oxidizer subsystems. By subjecting the system to real operating conditions, the tests will allow for a direct comparison between predicted and actual behaviour, including pressure evolution, mass flow rates, and temperature profiles within the tanks and lines.

It is expected that the tests will confirm the general trends predicted by the models. The regulator dynamics will be validated in representative operating conditions, together with the efficacy of the implemented regulation strategy. Thermal stratifications, the field of velocities of the gas inside the tank during the emptying, factors not captured in the 0D/1D models, will also be recorded during the test. These effects may influence the measured data and could lead to further discrepancies between experimental results and model predictions.

The test is expected to provide quantitative data on the pressure losses across the pressurisation system. These measurements will allow direct comparison with the predicted values from the 0D/1D models, validating the accuracy of the applied correlations (e.g., Idelchik). Discrepancies between model predictions and experimental results will help identify unmodelled effects, such as transient valve dynamics, flow separation, or thermal influences. Ultimately, the test campaign should confirm whether the current modelling approach captures the dominant mechanisms driving pressure losses, or whether refinements—such as component-specific calibration or higher-fidelity representations—are required. For each individual pressurisation subsystem, the hot-fire test is expected to validate the accuracy of the predicted pressure evolution, mass flow rates, and thermal behaviour. Particular attention will be given to the pressure losses along the lines, pressure regulator performance, and the thermal interaction between the pressurant and the propellant. The tests should confirm whether the simplified 0D/1D assumptions, such as uniform temperature distribution and steady-state correlations for pressure drop, provide sufficient fidelity to capture the real behaviour of each subsystem. Any discrepancies between measured and simulated data will help identify limitations of the models, such as unmodelled thermal effects, or transient phenomena not captured in the 0D/1D simulations.

Ultimately, the expected outcome of this test campaign is to achieve a high level of fidelity in the pressurisation system models, ensuring that the models accurately represent the physical system and can reliably guide design decisions and mission planning.

7

Conclusion and Recommendations

This final chapter summarizes the main findings of the study and reflects on their implications for the development of a robust pressurisation strategy in small launchers. The conclusions summarized the insights gained from the modelling work, the partial validation against test data, and the preparation of the hot-fire test plan, highlighting how the objectives set at the outset of the thesis have been addressed. At the same time, the inherent limitations of the work are acknowledged, particularly with regard to aspects of the validation that remain provisional.

Building on these conclusions, the chapter then presents a set of recommendations aimed at guiding future work in section 7.2. These recommendations focus on completing the validation of the models and leveraging forthcoming test campaigns to strengthen confidence in the methodology. Together, the conclusions and recommendations provide a bridge between the present work and the next steps required to advance the pressurisation system design toward full reliability in flight conditions.

7.1. Conclusion

The main objective of this thesis was to develop and partially validate a pressure regulation strategy for the fuel and oxidizer pressurisation systems of Maiaspace's mini-launcher. This objective is highly relevant, as reliable pressurisation is essential to guarantee that the tanks deliver propellants at the correct pressures throughout flight, directly impacting engine performance and ultimately mission success. Establishing a robust yet efficient methodology to design and validate such a strategy is therefore critical for agile launcher development, where time and resource constraints limit the possibility of exhaustive trial-and-error testing.

The work began with a review of the literature on pressurisation systems for launchers' first-stages, chapter 3. This review highlighted the different architectures that have been employed in practice, their advantages and drawbacks, and the typical challenges associated with maintaining stable tank pressures under varying flight conditions. From this survey, several gaps and open questions emerged, particularly concerning the need for flexible modelling approaches capable of balancing fidelity and speed, and the importance of structured validation to build confidence in the models. These insights directly informed the research proposal by motivating the choice of 0D/1D simulation models as the primary tool, complemented by a progressive validation plan including past test data and scheduled hot-fire tests.

Subsequently, the work shifted towards the development and refinement of the individual sub-systems models. This was done to have an initial analysis of the functionality of each sub-system model, focusing on verification of results and accuracy with respect to real conditions. Where major assumptions regarding specific phenomena (e.g., heat transfer, pressure losses) were made, they were explicitly stated and highlighted in the text to ensure transparency concerning the predictive capabilities of the models. The sub-system models were then integrated into the several configurations of complete pressurisation system models.

The outcomes of the simulations were presented and discussed, and gave important insights on the functionality of the pressurisation systems for different design options. Thanks to these results, the design baseline for both systems was refined, and significant non-negligible effects were investigated. For example, the oscillations in mass flow rate induced by the regulators provide valuable insights that can guide engineering decisions. These findings enable more detailed CFD studies of tank pressurisation, heat transfer, and velocity fields within the ullage, by supplying a more accurate mass flow rate that accounts for effects uniquely captured by this simulation.

Overall, this work helped answering the main research questions defined at the end of the literature study, and these answers are hereafter discussed.

RQ.1: What is the design of a pressurisation system for the various configurations of Maiaspace's launcher reusable main stage?

Within the scope of this thesis several pressurisation system designs options were proposed and studied. The activities conducted during this thesis contributed to verifying the functionality of these proposed preliminary design options by providing simulation results that offered a more comprehensive understanding of the system's behaviour, particularly regarding coupling and regulation effects. The first system proposed, consists in an inert-gas system with inert gas as a pressurant. The second system proposed, on the other hand, is an autogenous pressurisation system. This type of system constitutes a mass and volume-efficient option, suitable for reusability

RQ.1 SQ.1: What is the most effective strategy for pressure control within the pressurisation system of Maiaspace's main stage?

In particular, this thesis contributed to the definition of regulation strategies tailored to both pressurisation options. Two regulation strategies were established, the first for the option of the inert gas system and the second for the autogenous option. Both strategies consist in having different regulation phases, tailored to the system.

RQ.2: What are the numerical simulations that can be implemented on the software to study the pressurisation system in terms of: pressure losses experienced, performance, heat transfer effects on individual components or parts of the system and design modifications due to layout constraints?

The pressurisation system was modelled using a commercial software, particularly with custom components developed within the company. This 0D/1D simulation framework enables accurate estimations of system performance while maintaining relatively fast computation times. Although certain 3D effects are not modelled, the approach remains sufficiently precise for system-level studies and allows rapid evaluation of design modifications. This makes it possible to test several system iterations in a relatively short time compared to CFD. The methodology captures the essential functionality of the system in terms of pressure losses, thermodynamic behaviour, and fluid dynamics. In this context, the numerical simulations aim to investigate: (i) pressure losses experienced within the system, (ii) overall pressurisation performance, (iii) heat transfer effects on individual components or subsystems, and (iv) design modifications driven by layout constraints.

RQ.2 SQ.1: To what extent do the implemented simulations yield physically accurate and reliable outputs suitable for informing subsystem design decisions?

The models implemented during this thesis were thoroughly verified and partially validated. The partial nature of the validation arises from external factors, as the company's scheduled tests for the subsystem studied in this work are planned for the future. For all the physics that could not be validated, a comprehensive validation test plan for the upcoming hot-fire test.

7.2. Recommendations for Future Studies

To achieve full confidence in the pressurisation system models, future work should focus on complete experimental validation of both the fuel and oxidizer subsystems under representative operational conditions. This includes conducting the tests mentioned in this thesis to capture transient behaviours, thermal effects, and any interactions not fully represented in the current 0D/1D models, thereby enabling the models to be fully verified and refined for accurate predictive use in launcher design and mission planning.

Future work should focus on comparing the modelled heat transfer assumptions with measurements from test data, in order to refine the estimation of real heat transfer mechanisms and determine more accurate thermal coefficients for the system. Heat transfer modelling constitutes one of the main assumptions of this work. To improve accuracy with respect to real system behaviour, future studies should focus on defining heat transfer coefficients more rigorously through high-fidelity CFD analyses, supported by validation and tuning against experimental data.

Once these models are validated thus proven to be reliable, it is important to analyse the start-up phase, which represent the most critical phase for the pressurization system, since the mass flow rate is undergoing fast variations, which would lead to convergence problems in the simulation.

References

[1] A.Dufour. "PRESSURIZATION MODELING FOR LAUNCHER TANKS". In: Airbus Defence and Space.

[2] Stephen Barsi and Mohammad Kassemi. "Validation of tank self-pressurization models in normal gravity". In: *45th AIAA aerospace sciences meeting and exhibit*. 2007, p. 952.

[3] Ian H. Bell et al. "Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp". In: *Industrial & Engineering Chemistry Research* 53.6 (2014), pp. 2498–2508. DOI: `10.1021/ie4033999`. eprint: `http://pubs.acs.org/doi/pdf/10.1021/ie4033999`. URL: `http://pubs.acs.org/doi/abs/10.1021/ie4033999`.

[4] EJ Brock Jr, SA Leadbetter, and HW Leonard. *Design and fabrication considerations for a 1/10-scale replica model of the Apollo/Saturn V*. Tech. rep. 1967.

[5] David Bushnell. "Buckling of Shells—Pitfall for Designers". In: *AIAA JOURNAL* (1981).

[6] Lluıs Foreman Campins. "NewSpace and the European Space Economy". MSc dissertation. Universitat Politecnica de Catalunia, 2023.

[7] Jackson Carter. *Water Pump Cavitation*. Tech. rep. 2019.

[8] Yunus A Cengel and Afshin J Ghajar. *Heat and Mass Transfer (in SI Units)*. Mcgraw-Hill Education-Europe, London, 2014.

[9] Jihyoung Cha. "Numerical Simulation of Chemical Propulsion Systems: Survey and Fundamental Mathematical Modeling Approach". In: *Aerospace* 10 (Sept. 2023), p. 839. DOI: `10.3390/aerospace10100839`.

[10] C Christian, E Lehmann, and L Ruby. "Autogenous pressurization for space vehicle propulsion systems". In: *4th Propulsion Joint Specialist Conference*. 1968, p. 626.

[11] Bruce Ciccotosto and Daniel M Hauser. "Autogenous pressurization of a cryogenic tank using computational fluid dynamics". In: *AIAA Propulsion and Energy 2021 Forum*. 2021, p. 3558.

[12] Jeremy H Corpening. "Analytic Modeling of Pressurization and Cryogenic Propellant". In: *57th JANNAF Joint Propulsion Meeting*. M10-0427. 2010.

[13] Laurence De Quay and B Keith Hodge. "A history of collapse factor modeling and empirical data for cryogenic propellant tanks". In: *46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. 2010, p. 6559.

[14] Richard L De Witt et al. *Gaseous-helium requirements for the discharge of liquid hydrogen from a 1.52-meter/5-ft/diameter spherical tank*. Tech. rep. 1970.

[15] Etienne Dumont et al. "CALLISTO: towards reusability of a rocket stage: current status". In: (2022).

[16] M Epstein and RE Anderson. "An equation for the prediction of cryogenic pressurant requirements for axisymmetric propellant tanks". In: *Advances in Cryogenic Engineering: Proceedings of the 1967 Cryogenic Engineering Conference Stanford University Stanford, California August 21–23, 1967*. Springer. 1968, pp. 207–214.

[17] Jr. B . Sugarman F. W. Childs T. R. Horowitz Wm. Jenisch. *DESIGN GUIDE FOR PRESSURIZATION SYSTEM EVALUATION LIQUID PROPULSION ROCKET ENGINES*. Vol. Volume I - Use of Design Guide, General Design Data. AEROJET -GENERAL CORPORATION, 1962.

[18] DA Heald. *Reusable Centaur study. Volume 2*. Tech. rep. 1974.

[19] Dieter K Huzel. *Modern engineering for design of liquid-propellant rocket engines*. Vol. 147. AiAA, 1992.

[20] Isaak E Idelchik, MO Steinberg, and Oleg G Martynenko. *Handbook of hydraulic resistance*. Vol. 2. Hemisphere publishing corporation New York, 1986.

[21] Michael Interbartolo. *Saturn V Stage I (S-IC) Overview*. Tech. rep. 2009.

[22] Cheulwoong Kim et al. "Development of Liquid Oxygen/Liquid Methane Pressurization Systems for Launch Vehicles". In: *Proceedings of the Aerospace Europe Conference 2023 – 10th EUCASS – 9th CEAS*. EUCASS-CEAS. Lausanne, Switzerland, 2023. DOI: 10.13009/EUCASS2023-450.

[23] KH Kim et al. "Transient thermal analysis of a cryogenic oxidizer tank in the liquid rocket propulsion system during the prelaunch helium gas pressurization". In: *Journal of Engineering Thermophysics* 21.1 (2012), pp. 1–15.

[24] Erik Kulu. "Small launchers-2021 industry survey and market analysis". In: *72nd International Astronautical Congress (IAC 2021)*. Vol. 10. 2021.

[25] Erik Kulu. "Small launchers-2023 industry survey and market analysis". In: *74th International Astronautical Congress (IAC 2023)*. 2023.

[26] Raymond F Lacovic. *Comparison of experimental and calculated helium requirements for pressurization of a Centaur liquid oxygen tank*. Tech. rep. 1970.

[27] Wang Lei et al. "Experimental investigation on pressurization performance of cryogenic tank during high-temperature helium pressurization process". In: *Cryogenics* 66 (2015), pp. 43–52.

[28] P.J. Linstrom and W.G. Mallard. *NIST Chemistry WebBook*. Editors. DOI: 10.18434/T4D303. URL: https://doi.org/10.18434/T4D303.

[29] Carina Ludwig and ME Dreyer. "Investigations on thermodynamic phenomena of the active-pressurization process of a cryogenic propellant tank". In: *Cryogenics* 63 (2014), pp. 1–16.

[30] Carina Ludwig and Michael Dreyer. "Analyses of cryogenic propellant tank pressurization based upon experiments and numerical simulations". In: *5th European conference for aeronautics and space sciences (EUCASS)*. 2013.

[31] Qi Ma, Dong Song, and Bobing Liu. "Fault mode analysis and simulation verification of hydraulic system based on AMEsim". In: *Journal of Physics: Conference Series*. Vol. 2006. 1. IOP Publishing. 2021, p. 012013.

[32] ROMAIN MABBOUX. *Optimization of the pressurization system of the Themis reusable rocket first stage demonstrator*. 2020.

[33] Alok Majumdar and Todd Steadman. "Numerical modeling of pressurization of a propellant tank". In: *Journal of Propulsion and Power* 17.2 (2001), pp. 385–390.

[34] Philip A Masters. *Computer programs for pressurization (RAMP) and pressurized expulsion from a cryogenic liquid propellant tank*. Tech. rep. 1974.

[35] Stephen Mattick et al. "Progress in modeling pressurization in propellant tanks". In: *46th AIAA/ASME/SAE/ASEE joint propulsion conference & exhibit*. 2010, p. 6560.

[36] J Moral et al. "ESPSS simulation platform". In: *Space Propulsion* (2010).

[37] Felipe Motta, José Bezerra Pessoa Filho, and Alison de Oliveira Moraes. "Is there a market for micro-launch vehicles?" In: *Space Policy* 70 (2024), p. 101629. ISSN: 0265-9646. DOI: https://doi.org/10.1016/j.spacepol.2024.101629. URL: https://www.sciencedirect.com/science/article/pii/S0265964624000201.

[38] VI Naoumov et al. *Chemical kinetics in combustion and reactive flows: modeling tools and applications*. Cambridge University Press, 2019.

[39] Nathan Raphael do Nascimento Pinheiro and Luiz Carlos Sandoval Góes. "Modeling and simulation of a single engine aircraft fuel system". In: *Proceedings of*. Vol. 15. 2017, pp. 7–9.

[40] William L Oberkampf and Christopher J Roy. *Verification and validation in scientific computing*. Cambridge university press, 2010.

[41] William L Oberkampf and Timothy G Trucano. "Verification and validation in computational fluid dynamics". In: *Progress in aerospace sciences* 38.3 (2002), pp. 209–272.

[42] Sinyoung Park et al. "Comprehensive low-order analyses of control strategies for autogenous pressurization in liquid rocket systems". In: *Aerospace Science and Technology* 168 (2026), p. 110738. ISSN: 1270-9638. DOI: `https://doi.org/10.1016/j.ast.2025.110738`. URL: `https://www.sciencedirect.com/science/article/pii/S1270963825008090`.

[43] *Pressurization Systems for Liquid Rockets*. NASA, 1975.

[44] E. Ring. *Rocket Propellant and Pressurization Systems*. Prentice-Hall Inc., Englewood Cliffs, NJ, USA, 1964.

[45] William H Roudebush. *An analysis of the problem of tank pressurization during outflow*. Vol. 2585. National Aeronautics and Space Administration, 1965.

[46] *SMALL LAUNCHERS: A European perspective*. AAE-DGLR DOSSIER. Air and space Academy Deutsche Gesellschaft für Luft-und Raumfahrt, 2021. ISBN: 978-2-913331-91-4.

[47] George P Sutton and Oscar Biblarz. *Rocket propulsion elements*. John Wiley & Sons, 2011.

[48] H.E. Tacca, P. Rachov, and Diego Lentini. *Electric Feed Systems for Liquid Propellant Rocket Engines*. Tech. rep. Dec. 2010. DOI: `10.13140/2.1.4431.9042`.

[49] N Va. "Prediction of pressurant mass requirements for axisymmetric liquid hydrogen tanks". In: *31st Joint Propulsion Conference and Exhibit*, p. 2964.

[50] Jerome Vila and Jeremie Hassin. "Technology acceleration process for the THEMIS low cost and reusable prototype". In: *8th European conference for aeronautics and space sciences*. 2019, pp. 1–4.

[51] J Vilá et al. "An overview of the ESPSS libraries: Latest developments and future". In: *Proceedings of the Space Propulsion Conference*. 2018.

[52] Zheng Yan et al. "Modeling and Simulation of System Dynamics for Spacecraft Propulsion System". In: *Applied Mechanics and Materials* 229 (2012), pp. 2112–2116.

[53] Zheng Yan et al. "System dynamic characteristic simulation of spacecraft propulsion system based on AMESim". In: *Advanced Materials Research* 605 (2013), pp. 679–683.

[54] D Yeo and D Yeo. "A Summary of Industrial Verification". In: *Validation, and Uncertainty Quantification Procedures in Computational Fluid Dynamics* (2020).

[55] B.T.C. Zandbergen. *Thermal Rocket Propulsion*. 2022.

<div style="text-align: right; font-size: 3em;">A</div>
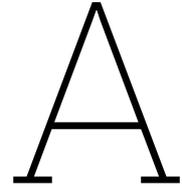
Pressure Losses Modelling and Verification

A.1. Idelchik Models

In this section, all the Idelchik models [20] used to calculate the pressure loss coefficients are introduced.

A.1.1. Straight Line: Circular Section

To model the pressure losses on a straight line with circular section, Diagrams 2.1 to 2.3 of the Idelchik Handbook were used.
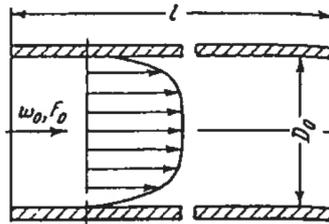

Figure A.1: Enter Caption

The hydraulic diameter D_h is defined as:

$$D_h = \frac{4F_0}{\Pi_0} \tag{A.1}$$

where Π_0 is the perimeter.

Darcy friction coefficient for laminar flow $Re < 2000$: $\lambda = \frac{64}{Re}$.

For a conduit with smooth walls:

1. $2000 < Re < 4000$: λ determined from the graph.
2. $4000 < Re < 100000$: $\lambda = \frac{0.3164}{\sqrt[4]{Re}}$
3. any $Re > 4000$: $\lambda = \frac{1}{(1.8 \log Re - 1.64)^2}$

Friction coefficient for a conduit with uniform wall roughness Δ:

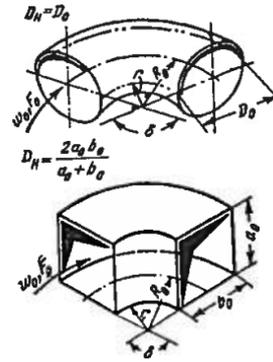$$Re > 2000 : \quad \lambda = \frac{1}{[a_1 b_1 \log(Re\sqrt{\lambda}) + c_1 \log \Delta]} \tag{A.2}$$

the coefficients a_1, b_1 and c_1 are determined from Table A.1.

Table A.1: Coefficients for different $\triangle Re\sqrt{\lambda}$ ranges

$\triangle Re\sqrt{\lambda}$	a_1	b_1	c_1
3.6 – 10	-0.800	2.000	0
10 – 20	0.068	1.130	-0.870
20 – 40	1.538	0.000	-2.000
40 – 191.2	2.471	-0.588	-2.588
> 191.2	1.138	0.000	-2.000

A.1.2. Elbow

The model for the elbow is taken from Diagram 6.1. For the elbows studied, only the model with $0.5 < R_0/D_h < 1.5$ and a bend angle $0 < \delta° < 180°$.

Figure A.2: Schematics Elbow Idelchik.

1. Assuming smooth walls ($\Delta = 0$): $\zeta = \zeta_M + \zeta_f$

where $\zeta_M = A_1 B_1 C_1$ with $C_1 = 1$ for a circular section, A_1 is calculated as reported in Table A.2 and B_1 as in Table A.3.

Table A.2: A_1 as Function of $\delta°$.

δ	$< 70°$	$90°$	$> 100°$
A_1	$0.9 sin\delta°$	1.0	$0.7 + 0.35\frac{\delta°}{90°}$

Table A.3: B_1 as Function of R_0/D_h.

R_0/D_h	$0.5 - 1.0$	> 1.0
B_1	$\frac{0.21}{\left(\frac{R_0}{D_h}\right)^{2.5}}$	$\frac{0.21}{\sqrt{R_0/D_h}}$

A.1.3. Tee

The tee component's pressure losses were modelled with Diagram 7.29 A.3 of a $90°$ symmetric tee, where two equivalent lateral streams, b1 and b2, join into a common stream c.

The adimensional pressure loss coefficient is calculated as:

$$\zeta = 1 + \left(\frac{F_c}{F_{b1}}\right)^2 + 3\left(\frac{F_c}{F_{b1}}\right)^2 \left(\left(\frac{Q_{b1}}{Q_c}\right)^2 - \left(\frac{Q_{b1}}{Q_c}\right)\right) \tag{A.3}$$

where Q_c and $Q_{b1} = Q_{b2}$ are the volumetric mass flow rates, F_c and $F_{b1} = F_{b2}$ the cross sections, respectively for the main branch and for one of the lateral streams.
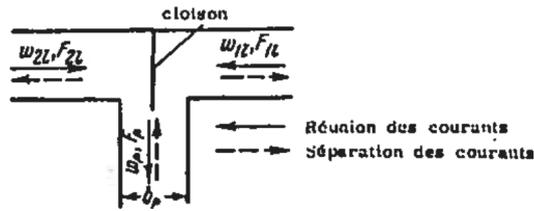
Figure A.3: Tee Schematics.

A.1.4. Buffer Tank

For this preliminary pressure loss evaluation, the buffer tank was modelled as the combination of pressure losses at the tank inlet (represented by a pipe with enlargement), the tank outlet (modelled as a transition from a larger volume to a pipe), and a line model (subsection A.1.1) accounting for pressure losses along the tank.

For the buffer tank entry, the model for a sudden expansion of a stream with uniform velocity distribution (Diagram 4.1, Figure A.4) was used. In this case, the cross section ratio between the smaller upstream pipe and the wider downstream volume can be considered close to zero. For this value of $F_0/F_2 \approx 0$, the corresponding pressure loss coefficient tabulated is $\zeta_{entry} = 1.0$.
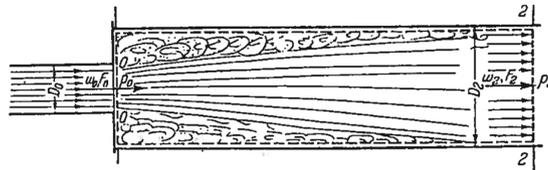

Figure A.4: Schematics Tank Entry.

The tank exit was approximated as an inlet with sudden contraction (Diagram 3.10, Figure A.5).
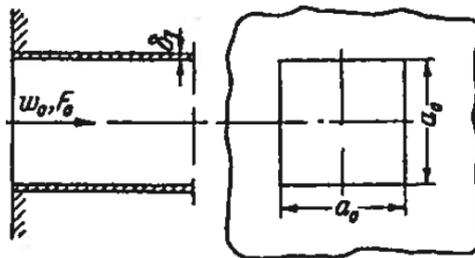
Figure A.5: Schematics Tank Exit.

Specifically, for an inlet with frontal walls on the four sides, the pressure loss coefficient given by Idelchik and used in the model is $\zeta_{exit} = 0.5$.

A.1.5. Orifice

Thick-edged ($l/D_h > 0.015$) orifice at the passage of the stream from a conduit of one size to another, from Diagram 4.11. e is the surface roughness, D_1 the entry pipe diameter, D_2 exit pipe diameter, D_0 orifice diameter. D_h is defined as in Equation A.1, and the Darcy friction factor λ is defined as in subsection A.1.1.

1. $Re > 10^5$: $\zeta_{orifice} = \zeta_0 + \lambda \frac{L}{D_h}$
2. $Re < 10^5$: $\zeta = \zeta_\varphi - \epsilon_0^{Re} \zeta_0$

Figure A.6: Orifice Schematics.

where ζ_φ and ϵ_0^{Re} defined by the Figure A.7, and ζ_0 defined by the formula:
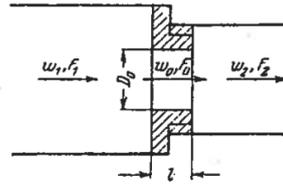
$$\zeta_0 = 0.5\left(1 - \frac{S_0}{S_1}\right) + \left(1 - \frac{S_0}{S_2}\right)^2 + r\sqrt{1 - \frac{S_0}{S_1}}\left(1 - \frac{S_0}{S_2}\right) \tag{A.4}$$
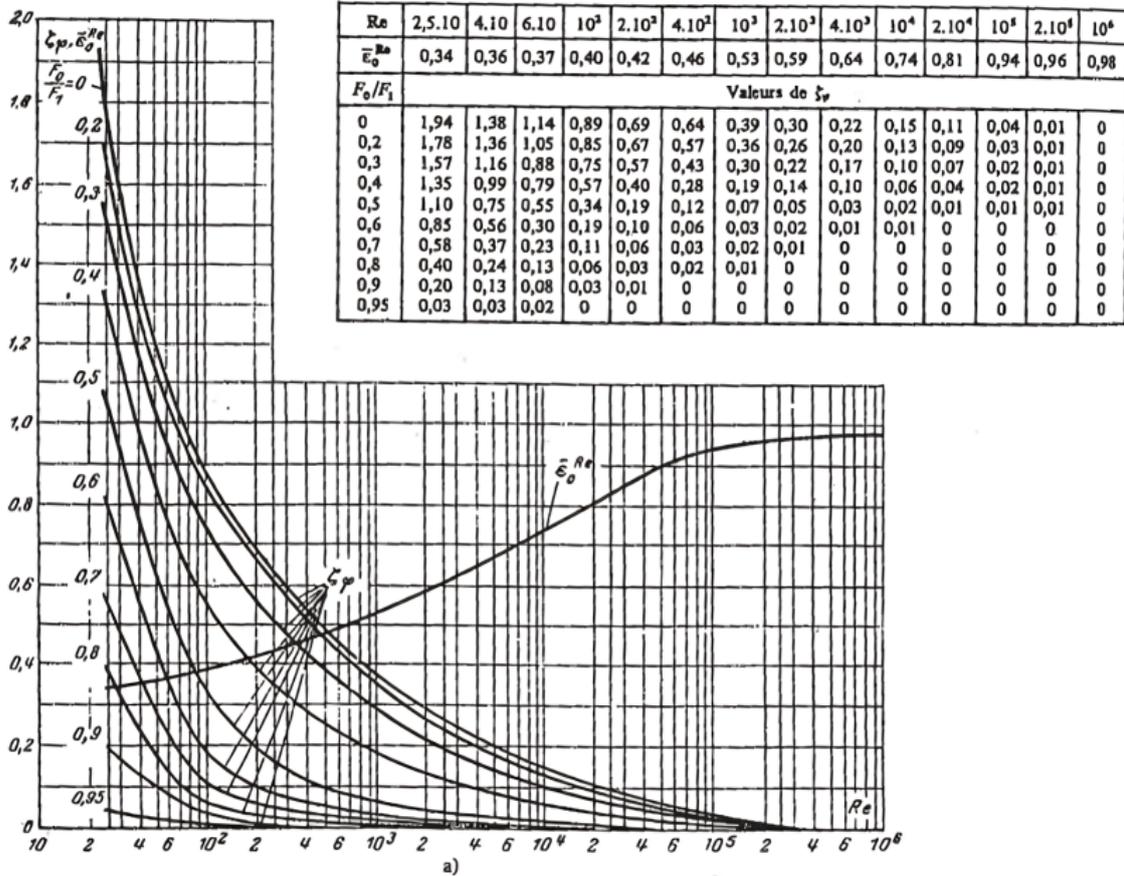

Re	2,5.10	4.10	6.10	10²	2.10²	4.10²	10³	2.10³	4.10³	10⁴	2.10⁴	10⁵	2.10⁵	10⁶
$\bar{\epsilon}_0^{Re}$	0,34	0,36	0,37	0,40	0,42	0,46	0,53	0,59	0,64	0,74	0,81	0,94	0,96	0,98
F_0/F_1	Valeurs de ζ_φ													
0	1,94	1,38	1,14	0,89	0,69	0,64	0,39	0,30	0,22	0,15	0,11	0,04	0,01	0
0,2	1,78	1,36	1,05	0,85	0,67	0,57	0,36	0,26	0,20	0,13	0,09	0,03	0,01	0
0,3	1,57	1,16	0,88	0,75	0,57	0,43	0,30	0,22	0,17	0,10	0,07	0,02	0,01	0
0,4	1,35	0,99	0,79	0,57	0,40	0,28	0,19	0,14	0,10	0,06	0,04	0,02	0,01	0
0,5	1,10	0,75	0,55	0,34	0,19	0,12	0,07	0,05	0,03	0,02	0,01	0,01	0,01	0
0,6	0,85	0,56	0,30	0,19	0,10	0,06	0,03	0,02	0,01	0,01	0	0	0	0
0,7	0,58	0,37	0,23	0,11	0,06	0,03	0,02	0,01	0	0	0	0	0	0
0,8	0,40	0,24	0,13	0,06	0,03	0,02	0,01	0	0	0	0	0	0	0
0,9	0,20	0,13	0,08	0,03	0,01	0	0	0	0	0	0	0	0	0
0,95	0,03	0,03	0,02	0	0	0	0	0	0	0	0	0	0	0

Figure A.7: Diagram and Tabulated Values for ζ_φ and ϵ_0^{Re} in Function of Re and F_0/F_1.

A.2. Filters

Several filters are present along the pressurization system. For these, the pressure loss coefficient was provided from the suppliers in terms of incompressible pressure loss coefficient K in $[1/m^4]$.

A.3. Pressure Regulator

The pressure loss of the tank pressure regulator was assumed based on what was considered applicable for the two options studied.